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Modern Methods of Airborne Electromagnetic Survey

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Abstract—Airborne electromagnetic methods are characterized in detail. A classification of airborne electromagnetic systems is presented. Modern active frequency-domain, time-domain and combined electromagnetic systems, and electromagnetic passive systems are discussed. The paper demonstrates specific aspects to be considered in the development and operation of airborne electromagnetic systems. The paper discusses aspects of processing of signals measured onboard, and techniques to improve system susceptibility, mobility and reliability. Survey results are presented. The paper shows what kind of problems can be effectively resolved today using airborne electromagnetic surveys.

Keywords: airborne electromagnetic survey, TEM, frequency-domain, time-domain

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INTRODUCTION

The first airborne electromagnetic system was developed in the middle of the last century. Over the following years, a great many airborne electromagnetic systems were developed, some were designed to be installed on the fuselage, others—on the external sling (Fountain, 1998; Sorensen et al., 2013; Kaufman et al., 2014; Smith, 2014; Legault, 2015; Sorensen, 2018).

The systems are classified into active, where both the transmitter and the receiver are used, and passive, where only the receiver is part of the instrument (Fig. 1). Regardless of the type, all airborne electromagnetic systems measure the variable component of the electromagnetic field.

The most widely used are induction sensors that measure the components of the variable electromagnetic field vector.

Over the last decade, sensor noise has been significantly reduced (Fig. 2).

PASSIVE AIRBORNE ELECTROMAGNETICS

Passive electromagnetic systems measure harmonic components of the vector of the Earth's variable magnetic field and, in certain instances, components of the vector of the variable electric field. Electromagnetic field sources can be of natural origin—near or distant storms, ionospheric disturbances produced by solar radiation, etc. (AFMAG—audio-frequency magnetics), as well as man-caused—low-frequency radio transmitters primarily intended for communication with submarines (VLF—very low frequency) (Palacky and West, 2008).

Passive systems with natural sources run at fairly low frequencies and offer the largest depth of investigation (Fig. 3) (Lo and Kuzmin, 2008).

There were semi-airborne systems (semi-AEM). These systems used a large loop or bipole transmitter laid out on the ground and a receiver was flown in the air (Chelovechkov et al., 2012).

ACTIVE AIRBORNE ELECTROMAGNETICS

In active airborne electromagnetics, the sounding field is generally produced by using the continuous harmonic or the pulse transient method. In the first case, the signal is a superposition of several fixed-frequency sinewave oscillations, and in the second case—a regular sequence of pulses with pauses between them. Accordingly, the signal interpretation principles are divided into frequency-domain (FD) systems (Fig. 4) and time-domain (TD) systems (Fig. 5).

In the classical paradigm of time-domain systems, the response signal follows the falling sounding pulse edge. The receiver measures the transient characteristic of the geoelectrical section with absolutely no influence of the primary field. Responses from objects with varying conductivity are distinguished by the rate of voltage drop in the receiving coils. The seeming simplicity of interpretation for the time-domain systems made them so popular.

Powerful time-domain systems are effective in detecting a good conductor in a relative insulator at large depths even with a conductive overlaying layer (Kaufman, 1989). In this case, the near-surface layers remain underinvestigated (Fig. 6). Time-domain sys-

