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Remote Operated Vehicle geophysical surveys on land (underground), air and submarine archaeology: General peculiarities of processing and interpretation

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The last Remote Operation Vehicles (ROV) generation – small and maneuvering vehicles with different geophysical sensors – can fly at levels of a few meters (and even tens of centimeters) over the earth's surface, to move on the earth's surface and in the inaccessible underground areas and to explore in underwater investigations (e.g., Mindel and Bingham, 2001; Rowlands and Sarris, 2006; Wilson et al., 2006; Rigaud, 2007; Eppelbaum, 2008; Patterson and Brescia, 2008; Sarris, 2008; Wang et al., 2009; Wu and Tian, 2010; Stall, 2011; Tezkan et al., 2011; Winn et al., 2012; El-Nahhas, 2013; Hadjimitsis et al., 2013; Hajiyev and Vural, 2013; Hugenholtz et al., 2013; Petzke et al., 2013; Pourier et al., 2013; Casana et al., 2014; Silverberg and Bieber, 2014). Such geophysical investigations should have an extremely low exploitation cost and can observe surface practically inaccessible archaeological sites (swampy areas, dense vegetation, rugged relief, over the areas of world recognized religious and cultural artifacts (Eppelbaum, 2010), etc.). Finally, measurements of geophysical fields at different observation levels could provide a new unique geological-geophysical information (Eppelbaum and Mishne, 2011).

Let's consider ROV airborne magnetic measurements as example. The modern magnetometric equipment enables to carry out magnetic measurements with a frequency of 50 times per second (and more) that taking into account the low ROV flight speed provides a necessary density of observations. For instance, frequency of observation of 50 times per second by ROV velocity of 40 km/hour gives density of observation about 0.2 m. It is obvious that the calculated step between observation points is more than sufficient one. Such observations will allow not only reduce the influence of some small artificial sources of noise, but also to obtain some additional data necessary for quantitative analysis (some interpretation methodologies need to have observations at two levels; upward analytical continuation does not always correspond to available criteria).

Besides this, the ROV observed magnetic data may be used for obtaining the averaged values of magnetization of the upper part of geological section along profiles flowing the inclined terrain relief (it follows from interpretation scheme presented for surface magnetic investigations in Khesin et al., 1996) and by combination of horizontal and inclined ROV flights over the flat relief (for air and underwater measurements) (Eppelbaum, 2010b, 2013b). In many cases the bodies (layers) composing upper part of archaeogeological section can be approximated by models of thick bed and thin horizontal plate and intermediate models that make possible application the aforementioned technologies.

The developed interpretation methodology for magnetic anomalies advanced analysis (Khesin et al., 1996; Eppelbaum et al., 2000, 2001; 2011a, 2013b, 2015a) may be successfully applied for any kind of ROV magnetic observations. This methodology includes: (1) non-conventional procedure for elimination of secondary effect of magnetic temporary variations, (2) calculation of rugged relief influence by the use of a correlation method, (3) estimation of medium magnetization, (4) application of various logical-heuristic, informational and wavelet algorithms for revealing low-amplitude anomalies against the noise background, (5) advanced procedures for magnetic anomalies quantitative analysis (they are applicable in conditions of rugged relief, inclined magnetization, and an unknown level of the total magnetic field for the models of thin bed, thick bed and horizontal circular cylinder; some of these procedures demand performing measurements at two levels over the earth's surface), (6) advanced 3D magnetic-gravity modeling for complex geological-archaeological media, and (7) development of 3D physical-archaeological model of the studied area. Integration of magnetic observations with other geophysical methods may be realized on the basis of multimodel (Eppelbaum and Yakubov, 2004), informational (Eppelbaum, 2014), or wavelet (Eppelbaum et al., 2011, 2014; Eppelbaum, 2015c) approaches. In Israel, a lot of positive results were derived from magnetic method employment with application of the abovementioned procedures at numerous archaeological sites (e.g., Eppelbaum, 2000; Eppelbaum et al., 2000, 2001; Eppelbaum and Itkis, 2003; 2003a; Eppelbaum et al., 2006, 2010; Eppelbaum, 2010a, 2011a, 2014, 2015a).

