Near Surface Geophysics, 2008, 245-252

A new broadband radiomagnetotelluric instrument: applications to near surface investigations

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Received August 2007, revision accepted May 2008

ABSTRACT
A new radiomagnetotelluric (RMT) instrument has been developed that can record time series of electric and magnetic fields in the frequency range from 10 kHz to 1 MHz. Military and civilian radio stations broadcasting in this frequency range are used as transmitters. Transfer functions (e.g., apparent resistivities and phases as a function of frequency) are determined by spectral analysis using a newly developed processing software. The transfer functions presented here are the first ones ever at frequencies above 300 kHz and they can lead to a better resolution of the shallow structure. The new RMT instrument enables quick and efficient mapping of shallow structures and supports tensor measurements thereby allowing a 2D or 3D interpretation of field data. The new RMT system was tested in the laboratory and then applied successfully in the field to several environmental and engineering problems. Case studies from applications in St. Petersburg, Russia and in Uzin, Ukraine will be presented. The observed apparent resistivities and phases are reliable and they show smooth frequency dependence. The data were inverted for 2D conductivity models under the assumption that the strike direction was known beforehand.

INTRODUCTION

The radiomagnetotelluric method (RMT) is a recent method of applied geophysics and it is used extensively in connection with near surface exploration (Tezkan 1999; Bastani 2001; Linde and Pedersen 2004a; Tezkan *et al.* 2005). The RMT method uses military and civilian radio stations broadcasting in a frequency range between 10 kHz and 1 MHz as transmitters. Electromagnetic waves from these transmitters diffuse in the conductive earth and induce current systems that are connected with alternating electrical and magnetic fields. The magnetic field can be measured for selected frequencies by a coil and the electric field by two grounded electrodes or by an electrical antenna yielding information about the conductivity distribution up to several hundred metres depending on the conductivity distribution beneath the investigated area. The displacement currents can be neglected in most cases ($\rho < 1000\ \Omega$m) and the plane wave assumption is valid for observation points located at least seven skin depths away from the transmitters. Well-developed and tested magnetotelluric modelling software (e.g., Rodi and Mackie 1991; Smith and Booker 1991; Mackie *et al.* 1997) therefore can be directly applied to the RMT data. 2D inversion techniques are routinely used to derive the 2D conductivity distribution of the subsurface from the RMT data.

Successful scalar RMT measurements were carried out by using a RMT instrument developed at the University of Neuchâtel (Müller 1983; Turberg *et al.* 1994; Turberg and Barker 1996; Zacher *et al* 1996; Tezkan *et al.* 2005). Tensor RMT measurements can be realized by the Enviro-MT system (Bastani 2001; Bastani and Pedersen 2001; Linde and Pedersen 2004a,b) up to a frequency of 250 kHz. In a project funded by the European Union a new RMT instrument was developed that records time series of horizontal components of the electric and magnetic fields in a wide frequency range from 10 kHz to 1 MHz simultaneously and thus enables tensor measurements. The RMT transfer functions are derived by spectral analysis from the time series, thus enabling a multidimensional inversion of the data.

THE NEW RADIOMAGNETOTELLURIC INSTRUMENT

The new RMT instrument (Fig. 1) is a four channel system that can be used for tensor measurements. The system consists of a receiver unit, an electrical antenna to observe the electric field and magnetic coils for the measurement of the horizontal components of the magnetic field. The magnetic field measurements are performed with a magnetic coil – a cylinder with a high permeability core of about 30 cm length and a multi-section coil. The electric antenna is represented by a symmetrical dipole with two arms. The electrical line can be grounded or ungrounded. The length of this line can vary from 4 to 20 m. The cable used for the ungrounded lines should have a significant weight. Test measurements show that the transfer functions observed by using grounded and ungrounded electrical lines are consistent.

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Time series of the electric and magnetic fields are recorded in two frequency bands: one from 10 kHz to 100 kHz with a sampling frequency of 312.5 kHz and the other from 100 kHz to 1 MHz with a sampling frequency of 2.5 MHz. Time series are saved in the receiver unit and transferred to a field PC via an ethernet connection in the field. The measured time series contain all the frequencies from 10 kHz to 1 MHz associated with powerful radio stations. The user can select the gain factor, frequency range and segment length of the time series by using the acquisition software installed in the receiver. The acquisition software also makes it possible to use the so-called spectral mode in which the user can predefine the frequencies to be observed and the system then measures only transfer functions of those frequencies. In the spectral mode, the data is not transferred to the PC; they are processed entirely in the receiver unit. In addition to the software installed in the receiver used to control and carry out measurements, data processing software was developed. This software was installed on a laptop and was used for displaying and processing the observed RMT time-series. These time series can be transferred in the field via an ethernet cable to the laptop so that they can be visualized, auto and cross-spectra can be calculated and displayed quickly (Fig. 2). In this way, the quality of the data can be examined in the field. Radio transmitters are easily identified in the power spectra as strong signals

