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ICE AND PERMAFROST ROCK PROPERTIES

MICROWAVE PROPERTIES OF FRESHWATER ICE COVERS UNDER PLASTIC DEFORMATION

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The results of freshwater ice cover radio sounding have been presented. The sensitivity of electromagnetic properties of ice to mechanical stress has been established. Non-coherent additional electromagnetic waves are supposed to occur in ice during its flow, increasing the intensity of scattering and propagating waves to a certain degree. This assumption has been confirmed in the experiment with the impulse pressure (~300 bar) in the ice body. It has been demonstrated that it is necessary to examine the electromagnetic properties of ice not only for static states but also for dynamic phenomena during the process of plastic deformation.

Freshwater ice, ice flowing, non-coherent additional waves, microwaves

INTRODUCTION

Currently 16 crystal modifications and 3 types of amorphous ice are known [*Loerting et al., 2011; Chaplin, 2013*]. Two crystal modifications Ih (common hexagonal ice) and Ic (cubic ice) exist in nature. Ice Ic has been discovered in a cold atmosphere [*Riikonen et al., 2000; Murray et al., 2005*]. Water is manifold, and ice IX and VIII has been found in the porous space, for example, in the pores of multi-layer carbon nanotubes at atmospheric pressure during water cooling, which had been previously observed under high pressures [*Jazdzewska et al., 2011*]. Molecular dynamics methods were used to discover 9 ice modifications in carbon tubes 0.9–1.7 nm in diameter when the air temperatures were changed from 160 to 290 K [*Takaiwa et al., 2008*].

Many properties of ice and frozen dispersive media, for example, electromagnetic properties, are studied under static conditions at constant atmospheric pressure, temperature and geometric shape of the samples. At the same time, when these parameters change, i.e. under dynamic conditions and especially under conditions of sharp fluctuations, the electromagnetic properties of ice have been studied insufficiently. One of the characteristics of ice Ih is its capacity of plastic deformation (flowing) when exposed to mechanical stress. This condition, under which quasi-liquid layers emerge in-between ice crystals, is characteristic of ice structures in the natural environment. Under gravity forces, flowing are continental glaciers and any other ice bodies when exposed to temperature changes, ice covers of cold planet satellites – when exposed to tidal forces, etc. However, when studying the electromagnetic properties of ice bodies, researchers do not always take the impact of plastic deformation, accompanying observations and parameter measurements, into account [*Bogorodskiy, 1983*].

The objective of this study was to demonstrate the necessity of considering dynamic phenomena, in particular, plastic deformation, on the microwave properties of ice bodies, using the example of freshwater ice covers. As it will be shown below, the effect of the impact of plastic deformation on the electromagnetic properties of ice is revealed even when the flowing (creep) of the ice cover is seemingly slow. This issue is of serious practical importance for solution of inverse problems in remote sensing of permafrost covers of the Earth.

THE RESULTS OF PREVIOUS EXPERIMENTS

Over the decades of investigations of ice covers and glaciers by the method of radio sounding, many results have been accumulated, which are difficult to interpret in the framework of the conventional concepts of the properties of ice [*Bogorodskiy, 1983; Bordonskiy et al., 1999, 2006, 2011a,b; Drews et al., 2009*]. In [*Bordonskiy et al., 1999, 2006, 2011a,b*] absorption of microwaves radiation in the ice covers of freshwater lakes was studied. The schematic of the experiments is shown in Fig. 1.

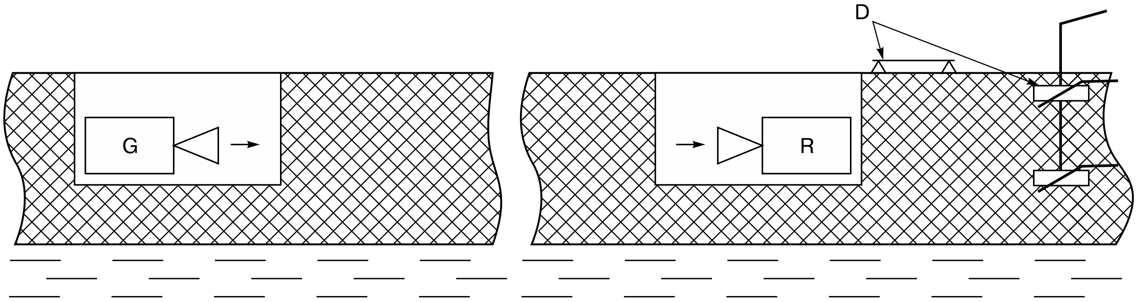

Fig. 1. A layout of equipment for radio sounding of the ice cover.