Similar effective techniques were developed for the interpretation of microgravity anomalies (Eppelbaum, 2009b, 2011b, 2015b), temperature anomalies (Eppelbaum, 2009a, 2013a), self-potential anomalies (Eppelbaum et al., 2003b; 2004), induced polarization anomalies (Khesin et al., 1997; Eppelbaum, 2000), piezoelectric anomalies (Neishtadt and Eppelbaum, 2012), Very Low Frequency (VLF) anomalies (Eppelbaum, 2000; Eppelbaum and Khesin, 2012). The theoretical analysis indicates that for all aforementioned geophysical methods a common interpretation methodology may be applied .

The main peculiarities of the developed non-conventional system for analysis of potential and quasi-potential geophysical fields are presented in Table 1.

Table 1. Elements of the developed system of geophysical fields processing and interpretation under complicated environments (on the basis of Khesin et al., 1996, Eppelbaum and Khesin, 2001; Eppelbaum et al., 2000, 2001, 2004; Eppelbaum and Yakubov, 2004; Eppelbaum et al., 2006; Eppelbaum, 2009a, 2009b; Eppelbaum, 2010a, 2010b; Eppelbaum et al., 2010, 2011; Eppelbaum and Mishne, 2011; Eppelbaum, 2011a, 2011b; Neishtadt and Eppelbaum, 2012; Eppelbaum, 2013a, 2013b, 2014; Eppelbaum and Kutasov, 2014; Eppelbaum et al., 2014; Eppelbaum, 2015a, 2015b, 2015c)

FIELD	Time variation correction	Terrain correction using correlation method	Informational, multimodel and and wavelet algorithms for combined identification of desired targets	Inverse problem solution in conditions of:				Integrated 3-D integrated modeling of complex archaeological media
				rugged relief	arbitrary polari-zation	approximation of anomalous object by		
						1 - 3 models	*4 - 5 models*	
Magnetic	+ ⊕	⊕	+ ⊕	⊕	⊕	⊕	⊕	+ ⊕
Gravity	+	⊕	+ ⊕	⊕	⊕	+ ⊕	−	⊕
Thermal	+ ⊕	⊕	+ ⊕	⊕	⊕	⊕	−	◊
Thermal (*ancient climate analysis*)	+ ⊕	⊕	+ ⊕	+ ⊕	∗	∗	∗	−
SP	+	+	+ ⊕	⊕	⊕	⊕	−	−
VLF	+ ⊕	⊕	+ ⊕	⊕	⊕	⊕	−	−
IP	∗	⊕	+ ⊕	⊕	⊕	⊕	−	−
Piezoelectric	∗	⊕	+ ⊕	⊕	⊕	⊕	−	−

Note. Symbols "$+$" and "$-$" designate availability and unavailability of procedures, respectively. "$\oplus$" – authors' modification, "$\Diamond$" – under preparing. Symbol "$*$" designates the absence of necessity for calculation

The effect of different heights of observation points and the techniques of its correction was first discussed in magnetic prospecting (Khesin et al., 1996; Eppelbaum et al., 2001). Taking into account that rugged relief may strongly disturb observed geophysical anomalies, the corresponding correction for non-flat relief influenced is of high importance.

In essence, there are only two types of general analytical expressions applicable to the description of these geophysical fields (Alexeyev et al., 1996; Khesin et al., 1996; Eppelbaum, 2000). They are

$$U_1\left(x,z\right) = P\int\limits_S \frac{\left(z_s - z\right)\cos\gamma_p + \left(x_s - x\right)\sin\gamma_p}{r^2} dx_s dz_s, \tag{1}$$

$$U_2\left(x,z\right) = P\int\limits_S \frac{\left[\left(z_s - z\right)^2 - \left(x_s - x\right)^2\right]\cos\gamma_p + 2\left(x_s - x\right)\left(z_s - z\right)\sin\gamma_p}{r^4} dx_s dz_s, \tag{2}$$

where $\gamma_p = 90^o - \varphi_p$, φ_p is the inclination angle of the polarization vector to the horizon, P is value of this vector (being a scalar in a particular case); S is the cross-section area of the body; **P** is the polarization vector (dipole moment of a unit volume); $r = \sqrt{\left(x_s - x\right)^2 + \left(z_s - z\right)^2}$is the distance from the observation point $M(x,\,z)$ to a certain point of the body $P\left(x_s, z_s\right)$

Therefore, it seems sufficient to illustrate the manipulations taking as examples Eqs. (1) and (2). The peculiarity of an inclined profile is that the height of the observation point is a linear function of the horizontal distance, namely

$$z = x\tan\omega_0, \tag{3}$$

where ω_0 is the inclination angle of the observation.

