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Frequency Soundings at Low Induction Numbers: Transformation and 1D Inversion Comparing to 2D ERT Inversion

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SUMMARY

The paper is devoted to an approach for calculating an apparent resistivity and a layered earth parameters from transformation and inversion of FEM soundings data. First part of study presents theoretical estimation of the sounding capability of the multifrequency sensor at simple layered earth model. Second part includes processing of the both FEM and DC ERT data sets collected at the same profiles. The results of transformation and 1D layered inversion of frequency soundings comparing to 2D ERT inversion are considered.

Introduction

Nowadays shallow depth electromagnetic induction (EMI) methods are quite popular for many geophysical investigations, particularly for ecological, geotechnical, archaeological and agricultural surveys. Over the past several decades a number of single and multiple frequency sensors have been successfully developed and widely applied (such as EM-31, EM-34, GEM-2, GEM3 etc.). In spite of definite progress in this field the capability and effectiveness of frequency sounding at low induction numbers, which are caused by frequency band and Tx-Rx separation, is still the points at issue.

The aim of current investigation is to theoretically estimate the sounding capability of the multifrequency sensor at simple layered earth model, perform the inversion of field FEM soundings and compare it with DC electrotomography (ERT) inversion results.

Frequency electromagnetic (FEM) sounding equipment

One of the recent equipment implementing EMI method is NEMFIS (Fig. 1, Manstein et al. 2003, Balkov et al. 2004). Being three coil device with fixed geometry it performs soundings within frequency range from 2.5 to 250 kHz and intended to explore the ground conductivity at the depth up to 10 m. Alternating magnetic field is generated consequently on several (up to 14) fixed frequencies that are chosen to be proportional to the skin depth. Receiver coils are arranged in the transmitter plane lying at straight line (Fig. 1) and those are specifically designed to cancel a primary field. Receivers cancel the primary field in the air by obeying the following relation: $M_1/r_1^3 = M_2/r_2^3$, where M_i and r_i– are moments of the receivers and distances to the transmitter.

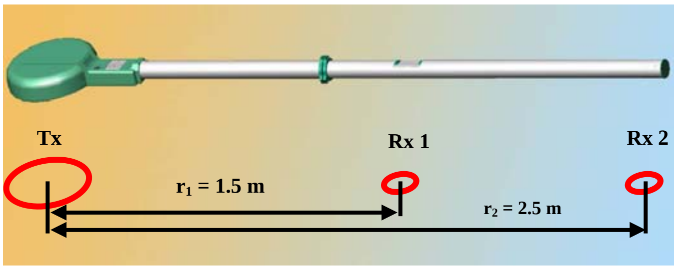

***Figure 1** NEMFIS equipment.*

Theoretical background

Horizontally layered model with two layers (ρ_0 -air resistivity, ρ_1, ρ_2 -resistivity of the layers and h - is the thickness of the first one) is used in this study. The vertical magnetic dipole with moment (M_tC placed on the surface is the transmitter. The expression of vertical component of magnetic field (H_z) for such a case follows

$$H_z = \frac{M_t}{2\pi} \int_0^\infty \lambda^3 J_0(\lambda r) X \, d\lambda .$$

Here X – layered function of the medium, that for the case of two layers is

$$X = \frac{p_1 \cdot ch(p_1 \cdot h) + p_2 \cdot sh(p_1 \cdot h)}{(p_0 \cdot p_1 + p_1 \cdot p_2) \cdot ch(p_1 \cdot h) + (p_1^2 + p_0 \cdot p_2) \cdot sh(p_1 \cdot h)},$$

where $p_j^2 = \lambda^2 + k_j^2, k_j^2 = i\omega\mu_0 / \rho_j, \; j = 0..2$.

Differential electromotive force measured by NEMFIS is

$$\varepsilon = \varepsilon_1 - \varepsilon_2 = i\omega\mu_0 \left(M_1 H_z(r_1) - M_2 H_z(r_2) \right),$$

where ω – is the circular frequency, μ_0 – magnetic permeability of the vacuum.

A model of a homogeneous half space is used to transform soundings (Balkov et al. 2004). The solution of the following transcendental equation yields the apparent value of resistivity (ρ_a):

$$\varepsilon = \varepsilon_1 - \varepsilon_2 = -i\omega\mu \frac{M_T}{2\pi k^2}\left\{ \frac{M_1}{r_1^5}\left[9-\left(9+9kr_1+4k^2r_1^2+k^3r_1^3\right)e^{-kr_1}\right] - \right.$$
$$\left. -\frac{M_2}{r_2^5}\left[9-\left(9+9kr_2+4k^2r_2^2+k^3r_2^3\right)e^{-kr_2}\right]\right\},\ k^2 = i\omega\mu_0/\rho_a .$$

Traditional inversion techniques for solving nonlinear inverse problems were used. An objective function was minimized to fitting the experimental data in the least-squares sense using a quasi-Newton method and a finite-difference gradient (Balkov et al. 2004).

