Receiver positioning by means of EM field measurements

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ABSTRACT

Intensive development of airborne geophysical methods is associated with employment of new technologies for navigation tasks of surveying process. Airborne electromagnetics is not an exception. Use of airborne EM systems with unstable transmitter-receiver geometry is associated with some difficulties. First, geometry changing forces primary field variations in the receiving point, and they significantly exceed secondary field. Second, information about system geometry is necessary for data interpretation, especially in conductive environment. These factors requires transmitter-receiver positioning problem to be solved. There are many navigation methods and technologies, but almost all of them have limitations for use in airborne EM. The most reasonable is one based on EM field measurements.

The objective of the paper is to describe the method of receiver positioning with use of three dipoles field measurements. A new positioning algorithm is given, and primary field separation problem is also discussed. The accuracy of distance measurement is comparable with the accuracy of the method that uses GPS in differential mode. The angles of relative orientation are measured with the accuracy better than one degree. The measurements of full response became available for both time-domain and frequency-domain systems with non-rigid geometry. It is confirmed by survey results of EM4H and EQUATOR systems.

Key words: transmitter-receiver geometry, primary field removing

INTRODUCTION

There is a number of active airborne electromagnetic systems, time-domain and frequency-domain, fixed-wing and helicopter borne, with unstable receiver-transmitter geometry (Fountain, 2008). Systems like MEGATEM (Fugro Airborne Surveys) or EM4H (Geotechnologies) use a transmitting loop mounted on an aircraft and a receiver towed in a bird. Other type of systems, like HeliGEOTEM (Fugro Airborne Surveys) or EQUATOR (Geotechnologies), use towed transmitting loop with receiver attached to the tow cable somewhere above the transmitter.

Consider two problems of such type of AEM systems. First one is how to separate primary and secondary field (Smith, 2001a). Receiver-transmitter geometry changing forces primary field variations in the receiving point, and they significantly exceed secondary field. By removing primary signal from measurements we are able to use total response, not only off-time or quadrature parts. The second problem is the fact that low precision of geometry measurements can affect results of data interpretation (Hefford et al., 2006). The more conductive environment, the more precise geometry parameters are needed.

Many methods of the receiver positioning based on different principles are described by Smith (2001b) and by Pavlov et al. (2010) as technologies with limited use. Laser range finder, photographer, precise relative satellite navigation etc. are among them, and no one is good enough to satisfy all requirements.

As an alternative approach Smith (2001b) suggested to use primary-field measurements for dynamical estimation of receiver position. It was a very good idea because it gave coordinates with respect to transmitter dipole, and exactly this position is needed for all applications in EM data processing. Unfortunately, one transmitting dipole gives a set of solutions, so some additional information is needed to select a single position. The first assumption is that receiver trajectory is physically reasonable. Mathematically it means that receiver axes' orientation with respect to transmitting loop should be chosen somehow. The second assumption concerns secondary field influence: should it be neglected or considered, i.e. one of the models:

'free space' or 'inductive limit' should be used (Vrbancich and Smith, 2005).
Another idea was described by Raab (1977). The point is to use more complicated field source.
For example, three orthogonal sources transmitting alternating magnetic field on different frequencies.

Combining these approaches Pavlov et al. (2010) suggested a new one with use of three dipoles. In this case three field vectors are measured and full information about receiver coordinates and orientation is available.

In this paper a development for three dipoles method is reported, mutual orthogonality of dipoles is no more needed. A new positioning algorithm is given, and application for primary field separation is discussed.

