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HELICOPTER RADIOMETER MEASUREMENTS OF THIN LAKE ICE AND OIL SPILLS ON LAKES AND SOIL

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We report the results of thermal radio emission measurements of oil spills on lakes and soil and of thin lake ice at wavelengths of 0.8 and 3 cm from an MI-8 helicopter in oil fields in Western Siberia. Methods of oil-film and ice thickness determination by measurements based on thermal radiation interference in a two-layer medium are developed.

1. INTRODUCTION

Many authors (see, e. g., [1-12]), have developed theories of thermal radio emission and experimentally investigated oil films and ice on water surfaces. It has been found that the strong dependence of the brightness temperature of the radiation on the upper-layer thickness in such two-layer media, which is due to the interference of the thermal radio emission retroreflected at the interface, can be used to determine this parameter from radiometric data.

The radiometric method of oil-film-thickness control and determination was first used in airplane measurements of oil spots spread over the sea surface [10, 11]. The observed effect is manifested as a strong dependence (contrasts by more than 100 K) of the brightness temperature of the ascending thermal radiation on oil film thickness. This allows the film-thickness distribution to be determined, using the method of cuts and, therefore, the total mass of spilled oil to be found, which cannot be done by radar techniques or ER measurements.

The use of the radiometric method under sea conditions is hindered by sea roughness, which gives rise to strong local inhomogeneities of the oil-depth distribution and impedes data interpretation, because the foam influences the emissivity of the sea surface. The methods of airplane measurement also have certain drawbacks. First of all, the speed of flight is too high in any case. The scale of the oil spot and characteristic oil-film irregularities must be not less than a few kilometers to avoid flattening of the fine features of the oil-depth distribution. (The integration time of radiometers is usually 0.1-1 sec.)

In this paper, we present the results of investigations of oil contamination on lakes and soil near the city of Nizhnevartovsk using helicopter measurements at wavelengths of 0.8 and 3 cm under the order of the "Human Ecology" Scientific and Production Association for the "Laseganneft" Oil and Gas Production Department and the results of simultaneous lake ice measurements. These results have been partially reported in [13, 14].

In the radiometric measurement of oil contamination in Western Siberia we must take local conditions into account. The characteristic scale of oil spots is from about a few hundreds of meters to 1 or 2 km there. This makes airplane measurements very difficult. Oil spots are concentrated on lakes, where oil accumulates during spring floods, and on soil. For data-processing algorithms, we must perform all the necessary calculations for surfaces with other than sea-water permittivities and estimate the effect of the soil surface roughness on the emissivity of oil spots on soil. The absence of sea roughness is a positive factor in this case.

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2. MEASUREMENT PROCEDURE

The integrated radiometric test bed consists of two radiometers, which receive thermal radio emission at wavelengths of 0.8 and 3 cm, and a two-channel tape-recording system.

Parameters of the radiometer with λ — 0.8 cm:

- Sensitivity — 0.08 K
- Signal integration time — 1 sec
- Beamwidth of the horn-scalar antenna — 6°

Parameters of the radiometer with λ = 3 cm:

- Sensitivity — 0.1 K
- Signal integration time — 1 sec
- Beamwidth of the horn antenna — 20°

The tape-recording system converts the output signals of the radiometers to audio signals, which are recorded in the two channels of a stereo tape recorder.

We performed two series of measurements of the North Current oil field from on board a helicopter. The first series was run at the end of May and the second series was run at the beginning of October in 1992. In particular, the choice of measurement time was determined by the rigorous temperature control requirements. In the chosen periods of the year, the water and air temperatures are about 0°C on lakes covered in part with ice and are ideal for the calibration method which we use.

The radiometers were mounted in the open bottom hatch. The rigidly fixed horns of the antenna were directed vertically downward and protruded below the helicopter bottom.

