Early-Time and Late-Time Limitations on the Performance of Near-Surface TEM Measuring Systems

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Early-Time and Late-Time Limitations on the Performance of Near-Surface TEM Measuring Systems

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Summary

Reducing the exploration depth of the TEM sounding method by measurement at earlier times necessitates decreasing size of the transmitter loop. This causes problems in measuring TEM response at both early and late times. The early time problem is associated with fundamental constraint caused predominantly by the transmitter loop inertia. As the transmitter loop decreases, its intrinsic response decreases much slower compared to that of the earth. At late times, instead of measuring the earth's transient response one measures the receiving unit's intrinsic response. Its initial amplitude is small, but it decreases so slowly that, eventually, its contribution to the total transient response becomes predominant. This problem is technical. It can be solved by eliminating or reducing the impact of the voltage pulse induced in the receiver loop during the current turn-off in the transmitter loop.

Introduction

Currently, there is a tendency for decreasing the TEM sounding depth due to measurements at increasingly earlier times (Sharlov et al., 2017). This entails the need to reduce the inertia of the TEM system, which is achieved by decreasing the size of transmitter and receiving loops. Since usually the transmitter loop is larger than the receiving one, it is the transmitter loop that mainly determines the performance of the TEM system at early times. However, when decreasing the transmitter loop, one faces problems that complicate measurements at both early at later times.

Early times

Fig. 1a shows transmitter (Tx) and receiver (Rx) loops located on the surface of a homogeneous conducting half-space. The effective sounding depth (in meters) can be estimated as (Meju, 1995)

$$h = k\sqrt{\rho\, t}\,, \quad (1)$$

where ρ is the earth's resistivity (in Ω·m); t is time (in s) elapsed after transmitter current turn-off; k is a coefficient, the value of which lies somewhere between 400 and 700, averaging at about 500. Designate the desired minimum sounding depth as h_{min}. It follows from (1) that the earliest measurement time has to be as small as

$$t_{\min} = \frac{h_{\min}^2}{k^2\rho}. \quad (2)$$

According to (2), the earliest measurement time is proportional to the square of the minimum depth and inversely proportional to the earth's resistivity. Therefore, decrease in h_{min} leads to the measurements at very early times, especially when studying resistive ground (Fig. 2 b)

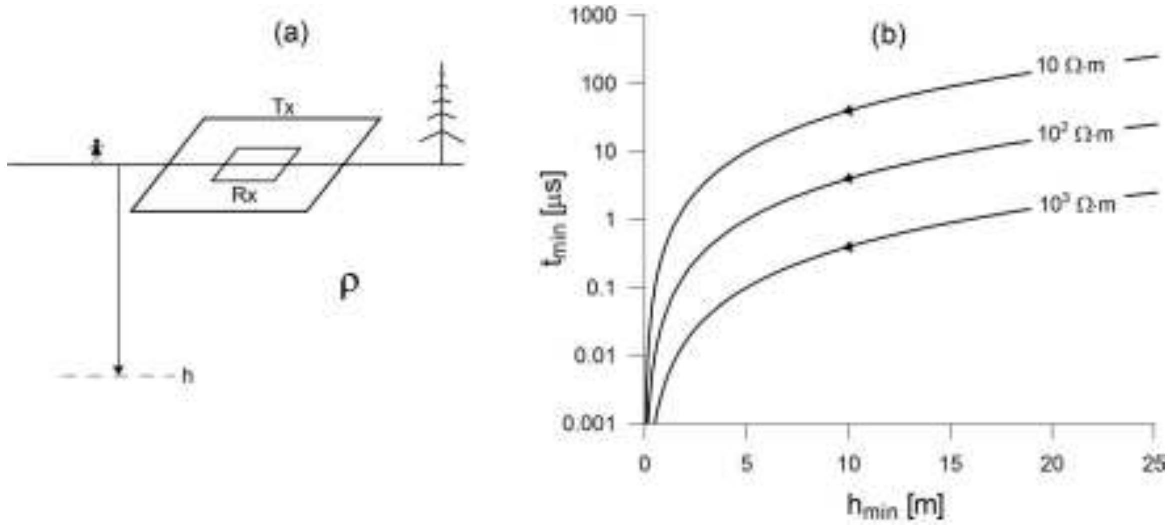

***Figure 1** Transmitter and receiving loops on the surface of a homogeneous conducting half-space (a); t_{min} versus h_{min} graphs (b). It can be seen that decrease in h_{min} necessitates measurements at very early times, especially at high resistivities.*

