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Radio wave borehole measurements to determine the in situ electric property distribution in a massif

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[1] The investigation of the Martian cryosphere, by ground-penetrating radar and other electromagnetic techniques, requires accurate knowledge of the electrical properties of the planet's regolith and crust. In similar investigations of frozen ground in Siberia, this problem has been addressed by a technique called Radio Wave Geo-Introscopy (RWGI), which is implemented by examining electromagnetic wave propagation between neighboring boreholes. In this way, temporal and spatial variations in the effective electrical resistivity and dielectric permittivity of the intervening frozen ground can be measured. This paper discusses the main principles of RWGI; the procedures, equipment and measurements needed to implement it; how the data is interpreted; and some applications of this technique to investigations of the terrestrial cryolithozone. *INDEX TERMS:* 0915 Exploration Geophysics: Downhole methods; 0925 Exploration Geophysics: Magnetic and electrical methods; 0994 Exploration Geophysics: Instruments and techniques; *KEYWORDS:* Radio wave geointroscopy, rock electric properties

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1. Introduction

[2] Ground-penetrating radar (GPR) and some other electromagnetic methods are the chief techniques that will be used to study the Martian cryosphere. One requirement for the successful interpretation of the resulting data is an accurate knowledge of the electrical properties of Martian frozen ground. Laboratory and field studies of terrestrial analogs [see, e.g., *Frolov*, 1998] provide only a general understanding of the potential range of these properties, leaving much uncertainty regarding their actual value. As a result, it is possible that the electrical properties of the Martian regolith may limit GPR investigations (even those operating at frequencies as low as a few MHz) to penetration depths no greater than ~100–200 m. However, regardless of the GPR's ultimate sounding depth, the electrical properties of the intervening medium must be determined. In this paper we describe a technique to assess these properties called Radio Wave Geo-Introscopy (RWGI) that has been used extensively in investigations of frozen ground in Siberia. RWGI is implemented by examining electromagnetic wave propagation between neighboring boreholes, providing measurements of temporal and spatial variations in the effective electrical resistivity and dielectric permittivity of the intervening frozen ground [*Borisov et al.*, 1993; *Frolov et al.*, 2001]. Given below is a brief discussion of the main principles of the method, as well as a description of the specialized borehole equipment, procedures, data processing, and some examples of RWGI use in cryolithozone studies in Siberia.

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2. Main Principles of RWGI

[3] The physical basis for the RWGI method is dependent on the relationship between the intensity of radio energy absorption along the wave path and the electrical characteristics of the local soils. The effective amplitudes of the electric components of an arbitrarily oriented dipole field in the wave zone may be expressed by the following equations:

$$E_\theta = E_0 \frac{e^{-k''R}}{R} F(\theta) \qquad E_r = \frac{2E_0}{|k|} \frac{e^{-k''R}}{R^2} F(\theta) \tag{1}$$

where E_0 is a parameter of the measuring device, R is the distance between the points of transmission and reception, $F(\theta)$ is the function which take into account the relative position of receiving and transmitting dipoles in space, and k'' is the coefficient of radio wave absorption, which depends on the electromagnetic field frequency and electrical properties of the medium:

$$k'' = \omega \left\{ \frac{\mu\varepsilon}{2} \left[\sqrt{1 + \left(\frac{1}{\rho\omega\varepsilon} \right)^2} - 1 \right] \right\}^{\frac{1}{2}} \tag{2}$$