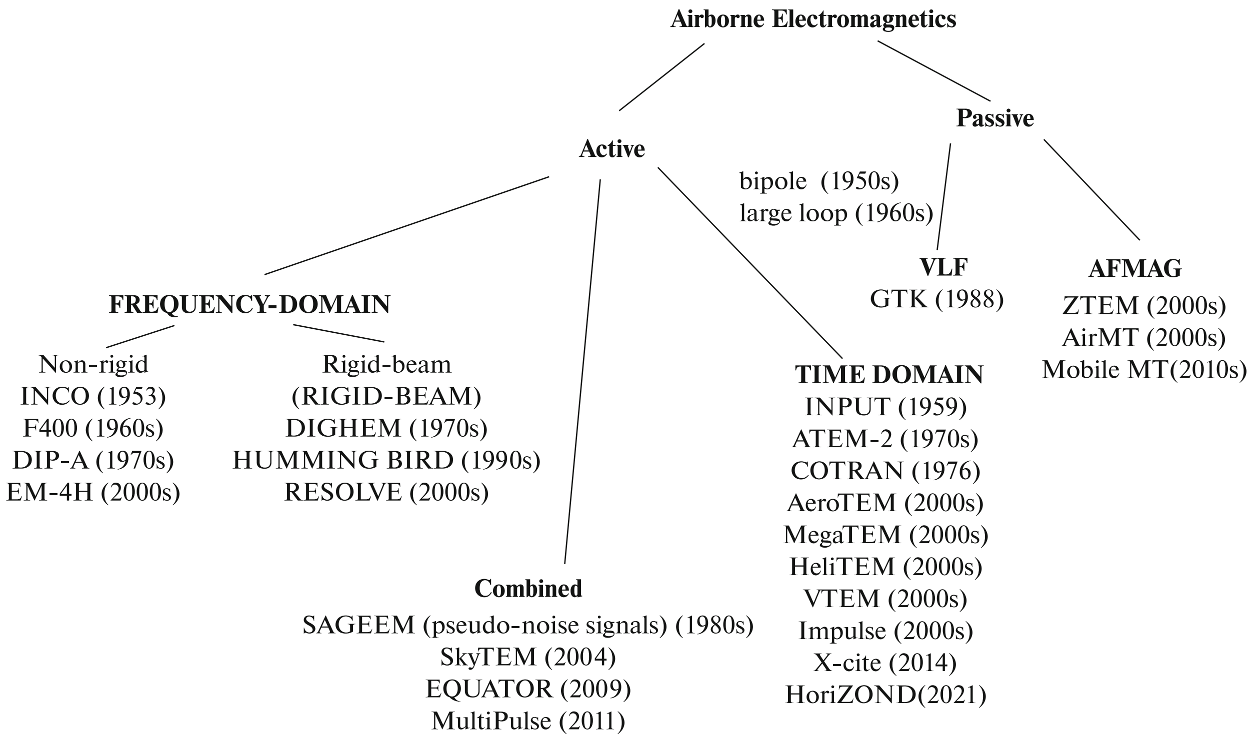

Fig. 1. A classification of basic airborne electromagnetic systems.

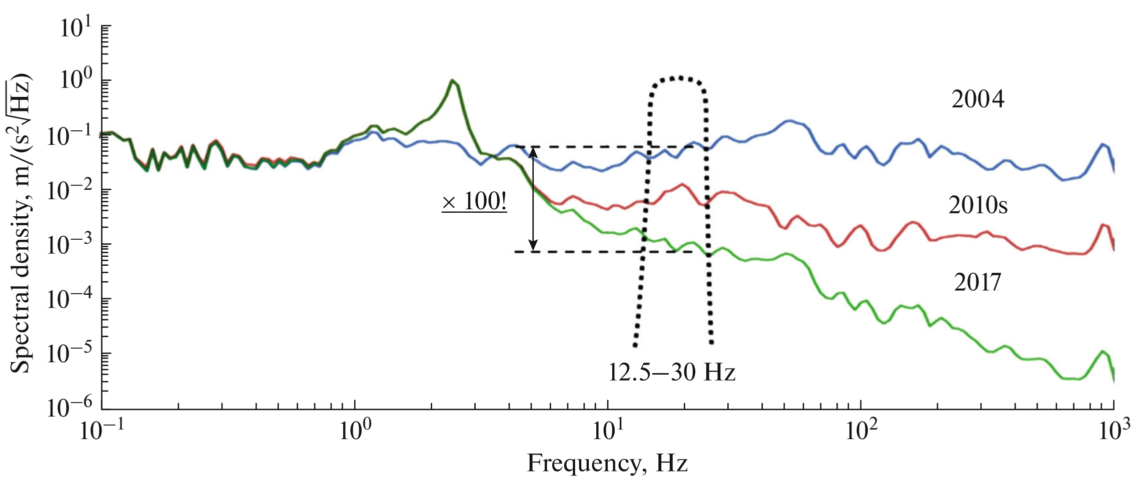

Fig. 2. Spectral density of measurements of noises in today's and previous generations of receivers (Sorensen, 2018).

tems have a low resolution for specific resistivity ranges above 1000 Ω m.

