N78-14609

PASSIVE MICROWAVE REMOTE SENSING OF SOIL MOISTURE

K. Ya. Kondratyev
V. V. Melentyev
Yu. I. Rabinovich
E. M. Shulgina

Department of Atmospheric Physics
Leningrad University
Institute of Physics
Leningrad 199164, USSR

Abstract

The paper summarizes the work accomplished in the Voyeykov Main Geophysical Observatory on passive microwave remote sensing of soil moisture. The theory and calculations of microwave emission from the medium with the depth-dependent physical properties are discussed; the possibility of determining the vertical profiles of temperature and humidity is considered; laboratory and aircraft measurements of the soil moisture are described; the technique for determining the productive-moisture content in soil, and the results of aircraft measurements are given.

1. Introduction

The determination of the state of the soil and especially of the soil moisture is one of the important applications of passive microwave remote sensing. The solution of such a problem is possible because of the strong dependence of soil microwave properties on moisture caused in its turn by humidity-dependent dielectric constants of soil.

Beginning from 1969, such studies are being performed in the Main Geophysical Observatory. Laboratory, field and aircraft measurements of microwave emission were made along with theoretical studies and model calculations. These studies were originally associated with remote sensing of soil temperature and moisture, the determination of their vertical profiles included. Then the main efforts were made in assessment of soil moisture and the productive-moisture content in soil, which was most important from the practical point of view.

2. The Theory of Microwave Emission from the Vertically-Inhomogeneous Medium

Actual objects emitting in microwave wavelength region are the solid non-magnetic media with continuously varying properties. The emission from such media is calculated with the phenomenological radiation-transfer equation, which is the equation of the energy balance for a medium [1]. The applicability of such a technique to calculations of microwave emission from an actual underlying surface (soil, in particular), the electrical characteristics of which can be heavily depth-dependent, is not properly grounded.

The thermal emission is a kind of fluctuations and can be described by the correlation theory for electrodynamical fluctuations of arbitrary quasi-equilibrium microscopic systems. The thermal emission theory is well-founded by A. Stogryn [2].

Calculations of the thermal emission by the numerical method of A. Stogryn are rather complicated, but in the case of the media with slowly varying properties they can be significantly simplified and reduced to the form comparable with the transfer equation (3). For the media with a large scale microinhomogeneities, for which the condition of

$$\left|\frac{d\varepsilon}{dz}\right| \ll \frac{\omega}{c}\varepsilon \tag{1}$$

is always met, the expression for radiobrightness temperature which corresponds to the thermal emission from an inhomogeneous medium (soil) into vacuum is as follows

$$T_{B\vec{p}} = (1-|R_{\vec{p}}|^2)\int_0^\infty T(z)\alpha(z)\cdot S(z)\times \exp\left[-\int_0^z \alpha(z')S(z')dz'\right]\cdot\frac{S(0)\cdot n(z)}{S(z)\cdot n(0)}\,dz \tag{2}$$

where $R_{\vec{p}}$ is Fresnel coefficients;

ε, n, $\varkappa$ are the dielectrical penetrability, and the indices of refraction and absorption of the medium, respectively;

$\alpha(z) = 2\frac{\omega}{c}\varkappa(z)$ is the absorption coefficient;

ω is the cyclic frequency of emission in vacuum;

c is the light velocity

$$S = \left(\frac{n^2-\varkappa^2-\sin^2\theta}{2\varkappa^2}\right)^{1/2}\left[\sqrt{1+\frac{4n^2\varkappa^2}{(n^2-\varkappa^2-\sin^2\theta)^2}}-1\right]^{1/2} \tag{3}$$

θ is the angle of sighting.

The expression obtained can be written as the product of the integral (which determines the emission intensity in the medium near the boundary) and the emissivity of the medium.

Expanding the S(z) and n(z) functions in the integrand of Equation (2) to the accuracy of the first order $S(z)\approx S(0)+S'(0)z$; $n(z)\approx n(0)+n'(0)z$ and using the averaging we obtain

$$T_{B\vec{p}} = \Sigma_{\vec{p}}\, T_e \tag{4}$$

where

$$T_e = \int_0^\infty T(z)\alpha(z)S(z)\exp\left[-\int_0^z \alpha(z')S(z')dz'\right]dz \tag{5}$$

is the effective temperature of emission from the medium; $\Sigma_{\vec{p}}$ is the emissivity of the medium

$$\Sigma_{\vec{p}} = \left(1-|R_{\vec{p}}|^2\right)\left[1-\left(\frac{S'(0)}{S(0)} - \frac{n'(0)}{n(0)}\right)\bar{Z}\right] \tag{6}$$

The result of averaging Z with the function K(z)

$$\mathcal{K}(z) = \alpha(z)\, S(z) \exp\left[-\int_0^z \alpha(z')\, S(z')\, dz'\right]$$

having the meaning of probability and meeting the condition of

$$\int_0^\infty \mathcal{K}(z)\, dz = 1$$

can be used as $\bar{Z}$.

The specific form of Equation (6) is determined by the approximate solution of the wave equation. For the higher accuracy, in Equations (4), (5) should be calculated following the current methods for determination of the inhomogeneous media emissivities. The values of the inhomogeneous media emissivities obtained by solving Rikkati equations will be presented below.

Consider the $S(\theta, Z)$ function. Transform Equations (2), (3) for the case of the relatively weak absorption ($\varkappa \ll n$).

Then

$$S(z) = \frac{n(z)}{[n^2(z) - \sin^2\theta]^{1/2}} = \sec\theta'(z) \tag{7}$$

where θ' determines the direction of propagation of the emission in the medium and

$$T_{b\vec{p}} = \Sigma_{\vec{p}} \int_0^\infty T(z)\,\alpha(z) \sec\theta'(z) \exp\left[-\int_0^z \alpha(z') \sec\theta'(z')\, dz'\right] dz \tag{8}$$

Exp. (8) coincides with solution of the radiation transfer equation. From the point of view of the general theory of electro-dynamical fluctuations of the thermal emission, one can set the limits to the phenomenological theory applicability. The phenomenological theory is totally applicable only for the negligibly absorbing $(\varkappa \ll n)$ weakly inhomogeneous media (see [1]).

Formulae (4)-(6) can be considered as general solution of the transfer equation (8) for the case of arbitrary absorption.

