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Coplanar Coils Response in a Borehole

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ABSTRACT

None of the traditional resistivity borehole devices possesses azimuthal investigation properties whereas the unconventional coplanar coil array has, by design, this attribute. Theoretical electromagnetic radial and vertical responses have been obtained for the conventional two coil coaxial system and the unconventional coplanar array. From the comparative studies of the responses of these two coil system we can conclude:
1) The skin effects for the coplanar coil array are stronger than coaxial, this disadvantage almost disappear after skin effects correction; 2) Polarization "horns" occur in coplanar profiles against the bed boundaries indicating their presence; and 3) The azimuthal attributes of the coplanar system can be explored in the investigations of the axially asymmetrical geological situations such as vugular or fracture zones, inclinded beds and invasion zones in horizontal wells.

INTRODUCTION

As yet, none of the traditional resistive and E.M. induction borehole devices possess azimuthal investigation properties, whereas the unconventional coplanar coils array has, by design, this attribute. This prompted us to investigate the applications of this array (Salvadoretti, 1990; Montenegro, 1991; Souza and Verma, 1995; and Carvalho and Verma, 1998).
For a better understanding of the coplanar coil system response in a borehole, we now elaborate theoretical studies initially attempted by Kaufman and Keller, 1989 and Costa and Rijo,1993. The radial response have been studied for homogeneous media and the vertical cylindrical interface coaxial with the borehole. While, the vertical response has been studied for the horizontal interfaces normal to the borehole. The cylindrical interface represent the invaded zone while the horizontal interfaces represent the bed boundaries. The responses of the coplanar and coaxial systems are compared to analyse their relative benefits and limitations. Figure 1 illustrates the model of horizontal interfaces.

