Analysis of the self-interference model and compensation methods in airborne electromagnetics

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SUMMARY

We compare various compensation methods for the EQUATOR system and for several modifications of the airborne electromagnetic system EM4H: with a transmitter loop attached to the fuselage of Mi-8 helicopter, with a loop attached to the fuselage of An-3 aircraft, and with a loop towed by Eurocopter AS350B3. We consider two ways of the transmitter signals interference modeling: in the form of a stationary systematic component of the measurements and in the form of a stationary field vector rigidly connected to the transmitter. To implement the second approach, the EM4H and the EQUATOR use two additional dipoles to determine the relative location of the transmitter and the receiver. At high altitude, in the absence of a response from the ground, the following statistical parameters of the signals remaining after interference compensation were analyzed: the standard deviation and the difference between the minimum and the maximum values.

Key words: compensation; relative electromagnetic positioning; magnetic dipole; EM4H; EQUATOR

INTRODUCTION

Airborne electromagnetics (AEM) is one of the most popular geophysical methods used in mineral exploration around the world (Legault, 2015). Their difference lies both in the design of the transmitter and the receiver, and in the method of compensating for various interferences. Sensitivity of measuring equipment is constantly growing. Hence, it is necessary to carry out an analysis of the correspondence between data processing methods and the level of sensitivity. In this work, we determine the degree of adequacy of existing models and methods for compensating for existing interference to the modern level of equipment sensitivity.

The main source of interference are uncontrolled eddy currents that occur in the conductive elements of the carrying frame. In the case when the field sources are installed on an airplane or a helicopter, these currents can create a field that is about 1% of the primary field. This significantly complicates the further separation of the secondary field from the ground against the background of the primary one (Vovenko *et al*, 2013). The simplest method is to take into account the interference field as a constant. This method is unreliable, since the field of eddy currents depends on the changing relative position of the transmitter and the receiver of the field. The more complicated way is based on the changing geometry of the installation. To determine the relative position of the receiver and the alternating magnetic field transmitter, we solve the inverse problem. It consists in determining the parameters of the dipole according to the parameters of the field that it creates (Smith, 2001; Pavlov *et al*, 2010; Tkhorenko *et al*, 2015). The analysis was carried out using the data of the EM4H (Vovenko *et al*, 2013) and the EQUATOR (Moilanen *et al*, 2013) systems widely used in modern surveys. Being time domain system, EQUATOR also provides frequency domain data for analysis.

FORMULATION OF THE PROBLEM

Airborne electromagnetic system includes a transmitter and a receiver (Figure. 1). With the help of the former, the primary field is generated. The latter, in the case of systems, considered in the work, is located in a towed bird and registers the parameters of the secondary field. When measuring an alternating field, the eddy current field must be taken into account. It occurs in conductive structural elements of the transmitter loop (ΔM). This influence is the cause of interference ΔH, which in practice is much larger than the amplitude of the anomalous component of the field. The vector ΔM is assumed to be constant, allowing for the geometry stability of the conductive parts of the aircraft or other elements on which the loop is mounted. The vector ΔH is not constant, since the relative position of the transmitter and the receiver changes.

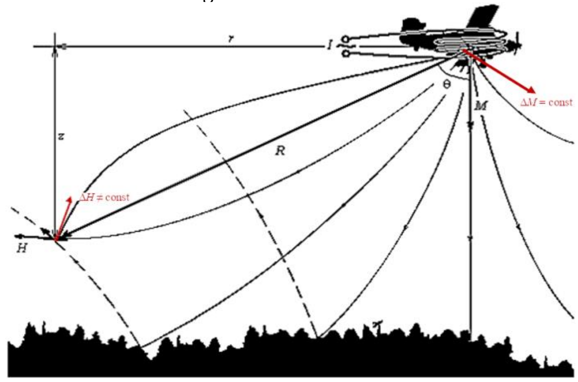

Figure 1. Airborne electromagnetic system EM4H. R - transmitter-receiver radius vector; M - vector of the magnetic moment of the exciting dipole; ΔM - vector of the magnetic moment of the eddy current field; H - magnetic field vector of the exciting dipole; ΔH – eddy current field vector.