The transformations are carried out in the following sequence. The inclined coordinate system $x'Oz'$ is introduced in such a way that

$$\left\{ \begin{array}{l} x = x' \cos\omega_0 - z' \sin\omega_0, \\ z = x' \sin\omega_0 - z' \cos\omega_0. \end{array} \right\} \tag{4}$$

The formulas for x_s and $z_s$are similar. The *Ox*'-axis in this system coincides with the inclined profile, which gives z' = 0 and results in Eq. (3).

In the *x'Oz'* system, Eqs. (1) and (2) are transformed to the following forms:

$$U_1\left(x, z\right) = P \int\limits_S \frac{z'_s \cos\left(\gamma_p + \omega_0\right) + \left(x'_s - x'\right) \sin\left(\gamma_p + \omega_0\right)}{r'^2} dx'_s dz'_s, \tag{5}$$

$$U_2\left(x, z\right) = P \int\limits_S \frac{{z'_s}^2 - \left(x'_s - x'\right) \cos\widehat{\gamma}_p + 2\left(x'_s - x'\right) z'_s \sin\widehat{\gamma}_p}{r'^4} dx'_s dz'_s, \tag{6}$$

where $r' = \left[\left(x'_s - x'\right)^2 + \left(z'_s - z'\right)^2\right]^{1/2}$ and $\widehat{\gamma}_p = \gamma_p + 2\omega_0$.

It is obvious that the right-hand sides of Eqs. (5) and (6) correspond to the functions $U'_1(x', 0), U'_2(x', 0)$ in the inclined system, but for a different inclination angle of the polarization vector. If a body in the initial system was vertically polarized, it turns out to be obliquely polarized (angles ω_0 or $2\omega_0$, respectively) in the inclined system, since the polarization vector does not intersect the *Ox*'-axis at a right angle.

Eqs. (5) and (6) can be essentially interpreted in the inclined coordinate system making use of the techniques developed for the horizontal profile, since the changing heights of observation points are not included there. To interpret in the initial system, we have to continue our manipulations in the following sequence.

The entire space with the anomalous object and the polarization vector is turned by the angle ω_0 and compressed at the compressibility coefficient of $(\cos\omega_0)$. In addition, when manipulating with Eq. (5), P is multiplied by $(\sec\omega_0)$. This done, the inclined profile *Ox*' coincides with the horizontal straight line, and the observation points on the profile pass along the vertical into the corresponding points on the horizontal straight line. An anomaly plot, constructed by these points (in horizontal projection) is a standard plot used routinely, although observations are made on an inclined relief. However, after the space rotation and compression the anomalous object occupies a different position with respect to the initial one. Its cross-section is smaller than the initial one, but the outline is similar.

After this transformation, Eqs. (5) and (6) acquire the following forms:

$$U_1\left(x, z\right) = U_{1f}\left(x, 0\right) = P_f \int\limits_{Sf} \frac{z_{sf} \cos\left(\gamma_p + \omega_0\right) + \left(x_{sf} - x\right) \sin\left(\gamma_p + \omega_0\right)}{r_f^2} dx_{sf} dz_{sf}, \tag{7}$$

$$U_2\left(x, z\right) = U_{2f}\left(x, 0\right) = P_f \int\limits_{Sf} \frac{\left[z_{sf}^2 - \left(x_{sf} - x\right)^2\right] \cos\widehat{\gamma}_p + 2\left(x_{sf} - x\right) z_{sf} \sin\widehat{\gamma}_p}{r_f^4} dx_{sf} dz_{sf}, \tag{8}$$

Here, the subscript "f" stands for the parameters of a fictitious body. When used with symbols U_1 and U_2, it denotes that they refer to a fictitious body.