G – a microwave generator, R – a receiver of waves, D – sensors of ice deformation and of temperature.

The experiments performed revealed sensitivity of the characteristics of sounding signals coming through ice to both fast and slow wave impacts on the ice cover of Lake Arakhlei (near Chita, Zabaikalsky kray). The average ice mineralization rate was about one milligram per one kilogram. In particular, a tidal wave was registered, i.e., rather weak and slow deformations of lake ice, which are difficult to register by the existing conventional methods (relative tension stress of the earth's crust is of the order of 10^{-6}–10^{-7}) (Fig. 2).

Two particular features were revealed during the observations. The first one consists in a different character of changing the power of radiation taking place on two orthogonal linear polarizations. On the vertical polarization (VP) one extreme point was observed, which could be explained by the daily course of the medium. The second feature consists in the fact that in horizontal polarization (HP) two extremes of signal power were registered during a day, which coincided with the maximum values of the tidal waves. The experiments were conducted during a full moon, when the intensity of tidal waves is the highest. Microwaves in this experiment were generated with circular polarization, i.e. the original radiant powers were equal for VP and HP. The distance between the radiating element and the receiver was about 40 m. The instruments were placed near the lake shore at the distance of ~100 m from it with the depth of 3–4 m there and ice thickness 1.4 m. the equipment was placed at the depth of 0.7 m. The aerial axes were oriented on the east-west line. The average ice temperature in the upper part of the ice cover was –10 °C, with daily fluctuations within ±2 °C.

Relatively fast soliton waves were investigated in experiments in a seismic region on the ice of the Barguzin Bay of Lake Baikal in February 1998. Such waves may arise in a stressed ice cover during earthquakes and other impulse impacts on water bodies. The effect of manifestation of mechanical stress in a floating stressed ice block was theoretically considered, for example, in [*Goldshtein and Marchenko, 1989*]. It was found that with the stresses comparable with the ultimate compressive strength ~10^6 Pa, new types of bending gravity waves are generated in the block, which can be unstable depending on the problem parameters. Solutions were obtained, being soliton and cnoidal waves. The emerging nonlinear waves have characteristic lengths of about 1.000 m. In [*Goldshtein and Marchenko, 1989*] a conclusion was made that waves created additional stress and might also cause emergence and development of cracks.

In the experiments conducted on the ice of the Barguzin Bay, the instruments were placed on the bay ice 5 km away from the village of Maksimikha. The equipment was plunged into the ice to the depth of 0.4 m; ice thickness was 1 m. The instruments were oriented on the east-west line. On February 26, 1998,

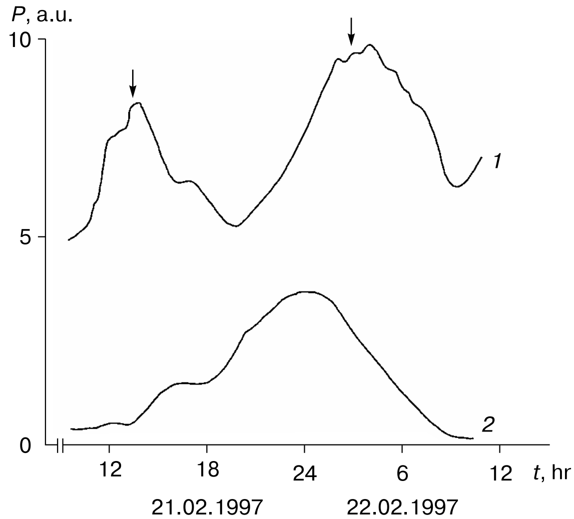

Fig. 2. The measured power of radiation P, which passed through the ice cover, at the wavelength of 2.3 cm at two orthogonal polarizations.

1 – horizontal, *2* – vertical; the arrows indicate the tide maxima, corresponding to the extreme positions of the Moon and the Sun for the given locality (the fool moon of February 21–22, 1997). The time is local.