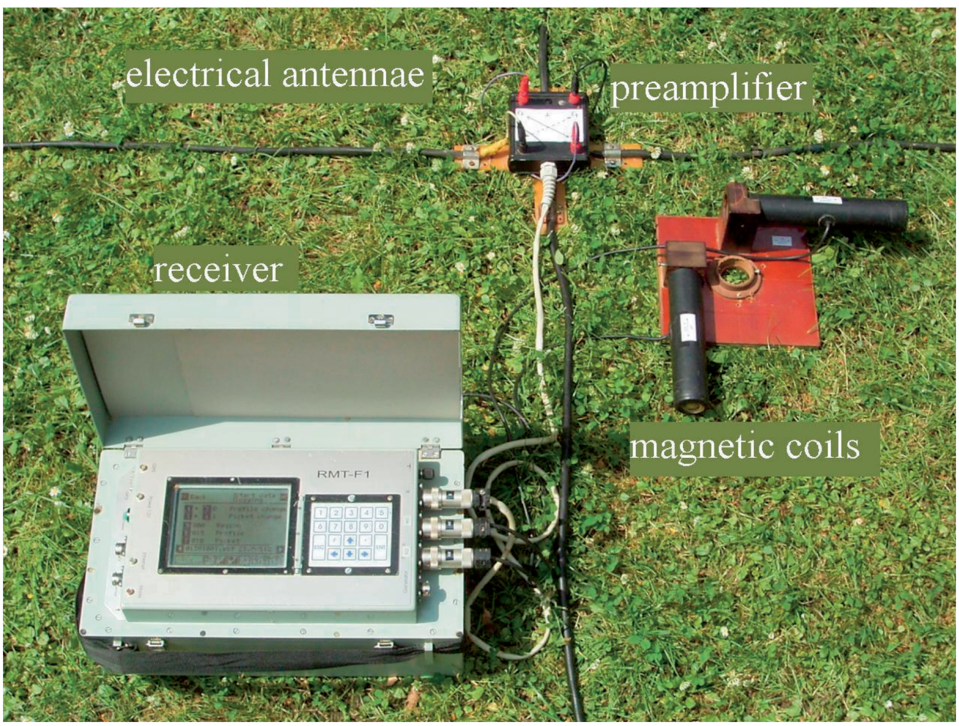

FIGURE 1
The new RMT system: digital receiver, electric antennae, magnetic coils, preamplifier for the electric field.

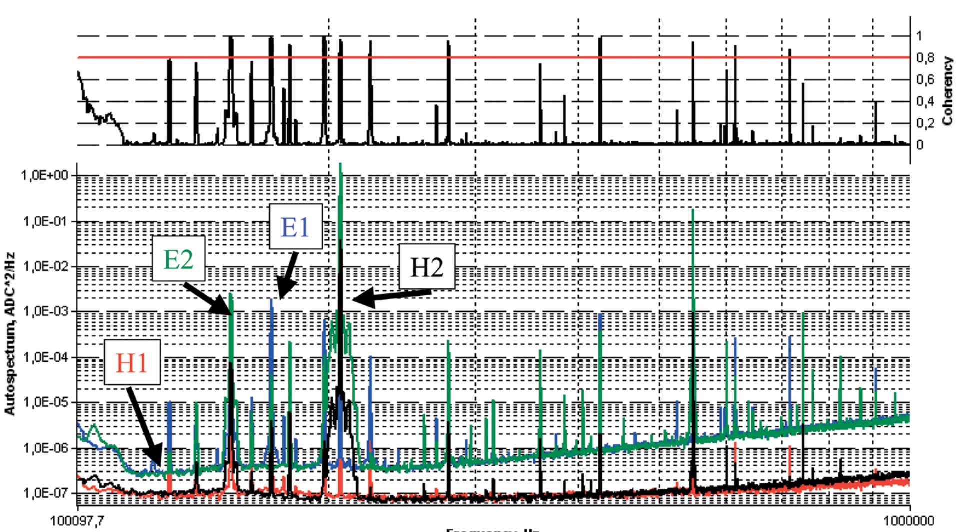

FIGURE 2
Auto spectra calculated from time series observed in Uzin, Ukraine in the frequency range of 100 kHz–1MHz. The existing radio transmitters can easily be seen in the spectra as dominant lines. H1 and H2 are showing the magnetic field in the northern and eastern direction. E1 and E2 are showing the corresponding electric fields in the eastern and northern directions respectively.

