EM telemetry assessment for horizontal drilling in part of the Tarim basin through numerical simulation

Olalekan Fayemi[1,2,3], Qingyun Di[1,2,3], Qihui Zhen[1,2,3]

[1]Key Laboratory of Shale Gas and Geoengineering, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, 100029 China, fayemiolalekan@mail.iggcas.ac.cn
[2]University of Chinese Academy of Sciences. Beijing, China
[3]Institutions of Earth Science, Chinese Academy of Sciences, Beijing, China

Abstract:

Electromagnetic telemetry is bi-directional transmission of borehole data for effective drilling, especially in unconventional wells. In this study, numerical simulations was used to investigate the possibility of applying EM telemetry for measurement while drilling (MWD) in an ultra-deep borehole in the Tahe region of the Tarim basin, using the drill string as an antenna excited as a gaped dipole source to quantify spatial variations of the electromagnetic field from subsurface to the surface. Results confirm that the distribution of the electric field along the drill string is sensitive to vertical variations of electric conductivity in the host rock. The simulated results show a high attenuation within the conductive formations, thereby limiting the effectiveness of EM telemetry in data transfer to the surface. In addition, the changes in thickness and resistivity of the target region affects the amplitude of the desired response.

Keywords: Electromagnetic telemetry; Tarim Basin; Finite Difference; MWD

The ultra-deep onshore reservoir of Tarim basin in Northwest China has attracted substantial and persistent interest (Lee, 1985). In particular, deeply buried strata (>5500 m) in the Tarim Basin have attracted considerable attention because carbonate reservoirs that have experienced fracture or dissolution have also been shown to demonstrate considerable hydrocarbon potential (Tian, et al 2016). However, detailed characterization of paleokarst reservoirs in the Tahe area is challenging particular because their depth of occurrence and the reservoir characteristics, such as, heterogeneous distribution and thin elongated reservoir structure with maximum thickness of about 220 m, which requires careful and accurate well landing and borehole navigation through multiple regions of HC accumulation and precise well completion process.

Electromagnetic telemetry is generally bi-directional transmission of data from Bottom Hole Assembly (BHA) to surface as the well is being drilled. The electromagnetic (EM) telemetry systems are widely used as evolving technology for measurement while-drilling (MWD), especially in horizontal drilling. However, it is generally only reliable to depths shallower than about 3,000 m, with maximum depth achieved so far as about 5,000 m (Schnitger and Macpherson, 2009). The deployment of EM telemetry systems is highly dependent on mud and formation resistivities. Therefore, a good knowledge of the attenuation characteristics with depth of an EM signal is a helpful guide for predicting successful deployment.

In this paper, numerical method for the simulation of EM telemetry in deviated and horizontal drilling is introduced. Studies on different attenuation profiles of geological model built using results from borehole study in the southern Tahe area was discussed. The numerical model employs the finite difference method to obtain a staggered grid system for simulating response from current excited drill string. The Borehole to surface modeling provides information about the expected signal trend. Other considered factors that influences EM transmission are the presence of extremely resistive or conductive thin beds in the formation and the distribution of surface resistivity.

Methodology:

The propagation of the electromagnetic waves through conductive media was derived from Maxwell's equations, relating the operating frequency and spatial variations of the electric and magnetic fields. Under the quasi-static approximation, they are given by:

$$\nabla \times E + i\omega B = 0 \tag{1}$$

$$\nabla \times H - J = S_x \tag{2}$$

where E is the electric field, B is the magnetic flux density, H is the magnetic field, J is the current density and S_x is the source current density.

We used staggered-grid approach (Yee, 1966) to describe the partial differential equations on the mesh. For this study, cartesian coordinate system is considered and rectangular cells were used for the mesh. In discretizing the Maxwell's equations, a system in the electric field and magnetic field (E-H formulation) was considered for 3D simulation;

$$CE + i\omega M_{\mu} H = 0 \tag{5}$$

$$CH - M_{\sigma} E = J_{se} \tag{6}$$

where E and H are vectors of the discrete EM fields, J_{se} the source term, C is the curl operation and M_a represents the edge or face inner product matrices for earth physical properties. The 2D formulation for electromagnetic field in TM mode given as;

$$\left(-D_z M_{\sigma x}^{-1} - D_x M_{\sigma z}^{-1} + k\right) H = D_z^e M_{\sigma x}^{-1} Js_x \tag{7}$$

where , $k = j\omega\mu$, was considered given that majority of the current is expected to flow vertically and radially. In each discrete system, the perfectly matched layer was used as an absorbing boundary condition on the grid surface. The above equation is solved as linear expression using LU decomposition technique.

