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Improving of electrical channels for magnetotelluric sounding instrumentation

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Abstract

The study of deep structure of the Earth's crust is of great interest for both applied (e.g. mineral exploration) and scientific research. For this the electromagnetic (EM) studies which enable to construct the distribution of electrical conductivity in the Earth's crust are of great use. The most common method of EM exploration is magnetotelluric sounding (MT). This passive method of research uses a wide range of natural geomagnetic variations as a powerful source of electromagnetic induction in the Earth, producing there telluric currents variations. It includes the measurements of variations of natural electric and magnetic fields in orthogonal directions at the surface of the Earth. By this, the measurements of electric field are much more complicated metrological process, and namely they are limiting the precision of MT prospecting. This is especially complicated at deep sounding when measurements of long periods are of interest. The increase of the accuracy of the electric field measurement can significantly improve the quality of MT data. Because of this the development of new version of instrument for the measurements of electric field at MT – both electric field sensors and the electrometer – with higher relative to the known instruments parameters level were initiated. The paper deals with the peculiarities of this development and the results of experimental tests of the new sensors and electrometer included as a unit in the long-period magnetotelluric station LEMI-420 are given.

1 Introduction

The study of deep structure of the Earth's crust is of great interest for both applied (e.g. mineral exploration) and scientific research. The most common method of EM exploration is magnetotelluric sounding (MT) method proposed by Tikhonov (1950) and Cagniard (1953) in the 50s of last century. This is a passive method of research, which uses a wide range of natural geomagnetic variations as a powerful source of electromagnetic induction in the Earth. MT technique includes the measurements of variations of natural electric and magnetic fields in orthogonal directions at the surface of the Earth. Then the conductivity structure of the Earth's crust is determined by the obtained data processing. As a result the geoelectric cross-section for the depths from several tens of meters to several hundred kilometres is constructed (Simpson and Bahr, 2005).

Like other methods, MT has its limitations. Particularly, the 3-D models analysis which is built on the basis of magnetotelluric data shows that the distribution of electrical conductivity in the deep or subsurface structures which contain conducting inclusions makes it possible to select the faults based on the MT data only in cases of the fault's great length. Furthermore, the magnetotelluric data interpretation is greatly complicated by 3-D subsurface heterogeneity. Fault zone with high electrical conductivity cause vertical redistribution of telluric currents, which in turn leads to an increase in the MT field response from the conductive zones in the Earth's crust which makes the interpretation difficult.

It is known that the measurement of the electric field is the biggest problem during the MT. At the present stage of instrumentation technique development it is possible practically to reduce the influence of the accuracy of magnetic measurements on MT results to a negligible level. At the same time the electrical measurements, in particular for deep research when the measurements are required for a long time, are serious methodological and hardware problem (Chave and Jones, 2012). First of all, this is due to quite small values of the measured variations of the electric field compared to the so-called contact potential arising at the interface of the contact of the electrode with the environment. Figure 1 shows the evaluation of the level of natural variations of the electric and magnetic fields, taken from Serson (1973). Because of the complex electrochemical reactions occurring at the electrode surface, the magnitude of the contact potential, and especially its instability, they both essentially depend on a number of physical and chemical processes in the environment.

The first method to reduce the influence of the contact potential difference instability, that is increasing the signal/noise ratio in electrical measurements, is to increase the distance between the measuring electrodes (length of electrical lines). This solution gave a positive result under deep MT which allowed estimate conductivity up to the Earth's mantle (Egbert and Booker, 1992; Semenov et al., 2008). But it is not always applicable, especially when working in populated or mountainous areas where you cannot expand the long lines for the necessary long time. Another approach is to improve the quality of the measuring electrodes and electrical channels of MT stations by reducing the level of their own noise, sensitivity and temporal stability increasing. This paper is dedicated to this second approach implementation.