Frequency-domain systems allow measuring resistivity within a much wider span than time-domain data (Hodges, 2013) (Fig. 7, Fig. 8). They have higher frequency range. This helps to detect heterogeneities in high-resistive areas and in near-surface layers. As a result, less powerful but higher-frequency frequency-domain systems appear to be more effective in finding low-conductive objects.

As receiver-amplifier electronics of any time-domain airborne electromagnetic system has a limited frequency range, the spectrum of a really measured signal is represented by a discrete set of harmonics of the base frequency. By using the classical frequency-domain method to determine the amplitude and the phase of respective harmonics and applying the inverse Fourier transform to the obtained set, we derive initial signal with all its distortions. The possibility of such frequency-domain processing and inter-

Fig. 3. The passive MobileMT system (Prikhodko et al., 2020).

pretation was referred to by the authors of (Becker et al., 1990) when analyzing the advantages of COTRAN (correlation of transients).

The system was based on concepts absolutely revolutionary for that time. A two-component (*XZ*) receiver recorded the response signal not only during a pause (off-time) but also during the pulse (on-time).

COMBINED SYSTEMS

Along with traditional TD, today two solutions are suggested for the investigation of the near-surface layers:

• a long and high-power base pulse is combined with a short small-amplitude additional pulse (SkyTEM, MultiPulse) (Fig. 9, Fig. 10);

Fig. 4. The rigid-boom frequency-domain system Texas Gulf Sulphur, 1964.

Fig. 5. An active system implementing the airborne transient electromagnetic method ATEM-2, 1970s.