Now, determine the difference between Equation (7) and (8) in the presence of absorption. Figure 1 shows the angular dependences of the $S(\theta)$ and sec θ'functions for different values of n and $\varkappa$. These values of dielectric constants are taken from Reference [4] for the soil with 11% humidity at the wavelength of 0.81 cm. It should be noted that for all the other values of dielectric characteristics of real soil, the difference between the functions of $S(\theta)$ and sec θ' is less than that shown in Figure 1. The difference between the greatest values of $S(\theta)$ and sec θ' for $= 90°$ does not exceed 2 percent of the sec θ' value.

There is one more fact which reduces the effect of the difference between the $S(\theta)$ and sec θ' functions in calculations of radiobrightness temperatures with formulae (4) and (8). For the great values of the absorption index $\varkappa$, with the greatest possible difference between $S(\theta)$ and sec θ', the absorption coefficient $\alpha(Z)$ is sufficiently great for the effective emitting layer to be negligibly thin. In this case the radiobrightness temperature is independent of the specific form of the integrand functions. Actually, the calculations of radiobrightness temperatures for the wide range of real temperature profiles and dielectric properties of the medium have shown that the differences in radiobrightness temperatures evaluated with the $S(\theta)$ and sec θ' functions do not exceed a few hundredths of a degree.

Thus, the analysis given above shows that in the case of actual emitting media with slowly varying physical characteristics the expression for radiobrightness temperatures obtained on the basis of the theory of electrodynamic fluctuations, coincides practically with a simpler expression used in the phenomenological theory.

Then, one can evaluate the effect of depth-dependent inhomogeneity of the soil on its emissivity. In the microwave region, the dielectrical penetrability of the soil increases with the increase of humidity, and, in some authors' opinion, this dependence is almost linear [5,6]. The humidity, in its turn, varies with depth, this variation being sufficiently diverse. But in a number of cases, humidity can be considered linearly varying with depth throughout the effective emitting layer.

In this case the variation of the dielectric constant coincide with the dependence of humidity on depth. In Ref. [7] we considered the emissivity of the vertically inhomogeneous soil. The reflection coefficient, R, for such a model of soil, closely related to emissivity, was evaluated by solving the Rikkati integral equation with boundary condition of $\underset{Z \to \infty}{R \to 0}$ given in Ref. [8]. This equation was solved by successive approximation technique, and the result was obtained as a sum of the Fresnel reflection coefficients and the correction which depended on the wavelength, the absolute value and gradient of the soil dielectric penetrability, and the sighting angle. The absolute value of corrections to Fresnel coefficient determined by the vertical inhomogeneity of the soil, increases with the increase of the wavelength, λ, dielectric penetrability gradient, a, and with the decrease of the boundary value, ε_0. The angular dependences of corrections calculated for $\varepsilon_0 = 1.7$; $\lambda = 60$ cm; $a = 10\ \mathrm{m}^{-1}$ **are** shown in Figure 2. The corrections for both polarizations are negative and equal for $\theta = 0$. When the sighting angle increases, the absolute value of correction increases for horizontal polarization being the monotonous function of the angle, and decreases for the vertical polarization, reaching the minimum at the angle close to that of Brewster. The analysis of the calculation results has shown that in microwave sensing of the humid soil, the Fresnel formulae can be used to calculate the soil emissivity.

Thus, the theoretical analysis of the electromagnetic waves' propagation through the vertically inhomogeneous soil has shown that in most cases the approximation of the phenomenological theory of radiation transfer is precise enough to evaluate the microwave emission.

3. Remote Sensing of the Physical Parameters of Soil, and its Possibilities

Microwave emission from natural surfaces contains significant information about the physical state of the surface and subsurface layers and can be applied to remote sensing of natural formations, and a strong dependence of microwave emission on the state of soil contribute to the solution of such a problem. Besides, the absorption coefficients are much smaller throughout the soil thickness in the microwave region as compared to the IR region.

This makes it possible to obtain the information not only about the state of the surface but also about the physical parameters of the soil. In the microwave region, the dielectric constant, ε, and the absorption coefficient of the soil, α, increase with the increase of humidity, ω. Humidity and temperature of the soil vary with depth, $T(Z)$ and $\omega(Z)$. Thus, the radiobrightness temperature of the soil, being the functional of $T(Z)$ and $\omega(Z)$, depends on the type of soil and the parameters of the surface state (roughness, the presence and type of vegetation, etc.).

Naturally, a great number of parameters affecting the microwave emission, hampers significantly the indirect sounding of the soil. To determine the radiobrightness temperature sensitivity to variations of different parameters of the soil physical state, a numerical experiment was accomplished [9].

Radiobrightness temperatures were evaluated for sand and clay (which are the extreme types of soil as to their dielectric characteristics) in the wavelength region of 0.8-60 cm, under various physical conditions of their state.

Figure 3 shows the curves of radiobrightness temperatures of the soil with positive and negative temperature lapse rate vs. soil moisture for three wavelengths. At all the wavelengths, the decrease of radiobrightness temperatures is seen to be due to the increase of dielectric penetrability of medium taking place when soil moisture increases and emissivity decreases.

Radiobrightness temperature of the microwave emission from soil varies from 60 up to 90K due to emissivity variations when soil moisture increases from 2 up to 15% depending on the type of soil, wavelength and surface temperature.

The temperature lapse rate affects the radiobrightness temperature for all the humidity values only at the wavelengths greater than 18 cm due to a sufficiently thick emitting layer at these wavelengths. At λ - 3 cm, the effect of the temperature profile shows only for the absolutely dry soil ($\omega = 2\%$).

For low soil moisture and longer wavelengths ($\lambda \geq 20$ cm), the radiobrightness temperature contrasts can reach 10-20K due to the soil temperature profile variations, i.e., the sign and value of the lapse rate. Radiobrightness temperature dependence on humidity gradient is determined by the value of temperature gradient. However, these variations do not exceed 3K even for great temperature gradients. Such a weak dependence of radiobrightness temperature on humidity gradient testifies the difficulty in indirect evaluation of soil moisture vertical profile from radiobrightness temperature measurements.

In order to increase the humidity gradient contribution to the received signal, we suggest a differential technique for radiobrightness temperature measurements [12]. This technique enables one to eliminate the soil temperature component from the observed data. The calculations made with this technique have shown, however, that the first harmonic of the signal not containing the soil temperature is equal to several degrees, though humidity gradient contribution can reach 50 percent of this value.

Taking account of the fact that the total error due to the uncertainties in radiobrightness temperature measurements and soil characteristics exceeds the first harmonic in Fourier-expansion of the signal, we can say that it is practically impossible to determine the humidity vertical gradient from microwave measurements.