2 Analysis, design and implementation of electrical measurement channel

For the measurements of the electric field in geophysics the so-called "non-polarized" electrodes are used. By this it is assumed that these electrodes are not chemically interacting with the environment and provide low drift during long-run measurements of the electric field, what is not true. In reality, between the electrode surface and environment in which the electrode is immersed there is always electrochemical interaction creating so called polarization potential of the electrode. Measuring electric field as the potential difference between two electrodes, we always have at the electrode pair output the voltage equal to the sum of the useful signal proportional to the electric field value in the environment and difference of such polarization potentials. By this the second term in practice is much greater than the useful signal. There are many works devoted to the investigation of the electrochemical interaction of the electrode with the surrounding conducting medium and to the methods to decrease the polarization potentials, e.g. Frumkin et al. (1952), Conway (1965), Yu and Ji (1993). As an issue of their finding, we may state that in order to minimize the polarization effect the electrodes have to be manufactured using the metal immersed in its salt, and then the salt has to be in contact with the ground. The most common in geophysical practice are the electrodes from the following manufacturers: GMC (Ag-AgCl), Phoenix Geophysics (Pb-PbCl), GISCO (Cu-CuSo$_4$) and BGP (Pb-PbCl), and recently LEMI (Cu-CuSo$_4$).

For these electrodes the magnitude of the contact potential difference when immersed in a conductive medium that models the wet soil was determined experimentally (Table 1). But, as it was stated above, for MT the most important parameter is not the contact potential difference value, but this difference change with time and temperature. This quantity determines the quality of the electrodes, and the accuracy and interpretation of measurements depends on it. However, this parameter was never given in the technical documentation for the electrodes; the only published data were found in Petiau (2000). For described here in lead electrode and its salt (Pb-PbCl) temporal drift is about 1 mV month^{-1}, what requires, if to see Fig. 1 for reference, the electric line length at least ∼ 1000 m if we wish to have the same order of magnitude of the measured daily variations of the electric field, what is difficult to realize in practice.

Recently new regulations in Europe require the elimination of lead and its composites of use. This fostered to resume the study of other possible materials and structures of the electrodes. As a starting point, the electrode on the basis of copper and copper sulphate (Cu-CuSO$_4$) was adopted. The shortcomings of such a construction of non-polarized electrode based on the combination of Cu-CuSO$_4$ were studied (Korepanov et al., 2007) and in the result a new improved design of non-polarized LEMI-701 electrode was proposed (www.isr.lviv.ua).

Geophysical electrodes LEMI-701, except environmental safety (Cu salt works as fertilizer) possess significant advantages as compared with lead electrodes. For comparison, the measured noise level of randomly selected pairs of electrodes LEMI-701 is ∼ 20 nV at 1 Hz vs. 0.4 mV for Pb-PbCl (Petiau, 2000). For matched pairs after calibration and specially designed selection procedure average drift over 4 months was 50–60 µV for LEMI-701 (Korepanov et al., 2007), see Fig. 2, against 1 mV month^{-1} for Pb-PbCl electrodes (Petiau, 2000). With such level of the drift the requirements to the electrode line length become much more practical: referring again to the Fig. 1, we may conclude that the baseline about 50–60 m is already admissible to get signal/noise ratio for diurnal variations close to unity.

Apart the electrodes, the parameters of the used measuring equipment – electrometer – also play important role in improving the quality of the electric field measurement. A number of specific requirements should be taken into account at such instrument design because it must measure signals with periods ranging from fractions of seconds to about 100 000 s with minimal error in field conditions at sufficiently large environmental temperature variations. By this the very important requirement is the absence of the currents in the input circuits – if they are flowing through the electrodes and ground, they are infringing the electrochemical equilibrium at the contact surface "electrode-environment". Simultaneous demands to transmit of practically DC signals and input current minimization greatly complicate the task of electrometers development. To solve this task the sophisticated technology of input circuits galvanic isolation while simultaneously meeting the requirements of high input resistance is used. To this, as the Fig. 1 gives, the sensitivity threshold of the electrometer should not exceed $0.1\,\mu\mathrm{V\,m^{-1}}$ in order to provide sufficient accuracy. Typically the length of the measuring line is selected in the range of 50 to 200 m, which gives the minimum input signal level about 0.05 mV while soil resistance can reach up to several hundred kohm (for frozen ground). Depending on the soil resistance and the electrodes quality the initial level of the input signal can reach hundreds of mV, we will reserve a maximum value equal to 1 V. Also as much as possible low power consumption is an essential requirement.

Last but not least is the necessity to have the protection of input stages from nearby lightnings being often during field season – the long electric line presents an excellent antenna to create large voltages at its output at nearby lightning discharge.