BASIC POSITIONING ALGORITHM

Theoretical basis

According to Smith (2001b), primary field in receiving point is given by formula

$$\boldsymbol{H}(\boldsymbol{r}) = \frac{1}{4\pi r^3}\left(\frac{3\boldsymbol{M}\times\boldsymbol{r}}{r^2}\boldsymbol{r} - \boldsymbol{M}\right), \quad (1)$$

where $\boldsymbol{H}$ is the primary field vector, $\boldsymbol{M}$ – dipole moment vector, $\boldsymbol{r}$ is the vector offset between transmitter and receiver. Non-bold symbols denote magnitude of corresponding vector, symbol × is used for the cross product of vectors, otherwise the dot product is meant. This equation can be expressed in a more convenient matrix form (Pavlov et al., 2010):

$$\boldsymbol{H}(\boldsymbol{r}) = \Omega(\boldsymbol{r})\boldsymbol{M}, \quad (2)$$

where matrix $\Omega(\boldsymbol{r})$ can be obtained in the following form:

$$\Omega(\boldsymbol{r}) = \frac{1}{4\pi r^3}(3\boldsymbol{e}_r \otimes \boldsymbol{e}_r - I). \quad (3)$$

Here I is the identity matrix 3x3, $\boldsymbol{e}_r = (\boldsymbol{e}_1, \boldsymbol{e}_2, \boldsymbol{e}_3)$ is the unit vector collinear with $\boldsymbol{r}$, ⊗ denotes dyadic product with result expressed as following matrix:

$$\begin{pmatrix} e_1e_1 & e_1e_2 & e_1e_3 \\ e_1e_2 & e_2e_2 & e_2e_3 \\ e_1e_3 & e_2e_3 & e_3e_3 \end{pmatrix} \quad (4)$$

The most important property of matrix $\Omega(\boldsymbol{r})$ is non-singularity wherever it is defined, i.e. everywhere except point $\boldsymbol{r} = 0$. Therefore the inversed matrix can be found everywhere:

$$\Theta(\boldsymbol{r}) = \left[\Omega(\boldsymbol{r})\right]^{-1} = 2\pi r^3(3\boldsymbol{e}_r \otimes \boldsymbol{e}_r - 2I). \quad (5)$$

Suppose the magnitude of the inducing dipole M is known and vector $\boldsymbol{H}$ components are measured in some system of coordinates. Then there is only one point for each direction of vector $\boldsymbol{e}_r$ where the transmitting dipole can be placed to give measured value of the field. And equation

$$\boldsymbol{M} = \Theta(\boldsymbol{r})\boldsymbol{H} \quad (6)$$

defines the direction of the dipole moment vector $\boldsymbol{M}$ uniquely. The distance to this point can be found as

$$r = \sqrt[3]{\frac{M}{\left|(3\boldsymbol{e}_r \otimes \boldsymbol{e}_r - 2I)\boldsymbol{H}\right|}}. \quad (7)$$

Equation (7) describes a closed convex centrally symmetric surface, which is a locus of possible dipole positions.

Consider three dipoles, which are placed in one point and have moment vectors of essentially different directions so they are linearly independent. This situation is possible if loops are mounted in different planes and their centers are coincident. For time-domain EM systems there can be a time shift between signals in three loops. For frequency-domain systems, different signal spectra in different loops is enough. This allows to separate field vectors of three dipoles in a receiving point. Using the assumption that the amplitudes of inducing moments are known, it is possible to find the intersection of three surfaces, which is the locus of possible dipoles position. And it consists of eight points in most general case. Actually, only two of them make sense.

Equations for position estimation

One of the main difficulties on the way to receiver positioning is the fact that field vectors are measured in the coordinate system related to receiver while dipoles moment vectors are known in the coordinate system of transmitter. Volkovitsky (2012) overcame it using (6) to find dot products of different pairs:

$$\boldsymbol{M}_i\boldsymbol{M}_j = \boldsymbol{H}_i\Theta^2(\boldsymbol{r})\boldsymbol{H}_j, \quad i, j = 1,2,3, \quad i \geq j, \quad (8)$$

where components of vectors $\boldsymbol{M}_i$ are given in transmitter system of coordinates, vectors $\boldsymbol{H}_i$ are given in receiver system of coordinates, as well as the unknown parameters of vector $\boldsymbol{r}$. In the right part of equations (8) there are quadratic forms with matrix

$$\Theta^2(\boldsymbol{r}) = 4\pi^2 r^6 \left(-3\boldsymbol{e}_r \otimes \boldsymbol{e}_r + 4I\right). \quad (9)$$