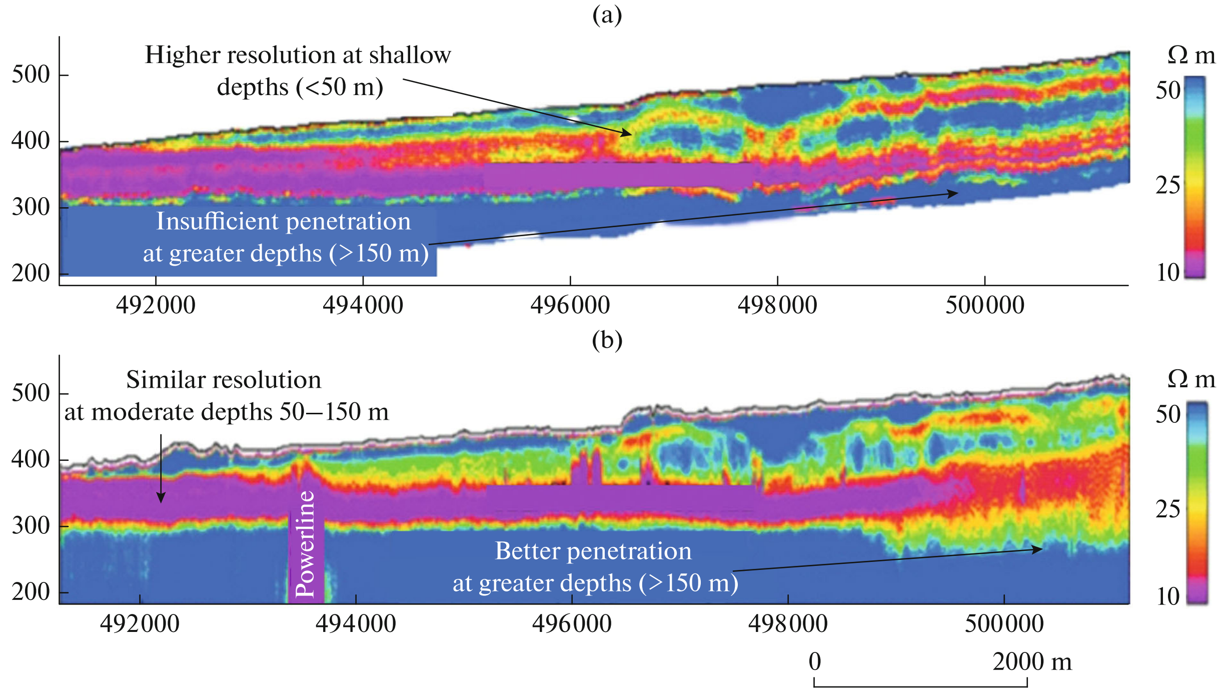

Fig. 6. Conductivity depth images constructed for (a) a frequency-domain system and (b) a time-domain system, illustrating differences and similarities in depth-resolution between systems (Chen et al., 2014).

• a long and high-power base pulse is combined with high-frequency signals (EQUATOR) (Fig. 11, Fig. 12).

The combined form of the primary signal, shown in Fig. 11, and continuous measurements allowed to effective frequency-domain data processing (Volkovitsky and Karshakov, 2013).

SIGNAL PROCESSING ASPECTS

For the correct processing of the secondary field contrasted with the changing primary field, it is necessary to be able to control to a fairly high precision (at 1 ppm) the transmitter-receiver positioning. This can be done either physically, by creating rigid system, or algorithmically. The latter option uses additional sources emitting signals of own fixed frequencies (Pavlov et al., 2010). Measurements of such signals are used for determining the geometrical parameters of the transmitter-receiver as well as for modelling the aircraft field when the transmitter is located on the fuselage.

The problem is that even precision computations in differential mode of satellite navigation systems do not guarantee the required precision of the transmitter-receiver geometry.

Apart from helping to compensate the effect of the primary field, transmitter-receiver positioning and measuring systems is useful in interpretation. Until recently, data processing techniques did not consider changes in the position of the receiver (Collet, 1986; Green and Lane, 2003). The problem needed to be solved with the enhancement of instrumentation sensitivity. It explains, in many respects, why coincide transmitter-receiver geometry systems have gained great popularity. An alternative to fixed geometry is detecting the receiver position using the data of the airborne electromagnetic system itself, i.e. on the basis of the transmitter field measurements (Smith, 2001; Pavlov et al., 2010).

Airborne electromagnetic system needs adjustment, compensation and calibration before any survey operations (Kaufman, 2014). The three processes significantly improve the measuring accuracy given the impact of hardly controllable destabilizing factors such as atmospheric humidity, mechanical fatigue deformations, etc.

FREQUENCY- AND TIME-DOMAIN PROCESSING

Conversion of Signals in Frequency-Domain Systems

In frequency-domain systems, the waveform of the current and, accordingly, the sounding field in time is set by the expression $\mathbf{H}(t) = \mathbf{H}_0 \cos(\omega t + \varphi)$, which is remarkable by the fact that on a quasi-stationary assumption with slow variations in geometrical parameters and spatial position of the measuring unit the vector of the amplitude of the field $\mathbf{H}_0$ can be treated as a constant and can be measured by using

Fig. 7. The rigid-boom frequency-domain system DIGHEM.

synchronous detection. At each of the operating frequencies ω, the following convolutions are calculated from the signal $u(t)$:

$$U_c(\omega,\varphi) = \frac{1}{l}\int_{-l}^{l} f(t)u(t)\cos(\omega t+\varphi)dt,$$

$$U_s(\omega,\varphi) = \frac{1}{l}\int_{-l}^{l} f(t)u(t)\sin(\omega t+\varphi)dt.$$

This process is sometimes referred to as coherent integration, $f(t)$—as the weight function of coherent integration, and φ—as the detection phase. In the derived real paired values, U_c is commonly referred to as the in-phase component and U_s—as the quadrature component of the received signal. The value of the complex signal amplitude $\breve{U}(\omega,\phi) = U_c(\omega,\phi) + i\,U_s(\omega,\phi)$ is derived by using Euler's formula and passing to a complex notation of the obtained values. In early frequency-domain systems synchronous detection was hardware-based; today, it appears to be more convenient first to digitalize the output signal of the receiving coil and then, for calculating convolutions, use a special-purpose digital computer.