Numerical Study:

Most telemetry system operates between the frequency range of 12 to 1 Hz. Therefore, the propagating frequency range will be limited to 15 - 1Hz. Our objective is to understand the characteristics of EM telemetry (borehole data transmission) in Tarim basin through numerical modelling. The underground formation is assumed to be horizontally layered media, and the long, metal drill string acts as an antenna that may be treated as a thin wire subdivided into multiple segments and excited by a gaped dipole source located near the drill bit (~50 m to 100 m away). We used a horizontal well having a combined conductivity of 10^6 S/m (casing effect is neglected), and air layer with conductivity of 10^5 Ωm. Subsurface resistivity model was built using resistivity log data (Rxo and Rt) from part of Tarim basin and previous surface to surface studies (He et al., 2010, Tian et al., 2017). 2D and 3D simulations for borehole source with dipole moment of 40 Am, at true vertical depth (TVD) of 6500 m and 5400 m and horizontal distance of 2500 m and 1000 m, for 2D and 3D models, respectively were carried out (Figure 1).

2D geo-stratigraphic layer interface as indicated by well information and respective EM diffusion characteristics are presented in figure 2. Conventional changes in diffusion pattern are observed at the interface between the resistive lower layers and conductive upper stratigraphy at depth of 4500 m. Large attenuation of EM signal is observed at this depth as indicated in figure 2, with sudden sharp changes on the Ez plot and sudden but gradual changes observed on the Ex plot. Similar characteristics is observed along the drill string with major deviation at interface with appreciable contrast in geoelectric property and high attenuation in conductive medium (Figure 3e). The plot of EM signal at the surface with source

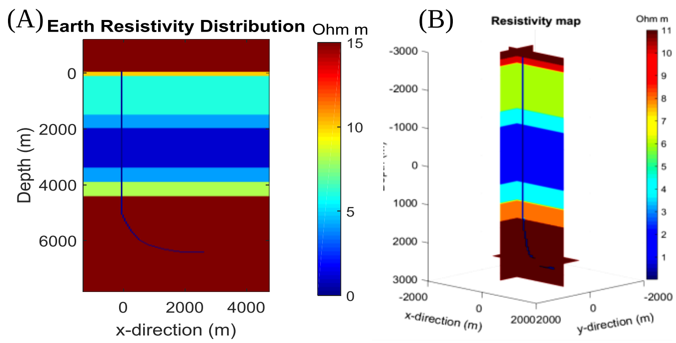

Figure 1. Earth resistivity model for Tarim basin area (a) 2D and (b)3D.

orientation (dip) varying from 0° to 75° is presented in figure 3(a-d). The observed result shows non-appreciable difference in magnitude of the EM field at 15 Hz frequency while no difference is observed at lower frequencies. Amplitude variation with frequency, is characterized by conventional increase in amplitude with decrease in frequency from an order of -6 to -12 at frequencies of 1 Hz and 15 Hz, respectively. Also, the 3D surface measurement agrees well with EM distribution result along drill string with variation in amplitude with frequency becoming conspicuous with decrease in depth along the vertical section of the borehole and is characterized by conventional increase in amplitude with decrease in propagating frequency from at 15Hz to at 5Hz (Figure 4). Very small steady change in amplitude was observed with drill string deviation to horizontal direction within the carbonate (limestone) formation (Figure 6c-d).