To study the possibilities of temperature and humidity profiles remote sensing, the thickness of the emitting soil layer was evaluated for different wavelengths. For very humid soil ($\omega \sim 20\%$) the emitting layer does not exceed 5 cm even for $\lambda = 18$ cm. The emission from only 10-cm layer reaches the surface at = 18 cm when the soil moisture is 10 percent. And only for the overdry soil (2%) the emitting layer thickness increases up to 20 cm. At the shorter wavelengths, the emitting layer is 2-5 cm.

When analyzing the microwave emission from soil, we have emphasized that the emission from soil is a complex functional of both humidity and temperature, the total effect of temperature and humidity profiles on the emission being observed at all the wavelengths and at all the sighting angles. The impossibility of separating the combined effects of humidity and temperature on the soil emission forces one to confine oneself to indirect evaluation of the temperature profile for a case of soil moisture, which is assumed to be independent on depth [10]. With this assumption made, the inverse problem can be reduced to solution of Fredholm integral equation of the first kind:

$$T(\lambda) = \Sigma \int_0^\infty T(z)\,\mathcal{K}(\lambda, z)\,dz \qquad (9)$$

where $\mathcal{K}(\lambda, z) = \alpha \cdot e^{-\alpha z}$ is the kernel of the integral equation (weighting function).

At present, the technique for solving such incorrect (in mathematical sense) problem has been thoroughly developed. In Ref. [10] we used the technique suggested by O. M. Pokrovsky which made it possible to analyze the information content of measurements [11].

Let us consider the characteristic features of the soil microwave emission. Figure 4 shows the kernels of Equation (9) for different soil moistures and two wavelengths. The comparison of these kernels with the similar ones, e.g., in reconstruction of vertical temperature profile of the atmosphere from the outgoing IR emission measurements (Figure 4b) shows that remote sensing of the soil temperature profile is limited. This is due to the following characteristic features of the kernels:

1. At all the wavelengths, the main portion of emission comes from the same surface layers. Thus, the vertical profile reconstruction becomes difficult even at the depth of 10-40 cm depending on soil moisture.

2. The kernels depend heavily on humidity, which verifies the necessity of its independent determination.

3. Due to the strong correlation between the kernels, the solution of the corresponding mathematical problem becomes significantly complicated, and the amount of information about temperature decreases.

The analysis of information content of radiobrightness temperature measurements performed for the kernels calculated for two soil moistures (3 and 12%) and 25 wavelengths over the range of 3-60 cm, has shown that for the measurement errors of 0.5-1K, only one or two independent parameters can be evaluated indirectly. Thus, one cannot expect a detailed information about temperature profile, even in the case of such an idealized inverse problem.

The possibility of solving the inverse problem was evaluated for sand. The program of numerical experiments included the solution of direct problem with Equation (9) as the basis, and of the inverse problem with different errors introduced.

If the measurement errors of radiobrightness temperature measurements is 0.5K, the temperature profile is reconstructed with a good accuracy (1-3K) under condition of exactly preset humidity and absorption characteristics of the soil. In real conditions, the remote sensing of the soil temperature becomes complicated due to the necessity of highly accurate simultaneous determination of the soil moisture.

Therefore, the conclusion is drawn that only the approximate evaluation of temperature profile is possible on the basis of microwave measurements. It should be pointed out that for complete evaluation of the usefulness of remote sensing technique, a detailed laboratory and field study is necessary to obtain reliable data on physical properties of the soil and to gain the experience in remote sensing of the soil in real conditions.

4. Laboratory Measurements

The Main Geophysical Observatory has developed the technique for experimental determination of emissivities of different underlying surfaces [13] in order to obtain the data on humidity dependence of the soil emissivity. In laboratory conditions, the radiobrightness temperature of the closed cavity with a sample of the soil investigated was measured twice.

First, the emission was measured from the sample illuminated by a heated blackbody mounted above this sample. The second measurement was taken with the absolute reflector placed above. The emissivity of the sampled surface is evaluated from these two independent measurements of the cavity's radiobrightness temperature:

$$\Sigma = 1 - \frac{T_{b_1} - T_{b_2}}{(\Sigma_{c_1}T_{c_1} - \Sigma_{c_2}T_{c_2}) + (1-\Sigma_{c_1})T_{b_1} - (1-\Sigma_{c_2})T_{b_2}} \qquad (10)$$

where T_{b_1}, T_{b_2} are the radiobrightness temperatures of the cavity measured in the presence of the blackbody or the absolute reflector as the upper surfaces; Σ_c is the emissivity of the upper cover; T_c is its thermodynamical temperature.

For several years, microwave emission from different underlying surfaces was being measured using the above method. Some results were published in Ref. [14]. This paper incorporates the results of laboratory multichannel measurements taken recently in different seasons. Table 1 lists the observed emissivities of different natural surfaces at wavelengths $\lambda = 3.2$ cm and 1.6 cm.

Measurements were made using the improved measuring arrangement with high-temperature blackbody, the emissivity of which was substantially increased, especially at the wavelengths shorter than 3.0 cm.

The emission coefficients were studied for sand and soil with different humidities, frost and thaw soil, the soil covered with snow and without it, the dry and moist grass, peat, clay, hard-surface road, and concrete, dry, moist and covered with snow. Humidity dependence of the soil microwave emission has evoked great interest in connection with the aircraft passive microwave remote sensing of humidity and moisture-content in the soil.

Some aspects of this problem were discussed in Ref. [15]. We measured the dependences of sand and sandy loam emissivities on humidity. Samples 25-30 cm thick were studied. To vary the soil moisture, the surface of the soil was moistened. The soil was sampled by a cutting cylinder both on the surface and at the depth. The soil moisture was determined by weighing, in percentage of moisture weight to that of the dry soil sample. When the soil is moistened, the 25 cm layer acquires a certain humidity profile. But when the soil is heavily moistened, the lower layer can be water-saturated. Figure 5 shows the emissivity of sand and soil vs. humidity at $\lambda = 3.2$ cm. These data verify the significant decrease of emission from river sand and sandy loam with the increase of surface humidity, which indicates, in its turn, the possibility of remote sensing of the soil moisture. At the same time the measurements have shown that the dependences of sand and soil on humidity are different. For sandy loam sample (the dots in Figure 5), the strongest dependence of emission on humidity shows for humidities greater than 20%. Such a variation of soil emissivity is similar to that of microwave emission from sand and clay at $\lambda = 1.55$ cm, reported in Ref. [16].

