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## Study of Azimuthal Resistivity Anisotropy with Dipole-Dipole Electromagnetic Profiling

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### SUMMARY

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Dipole-dipole electromagnetic profiling can be used for study of azimuthal resistivity anisotropy. Inductive method has some advantages before galvanic resistivity measurements. Theoretical formulas were obtained for several orientations of transmitter and receiver coils in near zone above anisotropic halfspace, calculations fulfilled and azimuthal diagrams presented. Practical results of anisotropy measurements with EM-34 are also presented.

## Introduction

Traditional technology to study azimuthal resistivity anisotropy consists in using azimuthal measurements with galvanic resistivity arrays. The same problem can be solved with dipole - dipole electromagnetic (inductive) profiling. We used EM-34 instrument of Geonics [EM34-3 & EM34-3XL..., 1998], working in near zone for array with two vertical magnetic dipoles (VMD) or with two horizontal magnetic dipoles (HMD) with their axis perpendicular to the distance between coils (equatorial array - EA). Measuring value in this case is imaging component of the secondary field normalized to the primary field, which is proportional to the earth conductivity, that is why EM - 34 readout is apparent conductivity  $\sigma_a$  [McNeill, 1980]:

$$\sigma_a = \frac{4}{\omega \mu_0 R^2} \left( \frac{H_s}{H_p} \right) \quad (1)$$

where  $R$  - is a distance between coils (10, 20 or 40 m),  $\omega$  - angular frequency,  $\mu_0$  - magnetic permeability. Apparent conductivity can be recalculated into apparent resistivity on formula  $\rho_a = 1000/\sigma_a$ . Coefficient 1000 is needed to obtain  $\rho_a$  in Ohm.m, when  $\sigma_a$  is measured in millisiemens per meter.

It is possible to find papers about EM-34 application for solving different geological problems (for example, on Geonics site - [www.geonics.com](http://www.geonics.com)), but for anisotropy study papers are rare [Sandberg et al., 1996; Sandberg and Jagel, 1996; Rust, Sandberg and Auken, 1997].

EM theory for EM-34 above anisotropic halfspace was described in the paper [al-Garni and Everett, 2003]. Here only VMD case was considered, and azimuthal diagrams were calculated for high anisotropy values  $\lambda$  (2.4 и 4.2), diagrams look strange and explications are not very convincing. In the paper [Le Masne and Vasseur, 1981] fields of electric and magnetic dipoles (only VMD case) above anisotropic medium were considered. The authors concluded that Hz component of VMD does not depend on azimuth and  $\lambda$ , that means this component is useless for studying azimuthal anisotropy. HMD source was not analyzed in both papers. That is why we decided to obtain formulas from the very beginning and study three cases: VMD, HMD-EA, when dipoles axis are perpendicular to the distance between coils and HMD-AA for coaxial orientation of coils. For calculation we used  $\lambda=2$ , such anisotropy sometimes can be found in practice.

### 1. Brief theory of magnetic field from magnetic dipole with alternate current above homogeneous anisotropic medium

Formulas for electric and magnetic field components from magnetic dipole with alternate current, depending from electrical parameters of anisotropic medium, frequency and position of transmitting and receiving coils can be obtained from forward problem solution for electrodynamic vector potential  $\mathbf{A}^M$  of magnetic type in homogeneous anisotropic medium. With different details these solutions were obtained in the papers [Karinsky, 2002, 2008; Karinsky, Daev, 2006, 2008; Moran and Gianzero, 1979]. In all these papers for vector potential  $\mathbf{A}^M$  calibration of Tikhonov [Tikhonov, 1959] was used.

