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Precise Indoor Gravity Measurements: From Metrology to Archaeology

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Abstract

Two gravity methods of discovering underground empties are compared and implemented in two old buildings in the city of Moscow. Variometric method is powerful and advantageous, but has a number of limitations. However it can be used for metrological investigation of precise gravimeters.

Investigation of historical and archeological objects in urban environment can be accomplished with variety of methods, including those that provide discovery of hidden underground rooms or passages, etc. Among other geophysical methods the microgravimetric method looks reliable and advantageous. Nowadays relative gravity measurements are made mainly with precise automatic gravimeters. The most common now is SCINTREX CG-5 gravimeter (Fig. 1a). It has extraordinary high sensitivity of 1.5 µgal (1 µgal corresponds to 10^{-9} g). Precise gravity data bring detailed picture of Δg on site, and this probably make evident presence of local underneath anomaly densities, positive or negative.

Another gravimetric method is based on Eötvös gradiometer torsion balance. Instruments of this type are out of production for long time and are very rare today. We have few instruments E-60 series (Fig. 1b) issued in Hungary in mid 1960s, which are able to register with extremely high precision values of second derivatives of gravity potential including horizontal gradients of gravity.

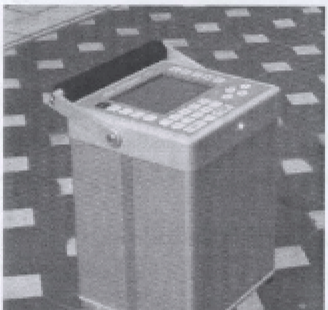

Fig. 1a:
Gravimeter
SCINTREX CG-5

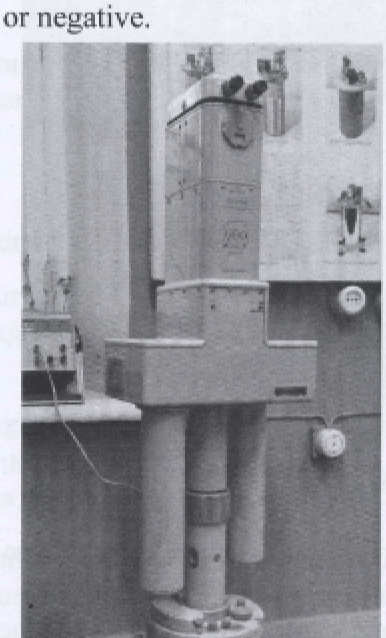

Fig. 1b:
Gravity variometer E-60

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Fig. 2a

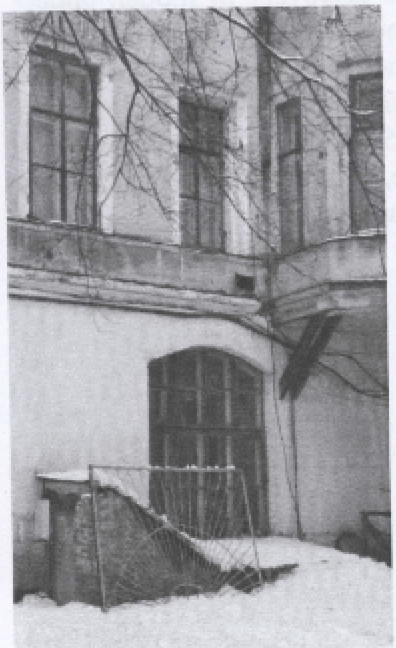


Fig. 2b

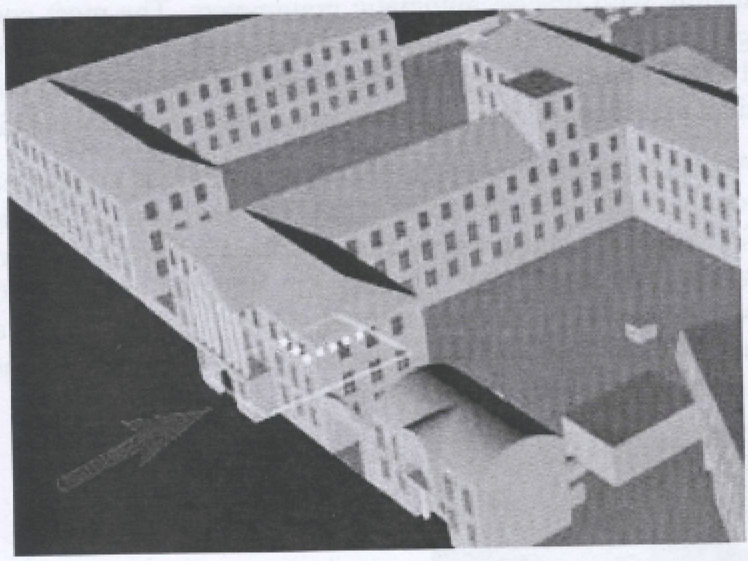


Fig. 2c

To verify the last method, we have created a special polygon for precise indoor gravity measurements. It is located inside our old building of MIIGAIK – now the University of Geodesy and Cartography, former Prince Konstantin's Land Surveying Institute, the second oldest high school educational institution in Moscow (after the University). The building was projected by famous architect Matvey Kazakov in 1791. Beyond the front entrance door (Fig. 2a), rarely used today, there is a large vestibule hall with columns (Fig. 2d). The hall is 13,1 x 7,0 meters size, it leads to old front stairs. The floor is covered with ceramic tile.

