# Airborne EM systems variety: what is the difference?

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## ABSTRACT

The challenge in developing airborne electromagnetic systems was followed by the appearance of a wide variety of different kinds of such systems. Even in the case of considering active inductive systems with only carried transmitters. Sometimes it seems that these different airborne electromagnetic systems are based on completely different laws of physics. But all of them, Time-Domain and Frequency-Domain, with different transmitter-receiver geometry, with use of different primary field waveform – are based on the same principles: time-variable magnetic field generated by any transmitter induces eddy currents in buried conductors and the secondary field of these currents measured by an inductive receiver can give us information about the geology structures.

The objective of this paper is to review the variety of systems from different points, especially in terms of signal structure, to analyse advantages and limitations of many existing systems and to suggest an approach that can make possible the ability to use the achievements in all of them during developing a new one. An attempt to realize this lead to the appearance of the system EQUATOR. The practice of using the system EQUATOR in both isolating and conductive environment for different type of targets fully confirms effectiveness of this approach.

**Key words:** time domain, frequency domain, transmitter-receiver geometry, EQUATOR

## INTRODUCTION

There is a wide variety of different kind of airborne electromagnetic systems and methods. They gained popularity in the geophysical world due to their high efficiency and technological abilities. Systems and methods of active inductive airborne electromagnetics with a field source carried by an aircraft are always in the focus of scientific and practical interests. The number of new developments in this area increases every year. Each direction is certainly a sovereign, so even modern classification of the systems faces serious difficulties (Fountain, 2008). Sometimes it seems that these different airborne electromagnetic systems are based on completely different laws of physics. However without exception time-variable magnetic field generated by any transmitter induces eddy currents in buried conductors and the secondary field of these currents measured by an inductive receiver can give us information about the geology structures.

Unfortunately, this information is not provided to the geophysicist as a map of mineral resources, and not even in terms of the values of physical fields, but only in the form of electrical signals. The choice of the methods for their measuring and interpretation is a matter of belonging to various scientific and engineering schools, each of them frequently uses only its achievements.

If we are not going to dogmatically follow one direction during developing new systems, we can successfully use the achievements in all of them. This paper is an attempt to show the practical effectiveness of this approach and illustrates it by the example of the system called EQUATOR.

## TIME-DOMAIN, FREQUENCY-DOMAIN

In practice in order to generate primary fields we usually use either a continuous harmonic or impulse method of induction. In the first case, the signal is a superposition of several sine waves with fixed frequencies, in the second - a regular sequence of pulses with a pause between them. Consequently, the principles of interpretation of signals, and also the systems themselves are divided into «Frequency-Domain» and «Time-Domain».

Information in Frequency-Domain system is presented as in-phase and quadrature signal components, or in a form of amplitude and phase. The results of measurements in each of the induced frequencies are presented in the form of values of complex coefficients of correlation between the transmitter and receiver.

Together they describe the frequency characteristics of signal propagation in the presence of a conductive environment. For interpretation, it's needed to build a frequency characteristic of geoelectric section, separating the response signal from the primary field which is much greater than the signal itself. Then we can judge the geology by the shape of frequency characteristic. Even in this simplified statement, interpretation is a difficult task.

In the classic paradigm of Time-Domain system, the response signal follows the roll off edge of primary field impulse. Receiver directly measures the transient response of geoelectric section. Responses from objects with different conductivities differ by the speed of voltage drop on the receiving coils' pins. The apparent simplicity of interpretation for Time-Domain systems predetermined their popularity.

The principles of technical implementation and interpretation for Frequency-Domain and Time-Domain systems seem to be quite different. However, if we look closer, a clear border between them becomes blurry. Similarity becomes particularly evident when we are talking not about physical fields, but the measured signals.

## SIGNAL FORM AND SPECTRUM FREQUENCY BAND

Let's look at the spectrum of the Time-Domain system's signal. Its shape follows the transient response of geoelectric section. The signal is periodic, so its spectrum is a discrete set of harmonics that are multiples of the pulse repetition frequency and the amplitude decreases with increasing the number of harmonics. If pulses of opposite polarity are in series, the spectrum contains only odd harmonics. Since the electronic components of receiving amplifier have a limited frequency range, the spectrum of the real signal is represented by only a few low-frequency harmonics. High frequency harmonics inevitably disappear and the shape of the signal is inevitably distorted at the same time. There is no reason to say that the Time-Domain systems measure the same thing as Frequency-Domain. Finding the amplitude of the corresponding harmonics using classic Frequency-Domain approach and applying Fourier transformation to it, we can get the same measured signal with all its distortions. Becker et al. (1990) pointed at the possibility of frequency processing and interpretation when they estimated benefits of the system COTRAN.

