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High-Precise Gravity Observations at Archaeological Sites: How We Can Improve the Interpretation Effectiveness and Reliability?

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Microgravity investigations are comparatively rarely used for searching of hidden ancient targets (e.g., Eppelbaum, 2013). It is caused mainly by small geometric size of the desired archaeological objects and various types of noise complicating the observed useful signal. At the same time, development of modern generation of field gravimetric equipment allows to register microGal (10^{-8} m/s^2) anomalies that offer a new challenge in this direction. Correspondingly, an accuracy of gravity variometers (gradientometers) is also sharply increased.

How we can improve the interpretation effectiveness and reliability? Undoubtedly, it must be a multi-stage process. I believe that we must begin since nonconventional methodologies for reducing topographic effect and terrain correction computation.

Topographic effect reducing

The possibilities of reducing topographic effects by grouping the points of additional gravimetric observations around the central point located on the survey network were demonstrated in (Khesin et al., 1996). A group of 4 to 8 additional points is located above and below along the relief approximately symmetrically and equidistant from the central point. The topographic effect is reduced to the obtained difference between the gravity field in the center of the group and its mean value for the whole group. Application of this methodology in the gold-pyrite deposit Gyzyl-Bulakh (Lesser Caucasus, western Azerbaijan) indicated its effectiveness.

Computation of terrain correction

Some geophysicists compare the new ideas in the field of terrain correction (TC) in gravimetry with the "*perpetuum mobile*" invention. However, when we speak about very detailed gravity observations, the problem of most optimal computation of surrounding relief influence is of a great importance. Let us will consider two approaches applied earlier in ore geophysics.

First approach

A first method was applied in the Gyzyl-Bulakh gold-pyrite deposit situated in the Mekhmana ore region of the Lesser Caucasus (western Azerbaijan) under conditions of rugged relief and complex geology. This deposit is well investigated by mining and drilling operations and therefore was used as a reference field polygon for testing this approach. A special scheme for obtaining the Bouguer anomalies has been employed to suppress the terrain relief effects dampening the anomaly effects from the objects of prospecting. The scheme is based on calculating the difference between the free-air anomaly and the gravity field determined from a 3D model of a uniform medium with a real topography. 3-D terrain relief model with an interval of its description of 80 km (the investigated 6 profiles of 800 m length are in the center of this interval) was employed to compute (by the use of *GSFC* software (Khesin et al., 1996)) the gravitational effect of the medium (σ = 2670 kg/m^3). With applying such a scheme the Bouguer anomalies were obtained with accuracy in two times higher than that of TC received by the conventional methods. As a result, on the basis of the improved Bouguer gravity with the precise TC data, the geological structure of the deposit was defined (Khesin et al., 1996).

Second approach

Second approach was employed at the complex Katekh pyrite-polymetallic deposit, which is located at the southern slope of the Greater Caucasus (northern Azerbaijan). The main peculiarities of this area are very rugged topography of SW-NE trend, complex geology and severe tectonics. Despite the availability of conventional Δg_B (TC far zones were computed up to 200 km), for the enhanced calculation of surrounding terrain topography a digital terrain relief model was created (Eppelbaum and Khesin, 2004). The SW-NE regional topography trend in the area of the Katekh deposit occurrence was computed as a rectangular digital terrain relief model (DTRM) of 20 km long and 600 m wide (our interpretation profile with a length of 800 m was located in the geometrical center of the DTRM). As a whole, about 1000 characteristic points were used to describe the DTRM (most frequently points were focused in the center of the DTRM and more rarely – on the margins). Thus, in the interactive 3D Δg_B modeling (by the use of *GSFC* software) was computed effect not only from geological bodies occurring in this area, but also from surrounding DTRM. In the issue of this scheme application, two new ore bodies were discovered.

Quantitative analysis of gravity anomalies

The trivial formulas of quantitative analysis (based on simple relationships between the gravity field intensity and geometrical parameters of the anomalous body) are widely presented in the geophysical literature (e.g., Telford et al., 1993; Parasnis, 1997). However, absence of reliable information about the normal gravity field in the studied areas strongly limits practical application of these methods.