Equations (8) form an overdetermined system of six non-linear equations for three parameters of radius-vector $\boldsymbol{r}$. Combining pairs of $\boldsymbol{e}_r$ components it is possible to make following substitution:

$$\nu_s = e_k e_l, \quad k,l = 1,2,3, \quad k \geq l, \quad s = 1,\ldots,6,$$
$$\nu_7 = 1/\left(4\pi r^6\right). \quad (10)$$

Together with condition for unity vector $\boldsymbol{e}_r\,\boldsymbol{e}_r = 1$ equations (8) give a system of seven linear algebraic equations for variables ν_s.

Volkovitsky (2012) proved existence and uniqueness of solution for this linear system. He also showed that inverse variable substitution always gives two opposite solutions: $\boldsymbol{r}$ and $-\boldsymbol{r}$. Indeed, calculating square root of variables ν_s related to $k = l$ in (10) we get eight combinations, but after accounting signs of ν_s related to $k \neq l$ only two solutions are left. Knowing about dipole field symmetry we could predict that having a solution we always have opposite one. Note, to choose actual transmitter position it is enough to know whether it upper or lower, or ahead of or behind the receiver.

Orientation matrix

After solving linear system and inverse substitution we can calculate three vectors $\boldsymbol{M}_i$ in the receiver system of coordinates using (6). But they are already known in the transmitter coordinate system. So, accounting linear independence of these vectors the orientation matrix can be easily calculated.

RESTRICTIONS AND NOTATIONS

The algorithm described can be used only if the following conditions are satisfied:

- The transmitter induces field of three dipoles with coincident centres and linearly independent moment vectors.
- All three dipole vectors are known in the transmitter system of coordinates.
- The receiver measures three components of alternating magnetic field vector and separates fields of different dipoles in time domain or in frequency domain.
- The receiver is far enough from the transmitter to consider field sources as magnetic dipoles, but near enough for quasi stationary field approximation and/or for acceptable signal to noise ratio.
- Secondary field can be neglected or accounted.

Note, if side deviations of receiver can be considered small, then positioning task can be solved in two dimensional formulation, as it was done for fixed-wing modification of EM4H (Pavlov et al., 2010). In this case only one additional dipole is needed. The dipole moment vector must lie in longitudinal plane.

An important question is how to choose appropriate signals to be induced in additional dipoles. In frequency-domain systems any frequency can be used if it well separated from the operating ones. For time-domain systems it seems convenient to use time shifted pulses. But the problem is that these signals contain all harmonics of operating signal spectrum. As a result, secondary field will be affected by additional pulses. If we remove them by convolution with additional signal waveform, we remove those components of secondary field which are in-phase with it. If we just cut them off we loose some time channels.

On the other hand, the operating signal spectrum is discrete because of periodical waveform. So, harmonic additional signals are also possible. There is one more reason for using them: a considerable secondary field influence. Vrbancich and Smith (2005) considered two approximations for time-domain systems: free space, when in-phase response is neglected, and inductive limit, when in-phase response is approximated by fully reflected signal. In the last case the response is calculated with use of altitude information and subtracted from measured in-phase signal to obtain primary field. For GEOTEM the distance difference for two approximations was significant: about 10%.

Nevertheless, accounting a well known frequency response form (Palacky and West, 1991), we can see that the in-phase secondary field on low frequencies is quite small even over conductive areas. So, using full time measurements it is possible to detect lowest frequency in spectrum and to use its' in-phase component as a primary field vector in free space approximation. Moreover, adding a high enough frequency to the induced spectrum it is possible to use it in inductive limit approximation. Combining low and high frequency measurements it is possible to estimate secondary field influence at any type of geoelectric section, even over the sea. Hence, the best form of signal in additional dipoles is dual-frequency. And a high frequency can be added to the signal of main sounding dipole for inductive limit approximation.