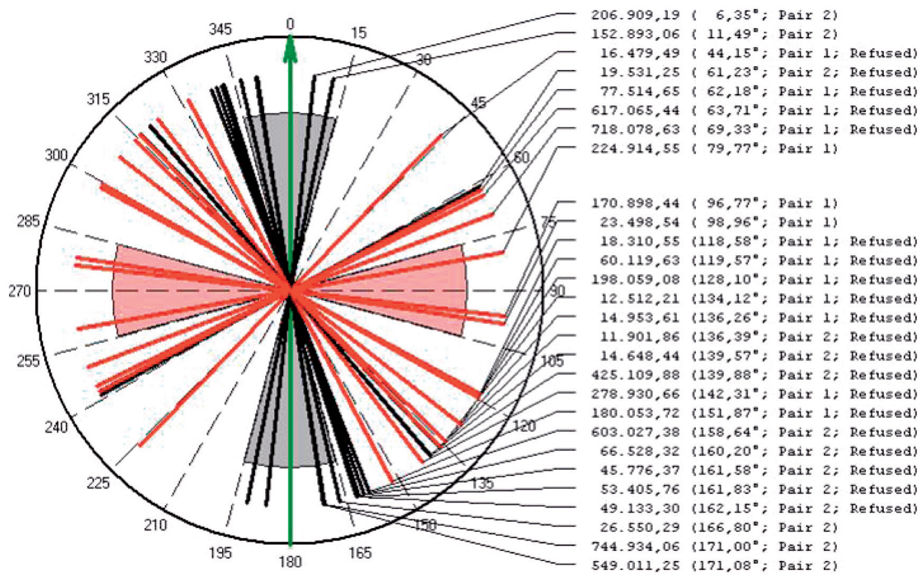

FIGURE 3
The azimuths of existing radio transmitters in Uzin, Ukraine. The transmitters located outside of the chosen interval are not selected.

over narrow frequency intervals. The entire system, including the magnetic and electric sensors, was calibrated in the laboratory. The calibration files were saved and included in the processing software. They are used to calibrate the cross- and power spectra in order to avoid instrumental effects and to calculate the transfer functions in real physical units. The correct determination of the azimuth of radio transmitters is very important for a radiomagnetotelluric survey. All the azimuths of the radio transmitters available in the survey area can be viewed by the software in the frequency band 10 kHz–100 kHz or in the frequency band 100 kHz–1 MHz. The azimuth is calculated relative to the magnetic field in the north direction and the user can define an azimuth range in which to select the available transmitters. As an example, Fig. 3 shows (from the field survey in Uzin, Ukraine) the azimuths of existing radio transmitters relative to the magnetic coil in the northern direction. The user can define an azimuth range (e.g., ±15°).

The coherency level, typically with a value of 0.8, can also be selected by the user (Fig. 2). Thus, the transfer functions only need to be calculated for the frequencies with coherencies greater than the selected coherency level and for radio transmitters located within the azimuth range defined by the user.

After having calculated the power and cross-spectra and after having determined the coherencies and azimuth angles, transfer functions (apparent resistivity and phase) are derived for each frequency from the power and cross-spectra. Presently, this is done in the scalar mode, i.e., calculations of the apparent resistivity and phase are based on the impedance tensor elements Z_{xy} and Z_{yx}. Although the new RMT instrument is a broadband system and is capable of recording time series in a broad frequency range from 10 kHz to 1 MHz our presentation does not use the full information of the data. It is assumed beforehand that the profile direction is perpendicular to the geoelectric strike direction. Under this assumption it is then possible to calculate TE and TM responses by simply combining orthogonal components of the horizontal electric and magnetic fields for the estimation of the corresponding impedances. The presented data represent the first application of the new instrument. Its full potential has still to be realized. Tensor calculations are possible, for example, by applying the processing procedure suggested by Bastiani and Pedersen (2001) because the power spectra of all components are calculated and saved in small frequency bands