The interpretation of the curves U_{1f} and U_{2f} results in obtaining parameters of a fictitious body, which are used to reconstruct those of a real body (denoted by "s" subscript) with the help of the following formulas of transition:

$$\left\{ \begin{array}{l} z_s = z_{sf} + x_{sf} \tan\omega_0, \\ x_s = -x_{sf} \tan\omega_0 + z_{sf}, \\ S = S_{sf} \sec^2\omega_0, \\ P = P_f \cos\omega_0 (\text{by } U_1 \text{ interpretation}) \\ P = P_f (\text{by } U_2 \text{ interpretation}) \\ \gamma_p = \gamma_{pf} - \omega_0 (\text{by } U_1 \text{ interpretation}) \\ \gamma_p = \gamma_{pf} - 2\omega_0 (\text{by } U_2 \text{ interpretation}) \end{array} \right\}. \tag{9}$$

Let us consider the analytical expression of the gravity anomaly caused by a certain anomalous body:

$$\Delta g = 2G\sigma \int\limits_S \frac{(z_s - z)\cos\gamma_g + (x_s - x)\sin\gamma_g}{r^2} ds, \tag{10}$$

where G is the universal gravity constant, σ is the density, and the value γ_g is an analogue of the value γ_p in Eq. (1).

This formula does not differ from the Eq. (1) by its structure. After the above manipulations it receives the following form:

$$\Delta g_f = 2G\sigma_f \int\limits_S \frac{r_{gf}\cos\gamma_{gf} + (x_{sf} - x)\sin\gamma_{gf}}{r_f^2} ds_f, \tag{11}$$

such that

$$\gamma_{gf} = \gamma_g + \omega_0. \tag{12}$$

Taking into account that γ_g = 0, we obtain γ_{gf} = ω_0. Hence, the anomaly of Δg observed on the inclined relief corresponds to that caused by a fictitious obliquely polarized body observed on the horizontal relief. The latter is affected both by vertical and horizontal gravity components. This is equivalent to the manifestation of "vector properties" of density on the inclined relief.

On the whole, the effect of the profile inclination is equivalent to an increased effect of oblique polarization, if the vector **P** and the relief have the same sense of slope, and to a weakened effect, if the relief and the vector **P** are inclined in opposite senses, up to their mutual neutralization. This fact determines the unified techniques for interpreting obliquely polarized bodies observed on the inclined relief. It facilitates the analysis of the distortions due to the effect of sloping relief, which can be completely attributed to the oblique polarization effect.

Thus, Eqs. (2) and (3) reduce the problem of interpretation of the potential fields observed on the inclined profile to the same problem for the horizontal profile. Eq. (4) describes the transition from the parameters obtained while interpreting a fictitious body to those of a real body.

The above data substantiate the conversion in the inclined semispace, since a field observed on the complex relief can be expressed using a certain inclined system of coordinates, the reduction being accomplished as in the normal system. The field in the observation points of the relief is converted to an inclined straight line along the normal to the latter.

The advantage of such reduction consists in that the inclined plane of the reduction may be selected as close as possible not only to the highest points, but also to many points of the relief. As a result, the amplitude decreases appreciably less than when converting to the horizontal level of the highest relief points.

REFERENCES

Alexeyev, V.V., Khesin, B.E. and Eppelbaum, L.V., 1996. Geophysical fields observed at different heights: A common interpretation technique. *Proceed. of the Meeting of Soc. of Explor. Geophys.*, Jakarta, 104-108.

Bendea, H., Chiabrando, Tonolo, F.G. and Marenchino, D., 2007. Mapping of archaeological areas using a low-cost UAV. The Augusta Bagiennorum test site. *Proceed. of the XXI Intern. CIPA Symp.*, 01–06 Oct. 2007, Athens, Greece, Available at: http://www.isprs.org/proceedings/XXXVI/5-C53/papers/FP025.pdf

Casana, J., Kantner, J., Wiewel, A. and Conthren, J., 2014. Archaeological aerial thermography: a case study at the Chaco-era Blue J community, New Mexico. *Journal of Archaeological Science*, **45**, 207-219.

El-Nahhas, F.M., 2013. Tunnelling and Underground Structures in Egypt: Past, Present and Future. *Arabian Tunelling Conference Exhibition*, Dec. 10-11, 2013. Dubai, United Arab Emirates, 348-357.

Eppelbaum, L.V., 2000. Applicability of geophysical methods for localization of archaeological targets: An introduction. *Geoinformatics*, **11**, No.1, 19-28.