Figure 5 shows also the emissivity of sand and clay vs. humidity (curve 1) calculated from dielectric constants taken from Ref. [17]. The theoretical dependence agrees with the observed one (curve 2). However, the observational data show that the dependence of microwave emission from sand on humidity is more prominent and differs significantly from the similar dependence of sandy loam, when it is moistened. Apparently, these differences are associated with the fact that the surface humidity of the soil characterizes inadequately its agrohydrological properties, and the processes of moistening the river sand and sandy loam are different.

Much attention was paid to microwave emission from snow cover, frost soil and unfrozen soil. The sample of soil, the emissivity of which was measured vs. humidity, was preserved in a special bath, and in spring it was frozen. During measurement, the air temperature was +1.2°C, the temperature of the sampled surface was -0.4°C, and its emissivity was 0.923 at $\lambda = 3.2$ cm.

After unfreezing, the emissivity of the sample dropped to 0.892. These data correspond to theoretical evidence and show the variation of dielectric constants of water when it freezes.

The data obtained show that the snow cover raises the emissivity of the soil up to 0.956 at $\lambda = 3.2$ cm. Thus, these data testify the possibility of microwave remote sensing of the soil when the snow melts and the soil gradually thaws.

Along with laboratory measurements of the soil samples, the field measurements of microwave emission from soil were taken using the 18-m hinge tower with radio equipment. The results of the field measurements are consistent with the laboratory data. We succeeded in reproducing and studying the daily variations of natural surfaces' emissivities in conditions of sharp temperature contrasts in spring and in the fall, as well as microwave emission variation during freezing and thawing of the soil. The above-mentioned theoretical and experimental studies have made it possible to move on to evaluation of soil moisture from aircraft.

5. Moisture and Water-Content in Soil as Inferred From Aircraft Passive Microwave Remote Sensing

The productive-water content in soil, i.e., the amount of water in the 1-m layer which can be used by plants, has the main influence on crop formation in the regions with insufficient or unstable moisture. The information about water content in soil accumulated in spring by the beginning of field work is of great practical importance. In some regions this is a main factor governing the growth and development of agricultural crops. However, the direct evaluation of water content in soil from microwave emission measurements is impossible, since, as has been stated above, it is impossible to reproduce the moisture profile in the 1-m layer of the soil. Preliminary calculations have lead us to a conclusion that for all real moistures of the soil, the upper layer contributes mostly to radiobrightness temperature.

The problem considered can be solved by obtaining correlations between the moistures of surface layers of different thicknesses evaluated from microwave emission at several wavelengths, and the humidity profile in the layer of interest.

In this connection, we consider the main agrohydrological characteristics of the soil. The main parameter determining the water content in soil is the soil moisture, i.e., the percentage of the water content to the weight of the dry soil (weight moisture) or to the volume of the dry soil (volume moisture). These two parameters are related as follows:

$$\omega_v = \omega_p \cdot D \tag{11}$$

where ω_v is the volume moisture in percent; ω_p is the weight moisture in percent; D is the volume weight of the soil in g/cm^3.

The volume weight of the soil is the weight of the unit volume of the absolutely dry soil of natural structure, in the undisturbed state. If the subsoil waters' level is at a sufficient depth, then, as the soil moistens, all the pores become filled with water. The amount of water in the saturated soil is called "total water-capacity". It is expressed in percentage of the dry-soil weight or in millimeters of precipitated water. The portion of the water filling all the pores of the soil, will seep deep into it, because its weight exceeds the force of the water-soil cohesion.

The remaining water, the weight of which is balanced by the force of cohesion with soil, is called "suspended water". The amount of suspended water is called the minimum field water-content. This is expressed in percentage of the dry-soil weight or in millimeters of precipitated water. The absolute amount of water in soil, or the total water content, is expressed in millimeters and determined from the following relationship:

$$Q_t = 0{,}1 \cdot \omega_p \cdot D \cdot Z \tag{12}$$

However, not all the water in soil can be used by growing plants. At some values of the soil moisture, other than zero, the plants fade. This remaining humidity is called fade coefficient and expressed in volume or weight percentage. According to this, the portion of the total water amount which can be absorbed by plants is called the productive-water content in soil and determined from the formula:

$$Q_p = 0{,}1\ (\omega_p - q) D \cdot Z \tag{13}$$

The values of the volume weight of soil (D) and of the fade coefficient (q) for each type of the soil are measured periodically and reported in the guides on agrohydrological properties of soil. The amount of productive-water content in the 1-m layer is usually of interest for agrometeorology.

It was said above, however, that in microwave measurements, only the moisture of the surface layer can be determined, which forms the main portion of emission. Thus, to solve this problem, it is necessary to determine correlation between the humidity of the surface layer and humidity profile in the 1-m layer. When the level of the subsoil waters is deep enough (deeper than 1-m), correlation should exist between the profile of the minimum field water-content and that of humidity.

The analysis of real humidity profiles obtained in spring from the agrometeorological stations of the Northern Kazakhstan, confirmed the assumption that the depth-dependence of humidity corresponds to a mean profile of the minimum field water-content for a given type of the soil. This is true only for equilibrium conditions, when the surface layer of the soil is not moistened by irrigation or precipitation. In any case, however, the humidity lapse rate corresponds at a sufficient depth to the profile of the minimum field water-content. Only the surface layer lapse rate is subjected to substantial variations.

Figure 6 shows humidity profiles obtained at one of the meteorological stations of Kazahkstan in April, 1975 to illustrate the agreement between the lapse rate of the real humidity profile and that of the minimum field water-content profile. The straight line corresponds to the mean profile of the minimum field water-content for black soil, and the dotted line is the supplementary profiles of the minimum field water-content reproduced from humidity at a depth of 5 cm.

To determine the water content in the 1-m layer, we use a two-parameter model of humidity profile based on correlation between humidity profile and that of the minimum field water-content. One parameter is the humidity of the 5-10 m layer determined from radiometric measurements at λ = 18 cm, IR measurements and the plot of emissivity vs. humidity. This made it possible to eliminate the effect of the highly variable undersurface layer. The other parameter is the lapse rate of the minimum field water-content profile.

The water content in the 1-m layer was calculated from real soil-humidity profiles obtained during the aircraft experiment. Calculations were made using our two-parameter model. The results have shown that the mean relative error is 13 percent, and the maximum error does not exceed 35 percent. Such an accuracy is quite satisfactory to obtain the operational data on water-content in soil.