In the radiometric measurements, we calibrated against natural objects whose brightness temperatures were known with high accuracy. In particular, we used a thick coniferous forest, the brightness temperature of which virtually coincides with the air temperature, and water, the brightness temperature of which is below 150 K and which can be accurately calculated if the water temperature is known. Those objects denned two levels L_w and L_f with known brightness temperatures T_w and T_f, according to which we found the brightness temperature T_b of the oil film to be measured:

$$T_b = (T_f - T_w)/(L_w - L_f)(L - L_f) + T_f . \quad (1)$$

It should be mentioned that it is exactly tlu calibration error due to inaccuracy of the parameters T_f and T_w that makes the main contribution to the total measurement error. Usually, the brightness temperature of the forest is close to the air temperature. Measurements show [15] that the variation in brightness temperature of the forest does not exceed 3 K even in the rain. The reflectivity of the forest is close to zero, and the illumination of the descending thermal radiation of the atmosphere has practically no effect in this case. Also, the brightness temperature of the ascending thermal radiation from the water surface, of course, can be calculated with accuracy better than 1 K, but the high reflectivity of water (near 0.5) causes the retroreflected descending thermal radiation of the atmosphere to affect greatly the brightness temperature of the received radiation.

In clear weather, the brightness temperature of the descending thermal radiation is about 5 K at a wavelength of 3 cm and 15 K at 0.8 cm. Knowing the pressure, temperature and humidity of the air, one can determine the contribution of the atmospheric illumination with accuracy not lower than 0.5 K at 3 cm and not lower than 1.5 K at 0.8 cm, as was expected in the first stage of this work. In cloudy weather, the situation is more difficult to analyze, since tie background of descending radiation increases several times and greatly impedes its exact evaluation. However, it can be shown that relation (1) is still valid if by the brightness temperature we understand the intrinsic thermal radiation of the underlying surface (it is precisely this radiation that is of interest to as) without taking into account the contribution of the retroreflected radiation and assuming that the kinetic temperatures .of the water and air are equal. The errors due to the effect of the retroreflected background radiation are fully compensated in this case. If the water and air temperatures are different, then the error is given by

$$\delta T_b = T_{bg}R(t_f - t_w)/(t_w - T_{bg}) , \qquad (2)$$

where T_{bg} is the brightness temperature of the background radiation, R is the reflectivity of the surface to be measured, and tf and t_w are the kinetic temperatures of the air (forest) and water, respectively. It follows from (2) that when T_{bg} = 50 K and the difference in the water and air temperatures is 10 K, the maximum error is 2.5 K for R — 0.5. It should be mentioned once again that if we want to focus on brightness-temperature measurement and take into account the contribution of the retroreflected atmospheric radiation, then we must use a calibration technique with exactly known brightness temperatures of the two reference calibration objects. However, in the case at hand, where the measurand is actually the reflectivity of the surface, we use the proportional distortion of the calibration scale, defined by (1), when the constant background radiation of the atmosphere is added.

Thus, the proposed analysis methods are actually all-weather. It is important to note that a necessary condition for applicability of (2) is constancy of the environment during the entire period of clean-water calibration and oil-spot measurement. Taking all these factors into account, the error in measurement is not greater than 5 K. Bearing in mind that the influence of oil is manifested as temperature contrasts of from a few tens to over 100 degrees, the measurements are informative enough for this level of accuracy.

We used two measurement techniques: the method of hovering over the contaminated place (for small oil spots) and the method of cuts with a velocity of 10 km/h. By making a few parallel cuts with an interval of about 50 m in the transverse direction, we found the surface distribution of oil contamination. The velocity was such that the distance covered by the directivity-pattern spot on the earth was much greater than the time required for signal integration (τ = 1 sec). Usually, the height at which measurements were performed was the lowest possible, because of the necessity to increase space resolution for the given beamwidth, but the air stream produced by the rotor began to disperse the oil film when the helicopter approached the earth too closely. Thus, usually, the measurements were performed at a height of 50 m. At that height, the directivity pattern spot on the earth was 10-15 m in diameter for the 0.8-cm radiometer and 25-30 m for the 3-cm radiometer, which ensured the resolution required for measurement of 100- to 200-m-long oil spots in the experiments.