In electrotechnical terms, the resulting complex number can be taken for the coupling factor in the "transmitter-earth-receiver" system. The value of the pair of the quadrature components U_c and U_s can be also converted to the harmonic signal amplitude and phase $|\breve{U}| = \sqrt{U_c^2 + U_s^2}$; $\varphi = \arctan\left(\frac{U_s}{U_c}\right)$.

Once received and amplified, a signal generally suffers distortions due to the non-ideality of the linear amplifier. The amplitude-phase correction at the detection frequency should be regarded as the basic processing technique for frequency-domain systems: the obtained complex amplitude value is multiplied by

Fig. 8. The frequency-domain system with a non-rigid transmitter-receiver geometry EM-4H during the survey, 2014.

Fig. 9. The combined system SkyTEM.

the complex amplitude-phase correction factor: $\breve{U}_C(\omega) = \breve{C}\breve{U}(\omega)$.

Conversion of Signals in Time-Domain Systems

Time-domain systems conventionally analyze the temporal signal behaviour: a response after a short pulse input, or a decay after a sudden shut-off of the magnetic field. In any case, such a signal has a pause between pulses.

For a physically realizable signal $u(t)$, such as $\int_{-\infty}^{+\infty} |u(t)| dt < \infty$, the Fourier transform can be done,

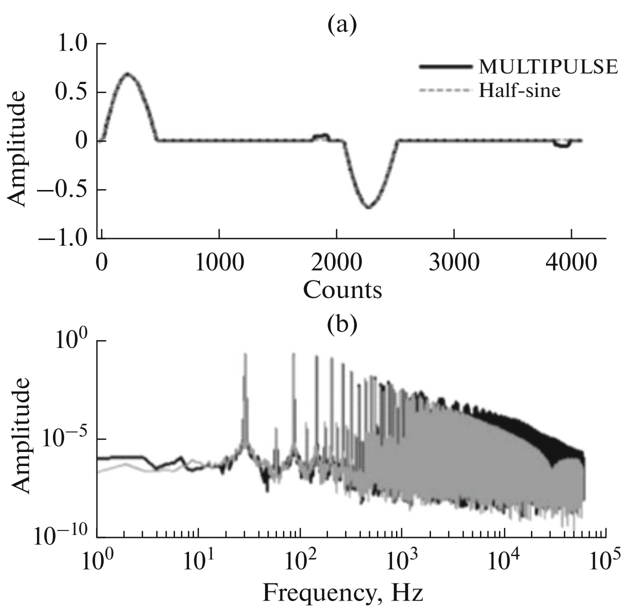

Fig. 10. (a) Signal waveform for MULTIPULSE and half-sine; (b) their spectra. The half-sine length is 4 ms, the peak—700000 Am^2.

i.e. the signal can be represented by a sum of harmonic functions (an infinite sum with pulse signals). If a signal being measured can be treated in a certain time interval as periodic, its spectrum is represented by a series of discrete harmonics, whose frequencies are multiple of the periodic signal frequency. In pulse transient systems, the lower frequency in the spectrum is an inverse of the duration of the repetition period, and the upper frequency tends to infinity (in literature on airborne electromagnetics, pulse transient systems are frequently referred to as wideband ones). Even at low rates of repetition of sounding pulses, for a relatively correct measurement of the signal the frequency response throughout the receiver-amplifier path across a wide band should remain linear. A real signal has a limited number of harmonics in the spectrum and, as a result, inevitably suffers distortions. Due to the fact that the amplitude of harmonics of real signals does decrease as the frequency increases, the waveform can be, to some extent, restored by applying frequency correction across the frequency range of the signal being measured: $\tilde{S}(\omega) = \frac{1}{k(\omega)} S(\omega)$, where S and $\tilde{S}$—the signal spectrum before and after correction; $k(\omega)$—the frequency response of the receiver-amplifier path. In early systems, such correction was hardware-based. Today, just as in frequency-domain systems, it appears to be more convenient to digitalize the signal and then perform its digital frequency correction.