All these requirements were taken into account at the development of an electrical channel of a new MT station LEMI-420 (www.isr.lviv.ua). The functional diagram of the LEMI-420 electrical channel is presented at Fig. 3. Such an electrometer has an extended measurement range of the input signal up to ±2450 mV, its sensitivity threshold is reduced to 0.08 µV, and the power consumption is less than 110 mW for four channels. The frequency response of the electrometer may be selected from the pre-programmed versions or to be controlled by the user. This paper presents the electrometer with the following parameters: gain is equal unity; digitizing frequency is equal to 225 Hz (these samples are averaged to 1 Hz). There are also following advantages of this design: the possibility to use low-pass digital filter with the desired frequency band and suppression factor, and to change the channel gain with a corresponding decrease of the input voltage operating range. Other advantage is the compensator absence: having the amplification factor only unity, this allows covering all really possible initial shifts of input voltage, and this also helps to reduce own noise level at low frequencies. Reduction of power consumption is achieved by using both galvanic separation in digital part of the circuit and galvanic isolation in power supply. In this case the electrodes potentials are measured relatively galvanically isolated ground.

Table 2 shows the comparative parameters of the MT stations of the leading producers at the world market. We selected MT stations with flux-gate magnetometer (FGM) only because we concentrate our study on the instruments for long-period survey.

3 Field tests results

To confirm the advantages of MT station LEMI-420 electric channels the comparative field tests with previous version of the MT station LEMI-417 were made at the site near the village of Kobaky, Ivano-Frankivsk region.

Special attention was paid to the electrodes installation, what is necessary for long-term measurements. First, the proper selection of places where the electrodes have to be buried was made: as much as possible similar places for the arrangement of two electrodes composing one measuring line were found using following principal requirements: the same soil composition and orographic features (i.e. hill-hill or valley-valley, under the tree-under the tree etc.) and especially moisture conditions. The setting of the LEMI-420 and LEMI-417 electrical lines is presented at Fig. 4.

To avoid daily thermal variations the holes depth for electrodes installation was made about 70–80 cm. There are two ways to install the electrodes at field works: "bottom-up" for long-term installations, more than one week (see Fig. 5a), and in tilted position for short time (see Fig. 5b). When preparing installation, the suspension has to be first prepared: it is made mixing the made ground taken from the installation place and 10 % $CuSO_4$ solution in quantity enough to cover the electrode.

The advantages of “bottom-up” installation are, first, that the surrounding soil in this position with time is permanently well contacting with the sensitive part of the electrode–porous partition (opposite to cable part on Fig. 5), and in tilted position the soil, though makes better contact with the partition than in direct position, but may come off this part with time. For long-term installation it is recommended, after the electrode burying into the ground, to pour on this place with 10 % $CuSO_4$ solution. Taking into account that Cu salt works as fertilizer, this will not spoil the environment, in contradistinction with salt solution used for Cl-based electrodes as above. For sandy soil, a special arrangement may be recommended if long-term installation is planned: the electrode is installed again in “bottom-up” position, but not directly in the ground, but in a plastic bucket open from above. This will save poured liquid and maintain lower resistance of the soil.

In our experiment, because the soil was clayish and the measurement time was rather short, we used installation showed on Fig. 5b. To verify the installation reliability the electrodes pair resistance was checked. By this very important is to avoid, as said upper, to create currents flowing through the electrodes. For this a voltmeter with input resistance ≥ 10 Mohm and $10\,\mu\mathrm{V}$ resolution and reference resistor have to be used. First the voltmeter has to be coupled to the output wires of electrodes and the voltage U_1 measured (see Fig. 6). Then to both electrodes outputs the reference resistor $R = 3$ kohm is connected for a short time and the voltage U_2 measured. The value of transient resistance R_l of electrodes to ground and soil was calculated as:

$$R_l = \frac{R(U_1 - U_2)}{U_2} \tag{1}$$

with $U_1 = 40\,\mathrm{mV}$, $U_2 = 10\,\mathrm{mV}$, $R = 3\,\mathrm{k\Omega}$ we get $R_l = 9\,\mathrm{k\Omega}$ what confirmed rather moderate soil resistance. Using of this method of resistance measuring may not always give good results. It does not work properly in areas with high electrical noise level, such as large cities, places near electric power lines, routes of electric trains. On the other hand it is no possible to obtain high quality data carrying measurements in such noisy places, so, the success of this test may also be an indicator of clean enough electromagnetic environment.