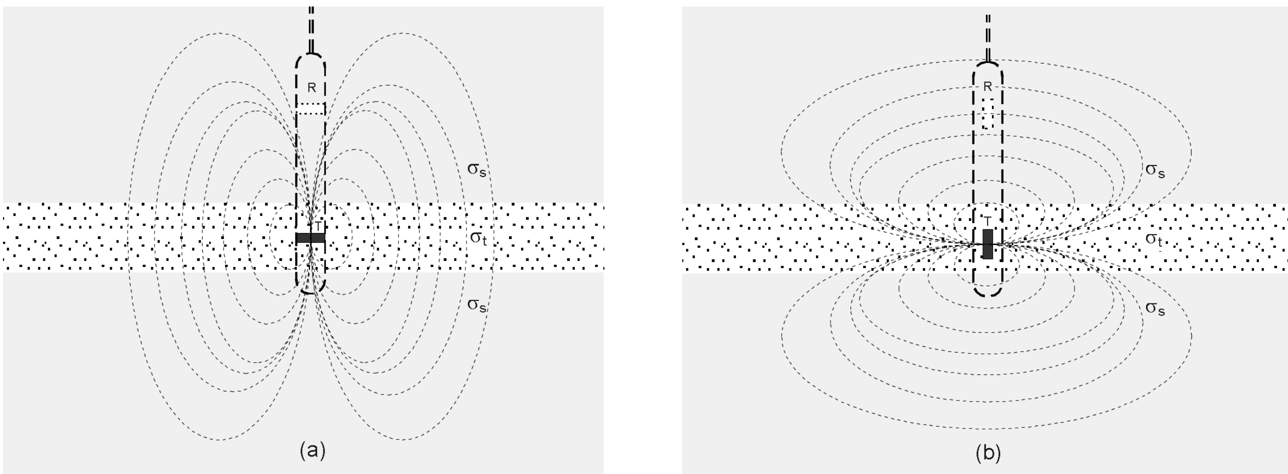

Figure 1 - (a) Coaxial and (b) coplanar arrays in a model with two planar-parallel interfaces, *i.e.,* a bed surrounded by two very thick beds. The magnetic field lines superimposed on them are due to vertical and horizontal transmitter dipoles in a homogeneous medium.
Superimposed on it are the hypothetical geometrical distribution of magnetic field lines due to vertical and horizontal transmitter dipoles in a homogeneous medium. Observe relatively higher horizontal concentrations of these lines due to the coplanar transmitter and their geometrical relation with the interfaces.
The theoretical treatment employed here is based on using the Schelkunoff vector potentials relating magnetic and electric fields (Harrington, 1961) . In the borehole tools the radius of the coils is very small compared to the coil spacing and the wavelength, therefore, they may be considered as magnetic dipoles. Accordingly, coaxial coils may be represented by vertical magnetic dipoles (VMD) and the coplanar coils by horizontal magnetic dipoles (HMD) in a vertical borehole.

RADIAL INVESTIGATION

Homogeneous Medium

The voltage induced in a receiver coil is $V = -i\omega\mu n_r H\pi a^2$, where $i = \sqrt{-1}$, ω the angular frequency, μ the magnetic permeability, n_r the number of turns, H the magnetic field normal to the plane of the coil of radius a. Divinding this voltage by the coplanar apparatus constant and expanding in powers of L/δ, where L is the coil separation and δ the skin depth defined as $\delta = \sqrt{2/\omega\mu\sigma}$, yields the components of the complex conductivity signal, σ_R (resistive) and σ_X (reactive) :

$$\sigma_R + i\sigma_X = \sigma - \frac{2i}{\omega\mu L^2} - \frac{4}{3}\left(\frac{L}{\delta}\right)\sigma(1+i) + \Lambda$$

In this equation the leading real term is equal to that obtained by geometrical factor theory, validating its correctness in the limit of zero frequency and infinite resistivity. The second term represents the mutual inductance between the transmitter and receiver coil in air and the third the conductivity dependent skin effects which are ignored in geometric factor theory. This means that after the mutual term is removed, the XF-signal provides a first order approximation of the skin effects.

Figure 02 shows that the skin effects are more intense in the coplanar array response than of the coaxial. The coplanar inphase response deviates from the linearity much earlier (near $\sigma_t = 10^2$ *S/m*) than coaxial response (near $\sigma_t = 10^3$ *S/m*) for all the coil spacings. But, this loss in the coplanar inphase response is compensated by its quadrature counterpart. Thus, after skin effect corrections (SEC) responses in both systems become almost equal.

