Modeling Frequency Dependences of Surface Impedance on Geoelectrical Structure of Frozen Ground in Range 1-10^8 Hz

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Abstract. The results of numerical modeling of frequency dependence of permafrost surface impedance in a band of 1 Hz to 100 MHz are shown for typical geoelectric sections (GESs) of Central Yakutia. Particular qualities of frequency dependence are represented by oscillation values in a wide frequency band. The role the displacement and conduction currents in permafrost for the given range of frequencies play is marked. Two main bilayer models of permafrost are discussed: weak-inductive and strong-inductive models. Additional three-six layer models are considered along with indication of their particular qualities and conformity with natural sections. The influence of effect of thin conductive layer in permafrost is shown by sites long half-period occurrence of oscillation of impedance module and argument values, caused by displacement currents predominance in the horizon of frozen mellow sediments and by conduction currents outweighing in the underlying horizon. One marks the significance the phase curves when used for determination of GES type under condition of approximate automatic interpretation of radio impedance and RMT methods data.

1. Introduction

Sharp difference (by a factor of 10 or more) in specific electrical resistance (SER) of horizontal layers appears to be a particular feature of geoelectric section in permafrost zone [1-4]. The difference is caused by a much higher SER value of a horizon of icy frozen mellow sediments (1000-30000 Ohm-m) in comparison with SER values of either underlying horizons of frozen and thawed bedrocks (100-3000 Ohm-m), or bridging horizon of seasonally thawed mellow sediments (20-100 Ohm-m). At the same time, values of relative permittivity for permafrost are quite stable (7-12 units) with small differences. The condition of the SER sharp difference makes it possible to apply effective high-frequency electrical prospecting techniques of geophysics, in particular, the method of surface impedance frequency sounding [5] in a radio wave band (radio comparison and direction finding) [6, 7], generally known as radio impedance [8] or radimagnetotellurics (RMT) [9, 10] sounding.

Besides the dramatic change in the SER values of known horizons, the permafrost zone has several structural features greatly affecting surface impedance. Thus, while conducting regional research on the territory of Yakutia in a frequency band 10...900 kHz, numerous radio impedance soundings have established a presence of thin conductive layer in the permafrost zone [11, 12]. Manifestations of the phenomenon were observed in different parts of frequency band. They demonstrated both substantial phase shift between electric and magnetic horizontal components of the field (45-80°) and increased
slope steep (> 26°) of frequency dependence asymptote of impedance module in logarithmic scale [13].

2. Methodical features

For bilayer models, in simple cases, one can apply an analytical approach to analyze the influence of lamination. However, generally, laminated models – when taking into consideration perception complexity of physical consequences of lamination influence expressed through multilink recurrence formulas, and when studying patterns of influence of main horizons’ parameters on surface impedance of permafrost zone – require applying of numerical modeling. This refers to computation of surface impedance of laminated environment sorting out variants of layers parameters allowable changing on the basis of developed models of geoelectric construction and typical geoelectric sections (GESs) of the permafrost. Frozen bedrocks (FBR) are taken for datum for permafrost modeling. The FBR capacity is determined by a depth of ground freezing; for Central Yakutia the capacity index is 200-300 meters below the surface. The known example of a thawed zone horizon, which changes its impedance frequency dependence at frequencies below 30 kHz, is thawed bedrocks (TBR) with the SER index band of 100…1000 Ohm·m. The horizon of frozen mellow sediments (FMS), overlapping FBR, is complicated in its structure, heterogeneous for different areas of Central Yakutia and is understudied in respect of geoelectricity. In certain areas, the FMS capacity index reaches a 150 meters value. Seasonally thawed layer (STL) of mellow sediments is easily available for study and is always present during warm seasons. The STL capacity index for this region is 2 m. It makes a significant impact on surface impedance throughout the entire frequency band. Besides the specified horizons, the modeling FMS zone of permafrost included intermediate layers: a thin conductive layer (TCL) and a thin poorly-conductive layer (TPCL).

Influence of those layers has been revealed, occurrence depth of which is simultaneously located within the active part of the underlying permafrost and is less than skin-layer thickness for this frequency [14].

Surface impedance of homogeneous isotropic non-magnetic ground, as a complex quantity, can be represented by a well-known formula [15]:

$$Z = \frac{120\pi}{\sqrt[4]{(\omega \varepsilon)^2 + \sigma^2}} e^{i 0.5 \arctg(\omega \varepsilon / \sigma)}$$

(1)

Here, the module of the surface impedance is:

$$|Z| = \frac{120\pi}{\sqrt[4]{\varepsilon^2 + (\sigma / \omega)^2}}$$

(2)

and its argument or phase is presented by:

$$\arg Z = 0.5 \arctg(\omega \varepsilon / \sigma)$$

(3)

Correlation between displacement currents and conduction currents in expressions (2-4) determines the nature of module and argument surface impedance frequency dependence.