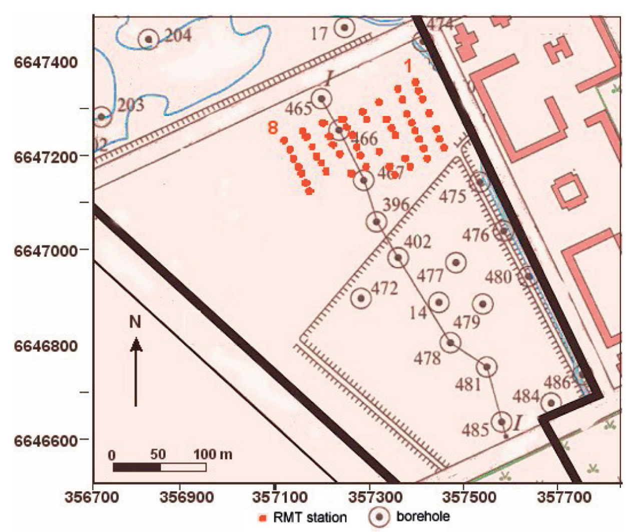

FIGURE 4
Location of the RMT stations and boreholes in the survey area located in the south-eastern part of St. Petersburg.

There is no device to compare the high-frequency range of the data. We have compared the low-frequency band data (10 kHz–240 kHz) with the device from Neuchâtel. There is nearly no

FIGURE 5
Panoramic view of the survey area where building activities are planned.

difference between observed phase values. However, the apparent resistivity values of the new device are shifted by a factor of 1.2 compared to the Neuchâtel device (Müller 1983).

CASE STUDIES

The newly developed RMT instrument has been applied to several environmental problems. In the following, two case studies will be presented. However, the main focus of this paper does not lie in the detailed exploration of the survey areas and the derivation of the conductivity structure beneath them but on the presentation of selected RMT data belonging to different profiles from different survey areas. The main aim is to show that reliable RMT transfer functions (10 kHz–1 MHz) can be observed by using the newly developed RMT instrument and to demonstrate that these transfer functions can be interpreted by 2D conductivity models.

RMT FIELD SURVEY IN ST. PETERSBURG

The survey area is located in the south-eastern part of St. Petersburg (Figs 4 and 5). Some years ago, the Russian railway company used the area as a slag heap and a residential house construction is now planned there. Therefore, the thickness of the slag heap and its spatial distribution is important for the construction industry. The aim of the measurements was to find out if the lower boundary of the slag can be mapped with the RMT method. According to borehole information, the lower boundary of the slag is located at a depth of 1–5 m. There is a clay layer beneath extending to about 12 m. RMT measurements were carried out on 8 profiles in N-S direction. At each station time series in the frequency range between 10 kHz– 1 MHz were recorded with the new RMT instrument. The apparent resistivity, phase and transmitter direction were calculated automatically if the coherency between the magnetic and the perpendicular electric field was bigger than 0.8. Figure 6 shows a data example of the first profile in Fig. 4. Two perpendicular directions (E1/H1 and E2/H2) are displayed. They represent the so-called TE mode: the electric field E1 is parallel to the strike of the 2D anomaly and the TM mode: the magnetic field H2 is parallel to the strike of the anomaly. In the field applications the magnetic H1 component points always into the profile direction and the corresponding electrical component E1 points perpendicular to it. It corresponds to the TE mode assuming that the profile direction is perpendicular to the strike of the 2D anomaly. In anology, the magnetic H2 component points perpendicular to the profile and the corresponding electrical component (E2) points to the direction of the profile (TM mode). In order to derive reliable conductivity models the transfer functions should not scatter and they must be smooth as a function of frequency. The presented data in Fig. 6 are smooth and the conductivity models derived from them are consistent.

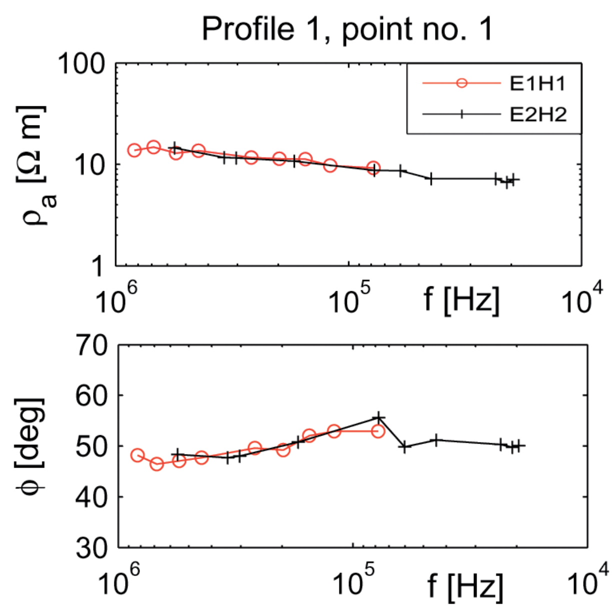

FIGURE 6
Apparent resistivity (top) and phase as a function of frequency derived by the radio transmitters in the profile direction (E1/H1) and perpendicular to it (E2/H2).