REMOVING THE PRIMARY FIELD

First of all, let's note that after positioning by described method it is impossible just to calculate primary field and to subtract it. The reason is the secondary field influence discussed before. But returning to frequency response form (Palacky and West, 1991) and accounting the fact that signals of all operating frequencies are induced by the same loop, we can obtain in-phase part of frequency response whether subtracting lowest frequency in-phase vector measurements (free space approximation in low conductive areas) or highest frequency in-phase vector after removing calculated reflected field (inductive limit approximation in high conductive areas). Obviously, a wide enough frequency band is needed.

In low conductive areas in-phase response on the lowest frequency can be estimated using quadractic interpolation (Palacky and West, 1991). This value now can be accounted for frequency response recalculation. Note, the result can also be used for positioning improvement. The obtained in-phase response in frequency domain can be transformed to time domain after multiplying by the primary field spectrum.

APPLICATION AND RESULTS

All described ideas were realised in two airborne EM systems: frequency-domain EM4H and time-domain EQUATOR. EM4H uses transmitting loops mounted on the aircraft and receiver towed in a bird by 70 meters long cable. Two additional dipoles have moment vectors in horizontal plane. Frequency band is from 130 Hz to 8,4 kHz. EQUATOR uses transmitting loops towed by helicopter and a receiver in a bird attached to the tow cable and located 30 meters above. Two additional dipoles are also used. Frequency band is from 77 Hz to 12 kHz.

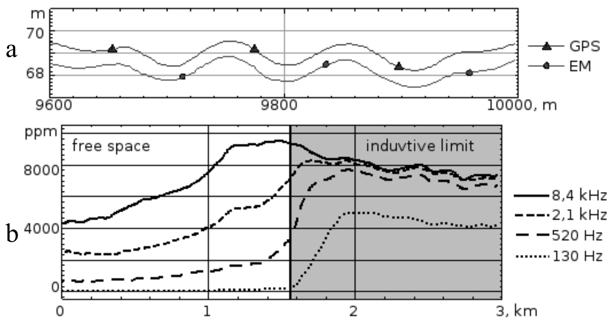

Figure 1. Transmitter-receiver distance measured by GPS and by EM method along flight path (a), in-phase response obtained using free space (shore) and inductive limit (salt lake) approximations (b)

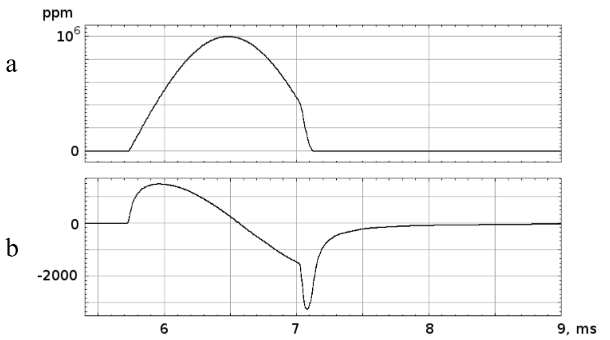

Figure 2. Primary (a) and secondary (b) field in time domain (B-field)

On Figure 1 there are results of positioning for EM4H in comparison with precise differential GPS solution. The difference caused by GPS antennas shifts. Also there are primary field removing results over quite low conductive area and over salt lake of about 15 S/m conductivity. On Figure 2 results of primary and secondary field separation after transform to time domain are presented (EQUATOR).

CONCLUSIONS

The solution of the described positioning problem is of great practical importance. First the accuracy of distance measurement is comparable with the accuracy of the method that uses GPS in differential mode. Second the angles of relative orientation are measured with the accuracy better than one degree. Third measurements of full response became available for airborne EM systems of the non-rigid geometry. All results achieved can be realized in both time-domain and frequency-domain systems. It is confirmed by survey practice of EM4H and EQUATOR systems.

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