The resulting noise spectra of electric channels for various modifications of stations are shown at Fig. 7. Here curves 1 and 2 are reflecting measured natural signals spectra along x and y components correspondingly; lower curves are noise levels measured with short-circuited inputs for former versions of MT stations (curves 3 and 4) and for LEMI-420 one (curve 5) divided by the length of electrical lines used at curves 1 and 2. As it is seen, the instrumental noise of the stations under test is about the same at longer periods but LEMI-420 has considerably lower noise level at shorter periods, what is very important: if we shall refer to Fig. 1 again, we may see that just in this range the signal level is much lower than for longer periods.

4 Conclusions

Development of EM methods for studying the Earth's interior requires the improvement of resolution and precision of the measuring instruments in order to get higher quality of the interpretation of field data. It is stated that the main limiting factor in improving the MT results is low accuracy of measurement of electrical fields. So, to raise the quality of electric channels of MT stations, both sensors and electronic unit, is the way to overcome this shortcoming. A new design of non-polarizing electrodes with lower noise level and higher stability in comparison with the existing analogs is suggested. In the result of the research, the upgraded version of the electric field meter was developed and tested. This newly created electrometer is included in the long-period magnetotelluric station LEMI-420. To confirm the benefits of MT station LEMI-420 its field tests were carried out and comparison of the instrumental noise level power spectra confirmed its advantage.

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Acknowledgements. The authors are grateful to V. Tregubenko for the assistance in field tests and the results discussion.

References

Cagniard, L.: Basic theory of the magneto-telluric method of geophysical prospecting, Geophysics, 18, 605–635, 1953.

Chave, A. D. and Jones, A. G.: The Magnetotelluric Method, Theory and Practice, Cambridge University Press, 2012.

Conway, B.: Theory and Principles of Electrode Processes, Ronald Press, New York, 1965.

Egbert, G. D. and Booker, J. R.: Very long period magnetotellurics at Tucson Observatory: implications for mantle conductivity, J. Geophys. Res., 97, 15099–15112, doi:10.1029/92JB01251, 1992.

Frumkin, A., Bagotsky, V., Iofa, Z., and Kabanov, V.: Kinetics of Electrode Processes, MGU, Moscow, 1952.

Korepanov, V. and Svenson, A.: High-Precision Non-Polarized Electrodes for Geophysical Prospecting, Naukova Dumka, Kiev, 2007.

LCISR: available at: www.isr.lviv.ua (last access: 25 March 2015), 2014.

Petiau, G.: Second generation of lead-lead chloride electrodes for geophysical applications, Pure Appl. Geophys., 157, 351–382, 2000.

Semenov, V., Pek, J., Ádám, A., Jóźwiak, W., Ladanivskyy, B., Logvinov, I. M., Pushkarev, P., Vozar, J., and Experimental Team of CEMES Project: Electrical structure of the upper mantle beneath central Europe: results of the CEMES Project, Acta Geophys., 56, 957–981, doi:10.2478/s11600-008-0058-2 2008.

Serson, P.: Instrumentation for induction studies on land, Phys. Earth Planet. Int., 7, 313–322, 1973.

Simpson, F. and Bahr, K.: Practical Magnetotellurics, Cambride University Press, 2005.

Tikhonov, A. N.: About the determination of electric characteristics of deep layers of Earth's crust, Reports of Academy of Sciences of USSR, 73, 295–297, 1950.

Yu, T. and Ji, G.: Electrochemical Methods in Soil and Water Research, Perg. Press, Oxford, 1993.

Table 1. Mean parameters of the electrodes immersed in wet soil.

Electrode type	Difference of potentials	Resistance
GMC	0.86 mV	30.0 kΩ
Phoenix	1.72 mV	1.9 kΩ
GISCO	0.88 mV	1.3 kΩ
BGP	3.30 mV	1.04 kΩ
LEMI	0.06 mV (selected pair)	0.5 kΩ

Table 2. Comparative table of main MT stations parameters of leading manufacturers.