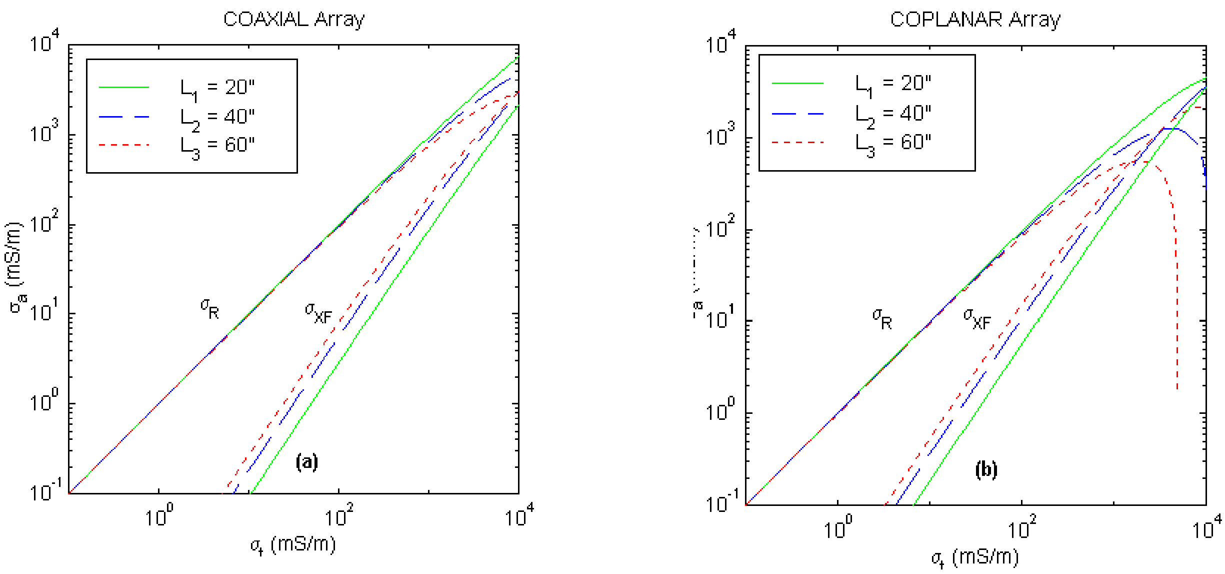

Figure 2 – (a) Coaxial and (b) coplanar arrays with their resistive (σ_R) and reactive (σ_{XF}) responses in a homogeneous medium.

Cylindrical Interface

In Figure 03 we can observe that for initial low invasion diameter **(**D_i**)** and for high σ_t values the coplanar raw (uncorrected) response is lower than the coaxial response. This is due to the higher skin effects in the former system.
With the increasing D_i the raw coplanar response increases gradualy and overtakes the coaxial response, and then appear peaks before it starts decreasing to reach σ_i value. But, at low D_i values the SEC responses in both coils

systems are almost same, *i.e.*, near σ_t value. After the initial D_i values, the SEC coplanar response maintains always higher than the coaxial response and the peaks become more prominent. Finally, at very high D_i values the curves approach σ_i values. These polarization peaks in the coplanar radial response are good indicator of the invasion front.

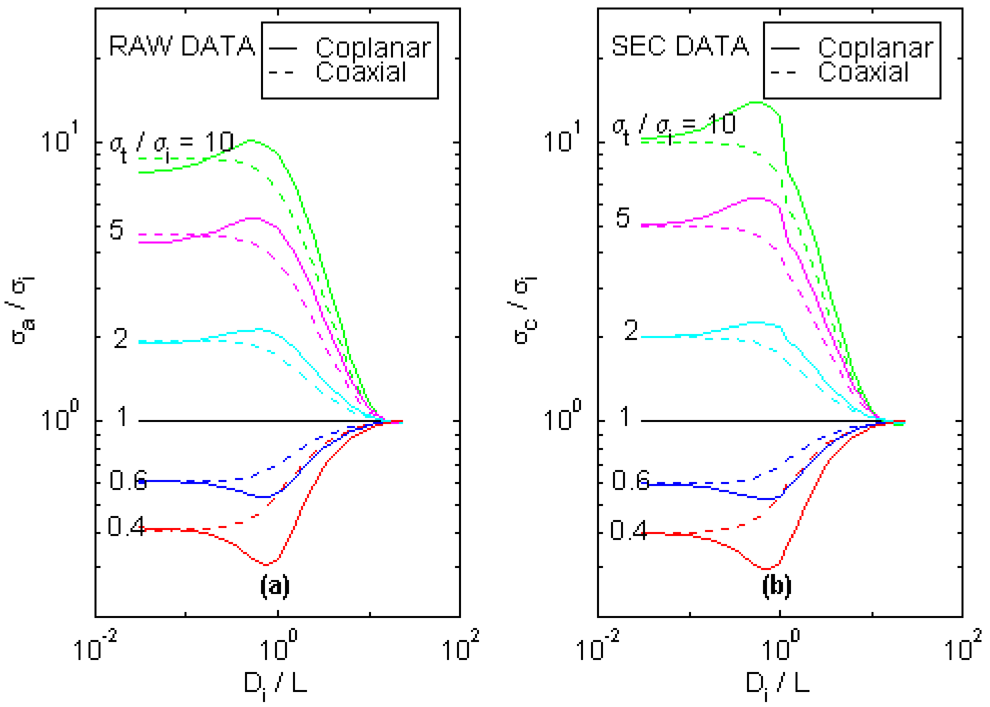

Figure 3 - Radial response of the coaxial and coplanar arrays of a model with a cylindrical interface representing a invaded zone . (a) Uncorrected (raw) , and (b) corrected (SEC) conductivities.