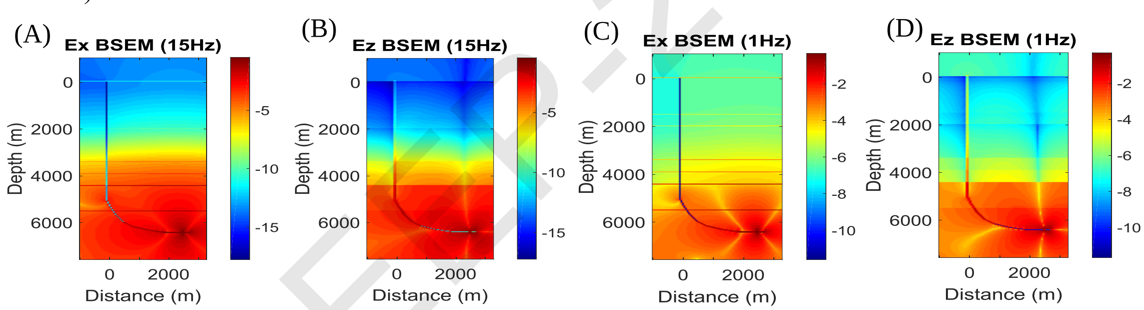

Figure 2. EM diffusion characteristics for borehole source in horizontal well.

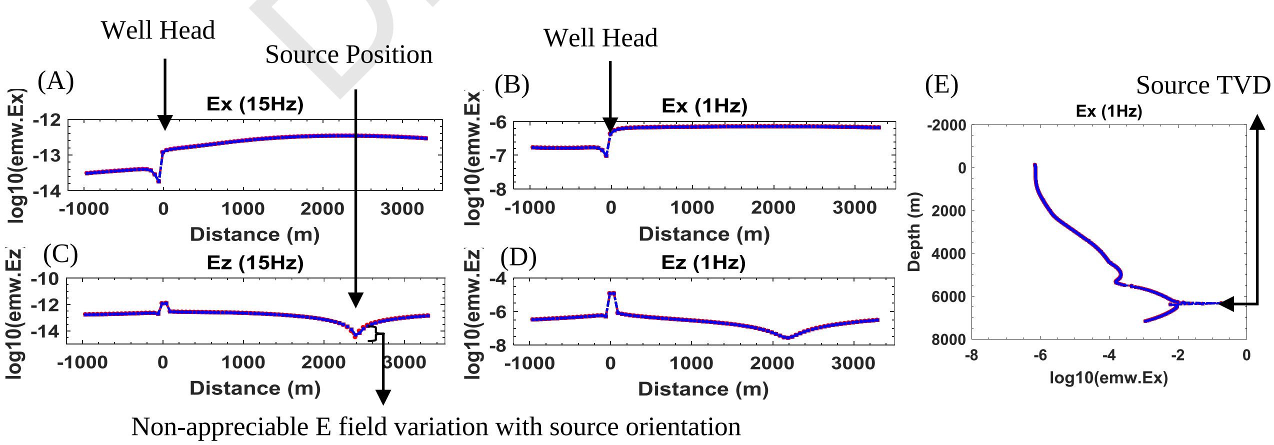

Figure 3. 2D EM distribution along the drill string and surface response for borehole source in horizontal well.

In addition, the direct source location on the surface is best observed by considering the z component of the electric field. The source position is characterized by minimum value on the Ez plot from the borehole

(Figure 3c-d). The 3D Surface response value in inline direction for Ex and crossline direction for Ey are presented in figures 4a-b. The amplitude response shows that the received signal is well below a general noise range of 10^{-0} to 10^{-4} mV and sensitivity range of most receiver system. Hence, this poses a challenge to the application of EM telemetry for ultra deep borehole drilling in Tarim basin area. Large attenuation of EM signal was recorded at higher frequencies, with largest reduction of an order of -12 for Ex and -13 for Ey signals recorded for propagating frequency of 15 Hz (Figure 4c-d). Similarly, changes in slope of varying curve of E fields represent changes in subsurface resistivity. Large slope, which is characterized as low signal attenuation with depth, is indicative of resistive layer and otherwise, a conductive layer.

Lastly, the effect of changes in cumulative resistivity and thickness of thin elongated layer at depth > 6000 m (within the limestone formation) on EM telemetry was studied. Maximum amplitude realized based on thickness - resistivity selection process is shown in Figure 5. The surface signal amplitude, which determines the effectiveness of EM telemetry, varied in relation to changes in thickness of the thin layer from 220 m and 360 m, with best cumulative resistivity value of 7 and 5 Ωm and 10 and 7 Ωm, respectively for frequencies 10 and 5Hz, respectively. In general, the cumulative resistivity range between 5-10 Ωm was observed to be most effective for resistivity and thickness range defined for the Tarim basin area. Also, sudden change in formation cumulative resistivity due to rapid advancement of water front could have large effect on telemetry data.