2D inversions, using the algorithm of Mackie *et al.* (1997), were carried out. 2D inversions were realized by using the TE mode data and the TM mode data separately. A joint inversion of TE and TM mode was also realized for all profiles. The smoothing parameter in the inversion procedure was determined by using the L-curve criteria (Hansen 1992; Hansen and O'Leary 1993). Figure 7 shows 2D inversion results for profiles 1, 2 and 4, using TE mode data as a representative example for the inversion of all profiles. The 2D inversion results of all profiles show similar structures. The clay layer could be resolved as a good conductive layer and the slag could be interpreted as a resistive structure above the clay layer, whereas the relatively resistive layer beneath the clay indicates a sandy layer. Similar structures were obtained for all profiles and the derived lithology from the 2D-RMT modelling is in good agreement with the existing borehole information of the survey area.

A good fitting between the observed and calculated apparent resistivity and phase data for all frequencies and for all profiles was achieved. The RMS error was below 3% for all inversion results. As an example, Fig. 8 shows a comparison between the observed apparent resistivity and the phase of the TM and TE mode (individual inversions) data for 2 frequencies collected along profile 1.

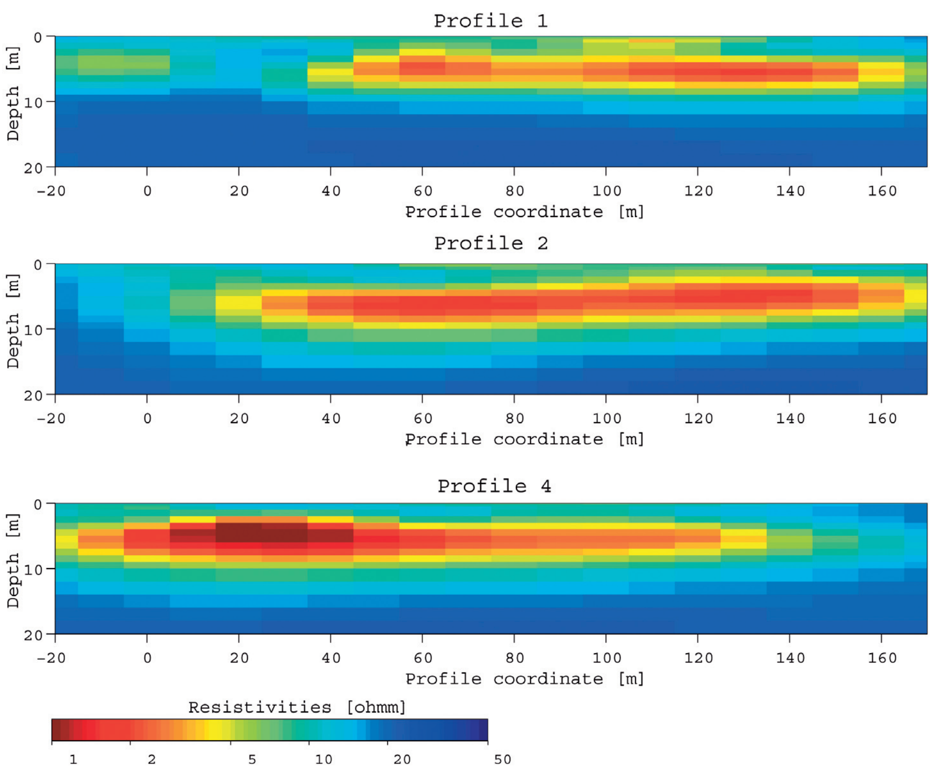

FIGURE 7
2D inversion results of the profiles 1, 2 and 4.