3. METHOD OF ANALYSIS

The method which we propose for determination of oil-film thickness is based on the dependence of the brightness temperature of the ascending thermal radiation on this parameter. In principle, measurements at one wavelength are sufficient for film-thickness determination, but it is more reasonable to use two or three wavelengths, because the dependence on film thickness is periodic, so that the interpretation of the results becomes ambiguous in a certain stage. Of course, we could choose a sufficiently large wavelength to ensure that the ambiguity domain begins outside the range of potential film thicknesses, but this would reduce accuracy in the measurement of thin films (the dependence $T_b(d)$ flattens). Therefore, it is reasonable to make measurements at two wavelengths, using a long-wave channel to avoid ambiguity and a short-wave channel to estimate exactly the oil-film thickness. It is convenient to perform two-frequency measurements in the $T_b(0.8)$- $T_b(3)$ plane. In this case, two brightness temperatures at two wavelengths are represented by a dot, and the dependence of its position in the plane on film thickness is represented by a curve. Thus, the simplest method of film-thickness determination is that of plotting the measured values of $T_b(0.8)$ and $T_b(3)$ in the plane in the form of a dot. The value corresponding to the nearest point on the curve is used as an estimate of the film thickness d. The domain of unambiguous estimation lies in the range of film thicknesses of not greater than 0.6 cm; accordingly, the estimate can become ambiguous in a wider range of film thicknesses. However, if the method of cuts is used and the oil film is uniformly distributed in thickness, then instead of one point, we obtain a definite portion of the curve in the plane, which eliminates ambiguity in the interpretation.

Experience shows that as a rule the observed brightness temperatures do not fall on the curve calculated for pure oil. We observed considerable deviations toward increase by a few tens of degrees, which was explained by liquid water inclusions in the oil film, since among the possible inclusions, only water has the high dielectric parameters required for the observed effect. More recently, that assumption was confirmed by sample analysis. Such an effect was also observed in sea measurements [10, 11]. In that case, it was explained by the fact that the water was agitated, forming a water and oil emulsion in a typical period of about one day.

In the case considered, it is natural to assume that oil on lakes forms a water and oil emulsion in the course of time as a result of rain, since small rain drops cannot infiltrate, because of the viscosity of the emulsion. As the oil loses its light fraction, the emulsion viscosity increases. Investigations show that this effect is characteristic of old oil spills and is absent in fresh spills.

To take into account humidity, which radically changes the permittivity of oil films, we used the well-known Clausius-Mosotti equation for moisture permittivity

$$\frac{\varepsilon_m - 1}{\varepsilon_m + 2} = \frac{\varepsilon_o - 1}{\varepsilon_o + 2}(1 - f) + \frac{\varepsilon_w - 1}{\varepsilon_w + 2}f\ , \tag{3}$$

where ε_m, ε_0 and ε_w are the permittivities of the mixture, oil, and water, respectively, and f is the relative volume content of water in the mixture. Equation (3) has been checked experimentally [10], but a more-rigorous approach, in which scattering by rain drops in the water and oil emulsion is taken into account, of course, must be used in further investigations, especially since the conditions of film formation on seas, lakes, and soils are very different.

This makes it necessary to evaluate one more parameter — the relative content of liquid water in the oil. This can be done on the basis of two-frequency measurements, since each value of moisture content corresponds to its own curve of possible values in the $T_b(0.8)$ - $T_b(3)$ plane. When the method of cuts is used and the oil film varies in thickness, we choose the closest root-mean-square theoretical curve by variation of the moisture content / on the resultant section of the curve in the $T_b(0.8)$ - $T_b(3)$ plane. By so doing, we determine both the water content and the film distribution in depth along the flight path. Also, it has been ascertained that the brightness temperature depends only slightly on the moisture content until the film thickness is more than $d = 0.2$ cm.

Such measurements of oil contamination on soil were performed for the first time in the described work. The procedure used for the analysis of oil spills on water is also acceptable in this case, in principle. The difference is mainly in the different permittivities of water and soil. Neglect of this factor can result in underestimation of the brightness temperature contrasts on soil. Depending on the proportional permittivities of the soil and oil contaminant, which is a water and oil emulsion too, the observed effect may be manifested as both an increase and a decrease in brightness temperature.