Gravity field intensity **F** is expressed as

$$\mathrm{F} = -grad\,W, \tag{1}$$

where W is the gravity potential.

For anomalous magnetic field $\mathbf{U}_a$ we can write (when magnetic susceptibility ≤ 0.1 SI unit) (Khesin et al., 1996):

$$\mathrm{U_a} = -grad\,V, \tag{2}$$

where V represents the magnetic potential.

Let's consider analytical expressions of some typical models employed in magnetic and gravity fields (Table 1).

Table 1. Comparison of some analytical expressions for magnetic and gravity fields

Field	Analytical expression	
Magnetic	Thin bed (TB) $Z_v = 2I2b\dfrac{z}{x^2+z^2}$ (3)	Point source (rod) $Z_v = \dfrac{mz}{(x^2+z^2)^{3/2}}$ (4)
Gravity	Horizontal Circular Cylinder (HCC) $\Delta g = 2G\sigma\dfrac{z}{x^2+z^2}$ (5)	Sphere $\Delta g = GM\dfrac{z}{(x^2+z^2)^{3/2}}$ (6)

Here Z_v is the vertical magnetic field component at vertical magnetization, I is the magnetization, b is the horizontal semi-thickness of TB, m is the elementary magnetic mass, z is the depth to a center of body (for HCC and sphere) and depth to the upper edge of TB and rod (point source), f is the universal gravity constant, and M is the mass of sphere.

It is clear that expressions (**??**) and (**??**) are analogical ones and equations (**??**) and (**??**), (**??**) and (**??**), respectively, are proportional ones.

Taking into account all above mentioned, we can apply for the gravity field analysis the advanced interpreting methodologies (improved versions of characteristic point and tangent methods as well as areal method) developed in magnetic prospecting for complex environments (superposition of anomalies of different orders, rugged terrain relief and oblique magnetization) (Khesin et al., 1996; Eppelbaum et al., 2001). For instance, we can interpret anomaly from the gravity HCC by the use of formulas applied for the magnetic TB (see Table 1).

We can also calculate the "gravity moment", which could be used for classification and ranging gravity anomalies from various types of targets. The "gravity moment" of HCC may be calculated by the use of corresponding formula for the magnetic TB (Eppelbaum, 2009):

$$M_{\Delta g} = {}^1\!/_2 \Delta g_a h, \tag{7}$$

where$M_{\Delta g}$is the gravity moment, $\Delta g_a$is the amplitude of gravity anomaly (in mGal) and h is depth of HCC occurrence (in meters).

3D modeling of gravity field

Analytical expression for the first vertical derivative of gravity potential of (m-1) angle horizontal prism has been obtained by integrating a common analytical expression:

$$W_{z'} = -\int\limits_{s} \frac{z}{(R+y)\,R} dxdz \left.\right|_{y_1}^{y_2}, \tag{8}$$

where $R = \sqrt{x^2 + y^2 + z^2}$, $S$is the area of normal section of the prism by the plane of xOz.

$$W_{z'T} = \left\{ \begin{array}{c} -f\sigma \sum\limits_{j=1}^{m-1} \\ \left[V_j \sin\alpha_j \left(\ln \frac{R_{12j}+y_2}{R_{22j}+y_2} - \ln \frac{R_{11j}+y_1}{R_{21j}+y_1}\right)\right. \\ +V_j \cos\alpha_j \left(sgn\left(y_2 V_j\right) \arccos \frac{V_j^2 R_{12j} R_{22j} + U_{1j} U_{2j} y_2^2}{r_{1j} r_{2j} \left(y_2^2 + V_j^2\right)} \right) \\ - \left(sgn\left(y_1 V_j\right) \arccos \frac{V_j^2 R_{11j} R_{21j} + U_{1j} U_{2j} y_1^2}{r_{1j} r_{2j} \left(y_2^2 + V_j^2\right)} \right) \\ \left. + \cos\alpha_j \left(y_2 \ln \frac{R_{12j}+U_{1j}}{R_{22j}+U_{2j}} - y_1 \ln \frac{R_{11j}+U_{1j}}{R_{21j}+U_{2j}} \right)\right] \end{array} \right\}, \tag{9}$$

where σ is the density of the body and α_j is the angle of the prism's side inclination.