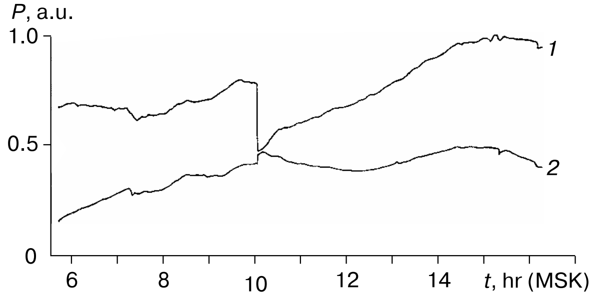

Fig. 3. The power of transmitted microwaves at the wavelength of 2.3 cm at two orthogonal polarizations.

1 – horizontal, *2* – vertical.

a phenomenon was registered, referring to the passage of a soliton wave (Fig. 3). A soliton wave was sensed by sharp short-term fluctuations of the ice cover and by the accompanying sound effect, which manifested itself like strong boom over the bay area. The probable origin of the wave is relief of the ice cover from mechanical stress caused by thermal ice expansion on the warming days. In this experiment, radiation with circular polarization and signal registration on two orthogonal linear polarizations were used.

Just as in the previous experiment (Fig. 2), first the results obtained could not be satisfactorily explained. The unusual character of the results obtained consisted in the following: firstly, the signal on HP sharply decreased at the time of the soliton wave passage and then it started growing slowly to reach the original level; and secondly, the signal on VP insignificantly grew, and the signals on two polarizations practically equaled for their intensity. If destruction of the ice body had arisen (with emergence of liquid water in the cracks), one could have expected simultaneous reduction in the signal intensity on both polarizations, but that did not happen.

THE QUALITATIVE THEORY OF THE EFFECTS OBSERVED

In [*Bordonskiy et al., 2011a,b*] arguments are provided explaining the anomalies of the electromagnetic properties of ice covers, related to the concept of existence of coherent and non-coherent additional waves in them. Coherent additional waves are such waves which may interfere among themselves, generating strong periodic radiation intensities; they emerge in media with spatial dispersion [*Agranovich, 1979*]. For such media, the components of dielectric capacitivity tensor depend on the wave vector, and two waves with equal polarization emerge, having different waves, i.e., together with the original one, there emerges an additional electromagnetic wave. It turned out that additional waves emerge not only in infinite media with spatial dispersion (an example is medium with periodic fluctuation of dielectric capacitivity, the period of which is comparable to the wavelength of transmitted radiation). They arise also in plane-layered medium in the thin layer between two half-infinite media [*Brekhovskikh, 1957*], which was confirmed by us for the specific case of microwave irradiation in freshwater ice cover [*Bordonskiy et al., 2006, 2011a,b*].

At the same time, special waves were discovered in the experiment [*Bordonskiy et al., 2011a,b*]. These are non-coherent additional waves, addition of which occurs non-coherently, i.e. in the point of reception their total intensity is registered, not the total amplitude of fields. Based on the results [*Bordonskiy et al., 2006*] a conclusion was made that non-coherent waves arise due to dissipation of radiation on films in the areas where hydrogen bonds are broken when the medium flow begins. Negative differential viscosity emerges when the fluidity threshold is exceeded. At these moments, deformation sharply increases, and the stress drops [*Petrenko, 2002*]. As water molecules are electrical dipoles, one can suppose emergence of negative differential resistance in such areas for the currents induced by external alternating electric field. As known, currents in a negative resistance circuit may be amplified to a certain degree to cause the growth of electromagnetic field intensity during its over-radiation. Due to chaotic spread of the crystal flow in the ice body and random values of the phases of individual radiation sources, there emerges a non-coherent field.

Resulting from the spread of monochromatic radiation in the ice cover, two types of waves emerge in it: coherent waves, related to numerous re-reflections from the boundaries of media, and non-coherent waves, arising during plastic deformation of ice. In the latter case, the effect is most noticeable for a medium with optic axes of ice crystals oriented in space in a specific way. Spatial regularity of the main optical axes of ice crystals (C-axes) is characteristic of lake ice [*Pounder, 1967*], which was also observed for the objects used in the experiments [*Bordonskiy et al., 1999, 2011a,b*]. Beginning with the depths of 20–30 cm of lake ice, C-axes were vertically oriented, i.e. the basis planes of the hexagonal crystals are located in parallel with the cover surfaces. It is known that ice crystals are easier to get deformed by being shifted along basic planes [*Petrenko, 2002*]. Hence, in the objects under study, with relatively weak stress values, plastic deformation should arise primarily in the planes parallel to the interface between the ice cover and the environment. As a result, transmitted radiation gets somewhat intensified on horizontal polarization, for which the direction of the electric field vector coincides with the basic planes of ice crystals.