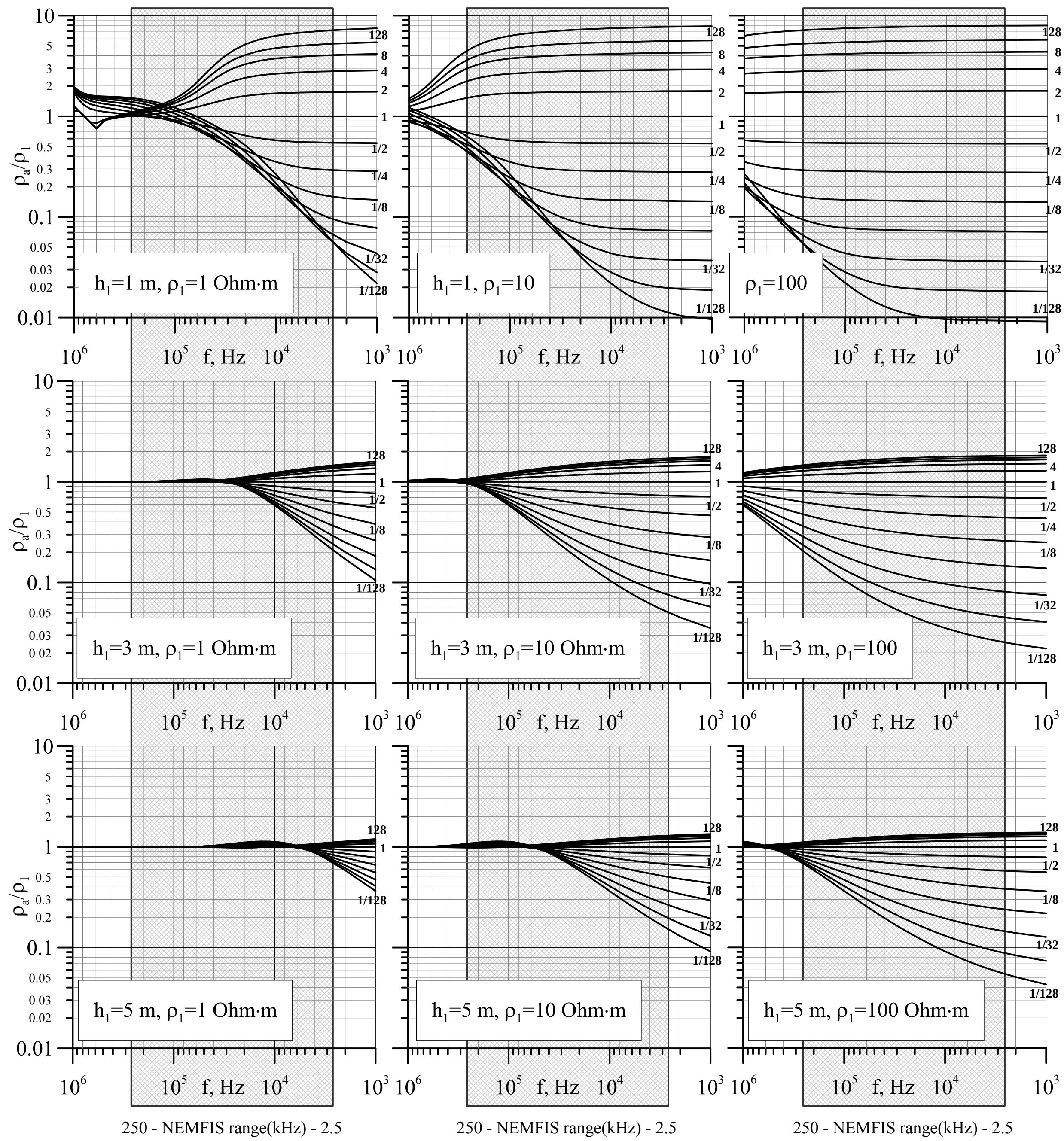

Figure 2 *Transformation of synthetic two-layered medium response. Each graph shows diagrams of relative apparent resistivity dependence on frequency for various relations between layers resistivity (1/128, …,1/2,1,2,…,128,) while the thickness of the first layer and its resistivity are fixed. Thickness andresistivity of the first layer are varied from graph to graph.*