Since in a certain time interval the signal can be treated as periodic, while processing we use weighting integration over several periods, similarly to coherent integration used in frequency-domain systems.

$$U(t') = \sum_{n=0}^{l} f_n u(t + nT), \quad 0 \le t' \le T.$$

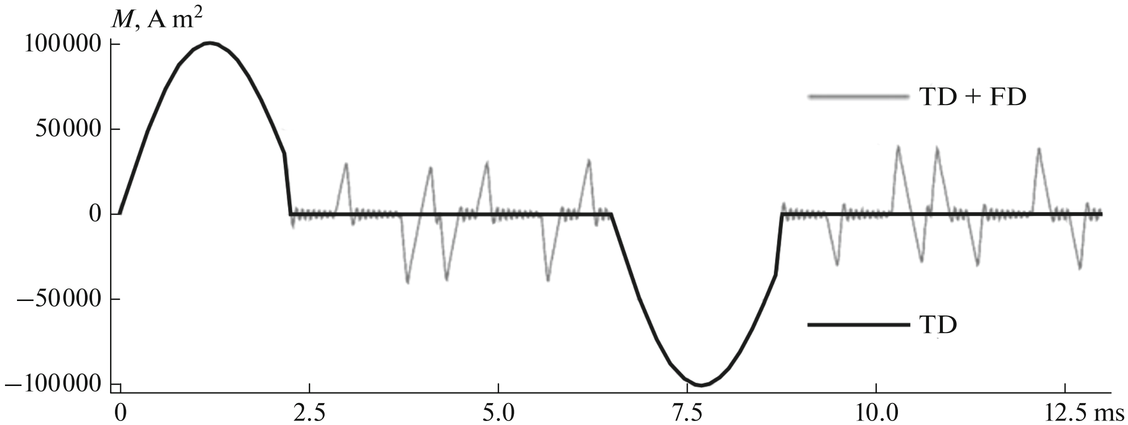

Fig. 11. Signals waveform for EQUATOR (TD + FD) and truncated half-sine (TD).

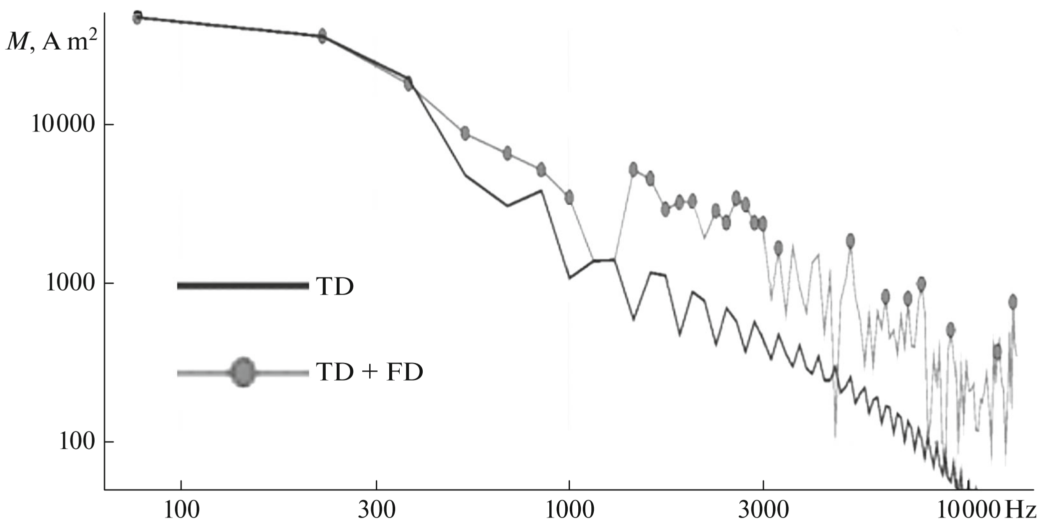

Fig. 12. Spectra for EQUATOR and truncated half-sine.