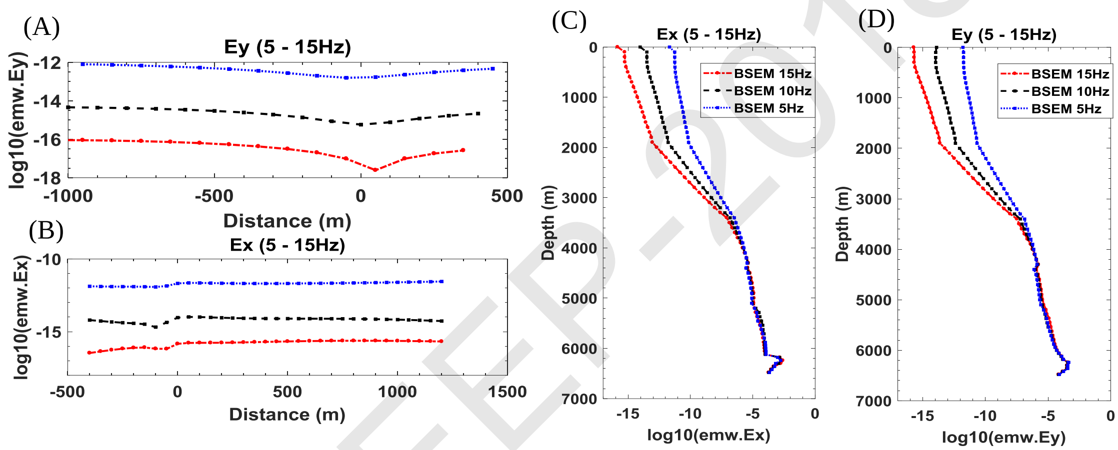

Figure 4. 3D EM distribution along the drill string and surface response for borehole source in horizontal well.

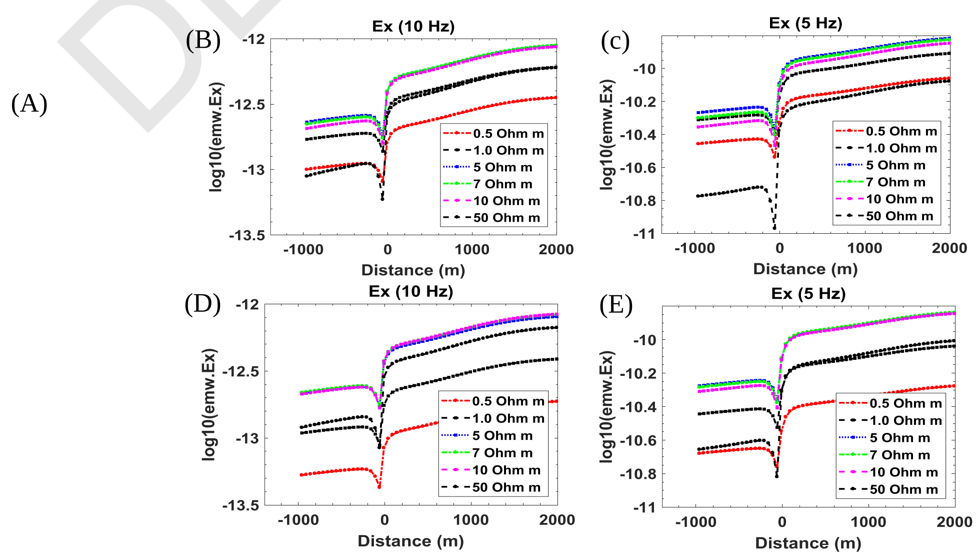

Figure 5. EM signal variation with change in resistivity - thickness of the target layer.

Conclusions:

2D and 3D study of borehole source EM response for horizontally placed MWD sensor with the intent of observing the visibility of EM telemetry in Tarim basin was carried out. Due to the EM signal attenuation pattern and depth of hydrocarbon occurrence, major challenge of low signal to noise ratio and signal lower than instrument sensitivity has to be considered in using EM telemetry in Tarim basin. EM attenuation pattern of the upper conductive formations reduces the effectiveness of EM telemetry within the study area and thus a major factor in determining the optimal configuration of the antennas in terms of operating frequency, injected current and additional materials or device to boost the transmitted signal. Further study, will focus on more efficient simulation methods and proffering solution to observed challenges.

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