MTS/parameter	LEMI-420	NIMS	ADU-07e	KMS-820
Channel number	7	5	10	6
Magnetic field meter type	FGM	FGM	FGM (also IM)	FGM (also IM)
Frequency range	DC–0.5 Hz	3×10^{-5}–0.5 Hz	2×10^{-5}–1000 Hz	DC–50 kHz
Magnetometer noise at 1 Hz	7 pT $\mathrm{Hz}^{-1/2}$	10 pT $\mathrm{Hz}^{-1/2}$	10 pT $\mathrm{Hz}^{-1/2}$	10 pT $\mathrm{Hz}^{-1/2}$
Electrometer measuring range (amplification)	±2450 mV (1)	±250 mV (10), ±25 mV (100)	–	±2.5 V (Up to 2500)
ADC digits, bit	32	24	24	24
Electrometer noise at 1 Hz (amplification)	$< 0.08\,\mu\mathrm{V\,Hz}^{-1/2}$ (1)	$< 0.11\,\mu\mathrm{V\,Hz}^{-1/2}$ (100)	No data	$< 0.08\,\mu\mathrm{V\,Hz}^{-1/2}$ (40)
Sampling rate	1 Hz	8 Hz	4096 Hz	100 kHz
Memory volume	32 GB	4 GB	32 GB	32GB
Supply voltage	5–28 V	+12 V	+12 V	7.5–32 V

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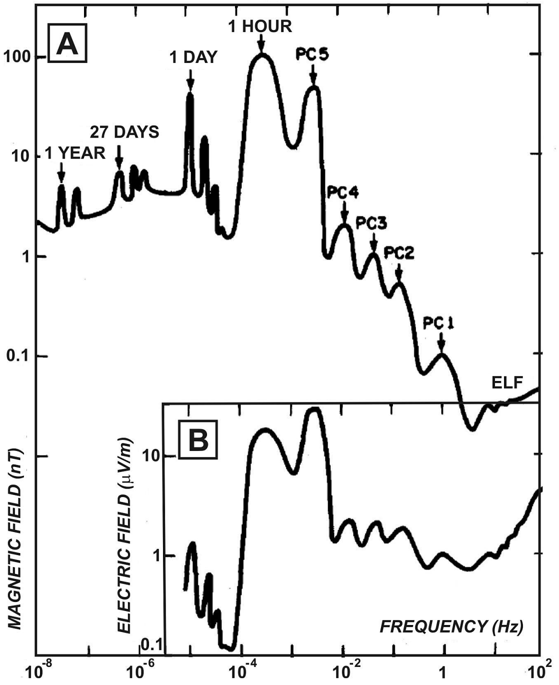

Figure 1. Natural variations of the electric and magnetic fields (from Serson, 1973).

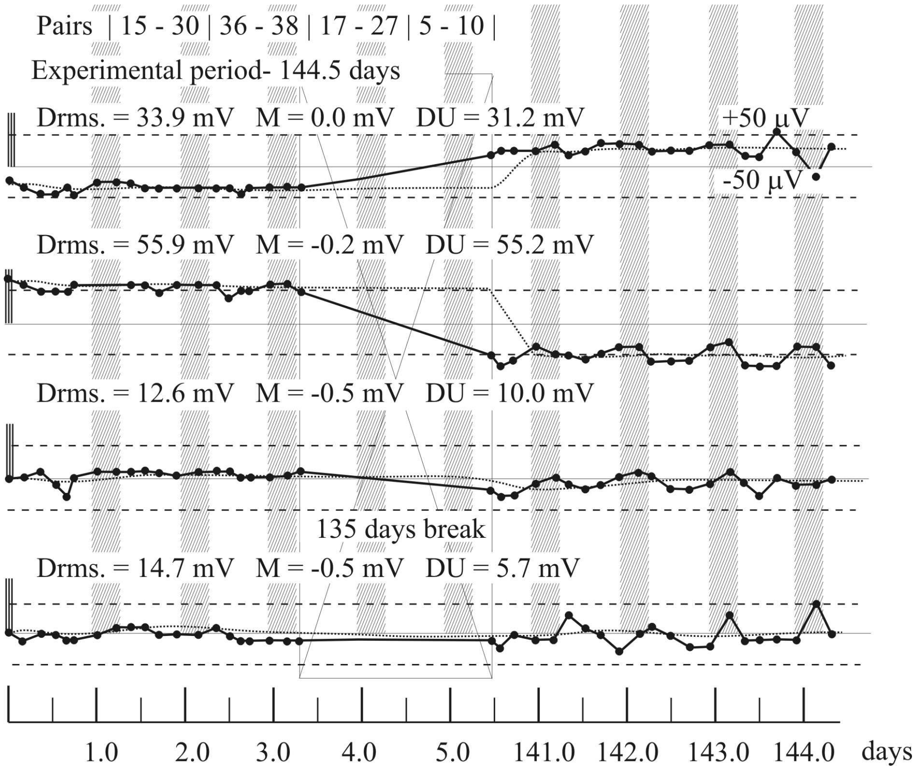

Figure 2. Long-term drift of the potential difference of selected pairs of electrodes, here: Drms – root mean square error; *M* – zero line shift; DU is averaged for one day dispersion.