Eppelbaum, L.V., 2005. Multilevel observations of magnetic field at archaeological sites as additional interpreting tool. *Proceed. of the 6^{th} Conference of Archaeological Prospection*, Roma, Italy, 1-4.

Eppelbaum, L.V., 2008. Remote operated vehicle geophysical survey using magnetic and VLF methods: proposed schemes for data processing and interpretation. *Collection of Selected Papers of the 2008 SAGEEP Conference*, **21**, Philadelphia, USA, 938-963.

Eppelbaum, L.V., 2009a. Near-surface temperature survey: An independent tool for buried archaeological targets delineation. *Journal of Cultural Heritage*, **12**, Suppl.1, e93-e103.

Eppelbaum, L.V., 2009b. Application of microgravity at archaeological sites in Israel: Some estimation derived from 3D modeling and quantitative analysis of gravity field. *Proceed. of the 2009 SAGEEP Conference*, Texas, USA, **22**, No. 1, 434-446.

Eppelbaum, L.V., 2010a. Archaeological geophysics in Israel: Past, Present and Future. *Advances in Geosciences*, **24**, 45-68.

Eppelbaum, L.V., 2010b. Methodology of Detailed Geophysical Examination of the Areas of World Recognized Religious and Cultural Artifacts. *Trans. of the 6th EUG Meet.*, Geophysical Research Abstracts, Vol. **12**, EGU2010-5859, Vienna, Austria, 1-3.

Eppelbaum, L.V., 2011a. Study of magnetic anomalies over archaeological targets in urban conditions. *Physics and Chemistry of the Earth*, **36**, No. 16, 1318-1330.

Eppelbaum, L.V., 2011b. Review of environmental and geological microgravity applications and feasibility of their implementation at archaeological sites in Israel. *International Journal of Geophysics*, doi: 10.1155/2011/927080, ID 927080, 1-9.

Eppelbaum, L.V., 2013a. Potential geophysical fields – inexpensive effective interpretation tool at archaeological sites in the Near East. *Izv. Acad. Sci. Azerb. Rep., Ser.: Earth Sciences*, No. 3, 23-42.

Eppelbaum, L.V., 2013b. ROV advanced magnetic survey for revealing archaeological targets and estimating medium magnetization. *Trans. of the 9th EUG Meet.*, Geophysical Research Abstracts, Vol. **15**, EGU2013-5913, Vienna, Austria, 2 pp.

Eppelbaum, L.V., 2014. Geophysical observations at archaeological sites: Estimating informational content. *Archaeological Prospection*, **21**, No. 2, 25-38.

Eppelbaum, L.V., 2015a. Quantitative interpretation of magnetic anomalies from thick bed, horizontal plate and intermediate models under complex physical-geological environments in archaeological prospection. *Archaeological Prospection*, **23**, No. 2, 255-268.

Eppelbaum, L.V., 2015b. High-Precise Gravity Observations at Archaeological Sites: How We Can Improve the Interpretation Effectiveness and Reliability? *Trans. of the 11th EUG Meet.*, Geophysical Research Abstracts, Vol. **17**, EGU2015-3012, Vienna, Austria, 1-4.

Eppelbaum, L.V., 2015c. Detecting Buried Archaeological Remains by the Use of Geophysical Data Processing with 'Diffusion Maps' Methodology. *Trans. of the 11th EUG Meet.*, Geophysical Research Abstracts, Vol. **17**, EGU2015-2793, Vienna, Austria, 1-3.

Eppelbaum, L.V., Alperovich, L., Zheludev, V. and Pechersky, A., 2011. Application of informational and wavelet approaches for integrated processing of geophysical data in complex environments. *Proceed. of the 2011 SAGEEP Conference*, Charleston, South Carolina, USA, **24**, 24-60.

Eppelbaum, L.V., Zheludev, V. and Averbuch, A., 2014. Diffusion maps as a powerful tool for integrated geophysical field analysis to detecting hidden karst terranes. *Izv. Acad. Sci. Azerb. Rep., Ser.: Earth Sciences*, No. 1-2, 36-46.

Eppelbaum, L.V., Kutasov, I.M. and Barak, G., 2006. Ground surface temperature histories inferred from 15 boreholes temperature profiles: Comparison of two approaches. *Earth Sciences Research Journal*, **10**, No. 1, 25-34.