In [12], the authors considered the influence of film-thickness variations due to the uneven soil surface within the limits of the directivity-pattern spot on the earth. It was assumed that the film-thickness inhomo-geneities in the spot area had a normal distribution and the characteristic dimension of the inhomogeneities was small as compared to the directivity-pattern spot and large as compared to the first Fresnel zone (which is 0.6-1.2 m in this particular case). It was found that the interference pattern flattened with an increase in film-thickness variation, but this effect is strong enough only if this variation is about 30% of the average film thickness and the latter is greater than 0.5 cm.

When a pure oil film is formed on soil with typical permittivity, this increases the brightness temperature of the thermal radiation from the soil surface and can also decrease it in the case of a water and oil emulsion. Determination of the oil-film thickness on soil requires prior determination of the soil permittivity (at least of the reed part of this permittivity). This can be done by moving the spot over the observed brightness temperatures of soil. However, the soil parameters outside the spot do not necessarily correspond ' to those inside the spot. Besides, errors increase because of difficulties in estimation of the role played by thermal-radiation scattering by soil roughness. Such measurements and an attempt to interpret them were made for the first time in the described, and we see prospects for further use of the radiometric method.

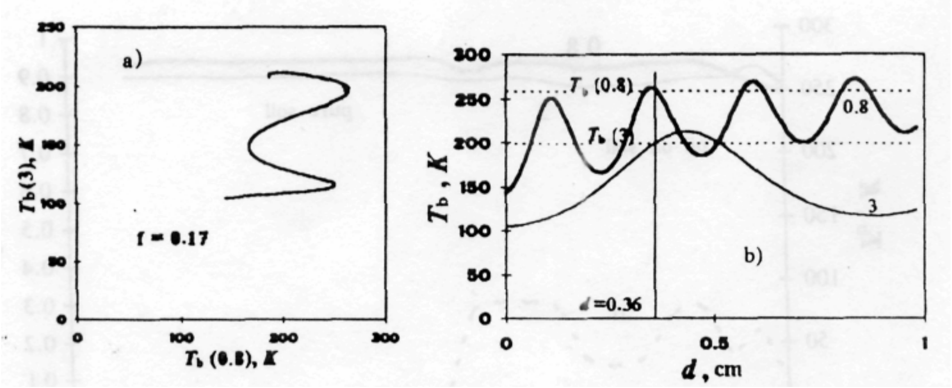


Fig. 1. Two-frequency method for determination of oil film thickness and moisture content in water and oil emulsions.

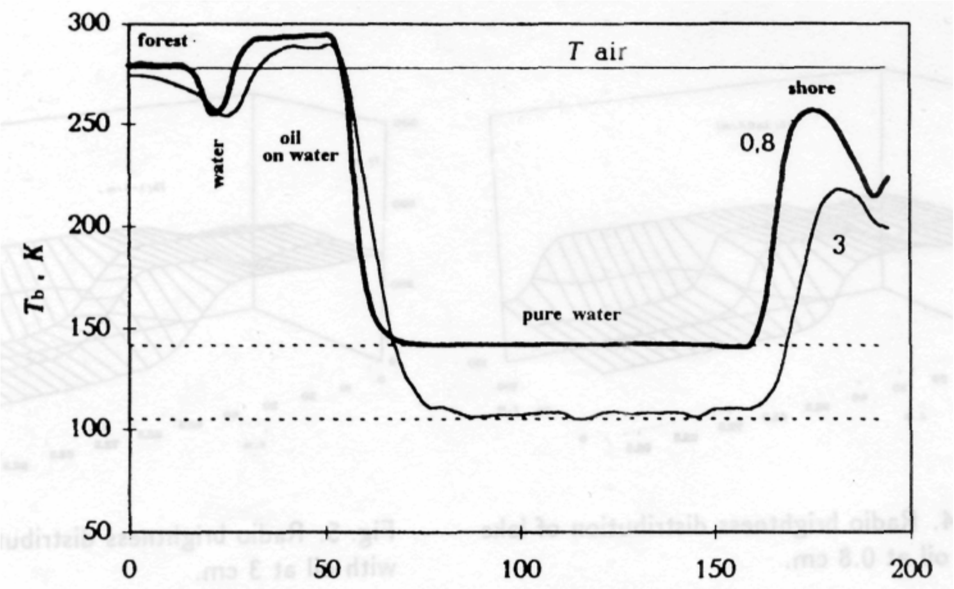


Fig. 2. Sectional view of lake with an oil spot heated by the Sun.