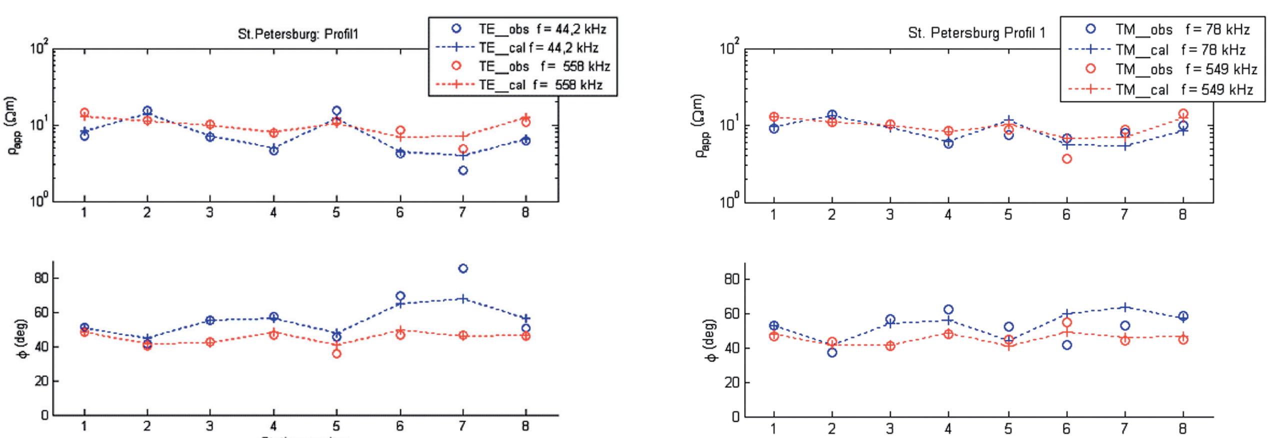

FIGURE 8
Comparison of the calculated and observed apparent resistivities and phases for two frequencies of profile 1. The TM mode frequencies are associated with the radio transmitters in the profile direction and the TE mode frequencies are associated with radio transmitters perpendicular to the profile direction. A good fitting between the observed and calculated data was observed.

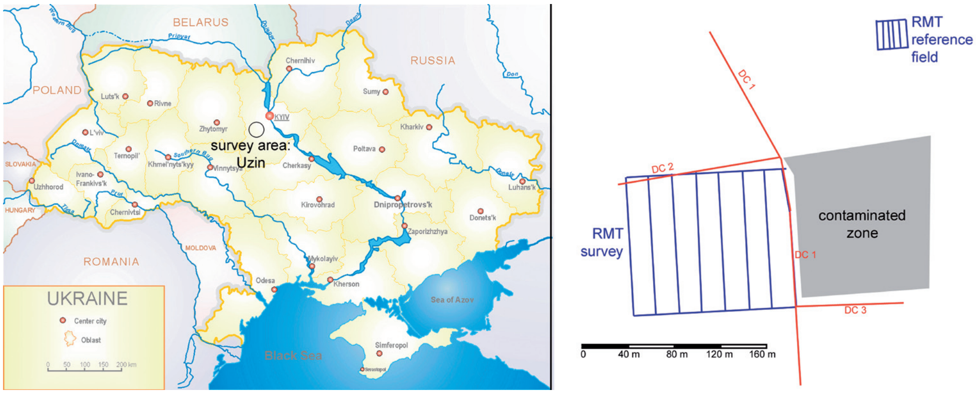

FIGURE 9
The RMT survey area in Ukraine (a) and the location of the RMT profiles (b).

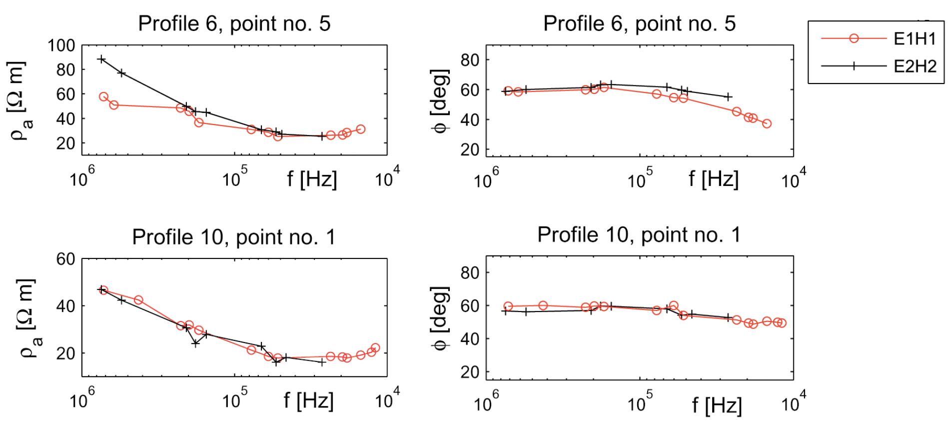

FIGURE 10
Apparent resistivity and phase values as a function of frequency observed at the reference (top) and contaminated (bottom) areas in Uzin, Ukraine.