To test the impact of the medium flow on microwave dissipation, experiments were conducted to create impulse pressure in fresh ice cover using explosions of small powder charges. In detail, the experiment architecture was similar to that described in [*Fomin, 1985*]. In the experiment, radiation was passed at different wavelengths through the area of explosion of a powder charge weighing several grams, which had been pre-frozen into the ice cover. According to [*Fomin, 1985*], created impulse pressure in the medium for such an experiment in a sphere equal to 10 charge diameter lengths reached 340 bar. The diameter of the charge used in the experiment was ~5 cm. The distance between the transmitter and the receiver was 5 m.

Shown in Fig. 4 are the results of one of the experiments for the radiation frequency of 13.7 GHz. The experiment was conducted on the freshwater ice cover of Lake Arakhley. The average ice mineralization rate was several milligrams per one kilogram. The mineralization rate of original water was about 0.1 g/l; ice thickness was 1.2 m. The depth of equipment submergence into the ice was 0.5 m. As seen from Fig. 4, immediately after the explosion, a short impulse of signal absorption by the time of approximately of 1 ms was registered. When the powder charge with the mass of 5 g was used, ice heating in the sphere with the diameter of 50 cm did not exceed 1 °C. The value of specific heat of powder combustion was used, equal to 3.8 MJ/kg. If all the energy had been used to form liquid, about 70 g of ice would have been melted, corresponding to a sphere with a radius of less than 3 cm. It seems that the energy of explosion is used to heat the medium, to form the liquid and to fulfill the work of plastic deformation. It can be seen from Fig. 4 that, after a short impulse of radiation absorption, the signal doubled for a period of 30–40 ms, when in the medium the high pressure dropped, i.e., it was "frozen", in accordance with the phase plot "pressure–temperature". This experiment was conducted with the ice temperature being several degrees less than 0 °C, when the ice fluidity limit is close to the least values [*Petrenko, 2002*].

In a similar experiment, the properties of ice from a salt lake were investigated, the main salts of which were sodium chloride and sodium carbonate. Total salt concentration in the ice was 3 g/kg. With the ice temperature −10 °C, the effect of amplification of transmitted radiation in the explosion area was not found. Then an experiment was conducted with the same ice cooled to the temperature of approximately −60 °C, which is essentially lower than the eutectic point of the salt captured in the ice. To cool a section of ice in the ice cover, notches were made, in which liquid nitrogen was poured. In that experiment, just as in the case with freshwater ice, a microwave impulse of increased intensity was discovered, when high pressure emerged in the medium during the charge explosion. Thus, it can be concluded that the

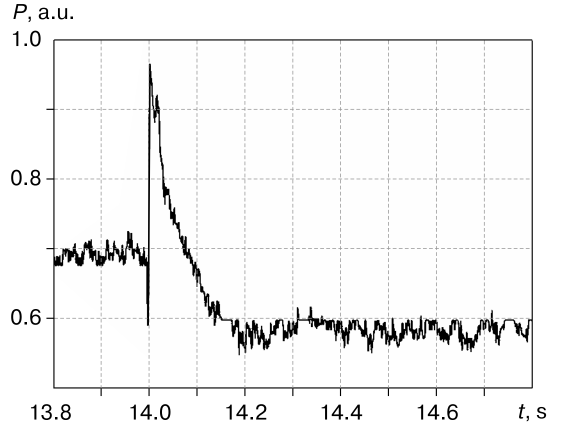

Fig. 4. Dependence of registered radiation power (at the frequency of 13.7 GHz) on time in initiating an explosion in ice.

growth of registered radiation emerges during a flow of ice crystals. For warmer salt ice containing liquid inclusions, deformations took place primarily without shifting of the parts of ice crystals in relation to each other or the liquid salt inclusions suppressed the electrical activity of the medium.

DISCUSSION

The provided description of the emergence of non-coherent additional waves allows the observed phenomena occurring during radio sounding of ice covers to be explained in Fig. 2, the medium flow with the extreme point of the tidal wave also reached its maximum and generated certain intensification of the signal in GP, while it was in that polarization that the electric field vector coincided with the basic plane of the medium crystals and hence the alternating electric currents also coincided with the planes, along which crystal parts slid. As there are two extreme points of the tidal wave during a day, two maxima of the intensity of transmitted radiation were observed. The only extreme point in VP is explained by the daily fluctuations of the air temperature.