Obviously, the effect of interference must be taken into account. For this to be done, a compensation is carried out, the essence of which is to move the system to a high altitude

(700 m), where the responses from the ground can be neglected. The parameters of the eddy-current field are defined there. Next, corrections are introduced into the field measurements at the height of the survey.

We have various approaches to the compensation method. If the receiver makes small movements relative to the transmitter, we can assume that the eddy-current field strength vector is constant in the receiver coordinate system. This method, based on the subtraction of the constant component, is used in many modern systems and is called "nulling".

Another approach is based on the variability of the ΔH vector. For this an analysis of the relative spatial and angular position of the transmitter and the receiver is carried out (Vovenko *et al*, 2013).

COMPENSATION WITH REFERENCE TO THE CHANGING RELATIVE POSITION OF THE TRANSMITTER AND THE RECEIVER

In this paper, we consider electromagnetic systems, which are systems with a controlled source. Usually we can represent the primary field a field of a dipole (Smith, 2001). Pavlov *et al* (2010) and Tkhorenko *et al* (2015) wrote it in a matrix form. Let us rewrite the relations for the field in the form

$$H = \frac{1}{4\pi|R|^3}\left(3\frac{RR^T}{|R|^2} - I\right)M = \Omega(R)M \qquad (1),$$

where H is the magnetic field vector, R is the position vector of the receiver relative to the transmitter, M is the vector of the magnetic moment of the dipole, I is the 3×3 identity matrix.

According to Vovenko *et al* (2013), the relation between the measured field, the generated moment, and the relative position of the transmitter and the receiver was derived. It is represented by the matrix $\Omega(R)$, which is absolutely the same for the dependence of ΔH on ΔM:

$$\Delta H = \Omega(R)\Delta M \qquad (2).$$

Case with 2 additional dipoles

It is proposed to introduce two additional dipoles with moments M_1 and M_2. With their help, the magnetic moment vector of the eddy-current field ΔM can be represented as a linear combination of known vectors:

$$\Delta M = k_0 M + k_1 M_1 + k_2 M_2, k_j \in R \qquad (3).$$

Applying (2) for (3), we get the same representation of the eddy-current field vector, where the coefficients will be the same as in expression (3):

$$\Delta H = k_0 H + k_1 H_1 + k_2 H_2 \quad (4).$$

The compensation step allows to determine the coefficients k_0, k_1, k_2 by the least square method. We minimize the quadrature response component and bring the in-phase response component to the same vector at all operating frequencies of the primaty field (the main sounding dipole usually excites several harmonics).

Case with 1 additional dipole

We have asked ourselves if it is possible to solve the compensation problem using only one additional dipole. Barabanova and Barabanov (2021) noted that there is a solution. Namely, the authors proposed an algorithm for solving the problem of electromagnetic positioning using the field of two dipoles. As a result, the following nonlinear expressions can be derived:

$$H'_2 = F_2(H, H_1),\ H'_1 = F_1(H, H_2) \qquad (5).$$

That is, we can substitute the true dipole with a calculated vector, for example, through the vector product of two available dipoles:

$$H'_2 = \Omega(R)(M \times M_1),\ H'_1 = \Omega(R)(M \times M_2) \quad (6).$$

Using (5), we can pass to a linear combination of the eddy-current field vector by substituting the obtained dependence into expression (4).

$$\Delta H = k_0 H + k_1 H_1 + k_2 (F_2(H, H_1)) \quad (7),$$
$$\Delta H = k_0 H + k_1 (F_1(H, H_2)) + k_2 H_2 \quad (8).$$

As we have mentioned, the receiver is moving with respect to transmitter, which affects the measurements obtained. It is also important that the value of the spatial displacement of the receiver and the transmitter during flight usually does not exceed 10 m. This observation gives a hope that dependence (5) can be linearized, while the accuracy of the linear approximation will be sufficient to perform the compensation. Then equations (7), (8) can be rewritten as:

$$\Delta H = p_{01}H + p_1 H_1 = p_{02}H + p_2 H_2 \quad (9).$$

Therefore, it is possible to use only one additional dipole M_1 or M_2. Further, we test this hypothesis on a series of dataset of the EQUATOR system and various modifications of the EM4H systems obtained during survey flights by Geotechnologies, Aerogeophysica and by Norilsk branch of A.P. Karpinsky Russian Geological Research Institute.