]Two layered earth response modelling

To theoretically investigate the sounding possibility of NEMFIS sensor the modelling and transformation for a broad band of medium and device parameters were performed. The following ranges and values were used: [1 kHz -:- 1 MHz] for frequency; [1,3,5 m] for thickness of the first layer (*h*); [1,10,100 Ohm per meter] for resistivity of the first layer (ρ_1); [1/128, …,1/2,1,2,…,128] for relation (ρ_2 / ρ_1) of layers resistivity. The results of synthetic response transformation are demonstrated at Figure 2. The filled regions bound the frequency range of NEMFIS equipment.

It can be seen that the more expressive and informative sounding curves are obtained in the case of conductive basement. Self-descriptiveness of the curves decreases either with increasing of the first layer resistivity while its thickness remains or with increasing of the thickness of conductive first layer. Generally diagrams show that frequency band of NEMFIS allows resolving the wide range of mediums.

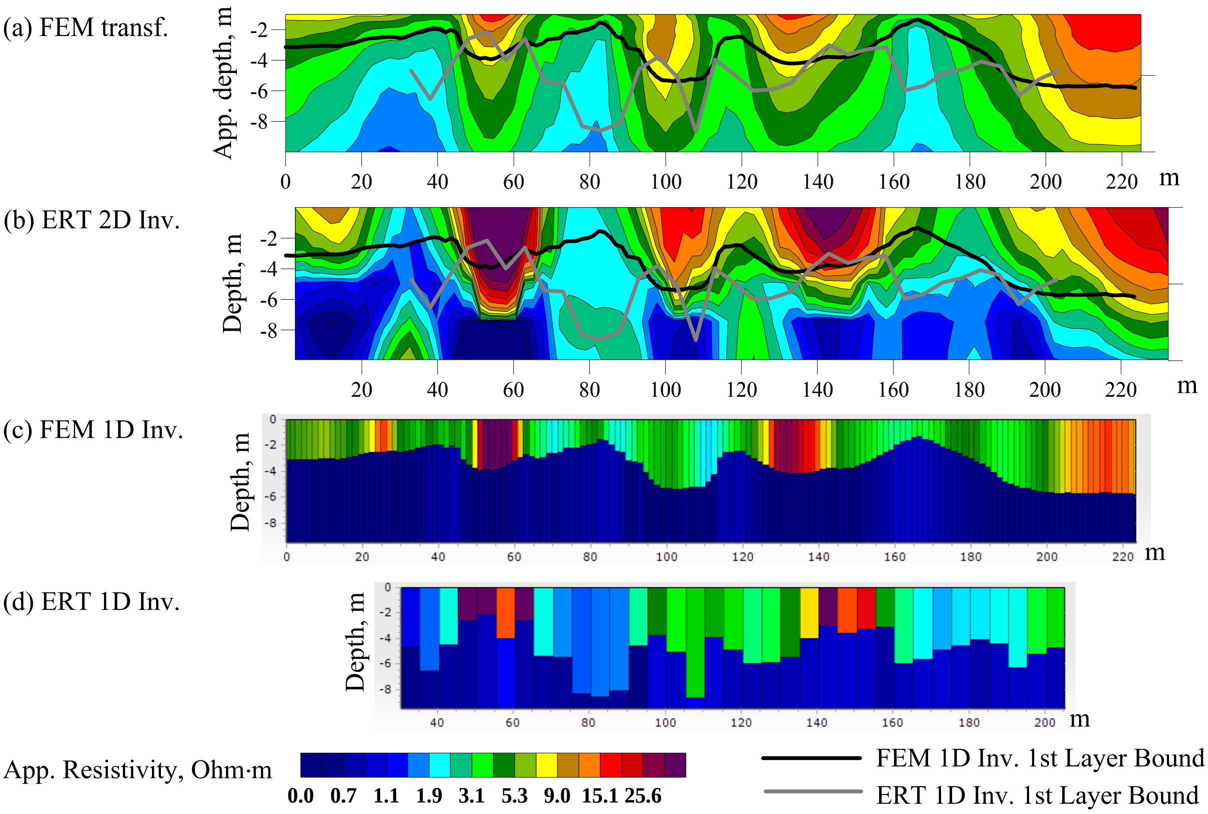

Figure 3 *Comparison of NEMFIS soundings and ERT data measured along the same line at the petroleum field of Uzon caldera (Kamchatka region, Russia). FEM measurements: 14 frequencies in the range of 2.5-250 kHz, 1.5 m step along the profile. ERT measurements: Schlumberger array with 5 m electrode step.*