CASE STUDY IN UZIN, UKRAINE

Figure 9(a) shows the location of the survey area in Ukraine. Kerosene contamination occurred in the vicinity of a military area. The kerosene floated on top of a groundwater table at about 5 m depth, which was confirmed by the neighbouring well. The investigation ought to clarify if the kerosene in the underground could be detected by the RMT technique with the newly developed instrument. We carried out RMT measurements on two long profiles, DC1/RMT02 (980 m) and DC2/RMT03 (280 m). The distance between the stations was 50 m on the DC1/RMT02 profile and 20 and 50 m on the DC2/RMT03 profile respectively. For comparison, reference measurements (with a station interval of 10 m) were carried out in the vicinity over the undisturbed geology. In addition RMT measurements were carried out on 10 profiles (250 m long each with a station interval of 10 m) on the contaminated area. The field setup is shown in Fig. 9(b).

About 200 RMT stations were measured; auto and cross-spectra were calculated. Transfer functions (e.g., apparent resistivity and phase) were then calculated from the spectra.

Figure 10 shows apparent resistivity and phase curves for the reference area and for the contaminated site. The apparent resistivity and phase curves in Fig. 10 are taken as representative examples indicating smooth transfer functions over a wide frequency range. The curves for the reference area show phases that are less than 45° indicating a resistive structure at depth. However, the curves for the contaminated area show phases greater than 45° for all frequencies, indicating a conductor at depth. All the observed data on the profiles shown in Fig. 9b were interpreted by 2D inversions (Mackie *et al.* 1997). Figures 11 and 12 show representative examples of such inversion results for the profiles 5, 6 and 7 and for the profiles 10, 13 and 15 from the reference and contaminated area respectively. These examples show the conductivity distribution down to a depth of 20 m. There is a clear resistive layer beneath 10 m in the reference area but not in the contaminated area. This indicates that the contamination reduced the resistivity (e.g., Sauck *et al.* 1998; Sauck 2000) and thus enabled its detection by the RMT method. Due to the screening effect of the high conductive contaminated layer the resistivity structure beneath the contamination could not be resolved.

The test measurements showed that the data observation with the new instrument is very fast (less than 30 s measurement time) and many frequencies from 10 kHz–1 MHz can be recorded at the same time. The observed data is reliable and can be inverted for the 2D models under the assumption that the conductivity structure is 2D and the strike direction is known beforehand.