Thus, the information about the surface layer moisture and type of the soil is needed for remote sensing of water content over large area.

The above-stated theoretical hypotheses were experimentally checked up during the complex expedition carried out to develop technique and measure the productive water-content in soil. The expedition was carried out in the Northern Kazakhstan before a seed-time, in the spring of 1975. Measurements of microwave emission from the underlying surface were taken from board the MGO IL-18 flying laboratory. The radiometric data (λ = 1.6 cm and 18 cm) and those of the IR radiometer (8-12μm) were then processed.

The results of microwave emission measurements were used to evaluate the surface humidity (λ = 1.6 cm) and the humidity in the 5+10 cm layer. Ground measurements of the soil moisture, water content and temperature profiles were taken at a network of the Hydrometeorological Service. Besides, the scientists of the Department of Soil Science of the Leningrad State University measured temperature, moisture and volume weight in the 1-m layers of different types of the soil in this region. Aircraft measurements were made during three days of each ten days of April, which enabled one to cover the whole investigated area of 150000 km^2.

During each survey, the aircraft measurements were made in such a way that the uniform covering of the whole area could be obtained.

During the expedition, the aircraft microwave data were processed by express-technique, and the operational information about water content in soil was obtained for practical application of the data on productive water content in soil. After the expedition, the data on radiobrightness temperature obtained at λ = 18 cm were processed and the productive water content in soil was evaluated using the two-parameter model.

Having compared the observed data with calculated ones, we found out a systematic discrepancy between the data of remote sensing and those of measurement. The analysis of all the possible sources of discrepancy showed that the values of soil emissivities used to interprete the results were much lower than the experimental values. This testifies the fact that the dielectrical constants for sand and clay reported in Ref. [17] and used in calculations of emissivity are somewhat higher as compared to real ones.

The comparison between the emission coefficients obtained from aircraft measurements and the real soil moisture in the 5-10 cm layer obtained from ground observations, has made it possible to specify the dependence of emissivity on soil moisture at $\lambda = 18$ cm. To illustrate the above-said Figure 7 gives emissivity vs. moisture calculated from the data of Ref. [17] (curve 1), and obtained aircraft measurements (curve 2). Note, that some authors [16,18] also report higher values of emissivity of real soil. Figure 7 shows experimental results cited from Ref. [16] (curve 3).

Figure 8 shows the productive water content in the 1-m layer in millimeters of precipitated water for the second ten days of April calculated from specified dielectrical constants. Examining the scheme, we can see a good agreement of the water-content values obtained by remote sensing, with the ground-truth measurements (the ground-truth data are given in Figure 8 in frame), especially if we take into account the difficulties arising in comparison of local ground-truth measurements with those averaged over large areas.

When analyzing the results of interpreting the aircraft microwave data, we should point out that such a parameter of the soil as the productive water content, varies significantly even at one geographical point. This is associated with wide variations of the fade coefficients in Equation (13). The difference between relative soil moisture and fade coefficient put in brackets is the difference between close values. The fade coefficient's variations lead, therefore, to considerable variations in the productive water content. Apparently, it is expedient to use not the productive water content but the total water content in the 1-m layer to characterize the spatial distribution of soil moisture, taking into account the resolution of the technique.

To calculate the productive water content, we use the averaged values of agrohydrological parameters of the soil obtained for the prevailing type of the soil on each site of the area under investigation.

Naturally, this may lead to appreciable discrepancy between the results of aircraft remote sensing and ground observations due to considerable variability of agrohydrological characteristics which depend heavily both on the type of soil and on the agro-background. Therefore, for practical use of remote sensing in determination of the water content in soil, special investigations should be undertaken to develop technique for obtaining the agrohydrological constants of the soil averaged over large territories.

To spatially averaged results of measurements also affect the accuracy of water-content remote sensing. The inhomogeneity of the underlying surface, and, in the first place, the presence of water reservoirs and the sites covered with forest and bushes, may lead to overestimation of water content in the first case and to underestimation in the second.

The analysis of the experimental data has shown that the technique suggested can be successfully applied to determination of soil water-content over large areas before a seed-time for spring crops or for fallow ground without vegetation. It is necessary also to further develop measuring and processing techniques, taking account of spatial inhomogeneities of agrometeorological constants and applicable in the case where the ground is covered with vegetation.

Apparently, it is expedient to increase a maximum wavelength which will make it possible to obtain more reliable data on the surface layer moisture, for high humidities of the soil, in particular.

Surface	Brief description	Wave-length (cm)	Air temp. °C	Σ
	Laboratory measurements			
Soil	Thickness: 20cm Moisture (w):			
	w = 6.4%	3.2	21	0.947
	w =19%	3.2	20	0.919
	$w_{surf.}$=21%	3.2	23	0.923
	$w_{h=20cm}$ = 20.1% $w_{surf.}$ = 34.6% $w_{h=20cm}$ = 17.5%	3.2	22.5	0.668
Soil	t_{soil} = -0.4°C w = 13.9%	3.2	1.2	0.923
Thaw soil	t_{soil} = +0.4°C w = 14%	3.2	0	0.892
Peat	w = 114%	3.2	18	0.943
	w = 159%	3.2	15	0.918
Clay	w = 9%	3.2	15	0.902
	Ground measurements			
Soil covered with snow	Snow layer = 20-30cm Density = 0.408 g/cm^3	3.2	1.2	0.956
Frozen soil	Frozen layer=11-12cm $w_{surf.}$ = 45.6%	3.2	0.4	0.941
	Grass cover Frozen layer=6cm $w_{surf.}$ = 32.5%	3.2	0.4	0.927

TABLE 1

REFERENCES

[1] Kondratyev, K.Ya., Timofeev, Yu.M., "Thermal sounding of the atmosphere from space", 1970, L., Gidrometeoizdat, 411 pp.

[2] Stogryn, A., "The brightness temperature of vertically structured medium", Radio Science, 1970, vol. 5, No. 12, p. 1397-1406.

[3] Shulgina, E.M., "Radioemission from the vertically inhomogeneous medium", Trudy GGO, 1975, issue 331, p. 64-72.

[4] Poe, G., Stogryn, A., Edgerton, A.T., "Determination of soil moisture content using microwave radiometry", Summary Report 1684 R-2, Contr. No. 0-35239, Aerojet-General Corp., El Monte, California, June 1971, 8 pp.

[5] Leschansky, Yu.I., Ananskikh, V.M., Lebedeva, G.N., "Electrical parameters of sand and clay at centimeter and decimeter wavelengths", Trudy MPhTI, 1962, issue 10.