As already mentioned, the most inertial element of the TEM system is the transmitter loop. Usually, the measurement of the TEM voltage response starts after the current in the transmitter loop is turned off. Denote the transmitter current off-time t_{off}. Obviously, the earliest measurement time should not be less than t_{off}: $t_{min} \geq t_{off}$. The current in a loop cannot be switched off faster than in a time equal to half the period (T_0) of the loop natural current oscillations (Kozhevnikov, 2016). Therefore, as an estimate of t_{min}, we assume that $t_{min} = T_0$, which implies the requirement for the natural frequency $f_0 = 1/T_0$:

$$f_0 = 1/t_{min}. \quad (3)$$

The natural frequency of current oscillation in a square loop with side length a is (Kozhevnikov, 2009)

$$f_0 = \frac{1}{8a\sqrt{LC}}, \quad (4)$$

where L and C are per unit length inductance and capacitance of the loop wire. Respectively,

$$a = \frac{1}{8 f_0 \sqrt{LC}}. \quad (5)$$

With regard to (2) and (3), we find that

$$a_{\min} = \frac{t_{\min}}{8\sqrt{LC}} = \frac{h_{\min}^2}{8k^2 \rho \sqrt{LC}}. \quad (6)$$

Expression (6) determines the size ($a_{\min}$) of the transmitter loop the current in which is turned off so fast that the initial sounding depth does not exceed $h_{\min}$. As well as the initial measurement time, $a_{\min}$ decreases in proportion to the square of the $h_{\min}$ and inversely proportional to ρ. Thus, decrease in $h_{\min}$ leads to a very rapid decrease in the transmitter loop size, especially in studies of resistive ground.

Let us use a central loop TEM array to consider how the transient voltage depends on $t_{\min}$ and ρ. The voltage induced in the receiving loop after switching off the transmitter current I is given by (Spies and Frischknecht, 1991):

$$V(t) = \frac{\mu_0^{5/2}}{20\pi^{3/2}} \cdot \frac{I a^2 b^2}{\rho^{3/2} t^{5/2}}, \quad (7)$$

where b is the side length of the receiving loop, $\mu_0 = 4\pi \cdot 10^{-7}$ H/m. Usually, the receiving loop is smaller than the transmitter one, so $b = k_1 a$, where $k_1 < 1$.

Substitution in (7) of (2) and (6) gives voltage $V(t_{\min})$ at the earliest measurement time (at later times the voltage will be obviously less):

$$V(t_{\min}) = \frac{I k_1^2 \mu_0^{5/2}}{20 \cdot 8^4 \pi^{3/2} k^3 (L \cdot C)^2} \left(\frac{h_{\min}}{\rho} \right)^3. \quad (8)$$

Estimates of $V(t_{\min})$ with formula (8) show that reducing $h_{\min}$ and/or increasing ρ makes it necessary to measure signals of so low level that it becomes hardly possible. Compensation of a drop in the voltage by increasing the transmitter loop would increase its inertia and, correspondingly, the initial measurement time. Increasing the effective area of the receiving loop or coil would result in a decrease of its natural frequency and thus, in the increase of $t_{\min}$.

Late times

When applying small transmitter loop, one runs into another problem: at late times, the voltage decay becomes anomalously slow ($\propto 1/t$), a phenomenon referred to as a long tail (Sharlov and Kozhevnikov, 2018; Sharlov et al., 2018). It is known that such voltage decay can be due to magnetic viscosity of the geological material underlying the TEM array (Spies and Frischknecht, 1991; Kozhevnikov and Antonov, 2012). However, long tails were observed in areas where there are no magnetically viscous rocks and even in TEM studies on the ice cover of Lake Baikal (Sharlov et al., 2017b). The long-tail effect is not directly related to geology and, all other things being equal, the more noticeable the smaller the transmitter loop and the more resistive geological environment. If the receiver loop is located outside the transmitter one, the effect is much less pronounced. We observed long tails when working with FastSnap and Tzikl equipment. There are cases when anomalously slow decaying transients were also measured with NANOTEM (Geidetzka, 2002) and TemFast (Descloitres et al., 2008) equipment.

Fig. 2a, b show the TEM voltage responses and apparent resistivity curves measured at the same location (near the village of Malaya Elanka in the vicinity of Irkutsk) using central loop array with transmitter loop of 100m by 100m (red graph) and 50m by 50m (blue graph). In both cases, the size of the receiving loop was 10m by 10m. According to interpretation of TEM sounding with 100m by 100m transmitter loop, the earth is hear geoelectrically close to a homogeneous half-space with resistivity of 30-40 Ω·m. However, at late (*t*>5ms) times, the voltage measured with the 50m x 50m transmitter loop decreases as 1/*t*. The apparent resistivity at late times also decreases as 1/*t*, becoming at *t*=40 ms as low as 4 Ω·m (Figure. 2b), which is inconsistent with known geology and sounding results obtained from the 100m by 100m transmitter loop data.