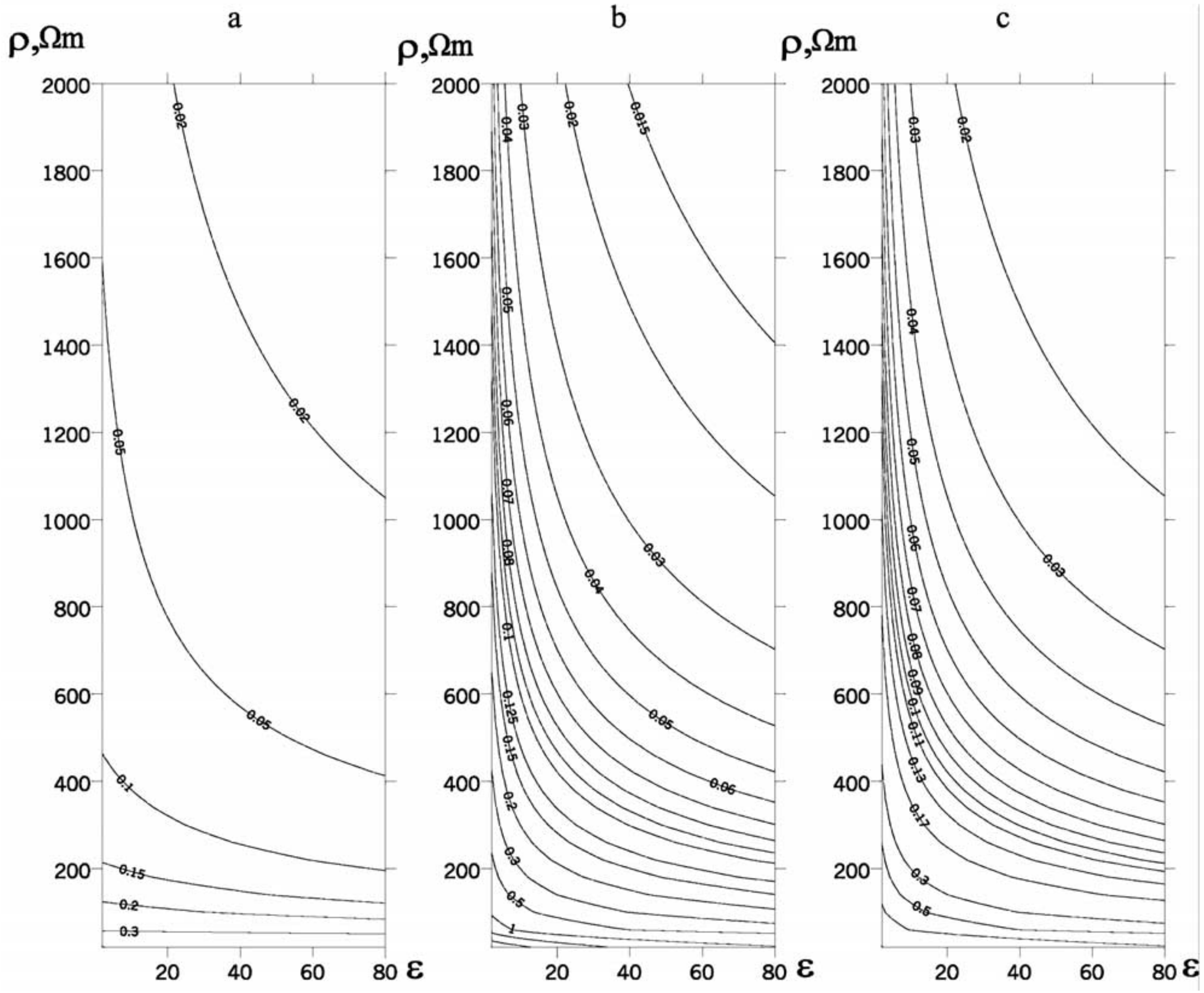

Figure 1. Calculated diagrams of absorption coefficient k″ (Np/m) as a function of ρ and ε at the various frequencies: (a) 1 MHz, (b) 30 MHz, and (c) 60 MHz.

where $\omega = 2\pi f$, F is operating frequency, $k = k' + i k''$ is the complex wave number, and μ, ε, and ρ are the corresponding magnetic and dielectric permittivities and electrical resistivity.

[4] As seen in Figure 1a, in soils with a resistivity less than 100 Ωm, the permittivity has little impact on radio wave energy absorption because the medium is a quasi-conductor. However, for frozen soils characterized by a high resistivity ($\sim 10^2 - 10^3$ Ωm) and permittivity $\varepsilon < 30$, energy absorption is strongly dependent on the permittivity for frequencies >30 MHz because the medium behaves as a quasi-dielectric (Figures 1b and 1c).

[5] When measurements are performed in an inhomogeneous medium, the coefficient of radio energy absorption k'' is replaced by an effective coefficient k''_e, which is an integral value summarizing all the local changes in the medium absorbing properties along the wave path, most importantly, within the first Fresnel zone. For this same reason, the medium resistivity and permittivity, calculated from measurements of k''_e, are also effective values (ρ_e and ε_e, respectively). Having performed measurements at two fixed frequencies, it is possible to calculate ρ_e and ε_e for the soils within the studied volume.

