B016

EM Induction Frequency Sounding - Estimation of Penetration Depth

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SUMMARY

One of the most important characteristics of any geophysical instrumentation is the penetration depth. Present paper is devoted to description of the approach for estimation of the penetration depth for frequency sounding method. The approach takes into account the accuracy of the instrumentation and geoelectrical model as well. It is more accurate than traditional one that based on skin depth estimation. The investigations are carried out for two types of target objects for EMI frequency sounding device EMS developed by authors.

Intro

The depth of signal penetration is the important property of any geophysical instrumentation.

Sometimes the penetration depth of frequency soundings is estimated by means of plane wave skin depth (fig. 1). This approach is quite popular (e.g. I.J. Won, 1996 and J.D. McNeil, 1996). But it is obvious that plane wave field attenuation strongly differs from the local source one. Skin depth as estimation of the penetration depth does not take in consideration the measurement instrument errors. Thus such approach can be used only for qualitative estimation of penetration depth that could strongly differs from really reachable values. Let's make the quantitative estimation of the frequency soundings penetration depth taking into consideration medium model as well as measurement characteristics of existing EMI frequency sounding device EMS (Y.A. Manstein, 2003 and E.V. Balkov, 2004).

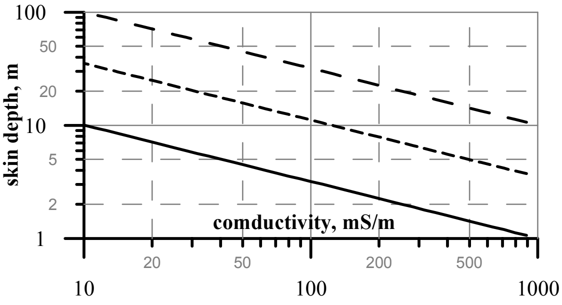

Fig. 1. Skin depth values depending on the conductivity of the half space

The estimation approach. Relative and absolute criterions

EMS is three coil device with single transmitter coil and two receiver coils. The first one excites the harmonic field within the range from 2.5 kHz up to 250 kHz. Receiver coils are placed in transmitter plane lying at straight line and constructed to cancel the primary field in air. The typical sizes allow considering the transmitter as magnetic dipole and calculating the signal at single point (do not consider the finite size of receiver loop).

Let's use for investigation the horizontally layered model with field exciting by vertical magnetic dipole placed on its surface. The expressions of vertical component of magnetic field H_z for such a case and differential electromotive force follow:

$$H_z = \frac{M_t}{2\pi}\int_0^\infty \lambda^3 J_0(\lambda r) X\, d\lambda \,;\, \varepsilon = i\omega\mu_0\left(M_1 H_z(r_1) - M_2 H_z(r_2)\right),$$

$$X = \frac{f_{l+0}}{f_{l-0}h_{l+0} - f_{l+0}h_{l-0}}\zeta(z), z < z_l;\; X = \frac{f_{l-0}}{f_{l-0}h_{l+0} - f_{l+0}h_{l-0}}\zeta(z), z > z_l,$$

where M_t, M_1, M_2 – momentums of transmitter and receivers respectively, r_1 и r_2 – distance between coils center, X – layered function of the medium, z_l – interface that contains the primary source of field, $f = \mu\zeta$, $h = \zeta_z^{'}$, $\zeta(z)$ can be calculated by recursion through its boundary values.

It is obvious that we should estimate penetration depth concerning particular test object (the target). We should take into consideration the model of the test object as well as model of host medium and metrological characteristics of the instrumentation as well.

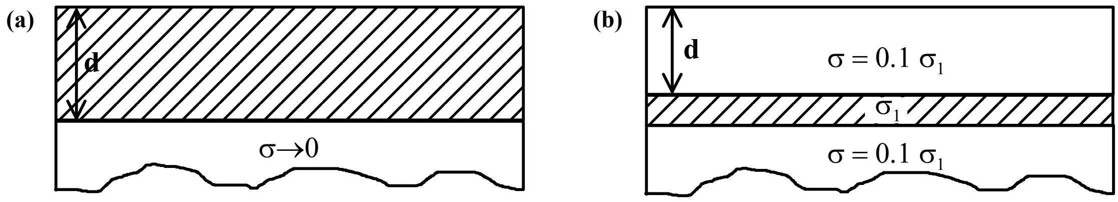

Fig 2. The test objects models (a) first type: conductive layer over the isolator
(b) second type: conductive layer in resistive half space

There is the approach of penetration depth evaluation based on the resolution analysis. Its main idea is to find out the depth range for what test object can be resolved with allowable accuracy under some resolution criterion.