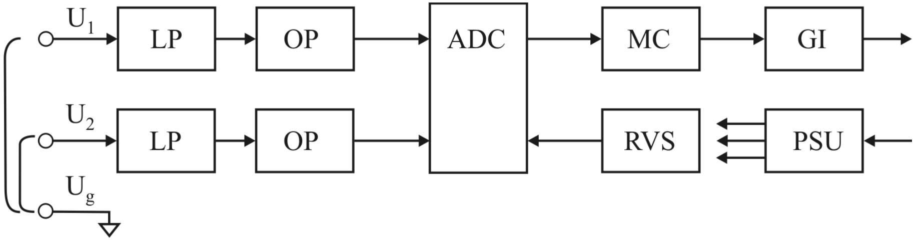

Figure 3. Functional diagram of the LEMI-420 channel for electrical measurements, here: U_1, U_2, U_g – input voltage; LP – circuit which protects against lightning induced large voltage; OP – operational amplifier; ADC – analog/digital converter; RVS – reference voltage source; MC – microcontroller; GI – galvanic isolation; PSU – power supply unit.

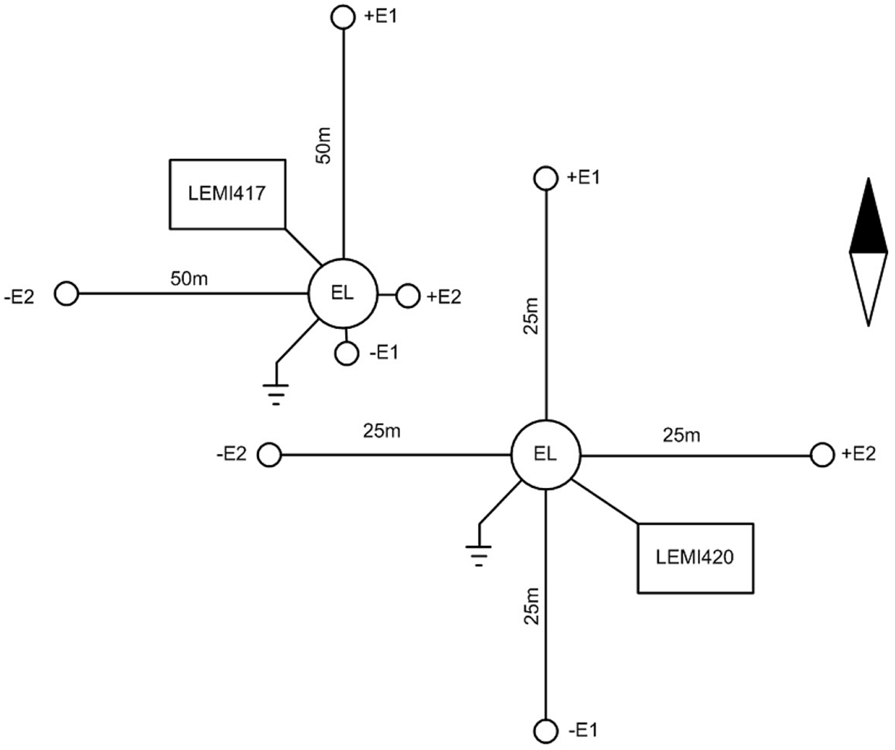

Figure 4. Electric channels setting.

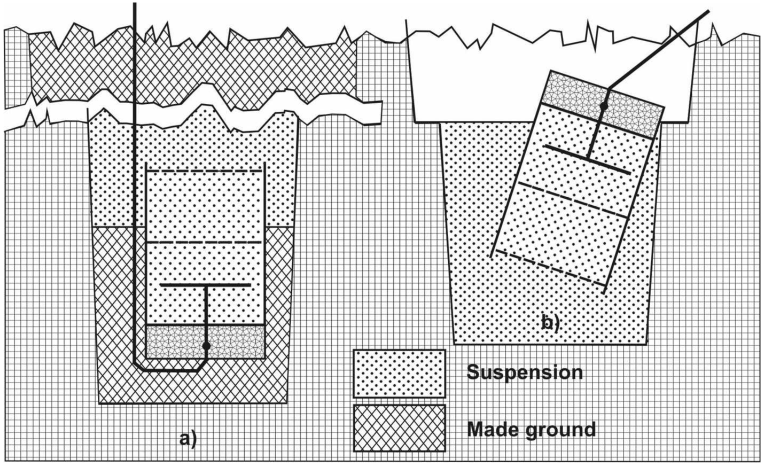

Figure 5. Electrode installation in operation position: **(a)** – long-term; **(b)** – short-term.