Eppelbaum, L., Ben-Avraham, Z. and Itkis, S., 2003a. Ancient Roman Remains in Israel provide a challenge for physical-archaeological modeling techniques. *First Break*, **21** , No. 2, 51-61.

Eppelbaum, L.V., Ben-Avraham, Z. and Itkis, S.E., 2003b. Integrated geophysical investigations at the Halutza archaeological site. *Proceed. of the* ***64*** *EAGE Conf.*, Florence, Italy, P151, 1-4.

Eppelbaum, L.V. and Itkis, S.E., 2003. Geophysical examination of the archaeological site Emmaus-Nicopolis (central Israel). *Collection of Papers of the XIXth International UNESCO Symposium "New Perspectives to Save the Cultural Heritage*", Antalya, Turkey, 395-400.

Eppelbaum, L.V., Itkis, S.E. and Khesin, B.E., 2000. Optimization of magnetic investigations in the archaeological sites in Israel, *In*: *Special Issue of Prospezioni Archeologiche* "Filtering, Modeling and Interpretation of Geophysical Fields at Archaeological Objects", 65-92.

Eppelbaum, L., Itkis, S. and Khesin, B., 2006. Detailed magnetic survey unmasks Prehistoric archaeological sites in Israel. *Proceed. of the 2006 SAGEEP Conf.*, **19**, Calgary, Canada, 1366-1373.

Eppelbaum, L.V. and Khesin, B.E., 2001. Disturbing Factors in Geophysical Investigations at Archaeological Sites and Ways of Their Elimination. *Proceed. of the **IV** Conf. on Archaeological Prospection*, Vienna, Austria, 99-101.

Eppelbaum, L.V. and Khesin, B.E., 2012. Geophysical Studies in the Caucasus. *Springer*, Dordrecht – NY – London.

Eppelbaum, L.V., Khesin, B.E. and Itkis, S.E., 2001. Prompt magnetic investigations of archaeological remains in areas of infrastructure development: Israeli experience. *Archaeological Prospection*, **8**, No.3, 163-185.

Eppelbaum, L.V., Khesin, B.E. and Itkis, S.E., 2010. Archaeological geophysics in arid environments: Examples from Israel. *Journal of Arid Environments*, **74**, No. 7, 849-860.

Eppelbaum, L.V., Khesin, B.E., Itkis S.E. and Ben-Avraham, Z., 2004. Advanced analysis of self-potential data in ore deposits and archaeological sites. *Proceed. of the 10th European Meeting of Environmental and Engineering Geophysics*, Utrecht, The Netherlands, 1-4.

Eppelbaum, L.V. and Kutasov, I.M., 2014. Advanced analysis of thermal data observed in subsurface wells unmasks the ancient climate. *Trans. of the* 10^{th} *EUG Meet.*, Geophysical Research Abstracts, Vol. **16**, EGU2014-3261, Vienna, Austria, 1-3.

Eppelbaum, L.V. and Mishne, A.R., 2011. Unmanned Airborne Magnetic and VLF investigations: Effective Geophysical Methodology of the Near Future. *Positioning*, **2**, No. 3, 112-133.

Eppelbaum, L.V. and Yakubov, Ya.S., 2004. Multimodel approach to processing and interpretation of potential geophysical fields at archaeological objects. *Trans. of the* 1^{st} *EUG Meet.*, Geophysical Research Abstracts, Nice, France, Vol. **VI**, No. 00137, 1-2.

Hadjimitsis, D.G., Agapiou, A., Themistocleous, K., Alexakis, D.D. and Sarris, A., 2013. Remote Sensing for Archaeological Applications: Management, Documentation and Monitoring. In: (Hadjimitsis, D. et al., Eds.), *Remote Sensing of Environment: Integrated Approaches,* InTech, 57-95.

Hajiyev, C. and Vural, S.Y., 2013. LQR controller with Kalman estimator applied to UAV longitudinal dynamics. *Positioning*, **13**, 36-41.

Hugenholtz, C.H., Whitehead, K., Brown, O.W., Barchyn, T.E., Moorman, B.J., LeClair, A., Riddell, K. and Hamilton, T., 2013. Geomorphological mapping with a small unmanned aircraft system (sUAS): Feature detection and accuracy assessment of a photogrammetrically-derived digital terrain model. *Geomorphology*, **194**, 16-24.