[6] Hoekstra, P., Delaney, A., "Dielectric properties of soils at VHF and microwave frequencies", J. Geoph.Res., 1974, vol. 79, No. 11, p. 1699.

[7] Shulgina, E.M., "Emissivity of soils with linearly inhomogeneous properties", Trudy GGO, 1973, issue 295, p. 98-107.

[8] Brekhovskikh, L.M., "Waves in vertically structured media", M., Izd. AN SSSR, 1957.

[9] Kondratyev, K.Ya., Shulgina, E.M., "Possibilities of remote sensing of soils (numerical experiment)", Trudy GGO, 1975, issue 331, p. 50-63.

[10] Kondratyev, K.Ya., Shulgina, E.M., Pokrovsky, O.M., Timofeev, Yu.M., "Possibilities of remote sensing of soil at centimeter wavelengths", Trudy GGO, 1973, issue 295.

[11] Pokrovsky, O.M., "On an established technique for solving the problems in the atmospheric optics", Collect. of papers "Problems in atmospheric physics", 1970, issue 8, Izd. LSU.

[12] Kondratyev, K.Ya., Shulgina, E.M., "Determination of some characteristics of soil from its observed microwave emission", Doklady AN SSSR, 1971, No.1.

[13] Melentyev, V.V., Rabinovich, Yu.I., "Technique for laboratory microwave measurements of emissivity", Trudy GGO, 1972, issue 291, p.3-8.

[14] Melentyev, V.V., Rabinovich, Yu.I., "Some results from laboratory measurements of emission coefficients for natural surfaces", Trudy GGO, 1972, issue 291, p. 14-17.

[15] Kondratyev, K.Ya., Melentyev, V.V., Rabinovich, Yu.I., Shulgina, E.M., "Remote sensing of water content in atmosphere and underlying surface", Water Resources, 1973, No.2, p. 58-68.

[16] Schmugge, T., Gloersen, P., Wilheit, T., Geiger, T., "Remote sensing of soil moisture with microwave radiometry", J. Geoph. Res., 1974, vol. 79, No. 2, p. 317-323.

[17] Leschansky, Yu.I., Lebedeva, G.N., Shumilin, V.D., "Electrical parameters of sand and clay at centimeter, and meter wavelengths", Izd. VUZ, Radiophizika, 1971, v. 14, No. 4, p. 562-569.

[18] Kroll, G.L., Sihley, T.G., Rouse, J.W., "On the measuring of soil moisture by microwave radiometric techniques", SWIEEECO, Rec. Techn.Pap. 25th Annu. South IEEE Conf. and Exhib., 1973, p. 76-80.

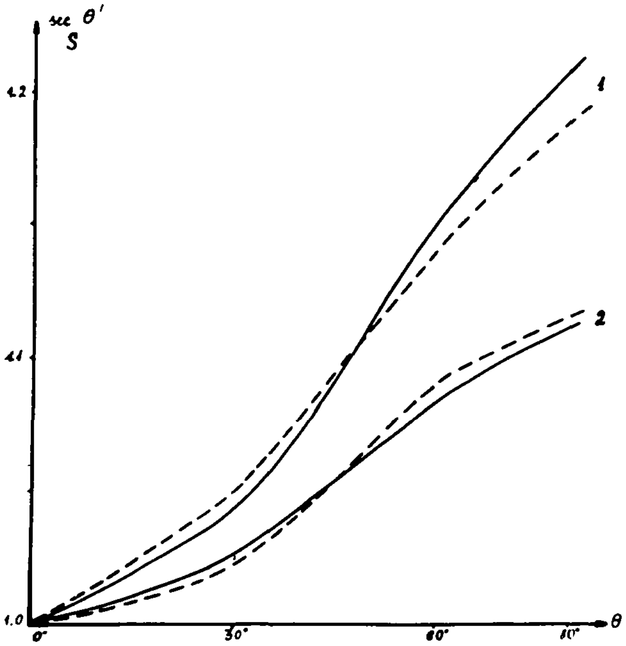

Fig. 1 Angular dependences of the functions $S(\theta)$ (---------)
and sec θ' (———) for n = 1.76 $\varkappa$ = 0.29 (1)
n = 2.28 $\varkappa$ = 0.44 (2)

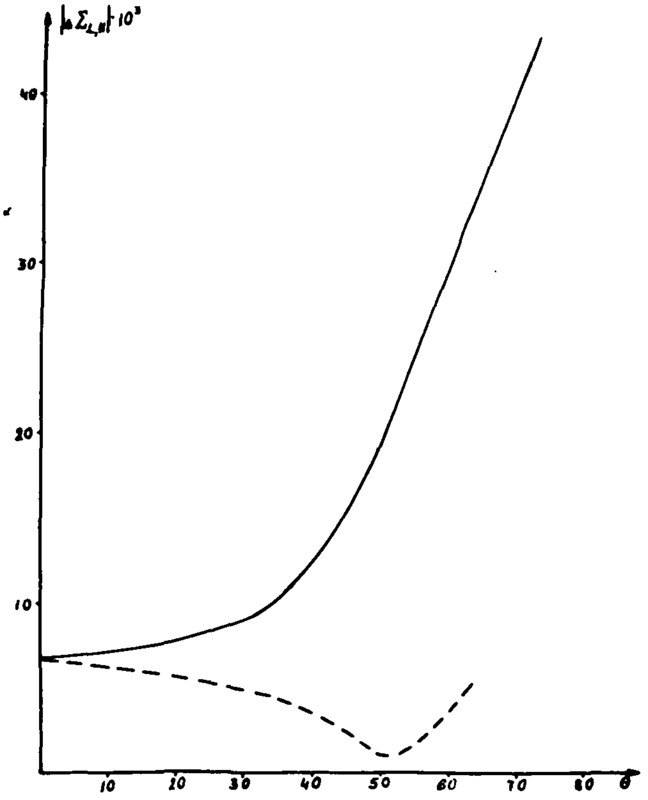

Fig. 2 Angular dependence of emissivity variations due to soil inhomogeneity at λ = 60cm, for the boundary value of dielectric constant, ε_0 = 1.7 and dielectric permeability gradient, 10 m^{-1}.