Where: f_n—weight factors, $u(t)$—the signal measured, t'—intraperiod time, l—the number of averaging periods.

Usually, after the signal correction and integration, the variable interval t' is broken into "windows", within which averaging takes place:

$$U_k = \int_{t'_k}^{t'_{k+1}} U(t')dt, \quad n = 0,1,2\ldots.$$

In concluding the analysis of the techniques on signal processing in frequency-domain and pulse-type systems, it should be noted that the actual flow chart for frequency-domain and pulse-type systems is identical: data acquisition → amplification and pre-filtering → digitalization→ computational processing. In terms of hardware environment, today there are hardly any distinct differences between frequency-domain and time-domain systems.

INTERPRETATION OF AIRBORNE ELECTROMAGNETIC DATA

Geophysical inversion methods based on a deterministic approach are described in the publications of M.N. Berdichevsky, A.A. Kaufman and M.S. Zhdanov (Zhdanov, 2002; Berdichevsky and Dmitriev, 2009; Kaufman et al., 2014). The fundamental principles of the stochastic approach can be found in Tarantola's research (Tarantola, 2005). The theory of solving linear estimation problems by the Kalman filtering and smoothing methods is presented, for example, in the works of V.V. Aleksandrov (Aleksandrov et al., 2005) and D. Simon (Simon, 2006). How the iterated extended Kalman filter can be used in addressing non-

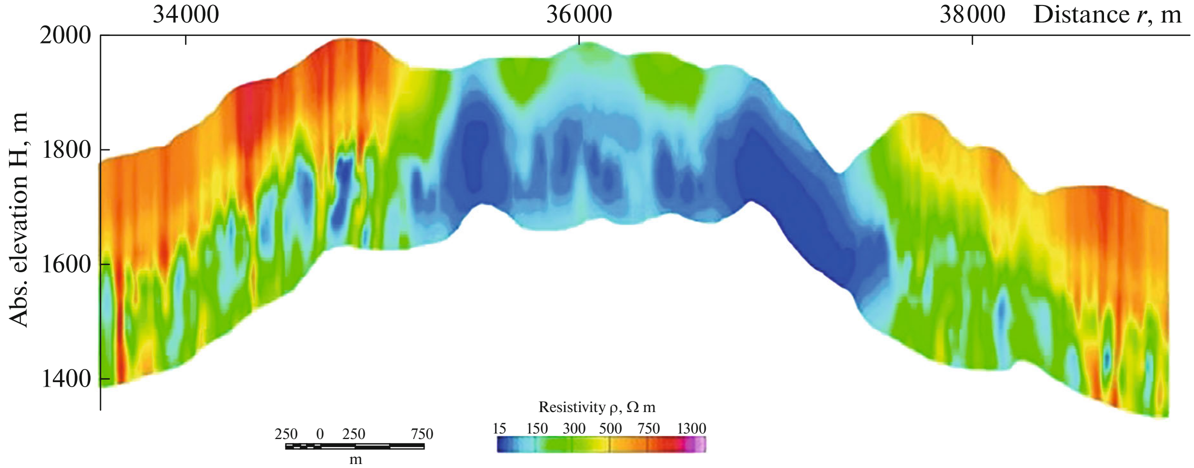

Fig. 13. A resistivity depth section constructed by time-domain data only.