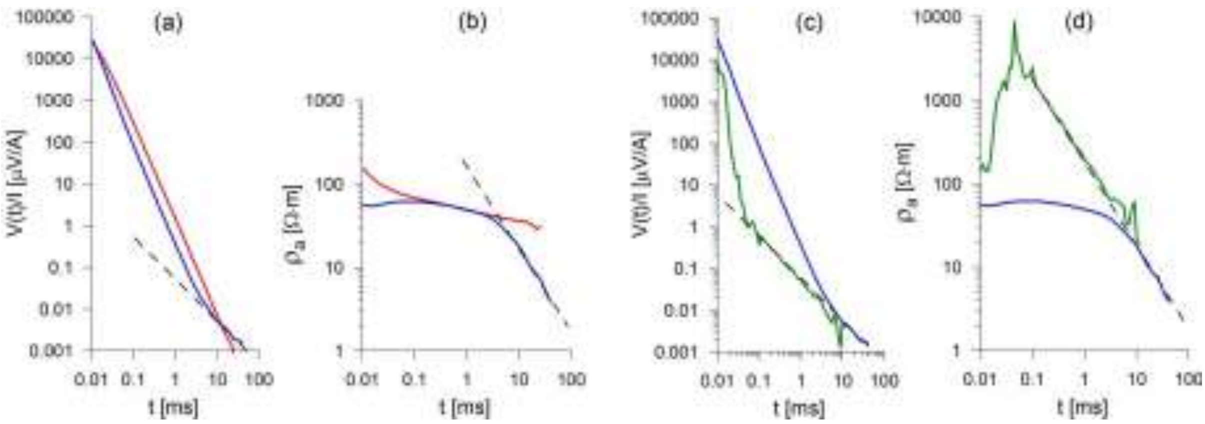

Figure 2 *Effect of the transmitter loop size (a, b) and earth's resistivity (c, d) on the manifestation of slowly decaying TEM system's intrinsic response. Dashed line illustrates the 1/t decay. The measurements were performed with FastSnap equipment. For detailed discussion, see the text.*

Fig. 2 c shows the TEM voltage responses measured with central loop array (50m by 50m transmitter, 10m by 10m receiver loops) on the Malaya Elanka site (blue graph) and in the Olkhon region near the western shore of Lake Baikal (green graph). The resistivity of rocks in the Olkhon region exceeds 10^3 Ω·m, therefore eddy currents in the earth have decayed in about 0.05ms. Starting from this time, only intrinsic response of the TEM system survives in the form of a slowly decreasing voltage. Interpretation of the apparent resistivity curve (Fig. 2d) indicates, at depth of about 300 m, rocks with resistivity as low as 5 Ω·m, which is geologically meaningless. At the Malaya Elanka site, where the rock resistivity is much lower than in the Olkhon region, the long tail becomes noticeable at *t*>5ms.

As shown by laboratory and field experiments (Sharlov and Kozhevnikov, 2018; Sharlov et al., 2018), the slowly decreasing voltage is an intrinsic response of the TEM equipment's elements, such as the preamplifier, to a voltage pulse induced in the receiver loop during current turn-off in the transmitter loop. The more the earth's resistivity and mutual inductance between transmitter and receiving loops, the higher the pulse amplitude. On the other hand, the more resistive the earth and the smaller the transmitter loop, the smaller the earth's TEM response. Therefore, the system's intrinsic response is observed primarily when small TEM arrays are used to study weakly conducting ground.

Conclusions

Reducing the exploration depth of the TEM sounding method by measurement at earlier times necessitates decreasing size of the transmitter loop. This causes problems in measuring TEM response at both early and late times. The early time problem is associated with fundamental constraints caused predominantly by the transmitter loop inertia. As the transmitter loop decreases, transmitter current turn-off duration decreases much slower compared to the earth's response. At late times, instead of measuring the earth's transient response one measures the receiving unit's intrinsic response. Its initial amplitude is small, but it decreases so slowly that, eventually, its contribution to the total transient response becomes predominant. This problem is technical. It can be solved by eliminating or reducing the impact of the voltage pulse induced in the receiver loop during the current turn-off in the transmitter loop.

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