VERTICAL INVESTIGATION

A 10 m thick horizontal bed of 2 S/m conductivity in a homogeneous medium of 0.5 S/m is the model chosen to study this response. The coaxial resistive response (σ_R), shown in Figure 4, is greater than the coplanar response but after the skin effects corrections (σ_c), both approach almost their true conductivity values σ_t. In the coplanar profiles polarization "horns" appear against the bed bondaries which can be used as a good indicator of these interfaces.

CAUSES OF THE POLARIZATIONS

In the coplanar system occur the oscillations in the radial response and "horns" in the vertical profiles because the induced electric field and their currents cross the cylindrical and horizontal interfaces in this coil system unlike the conventional coaxial system. Consequently, charges build-up at the boundaries due the discontinuity in the normal component of the electric field which act like a secondary transmitter imposing its signal on the responses in the proximity of the interfaces.

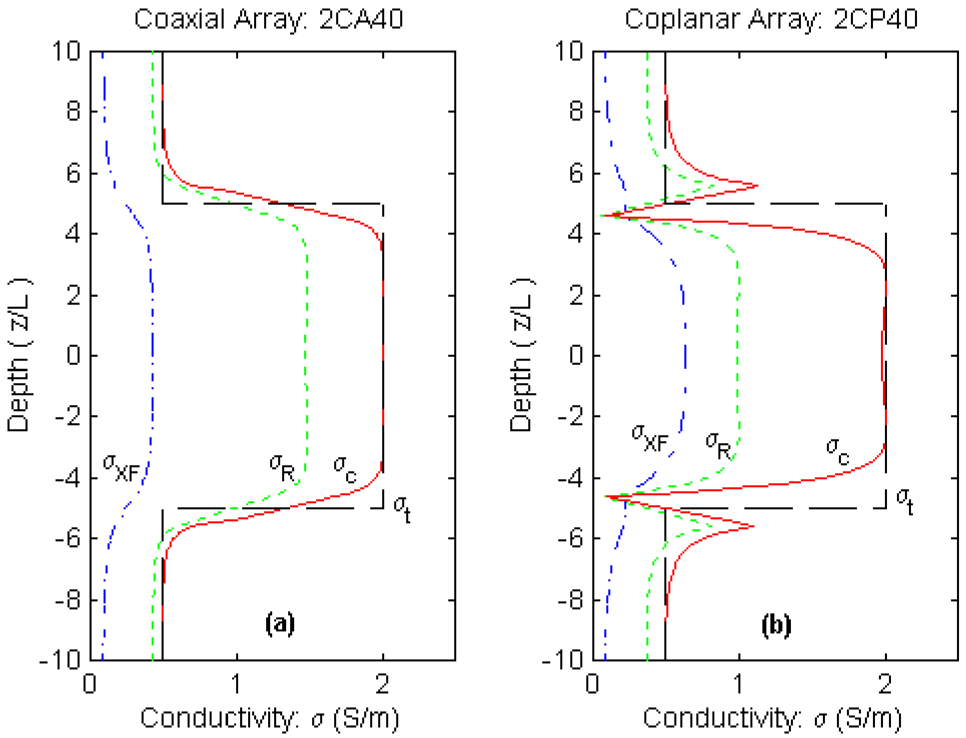

Figure 4 - Vertical responses of the (a) coaxial and (b) coplanar arrays of a model with two planar-parallel interfaces, *i.e.,* a bed surrounded by two very thick beds. σ_{XF}, σ_R, and σ_c are reactive, resistive and corrected conductivities.

CONCLUSIONS

The corrected (SEC) coplanar response, which takes into consideration both the reactive and resistive part of the signal, provides much better information than the coaxial response about the bed boundaries and the invasion front whilst delivering to the same degree of information about the conductivity. In addition, the azimuthal attributes of the coplanar system can be used in locating the axially asymmetrical anomalies.

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