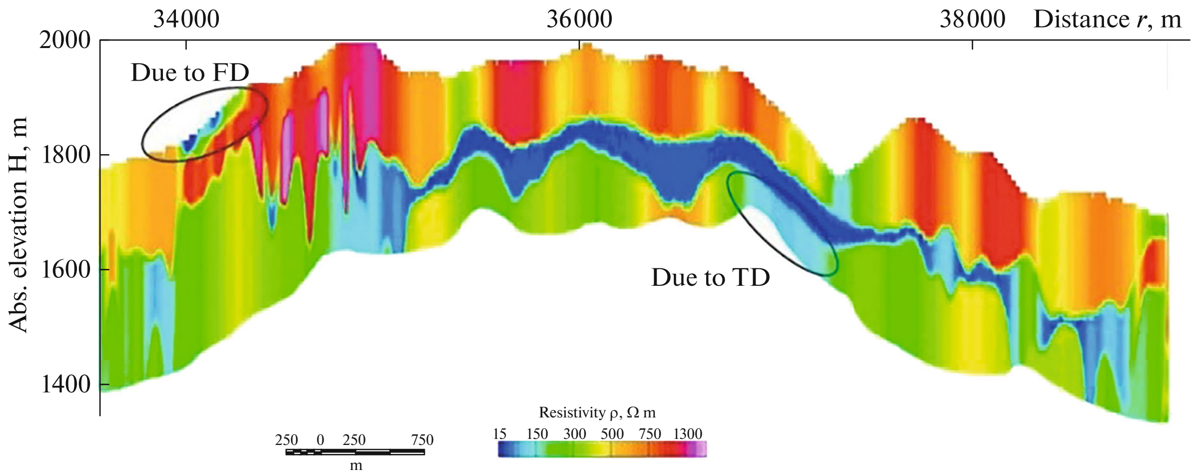

Fig. 14. Results of a combined (time-domain as well as frequency-domain) data inversion.

linear problems is explained in (Havlik and Straka, 2015; Karshakov, 2020).

Airborne electromagnetics, even with a narrow scope of investigation, deals with an inverse problem on a wide-range set of sounding surveys. For example, obtaining data when survey a small area (5000 line km) can take several weeks. The processing should produce a solution for approximately one million soundings. One can use the traditional Gauss-Newton methods but they can take too long. Preliminary interpretation implies using fast-track automated airborne electromagnetic inversions. Of particular mention are the works of J. Macnae, implemented in EM Flow (Macnae et al., 1998), solutions proposed by D. Oldenburg and C. Farquharson, implemented in EM1DFM and EM1DTM (Farquharson et al., 2003; Farquharson and Oldenburg, 2004). M. Meju and K.P. Sengpiel implemented Conductivity Depth Image (CDI) transforms using transfer functions (Sengpiel, 1988). Original are the studies devoted to the multiparametric inversion of airborne electromagnetic data in the presence of the IP (induced polarization) effect (Viezzoli et al., 2016; Kaminski and Viezzoli, 2017; Fiandaca et al., 2020).

Interpretation can be performed for time-domain data as well as for frequency domain data. In cases where data are obtained in both forms of representation, processing techniques can be combined. In doing so, the benefits of the two methods are pooled together to gain high sensitivity to depth conductors, by preserving detail in the near surface layers and a high resolution in high-resistive areas.

Figure 13 shows a resistivity depth section constructed only by the time-domain data of the airborne electromagnetic survey in Rwanda in 2017. Figure 14 shows the result of the combined 1D data inversion. In the near-surface area on the left of the section, a conductor was passed through. The depth conductor to the right is well visible even in the resistivity depth section.

CONCLUSIONS

Time-domain systems are the basic tool of modern airborne electromagnetics. The majority of such systems never use data on responses coming immediately during the pulse. This allows excluding from consideration aspects of the field of currents induced in the fuselage and other structural elements. Yet, in most cases near surface layers remains underinvestigated.

Combined systems are helpful in studying depth conductors and in discovering targets in the near-surface layers.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

ADDITIONAL INFORMATION

The article was translated by the author.

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