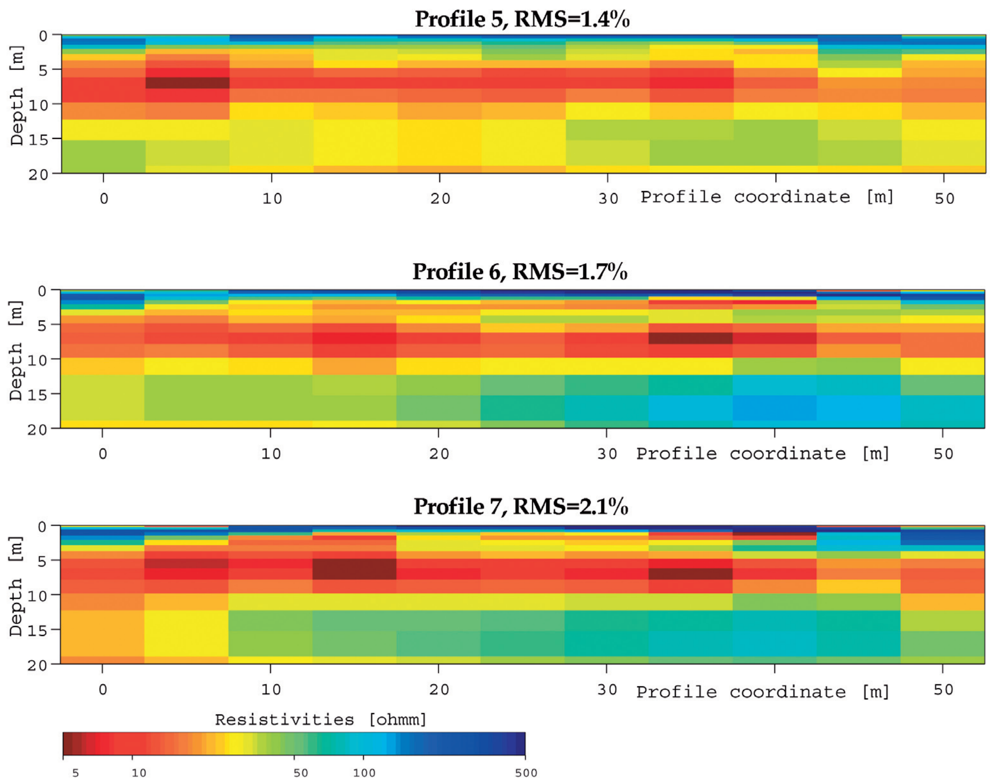

FIGURE 11
2D conductivity distribution beneath the profiles 5, 6 and 7 (Fig. 9b) from the reference area where no contamination was expected.

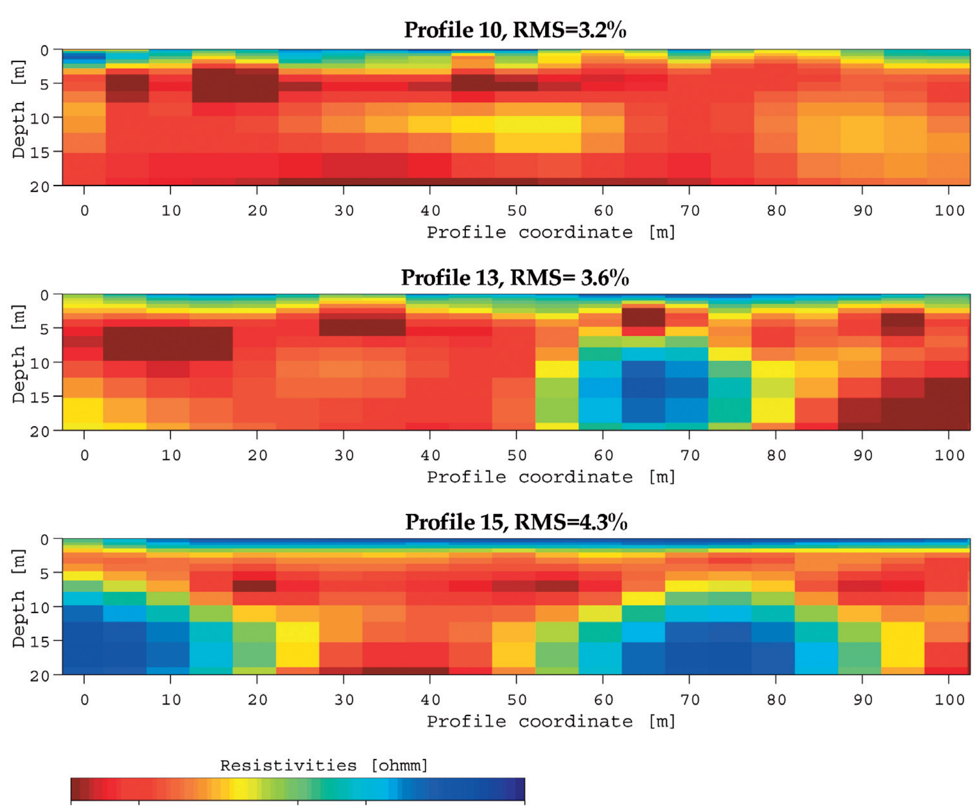

FIGURE 12
2D conductivity distribution beneath the profiles 10, 13 and 15 (Fig. 9b) from the area where strong kerosene contamination in the ground was expected.

CONCLUSIONS

A new RMT instrument was developed that can record time series of electric and magnetic fields in the frequency range between 10 kHz and 1 MHz. RMT transfer functions can be determined by spectral analysis and inverted for 2D conductivity models. The observed RMT transfer functions show a smooth behaviour. They represent the first RMT transfer functions in the frequency range above 300 kHz. The newly developed instrument was tested in the laboratory and was then successfully applied on several environmental test areas. The transfer functions are calculated in the scalar mode and proper tensor estimations will be realized in the near future.

ACKNOWLEDGEMENTS

The project was financed by the European Union under contract number ICA2-CT-2000-10055. The financial support of the EU is greatly acknowledged. Special thanks also to project partners N. B Christensen, P. Georgescu and V. Schuman for their scientific support during the project phase.

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