The results of film-thickness measurements on soil, of course, must be considered an interpretation within the scope of the model which we adopted.

During the measurements of oil contamination, we measured simultaneously thin lake ice in the spring series of experiments and fresh one-day ice in the fall. The problem of ice-thickness determination is fully equivalent to that of determination of the thickness of a pure oil film. The difference consists in small deviations of the permittivities.

4. RESULTS OF DATA PROCESSING

As an illustration of the method, we present the measurement data obtained at two wavelengths at one point when the helicopter hovered over a lake with a fresh oil spill (Fig. 1).

In Fig.1a, the asterisk denotes the point corresponding to the measured values of $T_b(0.8)$ and $T_b(3)$. This point is intersected by the curve of possible values of $T_b(0.8)$ and $T_b(3)$ when the moisture content $f = 0.17$. Figure 1b gives calculated quasi-periodic dependences $T_b(d)$ for these two wavelengths. The vertical line shows the numerical solution yielding $d = 0.36$ cm. The horizontal dashed lines show the measured values of $T_b(0.8)$ and $T_b(3)$, which intersect the calculated dependences for this value of d.

In the case presented in Fig. 2, we observed a "greenhouse effect" due to heating of the oil-covered

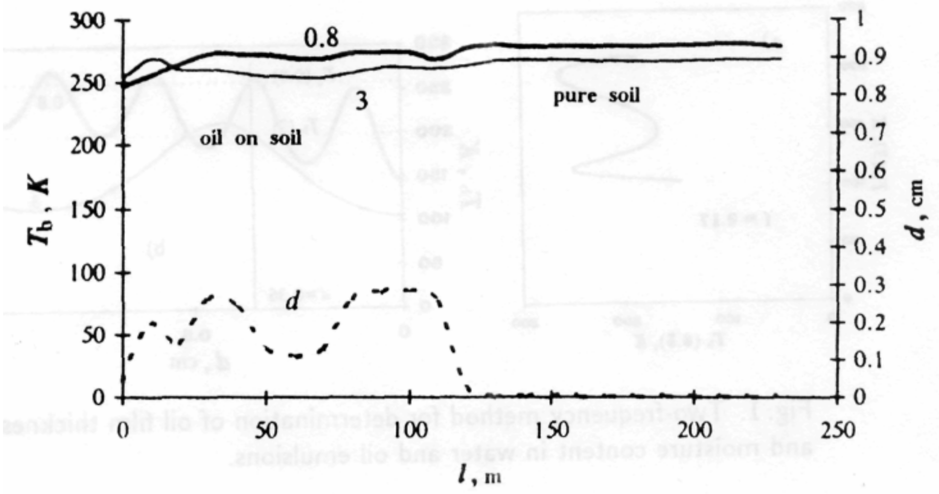
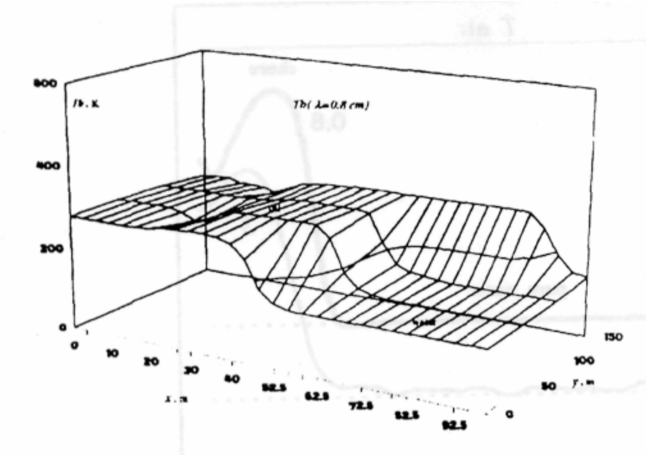