Substituting expression (1) in (4), we get that:

$$\frac{\omega \varepsilon}{\sigma} = \tan(2 \arg Z)$$

(4)

This implies that if conduction currents prevail in homogeneous environment, then \(\arg \delta \geq 42°\) and if bias currents – then \(\arg \delta \leq 3°\).
Numerical modeling is conducted – using parameters of typical (GESs), known by results of electrical prospecting at constant current – to investigate the impact made by laminated permafrost upon surface impedance. Module and argument (phase) surface impedance of laminated permafrost models’ surface impedance have been calculated using (2, 3) expressions taking into consideration a correction factor that estimates layers influence by a well-known recurrence relation [16]. Computations are made considering bias currents. Values are derived for alternatives network in a frequency band 1 Hz – 100 MHz. Varying GES parameters and taking into consideration electrical properties of frozen and thawed bedrocks, primary patterns of frequency dependence changing are established [11, 17].

3. Results and discussion

Radio impedance sounding uses a field of removed radio stations in a frequency band of 10-1000 kHz. The modeling of frequency dependence of permafrost’s surface impedance – conducted in the wider band from 1 Hz to 100 MHz – allowed obtaining complete frequency curves that led to ambiguous results.

Complete curves of surface impedance frequency dependence of permafrost denote more or less oscillation pronounced of impedance’s module and phase values along corresponding values for homogeneous half-space with electrical parameters of one of the layers. The layer is determined by its decisive role within the limits of skin-layers’ thickness for a frequency given. Oscillations are brought about by overlay of fields and emerge when different current types – displacement or conductivity – prevail in neighboring layers.

In his work, Bulgakov [18] explains the emergence of oscillations of surface impedance by interference of a direct and layer boundary reflected fields. He noted, that «surface impedance of bilayer environment shows oscillating properties at those frequencies on which displacement currents outweigh conduction ones in the upper layer».

The statement requires certain clarification. At first, emerging of oscillations of surface impedance of bilayer environment simultaneously requires a) displacement currents prevailing in the upper layer and b) conduction currents outweigh in the bottom layer. In the second, surface impedance is subjected to oscillations also at those frequencies on which conduction currents prevail in the upper layer, and displacement currents – in the bottom one layer.

Traditionally, one describes simple models of permafrost’s geoelectrical construction by two types of bilayer models: weak-ductive and strong inductive models. These names, originating from the theory of radio wave propagation, are analogous to terms referring to argument of complex impedance which are being used in the electric circuit theory, [19]. Models correspond to sections with conduction currents predominance in one of the layers (inductivity analogue) and with displacement currents outweighing in the other (electrical capacity analogue).

Having bilayer permafrost presented as electric circuit with distributed parameters, we obtain a series connection of either inductivity or electrical capacity, or vice versa. By capacity, we mean poorly conductive horizon of frozen mellow sediments, by inductivity – STL conductive horizon, or FBR relatively conductive horizon. Similarly to resonance in serial electrical circuit we obtain in first approximation two models of the permafrost zone. These bilayer models are considered as a basis for the following interpretation of frequency dependencies of module and argument of the laminated permafrost surface impedance.

Weak-ductive bilayer model (conductor on insulator) induces normal or low slope of frequency dependence curve of a module of surface impedance at low and average frequencies. Further frequency increasing makes the module value of the surface impedance with oscillation approach a curve corresponding to the upper layer (figure 1). Its’ argument value first decreases from 45° to 0° along with frequency’s amplifying, and then, increasing with oscillation, approaches the upper layer curve and remains oscillating around it with low amplitude (figure 1). The shapes of frequency dependencies are caused by a) outweighing of conduction currents in the upper layer with a low capacity in comparison with thickness of skin-layer, and b) by displacement currents predominance in
the bottom layer. In nature, the model complies with potent FMS horizon, overlapped by a thin layer of thawed mellow sediments with low SER value.

Strong-inductive bilayer model (insulator on conductor) at frequencies < 1000 kHz reveals increased slope steepness of frequency dependence curve of surface impedance (>27°) module and argument, both of which are continuously growing from 45° to 90° with increase of low and average frequencies. These forms represent entries, which at high frequencies turn into oscillations of values along the curves corresponding to the upper layer (figure 2). Such forms of frequency dependencies of module and argument of surface impedance appear to be a considerable manifestation of oscillation. At low frequencies, these forms represent oscillation maximums stretched over frequency scale. One can observe smooth oscillations when displacement currents slightly prevail over conduction ones in the upper layer, and in the bottom layer – conduction currents outweigh.