We obtained formulas for several arrays and their positions. In all cases transmitting magnetic dipole  $G$  with the moment  $M_G$  and measuring point are situated on the earth surface  $z=0$ , anisotropy axis  $n$  is parallel to axis  $X$  (anisotropy strike is oriented along axis  $Y$ ). Transmitter center is situated in point of origin  $O$  of coordinate system  $x, y, z$ , and  $L$  - is the distance between source and measuring dipoles. Angle between array axis and anisotropy axis  $n$  is  $\alpha$ . For short we give here only final formulas

#### 1, a) VMD array oriented across anisotropy strike

In near zone (at  $z=0$ ),  $y \rightarrow 0$ ,  $\alpha \rightarrow 0^\circ$ :

$$|\text{Im}(h_{zz})| \approx \frac{\omega\mu_0 L^2}{2} \sigma_n = \frac{\omega\mu_0 L^2}{2\rho_n}. \quad (2)$$

That means, that  $\text{Im}(h_{zz})$  value at  $\alpha \rightarrow 0^\circ$  depends on  $\rho_n$ .

### 1, b) VMD array oriented along anisotropy strike.

In near zone (at  $z=0$ ),  $x=0$ ,  $\alpha=90^\circ$

$$|\text{Im}(h_{zz})| \approx \frac{\omega\mu_0 L^2}{2} \sigma_t = \frac{\omega\mu_0 L^2}{2\rho_t}. \quad (3)$$

That means, that  $\text{Im}(h_{zz})$  value at  $\alpha \rightarrow 90^\circ$  depends on  $\rho_t$ .

After recalculation of measuring magnetic field into apparent resistivity we receive azimuthal diagram minimum along axis Y (along strike) and maximum  $\rho_a$  oriented along axis X (across strike). Azimuthal  $\rho_a$  diagram is elongated along X (across strike) (Fig.1). Axis ratio in ideal case is equal to  $\lambda^2$ . There is no anisotropy paradox.

### 2) Magnetic dipoles with horizontal moments

Transmitting dipole now has horizontal moment  $\mathbf{M}_G$ , perpendicular to axis Z. Both dipoles are situated in plain  $z=0$ .

#### 2a) HMD, equatorial array oriented across anisotropy strike (along X)

In near zone, at  $y \rightarrow 0$ ,  $\alpha \rightarrow 0$ :

$$|\text{Im}(h_{yy})| \approx \frac{\omega\mu_0 L^2}{2} \sigma_n = \frac{\omega\mu_0 L^2}{2\rho_n}. \quad (4)$$

At  $\alpha \rightarrow 0$   $\text{Im}(h_{yy})$  depends only on  $\rho_n = 1/\sigma_n$ .

#### 2b) HMD, equatorial array oriented along anisotropy strike (along Y).

In near zone, at  $x \rightarrow 0$ ,  $\alpha \rightarrow 90^\circ$

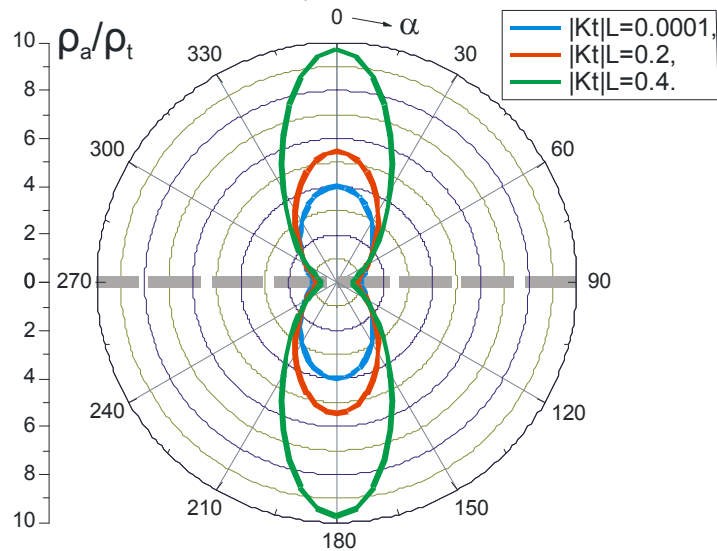
$$|\text{Im}(h_{xx})| \approx \frac{\omega\mu_0 L^2}{2} \sigma_t = \frac{\omega\mu_0 L^2}{2\rho_t}. \quad (5)$$

After recalculation of measuring magnetic field into apparent resistivity we receive azimuthal  $\rho_a$  diagram minimum along axis Y (along strike). Azimuthal  $\rho_a$  diagram is elongated along X (across strike) (similar to VMD case in Fig.1). Axis ratio in ideal case is equal to  $\lambda^2$ . There is no anisotropy paradox.