The specific features of the plots shown in Fig. 3 are explained as follows. When mechanical stress emerges in the ice cover during daily temperature fluctuations and the flow of crystals arose along the basic planes, the signal in GP turned out to be somewhat higher, compared to the signal in VP. At the moment of ice cover unloading from mechanical stress, accompanied by the transmission of a soliton wave, the flow of the medium stopped for some time, and the signals in two polarizations got leveled. The subsequent slow growth of radiation intensity in GP was determined by slow recovery of stress in the given section of the ice cover. Thus, assessing the character of signal changes in different polarizations during radio sounding may be used to determine the dynamics of mechanical stress in structured ice.

Similar phenomena were observed by other researchers, too. For example, in [*Matsuoka et al., 2003*] radar measurements of radiations dissipated from different layers of the Antarctic glaciers were made on two orthogonal polarizations. Essential excess of the signal from certain layers was detected, reaching 10 dB, in the polarization, for which the electric field vector is perpendicular to the direction of the glacier flow, compared to the other polarization. The chief optical axes of crystals inside the glacier were primarily oriented in the direction of its flow. The authors do not explain the anomaly observed [*Matsuoka et al., 2003*]. In this case, explanation of the effect may be related to amplification of the dissipated signal with plastic deformation and concurrence of the basic planes of the medium crystals with a direction of the electric field vector of an incident wave.

In [*Drews et al., 2009*] data are provided on the EFZ layer (echo-free zone – zone free from reflections) near the lower border of massive glaciers. The authors attribute the emergence of such a layer on records during registration of the reflection of radar impulses to the loss of coherence in the medium flow in the benthic part of the glacier, however, such a supposition was considered in detail.

Note certain possibilities of applying non-coherent additional waves. One of them is detecting mechanical waves arising in water medium and in ice covers (seismic, tidal, seiche waves, waves generated by artificial sources). A characteristic feature of such detection is the possibility of registering waves with a large period of oscillation – of the order of hours and days. Such measurements may be made not only with a receiver and transmitter placed at different locations but also with them placed on one carrier (car, airplane, artificial satellite). Another possibility is determined by the structural features of ice bodies in structuring various inclusions in them (liquid, gaseous, and solid particles and crystals) and by the differences of mechanical properties in the given directions. Medium anisotropy may be revealed by spectral multi-polarization radio sounding of such bodies.

It should be pointed out that the flow of medium may generate an additional wave also for acoustic radiation, as noted in [*Fomin, 1985*]. This issue requires further study. It seems necessary to conduct profound investigation of the physical properties of the crystal sections subject to flow (due to appearance of films and quasi-liquid layers). It can be noted that in [*Rybalko et al., 2008*], similarly to our results, amplification of the millimeter waves was detected but it was detected in superfluid liquid helium. It is believed that in superfluid helium there is instability of vortex structures at the frequencies used in the experiment. One can suppose a similar state in films between parts of ice crystals when negative viscosity emerges, when the fluidity limit is reached. In such films, self-organization processes are possible, for example, emergence of complex vortex structures [*Starr, 1971*].

CONCLUSIONS

1. Measuring the microwaves properties of freshwater ice cover has first showed that the electromagnetic properties of ice should be studied not only in a static form (for bodies with unchanged geometry and internal strains) but also in dynamics, under conditions of plastic deformation. Even a relatively weak flow, with externally not visible deformities of natural ice structures, may result in the appearance of special electromagnetic properties in them, for example, in the emergence of non-coherent additional waves.

2. The experiments have demonstrated a possibility of registering wave motions in the appearance of soliton and tidal waves in ice covers having preferred spatial orientation of the main optical axis of crystals, passing through the ice of centimeter microwaves during polarization measurements.

3. In measuring the feedthrough power of an external radiation source through an area in freshwater ice, where the pressure of about 300 bar was generated by initiating a powder charge in medium, the effect of amplifying microwaves was detected. It has also been found that this effect is absent in saline water (a sample with the mineralization rate of 3 g/kg was used) but it emerges in the same medium, if it is cooled to the temperature below the eutectic point of the salt inclusions.

4. The experimental data obtained indicate the possibility of creating new methods of investigating internal mechanical movements of ice structures using multi-polarization microwaves measurements, for example, registration of the beginning of glacier movement. Currently only optical images are used for such problems [*Petrakov et al., 2013*], which do not allow the internal state of ice bodies to be directly evaluated.

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