![Figure 1](image1.png)

**Figure 1.** Frequency dependence of module and argument (phase) surface impedance:
1 – weak-inductive bilayer model \( (\rho_1 = 50 \text{ Ohm}\cdot\text{m}, h_1 = 1\text{ m}, \rho_2 = 10000 \text{ Ohm}\cdot\text{m}) \);
2 – homogeneous half-space \( (\rho = 100000 \text{ Ohm}\cdot\text{m}) \);
3 – homogeneous half-space \( (\rho = 50 \text{ Ohm}\cdot\text{m}) \).

Strong-inductive model tends to have a greater scope of oscillation amplitude. As field frequency increases, oscillations become more vivid due to their period reduction. Under greater capacity values of the upper layer (> 20 m) oscillations shift toward low-frequency area, and their amplitude rises (figure 2). The model predicts existence of a much more conductive layer under homogeneous permafrost in absence of seasonal thawing. Depending on frequency, conductive horizon can be represented by any of the following. For low frequencies (<30 kHz) – it is a subpermafrost horizon of thawed bedrocks. For average and high frequencies (>30 kHz) – by potent interpermafrost thawed, aquifer, microfine or salted horizon in mellow sediments. This model corresponds more to widespread natural GESs of permafrost zones, than weak-inductive does. When field frequency increases to values indicating displacement currents predominance in the upper layer and excluding the bottom layer’s influence, oscillations of impedance’s module and argument become to damp and they approach horizontal asymptote. According to (3, 4), asymptotic value of impedance’s module will equal \(120\pi/\sqrt{\varepsilon}\); argument’s asymptotic value – 0°.

Implementation of numerical approach has revealed the following patterns common for both types of bilayer oscillation models.
1. Either enlargement of occurrence depth of the bottom layer, or conductivity reduction of the layers’ contrast band, leads to frequency drop of oscillation occurrence as well as to oscillation period decrease.
2. Either the bottom layer’s occurrence depth reduction, or conductivity enlargement of layers’ contrast band, results in magnifying of oscillation amplitude scope.
3. Longitudinal conductivity, lowering values of impedance’s module, is assumed to be the parameter that determines the influence of the upper conductive layer. The impact, referring to the upper poorly-conductive layer, is determined by its longitudinal resistivity that amplifies values of impedance’s module.

**Figure 2.** Frequency dependence of module and argument (phase) surface impedance:
1 – Strong-inductive bilayer model \( (\rho_1 = 10000 \text{ Ohm} \cdot \text{m}, h_1 = 1\text{m}, \rho_2 = 50\text{Ohm} \cdot \text{m}) \);
2 – homogeneous half-space \( (\rho = 10000 \text{Ohm} \cdot \text{m}) \);
3 - homogeneous half-space \( (\rho = 50\text{Ohm} \cdot \text{m}) \).

Next, three-six layer models, which are based on considered bilayer oscillation models, approach natural permafrost zones.

Three-layer model represents bilayer strong-inductive model supplemented with overhead thin conductive layer with capacity of 0.5-2 meters and SER value equal to 20-100 Ohm-m. The model characterizes main horizon of frozen bedrocks, overlapped by frozen mellow sediments with seasonally thawed surface that corresponds to the most common types of GES of permafrost. Supplementing an overhead conductive layer reduces oscillations’ amplitude caused by dominance of different current types in STL, FMS and FBR (curves’ label «1» on figure 3). Increase of STL longitudinal conductivity results in reduction of oscillations’ amplitude. It occurs due to the fact that STL.

**Figure 3.** Frequency dependence of module and argument (phase) surface impedance:
1 – three-layer model; 2 – four-layer model; 3 – five-layer model; 4 – six-layer model.
Four-layer model conforms to permafrost with a mellow sediments base surface that intrudes a thin conductive layer (TCL). In this case, TCL can be represented by cryogenic residuum or by microfine sediments. TCL intrusion amplifies amplitude of both modules’ oscillation and surface impedance’s argument (curves’ label «2» on figure 3).

Five-layer model is formed by TCL intrusion in FMS of three-layer model. This is consistent with the presence of either microfine sediments or aquifer, or cryopeg in FMS [12]. Conductive layer intrusion on a depth, less than that at which FBR horizon is located, leads to large amplification of both amplitude and period of oscillations of surface impedance’s module and argument at average frequencies (curves’ label «3» on figure 3).

Besides, five-layer model can as well reflect a situation when intermediate layer in FMS is formed by frequency dispersion of electrical conductivity [20] as result of presence of thin layers of ice.

Six-layer model represents permafrost with FMS intrusion that encompasses double-level TCLs (taliks, cryopegs). Superposition of oscillations that lead to substantial phase shifts in a band of low and average frequencies, is a typical feature of six-layer models (curves’ label «4» on figure 3).