Fig. 3. The results for oil contamination on dry soil



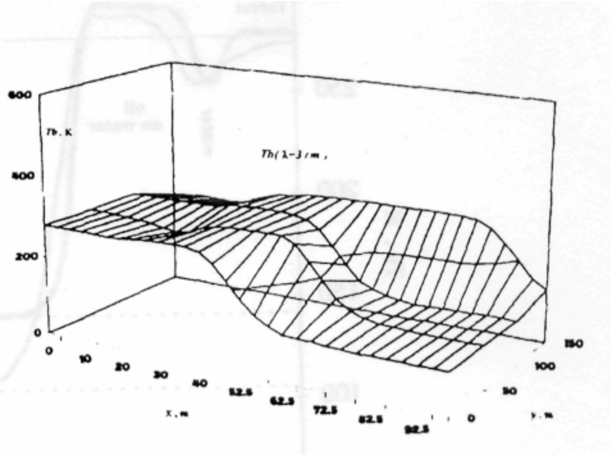


Fig. 4. Radio brightness distribution of lake with oil at 0.8 cm.

Fig. 5. Radio brightness distribution of lake with oil at 3 cm.

surface layer by solar radiation: the brightness temperature of the oil spot exceeded the calibration brightness temperature of the forest (air temperature T_{air}) by about 20 K at a wavelength of 0.8 cm for an air temperature of 6 °C and water temperature 2°C. If the scale of contamination is large, this can lead to serious ecological consequences due to overheating. The problem is that when solar radiation is absorbed by an opaque (fairly dense) surface layer of old oil, the natural heat outflow from the water surface due to evaporation ceases simultaneously.

Figure 3 shows the results for oil contamination on dry soil. It is seen that the transition from the contaminated area to clean (sandy) soil leads to an abrupt change in brightness temperature. The characteristic thickness of the oil layer agrees with the ground-based measurement data (at one point).

Complete information about the depth and total mass distribution of an oil spot can be obtained by the method of multiple cuts of the spot. Using this technique, we can reconstruct the film thickness distribution as a surface in three-dimensional space. Figures 4 and 5 show the three-dimensional distributions of brightness temperatures at wavelengths of 0.8 and 3 cm on a lake with an oil spot. The spot is seen as a hump in the distribution. Figure 6 shows the thickness distribution of the oil film reconstructed from these data. More-uniform transitions at the oil-water interface are observed at $\lambda = 3$ cm, because of the broader beamwidth at this wavelength than at $\lambda = 0.8$ cm.

In Fig. 6, despite the small number of flights used for the reconstruction of the oil-depth distribution over the lake surface, we can see characteristic features of the oil spot, its distinct boundary with the clean