3. Borehole Radio Wave Equipment

[6] Special digital borehole radio equipment of the RWGI-2F series was designed and manufactured by Radionda LTD for detailed studies and measurements of radio frequency electromagnetic field intensity using an electric (or magnetic) dipole antennae. The equipment includes a special receiver and transmitter, which are lowered into the boreholes on a single-conductor logging cable. To exclude the antenna effect of the cable, the borehole units are self-contained with their own power source (storage battery) and are connected to the cable through a dielectric insert (coupler) with a fiber-optical channel and optoelectroic converter. Both the receiver and transmitter have onboard processors and Analog Digital Transfer (ADT), which enables them to carry out two-way communication with the surface: to transmit data and receive control instructions. In addition to providing measurements of the electric (or

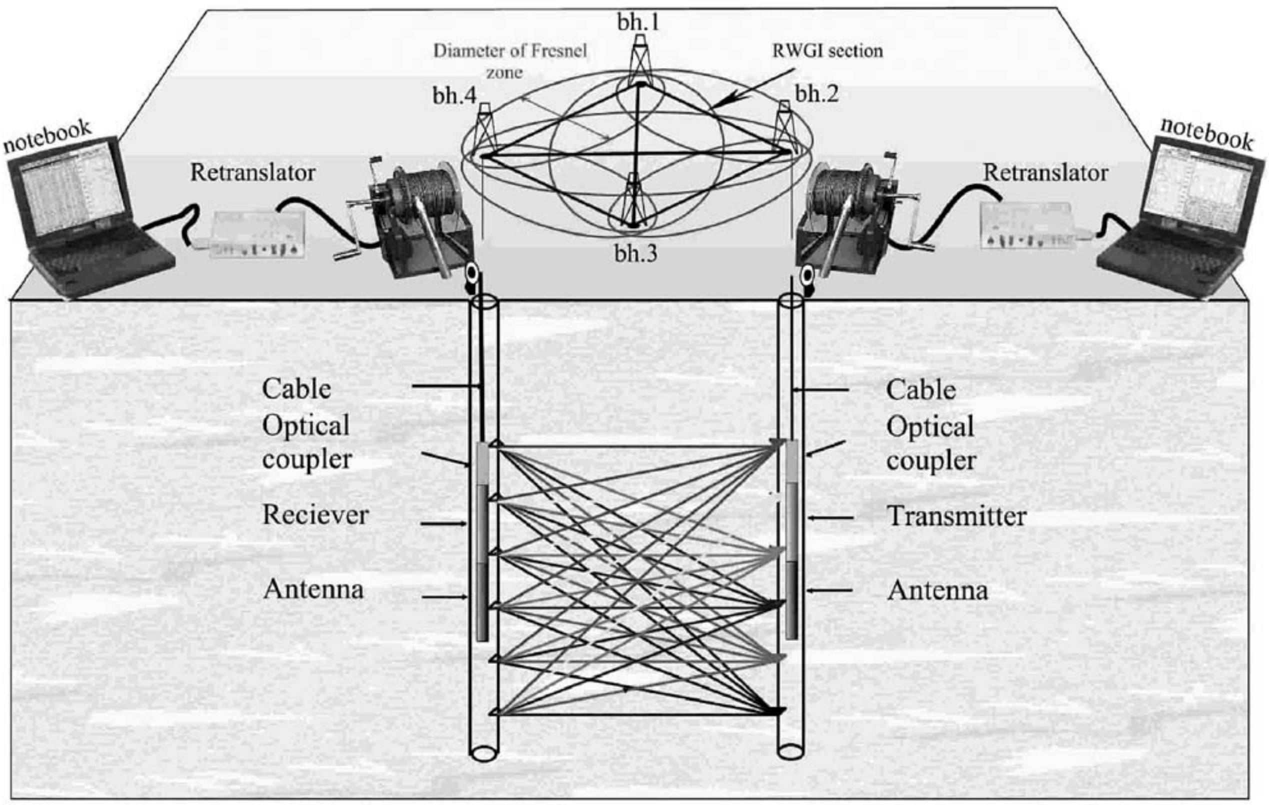

Figure 2. Principal scheme of the RWGI operation.

magnetic) field intensity at the receiver, and of the current in the transmitting antenna, such communication permits the fine-tuning of the antenna and transmitter at each position within the borehole, as well as control of the emission power, mode, and gain factor of the receiver. This capability ensures the stable operation of the device and maximizes the transmission range, even with a short antennae. Data logging and control instructions to borehole equipment are performed on the surface using a notebook computer connected to the winch through a translator. The functional diagram of the equipment is shown in Figure 2, and Table 1 gives its principal specifications.