COMPARISON OF COMPENSATION METHODS

The comparison of various compensation methods for several modifications of the EM4H system was carried out: with a transmitter loop attached to the fuselage of Mi-8 helicopter, with a loop attached to the fuselage of An-3 aircraft, and with a loop towed by Eurocopter AS350B3. (Figure 2).

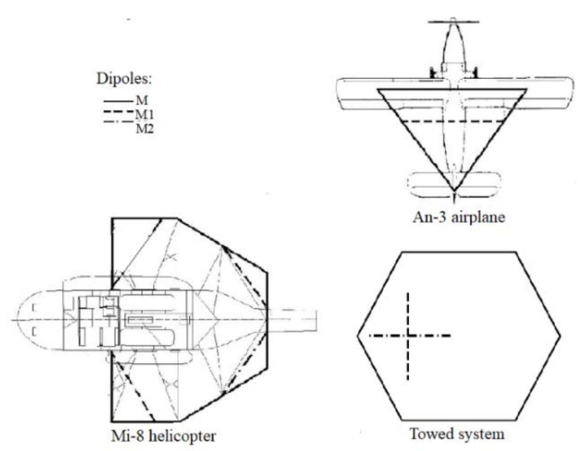

Figure 2. Loops installation for EM4H modifications.

The EQUATOR system now exists only in a towed version (Figure 3).

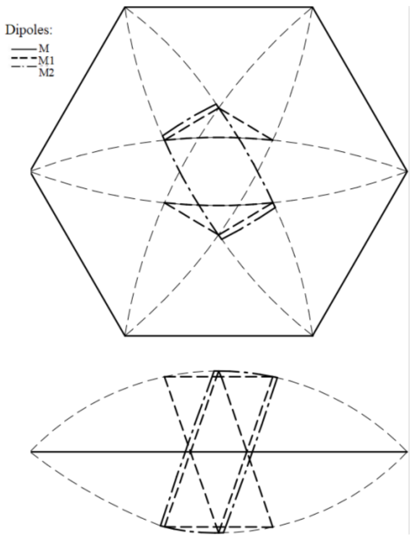

Figure 3. Loops installation for EQUATOR system.

At high altitude, in the absence of a response from the ground, we analized the following parameters of the signals remaining after interference compensation: the standard deviation and the difference between the minimum and the maximum values. The results of the comparison are shown in tables (Table 1, Table 2) and figures (Figure 4, Figure 5).

The tables contain the standard deviation (RMS) and peak-to-peak (max-min) for the quadrature component of the field. Under ideal conditions of no interference, it should be equal to zero. The values are shown after compensation of the receiver systematic offset (nulling, Figure 4B, Figure 5D, Figure 6D), also after determining the geometry parameters using the first (Figure 4A, Figure. 5B, Figure. 6B), the second (Figure 5C, Figure 6C) or two (Figure 5A, Figure 6A) additional dipoles. In the case when a fixed wing aircraft was used, the second additional dipole was absent (Figure. 4). One of the columns of the tables is the improvement factor, derived as the ratio of the corresponding values when using the nulling and the compensation using only the first additional dipole.

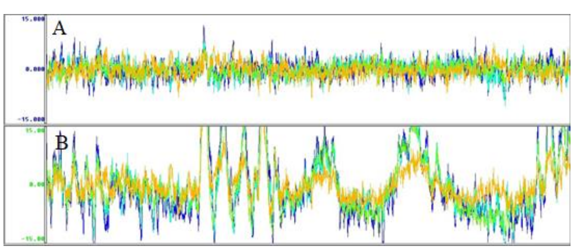

Figure 4. Quadrature component for the An-3 aircraft at 4 frequencies. A - after compensation, with using the measurements of the parameters of the additional dipole; B – nulling.