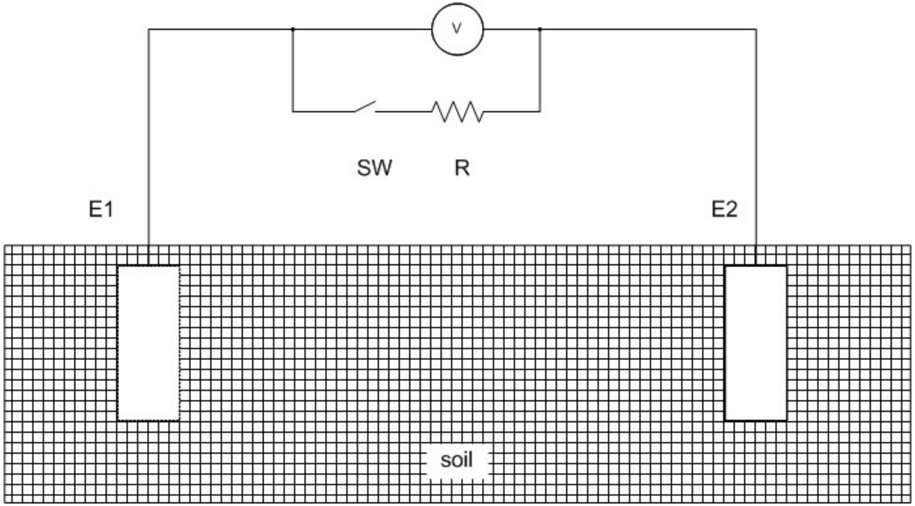

Figure 6. Electrodes resistance measurement diagram.

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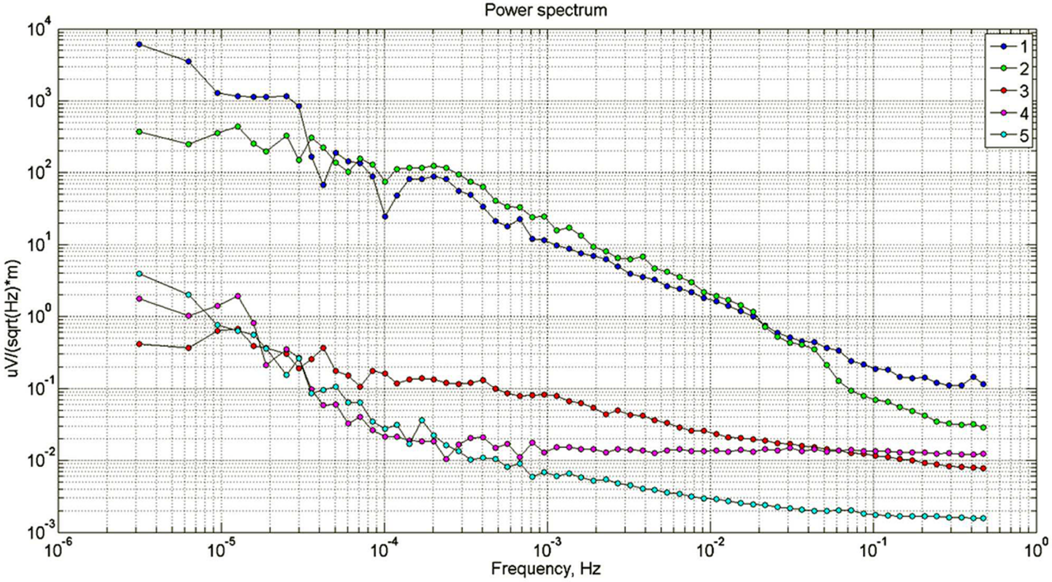

Figure 7. Power spectra of natural signals and instrumental noise levels. Here curves 1 and 2 are measured natural signals spectra along *x* and *y* components correspondingly. Curves 3 and 4 – noise levels measured with short-circuited inputs for former versions of MT stations and curve 5 – for station LEMI-420, both divided by the same inter-electrodes distance as for curves 1 and 2.