### 3) HMD, axial array (HMD -AA)

#### 3a) HMD -AA oriented across anisotropy strike (along X)

In near zone, at  $z=0$ ,  $y=0$ ,  $\alpha=0^\circ$ .



Array VMD-EA with vertical magnetic dipoles  
**Figure 1** Azimuthal  $\rho_a$  diagrams for VMD. Strike orientation is:  $90^\circ - 270^\circ$ . Diagrams for HMD - EA are very similar.

$$|\text{Im}(h_{xx})| \approx \frac{\omega\mu_0 L^2}{2} \sigma_t = \frac{\omega\mu_0 L^2}{2\rho_t}. \quad (6)$$

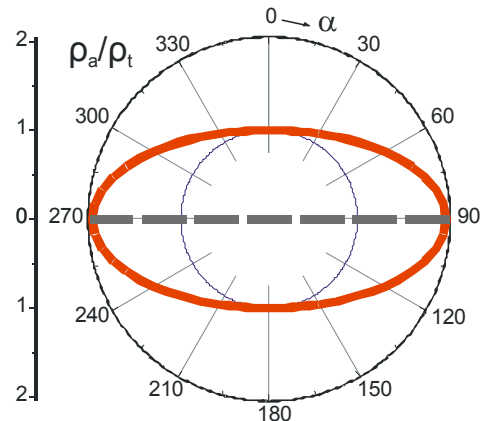
**3b) HMD - AA oriented along anisotropy strike (along Y).**

In near zone, at  $z=0, x=0, \alpha=90^\circ$ .

$$|\text{Im}(h_{yy})| \approx \frac{\omega\mu_0 L^2}{2} \sigma_m = \frac{\omega\mu_0 L^2}{2\rho_m}, \quad (7)$$

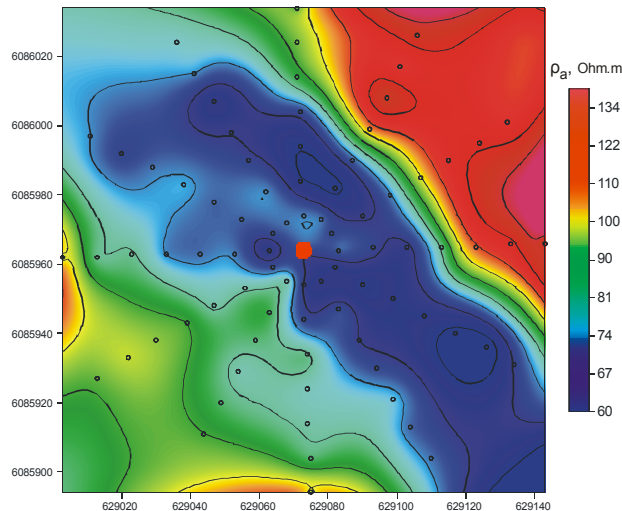
where  $\sigma_m = \sqrt{\sigma_t \cdot \sigma_n}$  and  $\rho_m = \sqrt{\rho_t \cdot \rho_n}$  - mean geometrical values of conductivity and resistivity of anisotropic medium. In this case  $\text{Im}(h_{yy})$  depends on  $\rho_m = 1/\sigma_m$ .

Azimuthal diagram for HMD - AA is elongated along Y (along strike), according to anisotropy paradox (Fig.2). Axis ratio in ideal case is equal to  $\lambda$ .