The set of frequencies of the Frequency-Domain systems is usually small, but the frequency range usually is much wider than in Time-Domain systems. For example, only four frequencies of EM4H system (130, 520, 2080 and 8320 Hz) cover 6 octaves diapason (Volkovitsky et al., 2008). Frequency-Domain systems with a small set of frequencies cannot measure the transient response section in detail, but on the other hand can roughly measure the frequency characteristic over a wide frequency range. At the same time, Time-Domain systems can measure frequency characteristics along with transient ones. But the transient characteristic is measured with distortion, while one frequency is in a narrow frequency range. There is no perfection in the world...

The conditions of the surveys in diverse geological conditions are quite different. To search for highly conductive sulphide ore deposits the Time-Domain system is very effective. However, significantly less powerful but more high-frequency Frequency-Domain systems are more helpful for finding less conductive objects (Smith et al., 2008).

In order to estimate preliminarily the exploration effectiveness of the airborne EM systems it's convenient to use the frequency domain form comparing the set of induced frequencies with the assumed frequency response of the section. The response from the highly conductive objects is observed mainly in the low frequency area and for low conductive objects in the high frequency area. Harmonics of Time-Domain systems are located in the low-frequency part of the spectrum. All of them are effective to search for the high conductive objects and the frequency range of a few hundred hertz is quite sufficient. If the survey area consists of low conducting rocks then the higher frequencies and wider frequency range are required. In the condition of low conductivity of geologic section, the amplitude of the response is very low. So the signal is getting "smeared" for impulse primary field and, at the same time, it becomes comparable to the level of measurement noise at each of the harmonics. In this case Frequency-Domain systems are more effective because all the energy of primary field is concentrated on a few frequencies and amplitude of the response to them can be confidently measured.

Also let's note that the geoelectric characteristics are subject to lognormal distribution: the frequency characteristic is usually built on a logarithmic frequency scale, the transition one is piecewise linear on a logarithmic scale of time, etc. This fact is usually considered as a rule during the design of Frequency-Domain systems. For example, in the EM4H system frequencies are arranged at equal intervals on a logarithmic scale. Based on the assumption that for real geological sections, the shape of the frequency characteristic is smooth, this "rare" system of induced frequencies is quite justified. This, of course, is a serious oversimplification, but in practice it is very efficient. It can be proved by the results of using the frequency system EM4H during many years of surveys (Volkovitsky et al., 2008).

Extension of the frequency range is also possible in Time-Domain systems. Thus, in the SKYTEM double pulse primary field is applied to increase the efficiency of measurements on isolating sections. Less powerful, but shorter impulses are generated along with powerful, rare and prolonged ones (Shamper and Auken, 2012). It does not interfere in the interpretation of Time-Domain ideology.

## *B*(*t*) AND *dB*(*t*)*/dt* MEASUREMENTS

As one of the indicators of Time-Domain systems' technical perfection we often can find the references to their ability to measure the response field $B(t)$ along with its derivate $dB(t)/dt$. Informational content of B-field measurements for interpretation was noticed (Smith and Annan, 1998). When we conduct physical experiments we usually measure either a "displacement" or a "velocity". So, why there is nothing like this exists in the airborne geoelectric prospecting?

The effectiveness of the Time-Domain method is usually explained by the example of the separation of responses from two local objects with different conductivity: the distant/good conductor and close/weak one (Kaufman, 1994). After turning the field off feedback signals of the exponential shape are added up, but the response field from highly conductive objects fades slowly. As time passes, the response field of the noise would be immeasurably small and the response field from the aiming object still remains measurable. But this is field, not signal! The signal on the contacts of the receiver's coil is proportional not to the magnetic field induction but to the speed of its change and is vanishingly small in slow decay. Moreover, the signal comprises measuring noise $s(t)$, which can be considered white in the operating frequency range. It turns out that the response from highly conductive objects is not well presented in the signal $dB/dt$ and the response of an ideal conductor is not presented at all.

In order to get the value of $B(t)$, the signal taken from a receiving coil has to be integrated. It is necessary to remember that spectrum for integral of the white noise with unit power spectral density is equal to $s(\omega)=1/\omega$, i.e. the amplitude of low-frequency noise increases by signal's integrating. On the other hand, the effect of noise in the Time-Domain system can be only dropped by reducing the sensitivity of the receiver and at the same time increasing the power of the source field.

To make the idea of the exponent's separation work, considerable interval between the sounding pulses is required. Usually Time-Domain systems are low-frequency (30 - 100 Hz) ones and have a large dipole moment – up to two million $Am^2$ (Fountain, 2008). At the same time, the high-frequency part of the spectrum is still not available.

Interpretation of the results of Frequency-Domain system is not as simple as that of the Time-Domain approach. Moreover, the measuring process itself is more complicated. Narrowband filtering and synchronous detection for each of the frequencies are required. The correspondent values of the same transformation of complex amplitudes $B$ and $dB/dt$ in the frequency domain are related by the expression $dB/dt = -i\omega B$.