Field examples and comparison with ERT

Two field examples are considered in the abstracts. Both of them are derived from the integrated investigation of geothermal areas at Kamchatka region (Russia). The aim was to survey a depth and special configuration of hydrothermal reservoir, gas channels etc. Studied mediums have resistive overburden and conductive base in the considered depth range. Along the profiles studied by the FEM method DC electrotomography was applied as well. Different type of data processing can be seen at Figure 3 and Figure 4. It show that in these cases FEM data transformation yields results that are quite close to ERT 2D inversion (Figure 3a, b; Figure 4a, b), that was made by commercial software Res2DInv (v.3.55). The geoelectrical bounds obtained by FEM 1D inversion are well correlated with

DC method result. ERT 1D inversion yields not correct results (Figure 3d) since the 2D structured medium and large electrode spacing. FEM measurements performed at quite small Tx-Rx base allow to quantitatively resolve 2D geological structures by 1D inversion (Figure 3c; Figure 4c).

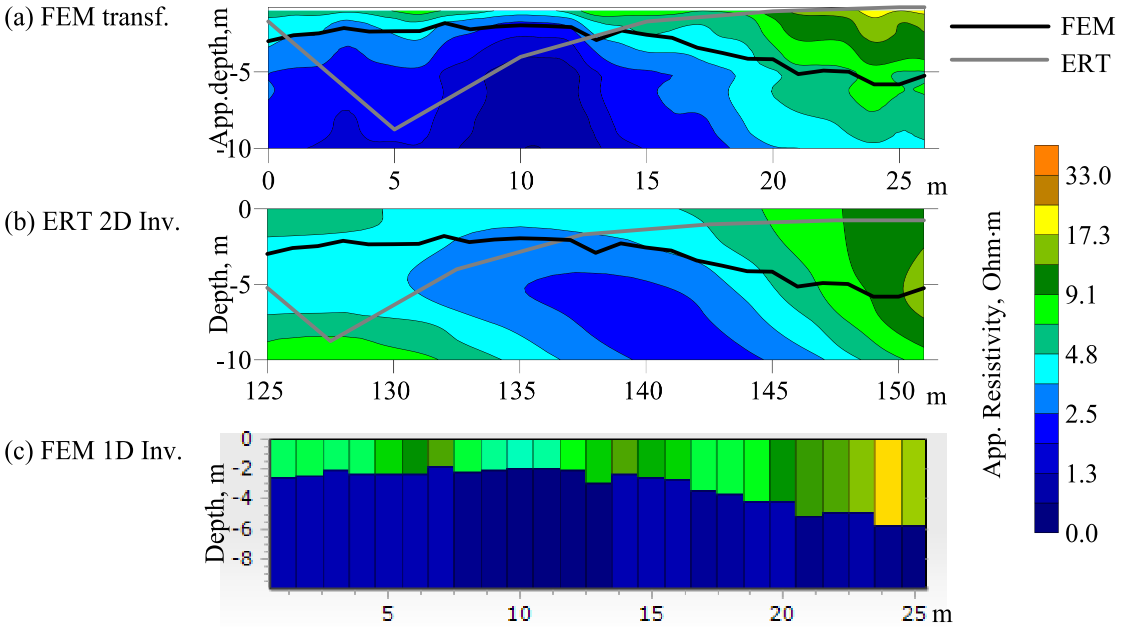

Figure 4 *Comparison of NEMFIS soundings and ERT data measured along the same line at the donnoe field of Mutnovsky volcano (Kamchatka region, Russia) . FEM measurements: 14 frequencies in the range of 2.5-250 kHz, 1 m step along the profile. ERT measurements: Schlumberger array with 5 m electrode step.*

Conclusions and Acknowledgements

Algorithms have been developed for calculating the apparent resistivity and layered earth parameters from the transformation and inversion of FEM soundings data. Analysis of sounding curves of portable fixed-base multifrequency sensor NEMFIS in a wide range of two layered earth parameters indicates that it is able to resolve simple shallow layered medium. The more favourable case for survey is the conductive base.

Field data FEM examples in comparison with ERT surveys show that transformation of NEMFIS soundings can yield good approximation of true 2D distribution of ground resistivity. 1D FEM inversion indicates that the localness of FEM sensor provides resolution of 2D geological structures that have slightly greater dimensions than sensor Tx-Rx base by 1D technique. Layered model obtained by 1D FEM inversion is good enough correlate with 2D ERT inversion.

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