4. Procedure of Measurements and Data Processing

[7] Borehole radio wave studies may be performed in any of three different ways:

[8] ● Cross-borehole measurements (CB - RWGI);

[9] ● Borehole-surface measurements (BS - RWGI);

[10] ● One-borehole radio wave profiling measurements (ORWP - RWGI).

[11] Cross-borehole measurements are usually performed to create a "tomographic survey," where the electromagnetic field is measured at each position of the transmitter in one borehole over the whole working range of receiver displacement in the other borehole, creating the "fan" pattern of relative oppositions seen in Figure 2. Measurements with the receiver are made at 0.2 to 1.0 m intervals along the borehole for the case of point-wise logging and at intervals of 0.01 to 0.1 m for continuous data recording. Figure 2 illustrates an application of CB-RWGI where measurements are taken along 6 sections/intervals of each of 4 boreholes (BH1–BH4). For each section (between any pair of holes) the contour of the first Fresnel zone is shown. To obtain reliable data, the operating frequency and depth interval must be chosen to provide significant overlap of these zones. This ensures the most complete and uniform study of the inter-hole space and that every inhomogeneity in the medium is explored at various angles. The borehole-surface technique (BS-RWGI) is implemented in a similar way, but in this approach, the receiver is moved over the surface, while the transmitter is moved within the borehole (as it is with CB-RWGI).

[12] In the case of a single borehole (ORWP-RWGI), electromagnetic profiling is performed along the whole shaft at two or more frequencies, with the receiving and transmitting antennae positioned at several fixed distances from each other. The data is then processed using an ORWP software package specially developed by Radionda Ltd. The package includes original iterative algorithms for direct

Table 1. Principal Specifications

Specification	Value
Operating frequencies	0.061, 0.156, .625, 1.250, 2.25, 10.0, 31.0 MHz
Receiver sensitivity	Not worse than 0.5 mV
Receiver dynamic range	110 dB
Transmitter power	1–10 W
Recording speed	600 m/h
Diameter of the borehole units	38 mm