$$\left. \begin{array}{l} \cos\alpha_j = \frac{x_{2j} - x_{1j}}{r_{12j}} \\ \sin\alpha_j = \frac{z_{2j} - z_{1j}}{r_{12j}} \end{array} \right\}, \tag{10}$$

x_{1j}, z_{1j} and x_{2j}, $z_{2j}$are coordinates of points P_{1j} and P_{2j} (angle points of j-side of (m-1) polyhedron); r_{12j} is the length of j-side of this polyhedron:

$$r_{12j} = \sqrt{(x_{2j} - x_{1j})^2 + (z_{2j} - z_{1j})^2}, \tag{11}$$

r_{1j} and r_{2j} are distances from the selected point M to the points P_{1j} and P_{2j}, respectively:

$$\left. \begin{array}{l} r_{1j} = \sqrt{x_{1j}^2 + z_{1j}^2} \\ r_{2j} = \sqrt{x_{2j}^2 + z_{2j}^2} \end{array} \right\}, \tag{12}$$

R_{11j}, R_{21j}, R_{12j}, R_{22j} are distances from the selected point M to angle points $R_{1j'}$, $R_{2j'}$, $R_{1j''}$ and $R_{2j''}$, respectively, for j-side of the prism:

$$\left. \begin{array}{l} R_{11j} = \sqrt{r_{1j}^2 + y_1^2} \\ R_{21j} = \sqrt{r_{2j}^2 + y_1^2} \\ R_{12j} = \sqrt{r_{1j}^2 + y_2^2} \\ R_{22j} = \sqrt{r_{2j}^2 + y_2^2} \end{array} \right\}. \tag{13}$$

U_{1j}, U_{2j} and V_j are the visible solid angles of corresponding parts of the prism'sj-th side.

The recent analysis indicates the necessity to apply additional correction associated with changing of density properties of sedimentary deposits over objects with different thermal properties (Gadirov and Eppelbaum, 2015). Of course, thickness of sedimentary deposits in archaeological sites usually is small and does not exceed 10 m. At the same time, for the objects with enhanced thermal properties this correction may reach 10-15 microGals that in some cases may be significant.

Vertical derivatives of gravity field

Taking into account small depth of archaeological targets and their not large geometrical size, observation of both vertical and horizontal derivatives of gravity field undoubtedly will permit to obtain new important information about the desired targets. Obviously, integrated analysis of gravity field and vertical and horizontal derivatives will significantly extend the possibilities of geophysical investigations at archaeological sites. It is necessary to underline that physical measurement of vertical gravity derivatives cannot be replaced by computing of this parameter obtained by any transformation procedures: the Δg_z values computed from the field Δg, as rule, show decreasing values comparing with the Δg_z obtained from physical measurements (Eppelbaum, 2011).

Gravity field transformations

Various transformations of gravity fields were tested: informational approach and third horizontal derivatives of gravity potential (Eppelbaum et al., 2008; Eppelbaum et al., 2010), entropy, wavelet and Morlet computations, and self-adjusting and adaptive filtering (Al-Zoubi et al., 2013; Eppelbaum et al., 2014). Selection of concrete transformation method strongly depends on the physical-archaeological models of the artifacts under study, measurement accuracy and level of the geological/environmental noise.

Analysis of the numerous archaeological and geological materials and publications as well as the author's investigation (e.g., Eppelbaum, 2009, 2010) indicates that the ancient objects supposed for examination by the use of microgravity survey may be classified (in the order of decreasing) by the following way: (a) buried (or partially hidden) ancient pyramids and associated targets (empty rooms), (b) underground ancient cavities and galleries, (c) walls, remains of temples, churches and various massive constructions, (d) pavements and tombs, (e) Roman aqueducts [under favorable physical-geological environments], (f) Areas of ancient primitive metallurgical activity (including furnaces) [under favorable physical-geological environments].

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