——————— horizontal polarization

--------- vertical polarization

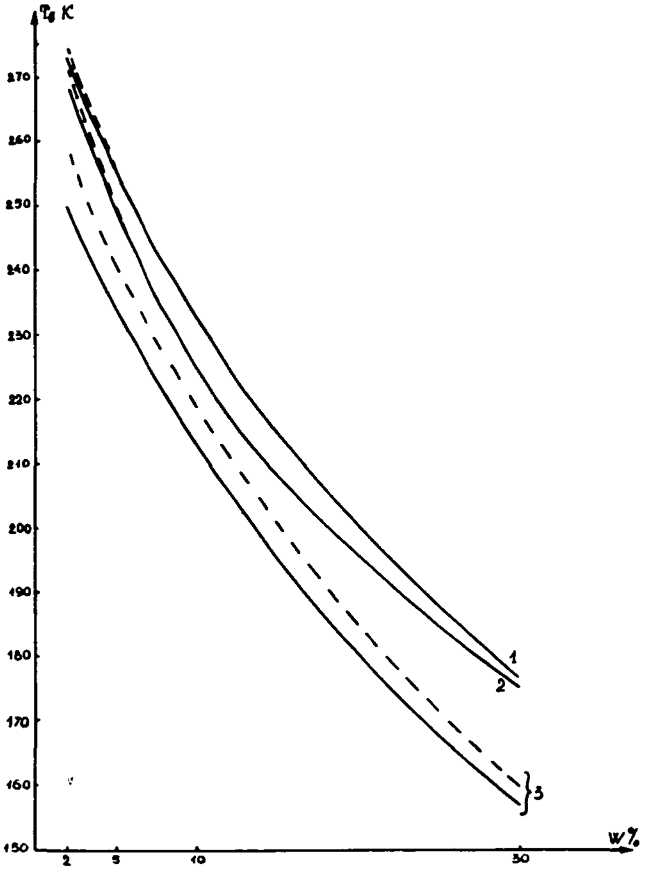

Fig. 3 Radiobrightness temperatures of the soil, T_{br}, with positive (------) and negative (———) temperature lapse rate vs. humidity, w , at λ = 0.8 cm (1), 2 cm (2), and 18 cm (3).

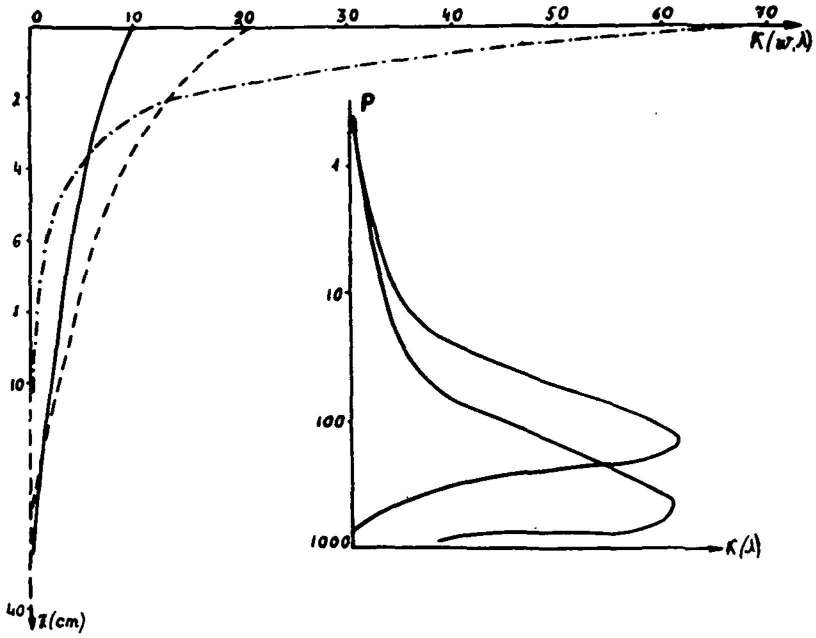

Fig. 4 Comparison between the kernels of the soil's temperature profile reconstruction problem (a) at different wavelengths, λ, for different soil moistures, w, and atmosphere humidities (b).

———— λ = 10cm w = 3%

-------- λ = 10cm w = 6%

-.-.-.-. λ = 3.3cm w = 3%

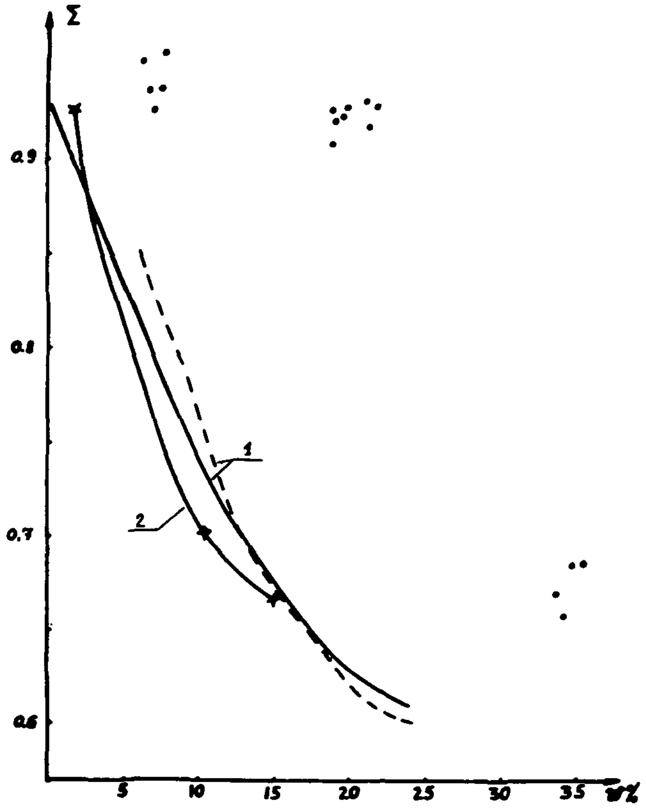

Fig. 5 Emissivity, Σ , vs. soil moisture, w .

1 - calculations from the data of Ref. [17]

———— sand

-------- clay

2 - measurement data - river sand

The dots indicate sandy loam.

