Signals of electromagnetic tool with toroidal coils in highly deviated wells

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Abstract. The research is aimed at expanding the applicability of the logging tool with toroidal coils from vertical to highly deviated wells. Its electromagnetic signals are computed with a three-dimensional finite-difference simulation algorithm on the computing resources of the Siberian Supercomputer Center of SB RAS, which is accompanied by a multi-aspect numerical analysis of the signals. We consider a wide range of geoelectric models with various resistivity contrasts: those of oil-, gas- and water-saturated reservoirs having a different number of horizontal boundaries and varying thicknesses, including the case of fine layering.

1. Introduction
Electromagnetic borehole sounding is extensively employed all over the world to study the petrophysical properties of hydrocarbon reservoirs. Within this research, we concentrate on logging with toroidal coils used as signal sources and receivers, which has been shown to offer several advantages over the conventional resistivity logging techniques [1]. For instance, there is a possibility in principle to evaluate thinly laminated electrically anisotropic sand-shale sequences [2]. There exist various approaches to calculating the signals from a toroidal source: the analytical, finite-difference and finite-element methods [3–6].

Previously, we carried out a mathematical substantiation of the logging tool with a metal non-magnetic stem comprising two transmitter and three receiver toroidal coils in-between [7], devised specialized software and algorithmic tools for two-dimensional finite-difference simulation, processing and inversion of the signals from vertical wells [8, 9], as well as developed interpretation procedures [10] and examined their application to the field data [11, 12]. Consequently, the next step to be taken in this context is three-dimensional numerical simulation of the tool’s signals in highly deviated wells, gained acceptance in many types of reservoirs. Only a few separate attempts seem to have been made in this regard [13, 14].

2. Problem statement
When the geoenvironment is isotropic, the problem of finding the amplitudes of the electric and magnetic fields from a toroidal source is reduced to Maxwell’s equations [8]:

\[
\begin{align*}
\text{rot}\vec{H} &= \sigma\vec{E} \\
\text{rot}\vec{E} &= i\omega\mu\vec{H} - j
\end{align*}
\]

(1)
where $\sigma = \rho^{-1}$ is the electrical conductivity, $\mu = \mu_0 = 4\pi \cdot 10^{-7}$ H/m is the magnetic permeability, $\omega$ is the cyclic frequency, $\bar{j}$ is the source of the external current (current density), $\bar{E}$ is the electric field, and $\bar{H}$ is the magnetic field.

The time dependence of the current is harmonic. The concerned toroidal coil far from it can be formally described by a circular magnetic current [15]. Therefore, this source in a cylindrical coordinate system is supposed to be specified in the form:

$$\bar{j}_0 = \{0, j_\varphi^\mu, 0\}^\mu, \hspace{1cm} j_\varphi^\mu = -i\omega \mu M_\varphi \delta(z - z_0) \delta(r - r_0),$$

where $M_\varphi$ is the magnetic moment, $\delta$ is the Dirac delta-function, and $r_0$ is the radius of the current ring.

Equation (1) can be transformed to the form:

$$\text{rot} (\rho \cdot \text{rot} \bar{H}) - i \omega \mu \bar{H} = -\bar{j}_\varphi^\mu. \hspace{1cm} (2)$$

Taking into account Maxwell’s equation $\text{div} \bar{H} = 0$ and selecting the Laplace operator explicitly, we arrive at an equivalent notation:

$$-\rho \Delta \bar{H} + \text{grad} \rho \times \text{rot} \bar{H} - i \omega \mu \bar{H} = -\bar{j}_\varphi^\mu. \hspace{1cm} (3)$$

In accordance with the radiation condition at infinity, the magnetic field decays with distance from the source: $|\bar{H}| \rightarrow 0$ as $r \rightarrow \infty$. This makes it possible to approximately set zero boundary conditions for the $H_r$, $H_\varphi$ and $H_z$ components far away from the source.

We are interested in a bounded solution for $r = 0$, which satisfies the condition $\lim_{r \rightarrow 0} \frac{\partial \bar{H}}{\partial r} = 0$. Hence, we have the Dirichlet problem for equation (3).

Through the conservative finite-difference scheme [16, 17], we approximate equation (3), giving consideration to the $\varphi$ periodicity and solution boundedness conditions.

After the discretization, we obtain a system of linear algebraic equations with a complex, non-Hermitian, non-symmetric matrix. This system was solved via the direct PARDISO method (parallel version for a computer cluster) from the Intel Math Kernel Library.