Khesin, B.E., Alexeyev, V.V. and Eppelbaum, L.V., 1996. Interpretation of Geophysical Fields in Complicated Environments. *Kluwer Academic Publishers* (*Springer*), ***Ser.: Modern Approaches in Geophysics,*** Boston - Dordrecht - London, 368 p.

Khesin, B.E., Alexeyev, V.V. and Eppelbaum, L.V., 1997. Rapid methods for interpretation of induced polarization anomalies. *Journal of Applied Geophysics*, **37**, No.2, 117-130.

Mindel, D. and Bingham, M., 2001. New archaeological uses of autonomous underwater vehicles. *Proceed. of IEEE Conf.*, Honolulu, 1-4.

Neishtadt, N.M. and Eppelbaum, L.V., 2012. Perspectives of application of piezoelectric and seismoelectric methods in applied geophysics. *Russian Geophysical Journal*, Nos. 51-52, 63-80.

Patterson, M.C.L. and Brescia, A., 2008. Integrated sensor systems for UAS. *Proceed. of the 23rd Bristol International Unmanned Air Vehicle Systems* (*UAVS Conference*), Bristol, United Kingdom, April 2008.

Petzke, M., Hofmeister, P., Hördt, A. and Glaßmeyer, K.H., 2013. Aeromagnetic with unmanned airship. *Trans. of the* 19^{th} *European Meet. of Environ. and Engin. Geophysics*, Bochum, Germany, MoP05: 1-5.

Pourier, N., Hautefeuille, R. and Calastrenc, C., 2013. Low altitude thermal survey by means of an automated unmanned aerial vehicle for the detection of archaeological buried structures. *Archaeological Prospection*, **20**, 303-307.

Rigaud, V., 2007. Innovation and operation with robotized underwater systems. *Journal of Field Robotics*, **24**, No. 6, 449-459.

Rowlands, A. and Sarris, A., 2006. Detection of exposed and subsurface archaeological remains using multi- sensor remote sensing. *Journal of Archaeological Science*, **34**, 795-803.

Sarris, A., 2008. Remote Sensing Approaches/Geophysical. In: (Rearsall, D.M., Ed.) *Encyclopedia of Archaeology*. Academic Press, New York, **3**, 1912-1921.

Silverberg, L.M. and Bieber, C., 2014. Central Command Architecture for High-Order Autonomous Unmanned Aerial Systems. *Intelligent Information Management*, **6**, 183-195.

Stoll, J.B., 2011. Unmanned aerial vehicles for rapid near surface geophysical measurements. *GEM Beijing 2011: International Workshop on Gravity, Electrical and Magnetic Methods and Their Applications*. Beijing, China, 13 October, 2011.

Tezkan, B., Stoll, J.B., Bergers, R. and Grossbach, H., 2011. Unmanned aircraft system proves itself as a geophysical measuring platform for aeromagnetic surveys. *First Break*, **29**, No. 4, 103-105.

Wang, J., Zhu, X., Tie, F., Zhao, T. and Xu X., 2009. Design of a Modular Robotic System for Archaeological Exploration. *Trans. of IEEE Conf. on Robotics and Automation*, Kobe, Japan, 1435-1440.

Wilson, S.S., Crawford, N.C., Croft, L.A., Howard, M., Miller, S. and Rippy, T., 2006. Autonomous robot for detecting subsurface voids and tunnels using microgravity. In: (E.M. Carapezza, Ed.), *Sensors, and Command, Control, Communications, and Intelligence (C3I) Technologies for Homeland Security and Homeland Defense V, Proc. of SPIE*, Vol. **6201**, doi: 10.1117/12.665030, 1-9.

Wu, L. and Tian, J., 2010. Automated gravity gradient tensor inversion for underwater object detection. *Jour. of Geophysics and Engineering*, **7**, 410-416.

Wynn, J., Williamson, M. and Fleming, J., 2012. Induced Polarization for subseafloor, Deep-Ocean Mapping Marine Induced Polarization Used for 3D Mapping of Subseafloor Minerals and 4D Oil-in-Seawater Characterization. Feature Article. http://www.sea-technology.com/features/2012/0912/induced_polarization.php