## COMBINING APPROACHES

Let's consider the mission of building ultra-wideband Time-Domain system as a perspective task. Then we have to notice that if the frequency characteristic of the section can be measured accurately in frequency domain, we can get the data and interpret it in terms of transient response after its convolution with a given spectrum of the primary field pulse. In practice, this method can use a classical pulse generator for inducing the primary field to get the required harmonics in the low frequency range, and the missing high-frequency harmonics can be added in a form of fixed frequency sinusoids. After these manipulations the signal in the time domain will not directly measure transient characteristics. Actually we "spoiled" the Time-Domain signal (Figure 1), but it does not mean that we lost an opportunity to interpret the transient response of geoelectric section (Figure 2).

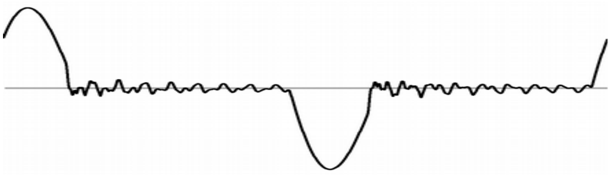

**Figure 1. EQUATOR primary field form (Current in the transmitting loop)**

A fast Fourier transformation algorithm can be successfully applied for filtering, detection, and quadrature calculation. Since detection for each frequency range is produced in a very narrow band, the suppression effect with spherical noise is achieved with a coefficient which is equal to the ratio of filter bandwidth to interval between adjacent frequencies. In the EQUATOR system this coefficient is equal to 5/130. This method of the coherence filtering allows significant reduction in the dipole moment of the transmitter and maintains sensitivity of Time-Domain system at the same time. Because the signal at frequencies between the narrow bands of synchronous detection have no effect on the measurement results, they can be used to stabilize the measurements and to control the geometrical parameters.

After receiving the measurement results not all frequencies, but only at the "right" ones, the frequency response shape throughout the remaining range can be determined with some accuracy, using interpolation in the frequency domain. We can hardly name this procedure the correct approach, but whether there is a priority to abandon the proposed method on that basis alone. In the words of Heaviside, "I do not refuse my dinner simply because I do not understand the process of digestion." Because the shape of the frequency characteristic for the physically realizable sections is smooth, the number of required high frequency "additives" in practice is small and quite amenable to implementation.

## RIGID AND VARIABLE GEOMETRY

The problem of extracting the response in the presence of many times greater than the signal of the primary field in Time-Domain, and in Frequency-Domain ideology is usually solved in one of two ways: either not register the entire response, but only a part of it (quadrature and off-time systems) or make the structure of the system rigid with the expectation that the signal of the primary field with stable geometric parameters can be compensated for. It is recognized that it's impossible to detect the full signal response in the system with unstable geometry. This kind of differentiation of the systems by principle of non-flexibility is largely arbitrary, since large rigid structures cannot be considered as unconditionally stable and the geometric parameters of the distributed system are amenable to high-precision control (Smith, 2001, Pavlov et al., 2010). Moreover, for good recognition of the response, accuracy and stability are not sufficient in both the first and in the second case.

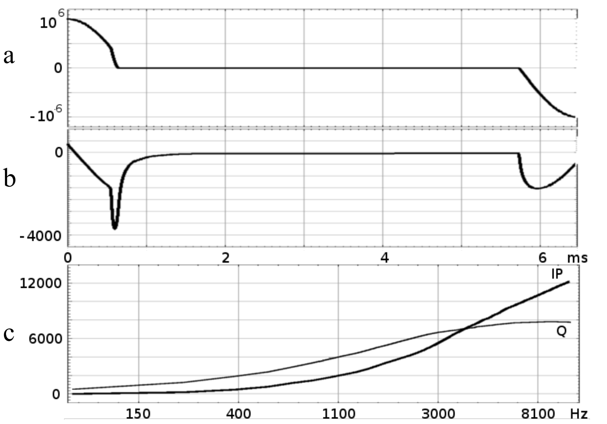


**Figure 2. Time domain primary (a) and secondary field (b), ppm; in-phase (IP) and quadrature (Q) frequency domain response, ppm (c)**

Frequency domain signal processing methods followed by separation of the frequency and transient characteristics of the response for the detection of the full response signal used in EQUATOR system give good results. The practice of using the system EQUATOR in both an isolating and conductive environment fully confirms it.

Figure 2 shows the result of separation of the full Time-Domain response signal on a real section with a complex geological structure, characterized by generally good conductivity. It is clear that the response signal is obtained both in on-time and off-time intervals in time domain and both in-phase and quadrature components in frequency domain.

## CONCLUSION

Analysis above shows that the differentiation of the airborne EM systems to Frequency-Domain and Time-Domain, as well as to the unstable and rigid categories is not very straight forward. An attempt to define the system's functionality as strictly a pair of these four definitions can greatly limit designing process and only means "what kind of illusions we have to overcome in the future to develop it". Flexible approach in combining different methods allows one to use most effectively all the achievements of modern airborne electromagnetics to build systems, develop and apply some methods of interpretation.

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