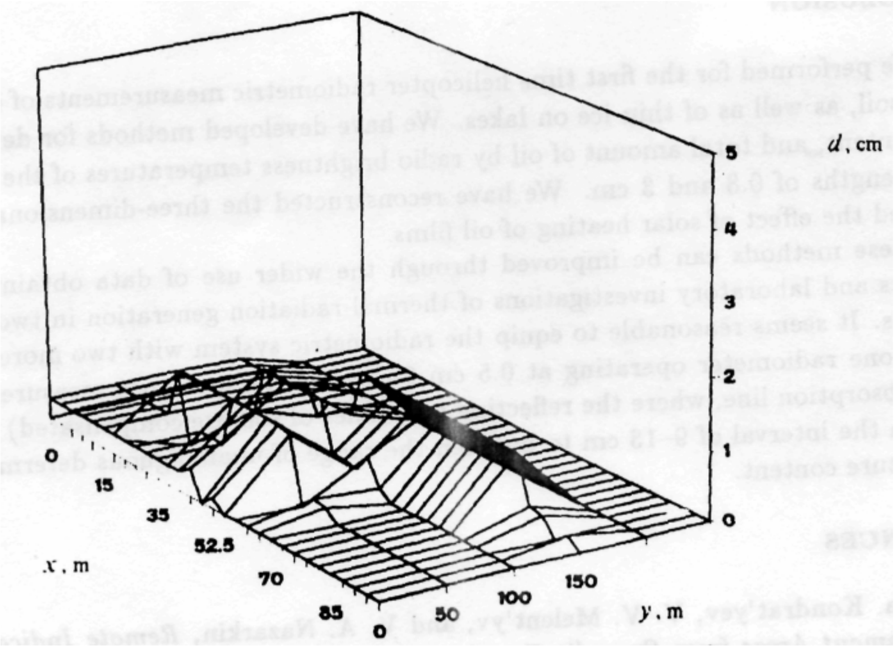


Fig. 6. Oil-depth distribution on lake calculated from the radiometric data presented in Figs. 4 and 5.

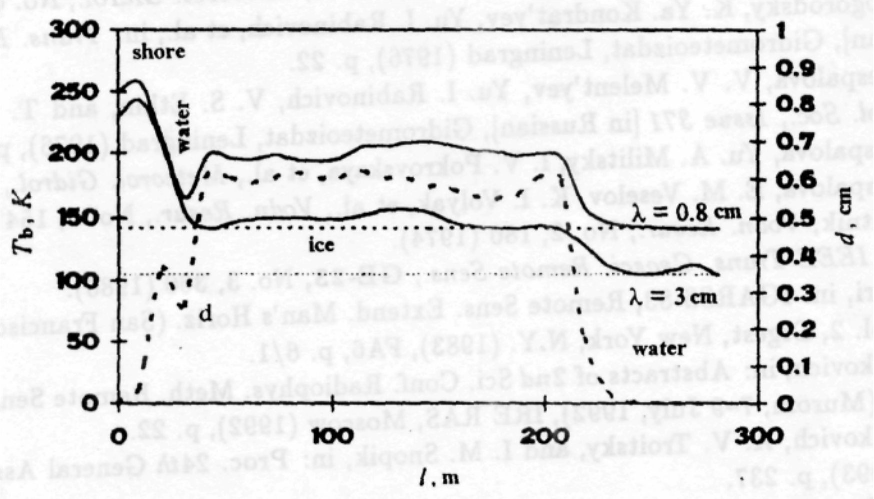


Fig. 7. Radiometric determination of lake ice thickness (the dashed line shows a cut across the lake).

water, and the thickest part of the spot, where the major portion of split oil is concentrated. Using these data as a basis, it is easy to calculate the total amount of oil on the lake which is 39 m^3.

Figure 7 shows radiometric data for a lake with thin spring ice and the results of ice thickness reconstruction from these data.

From this case, the measurements at two wavelengths agree under the assumption that the error is not less than 15 K, which, obviously, is due to scattering in the short-wave channel. In processing autumn measurement data for one-day ice, which is transparent even in the optical range, the second wavelength is unnecessary. The results show that such helicopter measurements are promising and can be performed on rivers and lakes covered with thin ice, for example for passability control in water basins, since radar measurements are difficult when the ice cover is thin.

5. CONCLUSION

We performed for the first time helicopter radiometric measurements of oil spots on fresh-water lakes and on soil, as well as of thin ice on lakes. We have developed methods for determination of the thickness, water content, and total amount of oil by radio brightness temperatures of the ascending thermal radiation at wavelengths of 0.8 and 3 cm. We have reconstructed the three-dimensional structures of oil films and discovered the effect of solar heating of oil films.

These methods can be improved through the wider use of data obtained from ground-based measurements and laboratory investigations of thermal-radiation generation in two-layer oil-soil and oil-water structures. It seems reasonable to equip the radiometric system with two more radiometers at other wavelengths: one radiometer operating at 0.5 cm for surface-temperature measurements (at the center of the oxygen-absorption line, where the reflecting properties of soil are compensated) and another radiometer operating in the interval of 9-13 cm to broaden the range of unambiguous determination of oil-film thickness and moisture content.

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