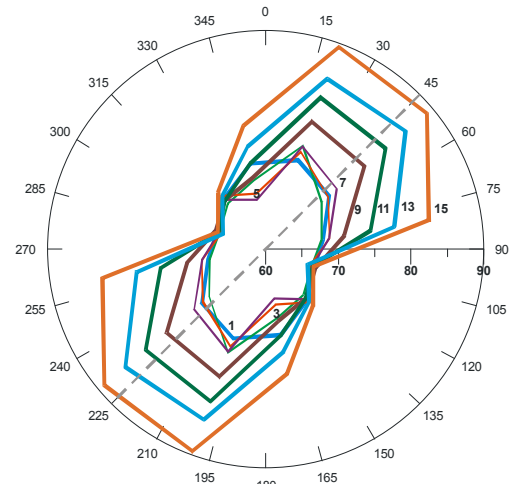
**Figure 2** Azimuthal diagrams  $\rho_a$  for array HMD – AA.

### Field example

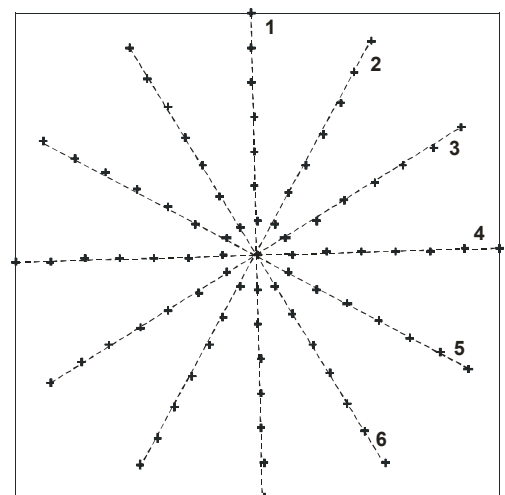


**Figure 3**  $\rho_a$  map obtained with EM-34. Red point means the center of azimuthal survey area.

Field measurements were performed with horizontal magnetic dipoles (HMD) with distance between coils 10 m and step along each azimuth 10 m (recommendation of Geonics) (Fig.5). 6 profiles, consisted in 15 measuring points each, cross in the center of the area. Using all  $\rho_a$  values a resistivity map of the area was obtained (Fig.3). Azimuthal diagrams were drawn for averaged values 1, 3, 5, 7, 9, 11, 13, 15 points situated symmetrically relatively the center (Fig.4). All diagrams have similar orientation perpendicular to river paleochannel in accordance with theoretical consideration. Such technology gives robust estimation of anisotropy parameters due to averaging and geoelectrical characteristic of the whole area due to resistivity map. Symmetrical averaging allows to study influence of filter length, whereas averaging on right and left halves allows create asymmetrical diagram to study influence of anisotropy and heterogeneity separately [Software...,



**Figure 4** Field azimuthal diagrams  $\rho_a$  for HMD-EA with EM-34,  $R=10$  m, averaging on 1, 3, 5, 7, 9, 11, 13, 15 points of profile.



**Figure 5** Scheme of azimuthal survey using Geonics technology with 6 crossing profiles.

1999].

Axis ratio for 15 points averaging is 1.34. Real anisotropy coefficient  $\lambda$  for this case is  $\lambda=1.13$ . In 1998-99 we performed 26 azimuthal measurements with galvanic resistivity arrays and obtained  $\lambda$  from 1.01 to 1.2 not far from this place [Bobachev et al., 2000]. New  $\lambda$  value obtained from EM inductive profiling is also in this interval.

## Conclusions

Formulas for EM inductive profiling above anisotropic medium were obtained. For VMD and HMD - EA in near zone there is no anisotropy paradox and axis ratio for ideal near zone is  $\lambda^2$ . When  $|kR|$  is smaller than 1, but far from ideal, the axis ratio is more than  $\lambda^2$ . For HMD - AA in near zone there is anisotropy paradox and axis ratio for ideal near zone is equal to  $\lambda$ .

Practical field measurements confirm theoretical results.

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