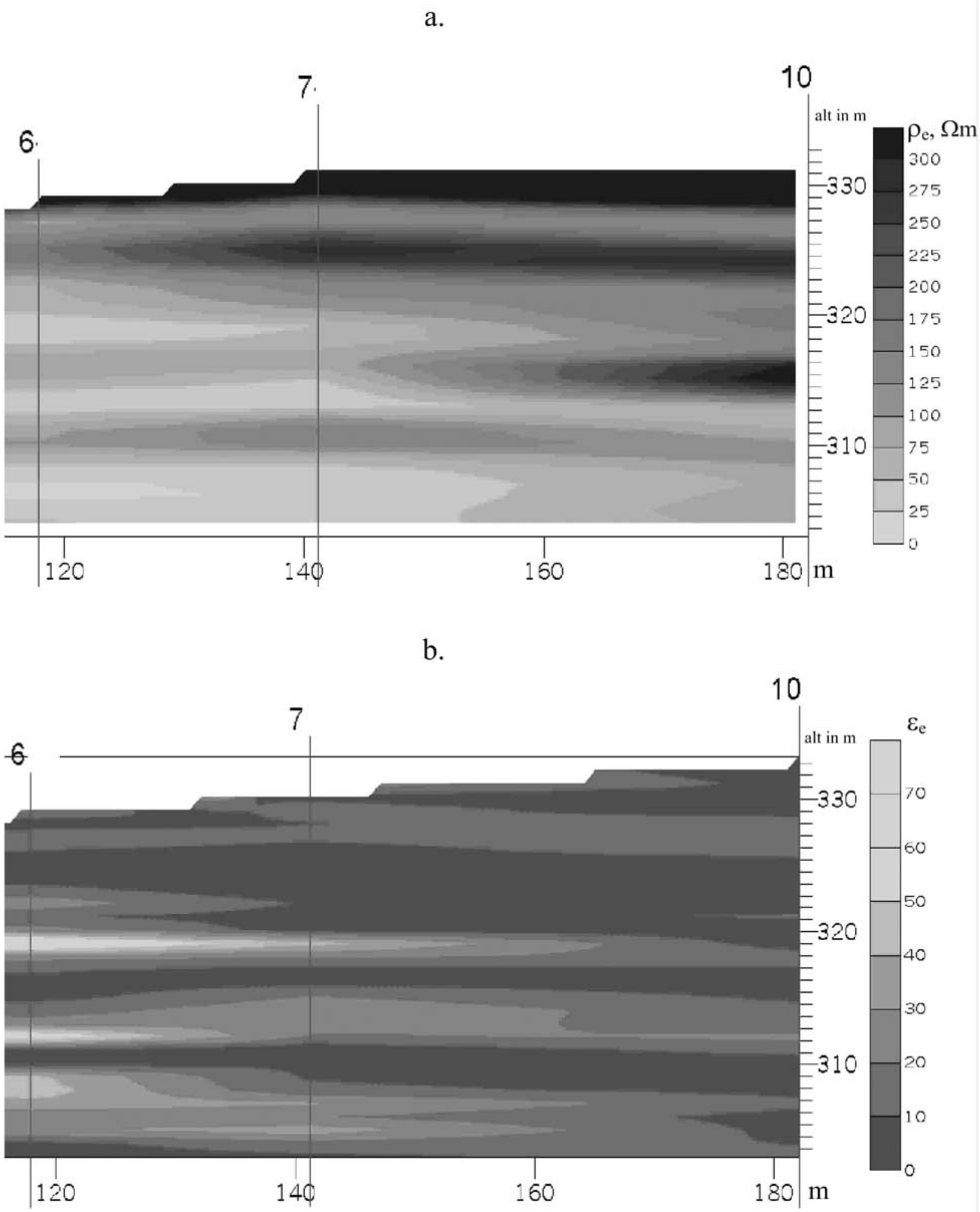

Figure 3. Examples of geoelectric sections of effective resistivity (a) and permittivity (b) from a 3D map compiled using field data obtained by the application of the ORWP-RWGI technique to the study of a water reservoir in a frozen massif along a shoreline in Western Yakutia, Siberia. (August 2001). These sections were obtained from three 30-m deep boreholes, spaced at surface intervals of 22 m and 40 m.

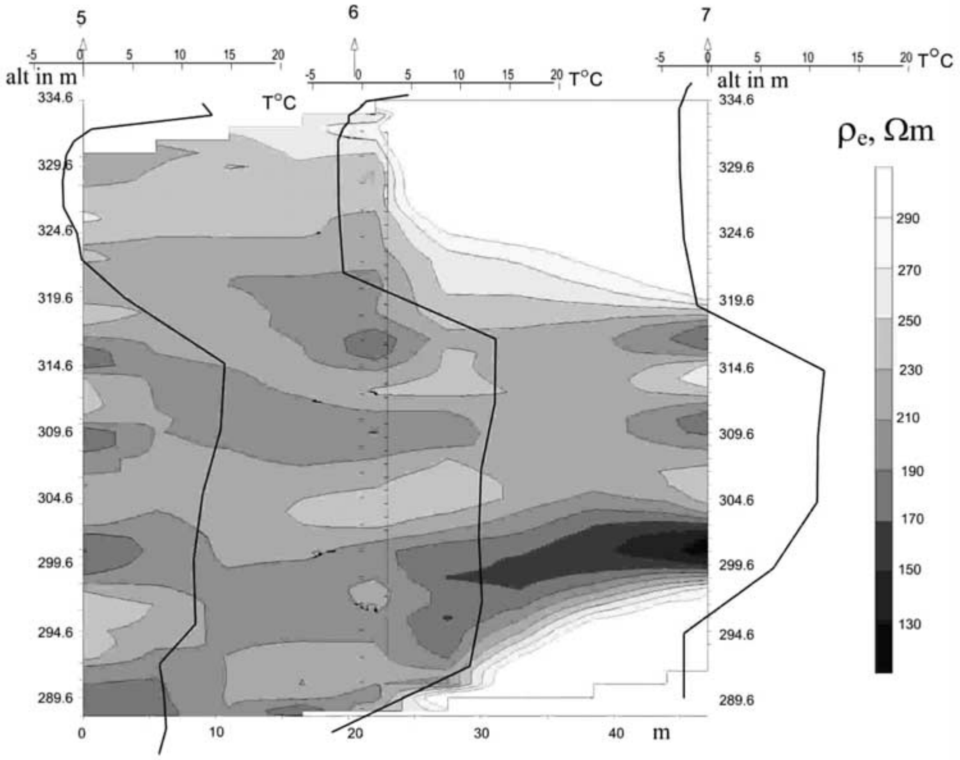

Figure 4. Example of geoelectric section of effective resistivity (portion of a 3D map) obtained from the field studies using the CB-RWGI technique (July 2000) between 2 boreholes (5 and 7) with the depth ~45 m. Black solid curve illustrates the results of borehole temperature measurements.

computations of the electric properties of the medium from complete equations for measuring components of electromagnetic field.