Let's choose two types of test objects: the first one is the conductive layer over the isolator (fig. 2a); the second type is the conductive layer in resistive half space (the contrast of conductivities between the layer and the host is 0.1). To define the resolution rule two criterions are introduced – relative and conductive. The rule is defined as the simultaneous satisfaction both of criterions.

The meaning of the relative and absolute criterions is following. The responses of two models are compared: the first one includes the test object at definite depth and the second model consists of only the host medium (without the object). Thus, there is the number of responses for the test model corresponding to different depths of test object. At the big depth of object lying the responses of test and host models differ only to the calculation error (it is strongly less than the error of the measurement). The absolute criterion is introduced by the following way. While the test object is moved in the surface direction it reaches the depth when the difference between the responses of test and host models is equal to the absolute error of the measurement tool. The relative criterion is introduced the same way – at some depth relative difference is equal to the relative error of the instrumentation.

The relative criterion defines the maximum of reachable penetration depth for the particular geoelectrical model, while the absolute one – achievable depth with the measurement errors and the sensitivity of the particular instrumentation. Using the first type test object we get the thickness of the conductive layer containing main part of induced current. The second type gives the depth of the layer top interface which lets the layer to produce the sufficient response. It is assumed that relative error of measurement is less than 5 %, the absolute error is less than 0.5 µV (the values are corresponding to characteristics of existing instrumentation EMS).

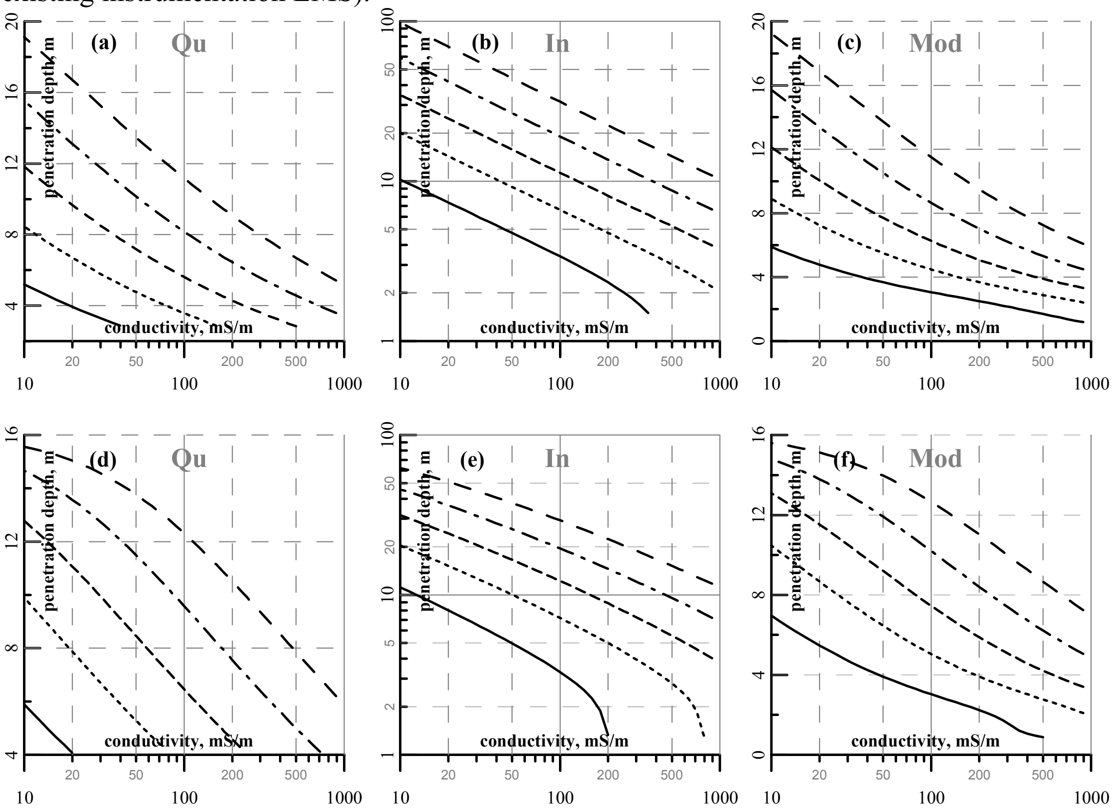

Fig. 3. Penetration depth under the relative criterion.
First type test object: estimation for quadrature (a), inphase (b) component and module (c) of signal. Second type test object: estimation for quadrature (d), inphase (e) component and module (f) of signal.