3. Numerical simulation examples

The signals under analysis, acquired on the NKS-1P supercomputer at the Siberian Supercomputer Center of SB RAS, are the real and imaginary parts of the vertical component of the electric field ($\text{Re} E_z$ and $\text{Im} E_z$) and those of the tangential component of the magnetic field ($\text{Re} H_\varphi$ and $\text{Im} H_\varphi$). The toroidal tool’s two operational regimes are summary and differential, the former implying the equality and unidirectionality of the transmitters’ currents, whereas the latter – equality but the opposite directions [7].

Further are some results for $\text{Re} H_\varphi$ and $\text{Im} E_z$, operating frequency 100 kHz and central receiver toroidal coil, which demonstrate the basic features of the signals in both regimes. The geoelectric model at issue is that of an oil-and-water reservoir (10 ohm-m) confined between more conductive host shales (5 ohm-m) and exposed by a borehole with fresh mud. The borehole deviation angle varies from $0^\circ$ to $80^\circ$ with a fixed step.

The $\text{Re} H_\varphi$ signal for the summary regime and borehole angle $0^\circ$ (figure 1) exhibits a substantial change when the reservoir thickness increases from 0.5 m to 4 m. More specifically, at a reservoir thickness of 0.5 m, $\text{Re} H_\varphi$ reaches a minimum value at a distance of 0.5 m above the top and below the bottom of the reservoir. In the reservoir interval, $\text{Re} H_\varphi$ is characterized by maximum values. When the thickness equals 1 m, the $\text{Re} H_\varphi$ signal generally has the same features as in the previous case, except the minima appearing at a distance of 0.2 m above the top and below the bottom, and the maximum in the middle being more pronounced. When the reservoir is 2 m thick, the $\text{Re} H_\varphi$ signal has five extrema: two local minima confined to the horizontal boundaries, one local minimum occurring in the middle of
the reservoir, and two local maxima at a distance of 0.5 m below the top and above the bottom. With reservoir thicknesses of 3 m and 4 m, the ReHφ signals have similar features. In particular, local minima appear opposite the horizontal boundaries, whereas the minima are reached in the central part of the reservoir. There are also maxima at a distance of 0.5 m below the top and above the bottom. The signals reach their asymptotic values at a distance of 1.5-2 m from the horizontal boundaries.

On a separate note, one can see the symmetry of all the summary regime logs relative to the center of the model, due to the symmetry of the logging system in question. Also, these ReHφ signals in the reservoir interval become smaller with the growing thickness, due to the decreasing influence of the conductive host rocks and the increasing effect of the oil-and-water productive part.

When the angle becomes 80° (figure 2), all the ReHφ logs, while remaining symmetric, smooth out and take simpler shapes. The minimum values are present in the reservoir area, without any other extrema originating. Moreover, as opposed to the case of 0°, ReHφ reaches the asymptotic value confined to the reservoir at its thicknesses of 3 m and 4 m. The asymptotic value associated with the host rocks is reached at a distance from the boundary not exceeding 1.5 m.

As for the ImEz signals in the differential regime (figures 3 and 4), they stand out significantly from the summary ones. In the vertical well (figure 3), at all the reservoir thicknesses, there exist maxima and minima that are 0.5 m distant above and below the horizontal boundaries, which is due to the peculiarities of the logging tool with toroidal coils on a metal stem. Let us also point to a type of the logs’ symmetry clearly distinguished from that in figures 1 and 2. Beyond that, the ImEz signals take on zero values in the center of the reservoir.

The angle increase from 0° to 80° at any reservoir thickness (figure 4) leads to the disappearance of all the pronounced extrema around the horizontal boundaries except those located directly opposite. Additionally, the following feature of ImEz can be seen: an insignificant extremum is evidenced in the boundary regions at a distance of 0.2 m above the top or below the bottom of the reservoir.

Thus, it follows from the results of the performed resource-intense three-dimensional simulation that the signals of both summary and differential regimes distinctly depend on the borehole deviation angle.
Figure 3. Signals in differential regime. Deviation angle 0°. Dashed lines show corresponding reservoir boundaries. Key is reservoir thickness.

Figure 4. Signals in differential regime. Deviation angle 80°.

4. Conclusion
In sum, we developed a finite-difference algorithm for three-dimensional simulation of signals from the logging tool with toroidal coils. Through the use of the computing resources of the Siberian Supercomputer Center of SB RAS, we calculated the electromagnetic responses in diverse geoelectric models of reservoirs exposed by highly deviated wells. In both regimes, the signals obtained in vertical and sub-horizontal wells differ significantly, which opens the way for addressing the problems of geosteering and formation evaluation from directional wells.

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