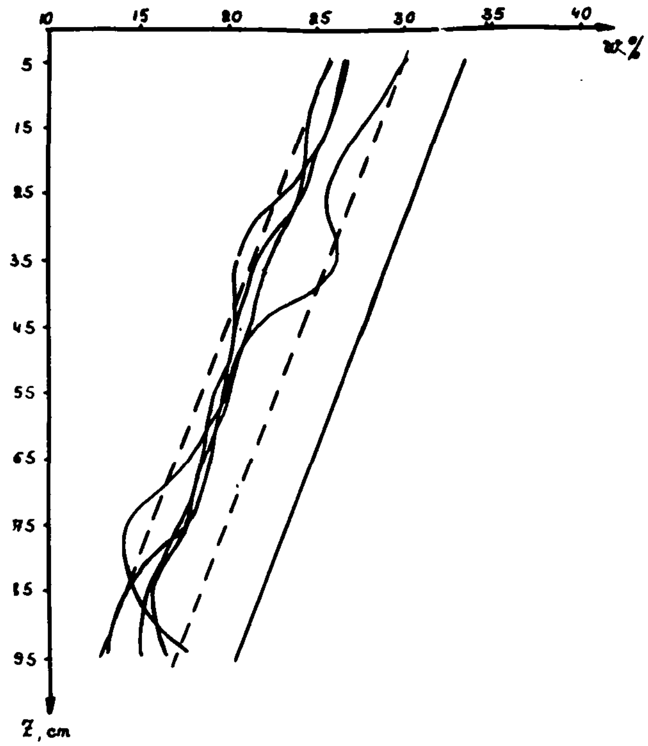

Fig. 6 Moisture profiles for black soil in April, 1975.

———— mean profile of the minimum field water content for black soil;

-------- supplementary profiles of the minimum field water content reconstructed from moisture at a depth of 5 cm.

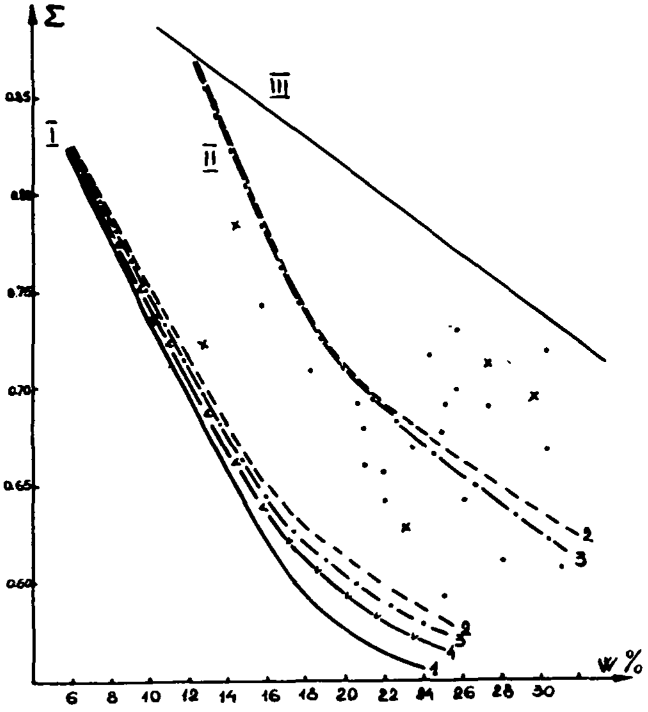

Fig. 7 Emissivities, Σ , of clay (1), black soil (2), light loam (3), and sand (4) vs. moisture, w , at λ = 18cm.

I - calculations from the data of Ref. [17];

II - from aircraft measurements (dots are experimental data) ;

III - experimental data from Ref. [16].

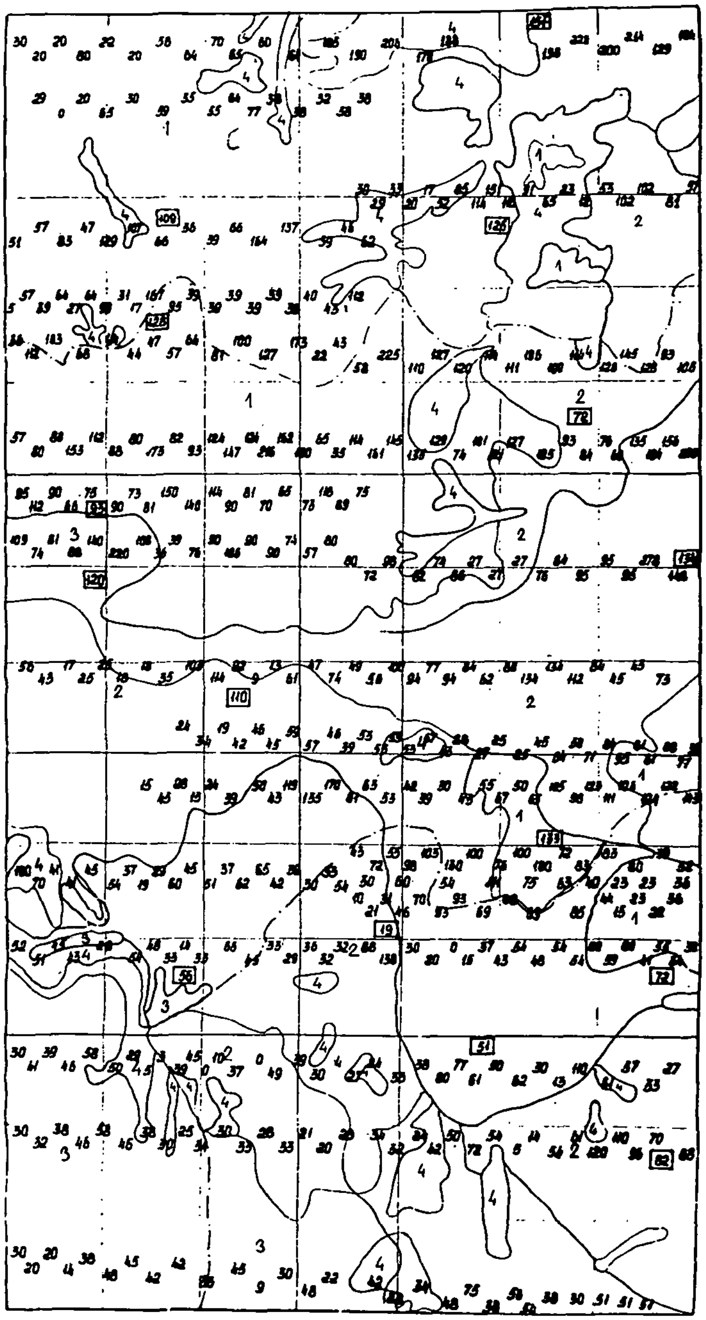

Fig. 8 Map of productive water content in soil (in mm) for 15-16 April, 1975.

1. Black Soils.
2. Dark chestnut soils.
3. Kight-chestnut soils.
4. Saline soils.