Estimation of the principal reachable depth

The estimation under chosen resolution rule can be performed for the quadrature or inphase signal component or for its module. Results of penetration depth estimation under the relative criterion for the both test object types are shown at fig. 3. The diagrams show the dependence of penetration depth from the conductivity of test model at the number of frequencies chose with geometrical step.

Let's consider result for the first object type. It can be seen that the quadrature component (fig. 3a) is more local. Signal module (fig. 3c) gives the results which are quite close to the quadrature component. The module penetration depth is slightly greater at the low values of wave number and less at high ones. The inphase component gives greatly larger penetration depth (fig. 3b). It should be noted that its values are quite close to the skin depths. Mainly the differences are less than 5 % and only for the big values of wave number (frequency > 100 kHz, conductivity > 1/3 mS/m) are larger than 10 %.

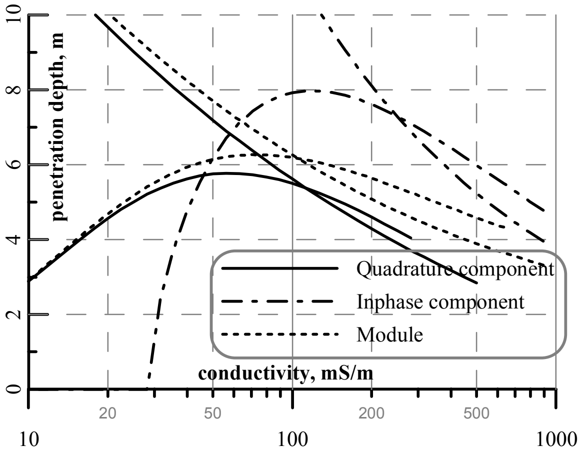

Fig. 4. Penetration depth under intersection of two criterions. Frequency 20.4 kHz.

Considering the values achieved for first object type the thickness of the layer in second type is chosen equal to 1 m. It should provide both the localness of the object and the sufficient signal values. The principal reachable penetration depths for the second test object type are close to results achieved for the first one. The penetration depth in this case slightly greater (around 1 m) at high values of wave number and it is the opposite situation (the differences up to 10 m) at the low values.