CONCLUSIONS

The best compensation result is given by an approach that takes into account the movement of the receiver relative to the field source. This is true for the EQUATOR and for all versions of the EM4H system.

For both towed systems when the transmitter is far from the helicopter fuselage, there is no eddy current field at low frequencies (77-540 Hz). However, at high frequencies (greater than 2 kHz) it is significant. Therefore, the installation geometry must be taken into account. This is also necessary for systems in the time domain, while high frequencies are associated with the early time gates.

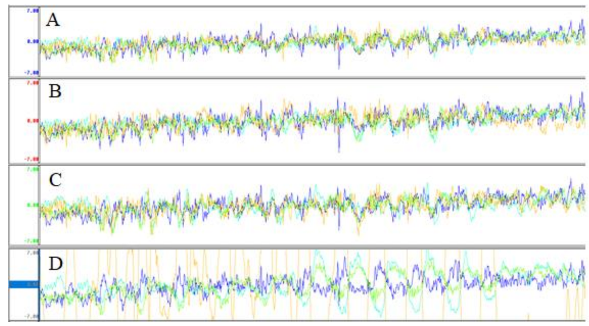

Figure 5. Quadrature component for the Mi-8 helicopter at 4 frequencies. A - after compensation, with using the measurements of the parameters of two additional dipoles; B - using the 1^{st} dipole, C - using the 2^{nd} dipole, D - nulling.

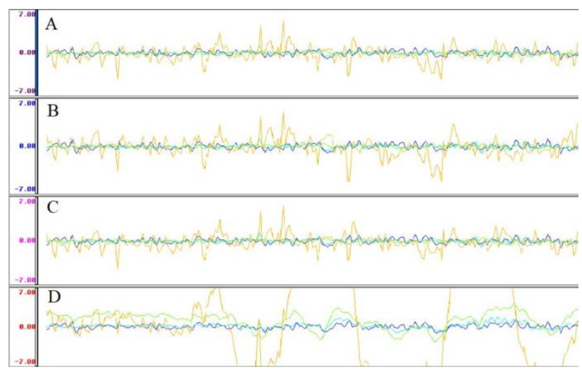

Figure 6. Quadrature component for the EQUATOR at 4 frequencies. A - after compensation, with using the measurements of the parameters of two additional dipoles; B - using the 1^{st} dipole, C - using the 2^{nd} dipole, D - nulling.

We use a linear model of the eddy current field as a function of the field of two dipoles. This is just as effective as using a full linear expansion in three dipoles. Therefore, it is possible to perform the receiver positioning described by Pavlov *et al.* (2010) with use of the field of two dipoles in a linear formulation.

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Table 1. Statistics for various compensation methods at high frequencies (8 kHz – EM4H, 6kHz – EQUATOR).

	nulling	1st and 2nd dipoles	1st dipole	2nd dipole	improvementfactor	
Airplane	4,53		2,17		2,1	RMS
	41,92		15,04		2,8	max-min
Helicopter Fixed	2,37	1,91	1,92	1,92	1,2	RMS
	14,97	13,01	12,76	13,16	1,2	max-min
Helicopter Towed	20,27	1,16	1,28	1,37	15,8	RMS
	92,88	8,14	8,10	9,34	11,5	max-min
EQUATOR	11,04	1,15	1,17	1,42	9,44	RMS
	53,47	9,59	10,08	10,75	5,30	max-min

Table 2.Statistics for various compensation methods at low frequencies (130 Hz – EM4H, 77 Hz – EQUATOR).

	nulling	1st and 2nd dipoles	1st dipole	2nd dipole	improvementfactor	
Airplane	12,61		2,52		5,0	RMS
	121,53		21,42		5,7	max-min
HelicopterFixed	2,82	1,42	1,46	1,4	1,9	RMS
	14,18	8,42	8,29	8,62	1,7	max-min
HelicopterTowed	1,73	1,44	1,46	1,46	1,2	RMS
	10,70	10,09	9,65	9,16	1,1	max-min
EQUATOR	0,29	0,22	0,22	0,23	1,3	RMS
	1,84	1,56	1,59	1,71	1,1	max-min