[13] As follows from equations (1) and (2), to calculate the interpretation parameters k_e'', ε_e, and ρ_e, the coefficient of measuring device (E_0) must be determined quantitatively. The latter depends on the current in the transmitting antenna and effective lengths of transmitting and receiving antennae. Measuring and recording the transmitter output current makes it easier to control the stability of this parameter and, if necessary, to make corresponding corrections during the data processing. To assess the spatial distribution of absorption properties within the inter-hole space, both 2-D and 3-D approaches to solving the inverse problem are used. The electric anisotropy of the medium can be found from the angular dependence of the absorption coefficients. The data can then be used to construct a 3-D geoelectric map of the site, using the technique of wave reconstruction. The map may be presented as a set of horizontal sections and arbitrarily oriented cross sections, with isolines of ρ_e and/or ε_e. Field experiments have demonstrated that such cross sections can reveal a variety of characteristics about the intervening medium, including stratigraphic structure, tectonic zones, fissured and water-saturated formations, etc.

5. Examples of Field Studies in Siberia

[14] Figure 3 shows two examples of the type of results obtained by the ORWP technique applied to studies of a water reservoir in a frozen massif along a shoreline in Western Yakutia. The measurements were obtained along a profile of boreholes perpendicular to the shoreline. The geoelectric sections presented in Figure 3 were compiled using linear interpolation of ORWP data with unified coefficients of anisotropy. As seen in Figure 3a, the changes in resistivity due to the presence of water and stratigraphic variations in rock lithology are quite distinct. With increasing distance from the shoreline, the resistivity of all lithologies gradually increases (although by differing degrees) toward borehole 10. In boreholes 6 and 7, within the vertical height intervals of 311–313 m and 317–319 m, the layers show a distinct decrease in resistivity that corresponds to the measurement of above-freezing temperatures within these intervals during the summer of 2000. Above freezing temperatures were measured for the first time in borehole 10 in August 2001. On the whole, the regularity revealed in the change of electric resistivity as a function of depth reflects the thawing of frozen ground due to the heat transported by the percolation of meltwater into the frozen massif. Comparison of geoelectric and temperature cross-sections obtained in August 2001 show that the zero-degree (Celsius) isotherms follow the base of the high resistivity layer in the 322–324 m interval. The geoelectric cross section of ε_e (Figure 3b) indicates that the layers with the highest values of ε_e (311–314) and (317–319) correspond to intervals possessing high above-freezing temperature gradients, as measured on August 2001. The higher values of ε_e recorded near borehole 6 in the interval 306–309 m also coincide with a local anomaly of above-freezing temperatures. Considered in total, the data suggest that the layers with high ε_e values are the routes of the most active water filtration.

[15] The correlation between electric resistivity and temperature, obtained at another location at the same site, is clearly seen in Figure 4. Here the boundary between frozen and thawed ground is clearly revealed by the data from cross-hole measurements performed in July 2000. Using this procedure, we can outline many of the same features seen in the previous section, but changes in the electric properties of the medium (between the boreholes) are seen in greater detail.

6. Conclusion

[16] A comparative analysis of in situ temperature data and the electrical properties of soils, as measured in boreholes during the period from July 2000 to August 2001, illustrates how the RWGI technique can be used to investigate dynamic changes in the distribution and state of permafrost in Siberia. This technique also appears well suited to Mars, where it could be employed in boreholes beginning at depths as shallow as $\sim 1-2$ m. It should be noted that in comparison with Mars, the Siberian results were obtained under conditions of fairly high temperature (i.e., within a few degrees of the freezing point), yielding relatively small changes in electric properties between the frozen and thawed state. For the much lower temperatures expected in the shallow subsurface of Mars, changes in the electric characteristics of permafrost are likely to be much more distinct. For these reasons, we recommend that the use of RWGI be considered as a reliable technique for measurements of the electric characteristics of frozen rock and soil formations on Mars.

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