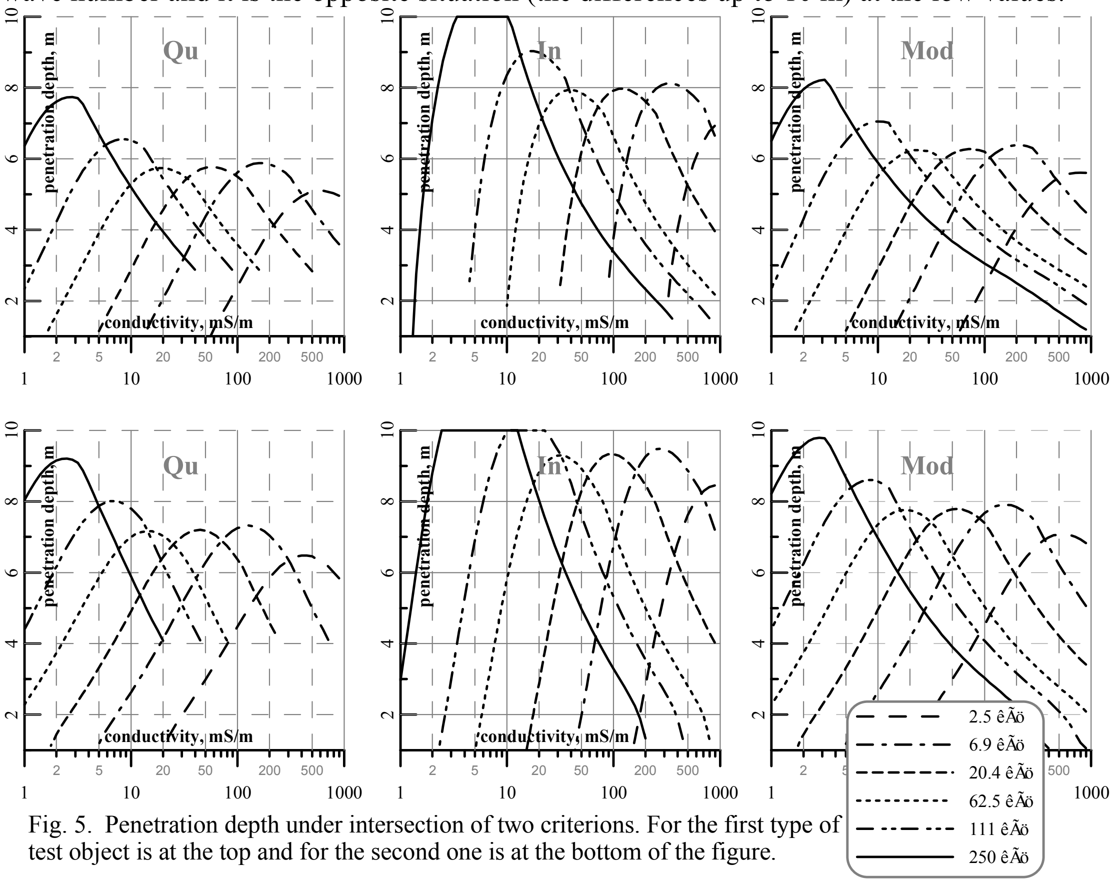

Fig. 5. Penetration depth under intersection of two criterions. For the first type of test object is at the top and for the second one is at the bottom of the figure.

The penetration depth limitation due to the response level

The fig. 3 shows the principal reachable penetration depth. At the same time it is clear that the penetration depth is limited by the attenuation of the response (the absolute criterion takes it into account). Fig. 4 shows the diagrams of penetration depth for the first test object type. For the clearness of intersecting of the relative and absolute criterions the pairs of diagrams of penetration depth are shown for quadrature and inphase components and module of the response at the single frequency (20.4 kHz). The pairs of diagrams for relative and absolute criterions are made of the same line style. It can be seen that the penetration depth is increasing with the decreasing of the medium conductivity (corresponding to relative criterion), but after particular values it becomes to decrease due to the low signal values (corresponding to absolute criterion).

Results of penetration depth estimation achieved by intersecting both of the criterions are shown at the fig. 5. It can be seen that all the advantage that inphase component has while using only the relative criterion is lost after introducing of the absolute criterion. Moreover the absolute criterion causes the contraction of conductivity range where inphase component can be used. The reason is that the inphase penetration depth under the absolute criterion attenuates faster with decreasing of the conductivity.

Conclusion

The described approach for penetration depth estimation is more accurate than traditional one. The penetration depth depends on measurement properties of the instrumentation. The penetration depth is greatly limited by the absolute criterion due to low level of signal that can be measured accurately. Most shallow component is the quadrature, the signal module is slightly deeper and the deepest values are achievable by using the inphase component.

The analysis of EMS device penetration depth for the investigated test objects gives the following results. The penetration depth for quadrature and inphase components reaches 7 and 9 meters respectively at the frequencies that less than 100 kHz, 9 and 12 for the higher ones. Module of response gives average depth results. It can be concluded that the instrumentation frequency range allows to apply it in the wide conductivity range (10-1000 mS/m) achieving the penetration depth not less than 5 m.

Let's note in conclusion that it would be more correct to define resolution rule under some inversion procedure investigating the sensitivity of e.g. the objective function to the test object parameters. But it could be stated that satisfying of described criterions is the necessary condition to resolve the test object under any inversion algorithm.

Acknowledgements

The research work is performed under the financial support of Russian fund of basic research (grants #03-06-80415-a, #06-06-80295-a) and the support of Siberian branch of Russian academy of sciences Presidium (grants #87, #109).

References

I.J. Won, D.A. Keiswetter, G.R.A. Fields, and L.C. Sutton, 1996, GEM-2: A new multifrequency electromagnetic sensor, Journal of Environmental and Engineering Geophysics, v. 1, No. 2, pp. 129-138.

McNeill, J.D., 1996,Why doesn't Geonics Limited Build a Multi-Frequency EM31 or EM38?. Geonics Limited Technical Note TN 30, November

Balkov, E.V., Epov, M.I., Manstein, A.K., Manstein, Y.A., 2004, Elements of Calibration and Data Interpretation of EMI Sounding Device EMS. Near Surface 2004 Extended Abstracts Book. 6-9 September, Utrecht, The Netherlands. P-014.

Manstein, A.K., Manstein, Y.A., Balkov, E.V., 2003, EMS Electromagnetic Sounding Device. 9th European Meeting of Environmental and Engineering Geophysics, August 31 – September 4, Prague, Czech Republic. P-059.