As both formulas, describing homogeneous half-space (2), and numerical modeling results of laminated environments, frequency dependence of surface impedance’s argument, rather than of module, is mainly characterized by proportion of and displacement conduction environment currents. Thus, interpretation of phase data at radio impedance sounding gains particular importance.

4. Conclusion
The extent of oscillations along homogeneous half-space values with electrical parameters, related to the main layer, determines the shape the frequency curves of module and argument (phase) of permafrost’s surface impedance take. The oscillations are caused by predominance of bias currents in one of the permafrost’s main layers, and of conduction currents – in the other. Depending on these horizons’ mutual location, one differs GESs with weak- or strong-inductive properties.

Main bilayer models (weak-inductive and strong-inductive correspondingly) proposed are able to describe any GESs of the permafrost in respect with the impact the overlapping and underlying layers have within the limits of the skin-layer thickness.

Measurement data of argument (phase) of surface impedance is of great importance at radio impedance sounding of permafrost in a frequency band of 10…1000 kHz. Phase data has considerable interpretation abilities that allow efficient determination of the GES type.

Manifestation of TCL effect in permafrost can be explained by areas of half-period occurrence of oscillation of impedance’ argument and module values, caused by The extent of oscillations along homogeneous half-space values with electrical parameters, related to the main layer, determines the shape the frequency curves of module and argument (phase) of permafrost’s surface impedance take. The oscillations are caused by predominance of bias currents in one of the permafrost’s main layers, and of conduction currents – in the other. Depending on these horizons’ mutual location, one differs GESs with weak- or strong-inductive properties.

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References

[1] Borovinsky V 1969 Electro- and seismometrice researches of permafrost of mountain breeds and glaciers (Moskow: Science) p 183
[2] Snegirev A 2002 Pile electrometry of permafrost zone in lithosphere (Moskow: publishing house SIP RIA) p 274
[3] Nekrasov I 1974 Regional distribution of permafrost breeds Permafrost-hydro-geological conditions of East Siberia (Novosibirsk: Science) pp 46-58
[4] Photiev S 1989 A structure and capacity of permafrost of breeds Geocriology USSR. Average Siberia (Moskow: Nedra) pp 261-263
[5] Berdichevsky M 1968 Electrical prospecting by means of MT profiling (Moscow: Bowels of the Earth)
[6] Veshev A and Egorov V 1966 About methodology of observation and interpretation of results of broadcast stations’ fields study Questions of geophysics. Scientific notes vol 16 (LGU) pp 172-189
[7] Gordeev G, Sedelnikov E and Tarhov A 1981 Electrical prospecting by means of radio comparison and direction finding (Moscow: Bowels of the Earth)
[8] Efremov V N 2013 Radioimpedance sounding of frozen ground (Yakutsk, Russia: Melnikov Permafrost Institute SB RAS) p 204
[9] Tezkan B and Saraev A 2008 New broadband radiomagnetotelluric instrument: applications to near surface investigations Near Surface Geophysics 6 pp 245-252
[10] Saraev A, Simakov A, Shlykov A 2014 Rariomagnetotelluric soundings method with a controlled source The Russian Geophysics Journal 1 pp 18-25
[11] Efremov V 1995 Surface impedance of cryolitozone at radio frequencies Geophysical investigations in Yakutia (Yakutsk, Russia) pp 70-80
[12] Efremov V 2006 About opportunity of application of thin conductive layers in permafrost grounds for rational grounding execution Power stations 1 pp 62-64
[13] Efremov V 2003 Central Yakutia grounds’ electrical features in a radio wave field Results of geocryological investigations in Yakutia in XX century in Prospects for further development (Yakutsk, Russia) pp150-167
[14] Efremov V, Dedyukina N and Shastkevich Y 1987 Thickness of an active part of underlying permafrost VLF-LF band Propagation of –km band radio waves (Apatity, Russia) pp 82-84
[15] Dolukhanov, Radio waves propagation (Moscow: Bond) 1972
[16] Tsydympov C, Tsydenov V and Bashkuev Y 1979 Investigation of electrical properties of underlying environment (Novosibirsk: Science)
[17] Efremov V 2007 Theoretical and experimental aspects of permafrost radio impedance sounding results interpretation Science and Education vol 48 (Yakutsk, Russia) pp 97-103
[18] Bulgakov A and Rysakov V 1962 About opportunity of application of electromagnetic high frequency oscillations in exploration geophysics Problems of diffraction and wave propagation 1st issue (G.I. L) pp 143-150
[19] Gyunninen E and Makarov G 1966 Field of point dipole over impedance surface Problems of diffraction and wave propagation 5th issue (G.I. L) pp 97-120
[20] Berdichevsky M, GubatenkoV and Svetov B 1995 Frequency dispersion of electrical properties of macro anisotropic environment Physics of the Earth vol 9 (Moskow: Science) pp 42-48