Deep 2 meters under the vestibule, opposite to the entrance door, lays narrow corridor of 1,2 m width, used in former times for heating supply purposes (Fig. 2b, 2c). The corridor is L-shaped and consists of two segments – the long (6 m) and the short (3 m). The corridor ends with a small room. Only the long segment and partly the short lay under the vestibule and thus accessible for gravity detection.

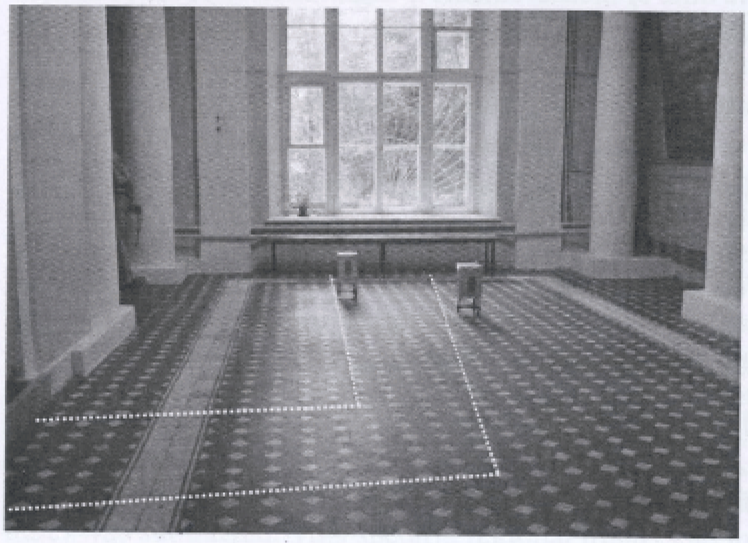


Fig. 2d

Gravity variometers can measure subset of four out of total six second derivatives of gravity potential W along the axis x and y (coordinate system on each point is unique and its origin coincides with the point) – W_{xz}, W_{yz}, W_{xy}, as well as their linear combination $W_\Delta = (W_{yy} - W_{xx})$. For detection of underground masses only two horizontal gradients are needed: W_{xz} and W_{yz}. These quantities are related to the gravity change Δg between two nearby points:

$$\Delta g = W_{xz}\,\Delta x + W_{yz}\,\Delta y - W_{zz}\,\Delta h \qquad (1)$$

where Δx, Δy – plane coordinate differences, Δh – height difference.

If the height difference between points is small (first centimeters), the vertical gradient $W_{zz} = -\partial g/\partial h$ is considered to be constant and its value equal to the normal: -3086 E ($1\mathrm{E} = 1 \cdot 10^{-9}\ \mathrm{sec}^{-1}$).

The interval of variometric survey must fit the size of existing horizontal gradients, so that the gradient value change could be considered linear. The survey interval should comply approximately half less the estimated size of the anomaly mass along the profile.

Observing in general the gravimetric method, we can point out its advantages and disadvantages.

Advantages:

- Passive method, no physical impact on environment or the object of interest;
- no influence from any other physical field – electrical, magnetic, etc (this is not the case for modern state of the art radar sensing methods);
- high sensitivity to nearby anomaly masses.

Disadvantages – stemming from the high sensitivity:

- Specific requirements for indoor conditions: rigid floor coverage (stone, tile or concrete);
- minimal seismic noise required – no moving people in the building and no streets with high traffic nearby;
- for the above reasons – preferable time of measurements is nighttime, however even then the natural seismic noise (far earthquakes, etc.) may exceed the critical level appropriate for measurements;
- discrete survey requires small intervals between points, so increase work time;
- measurements close to massive walls and vertical structures are inexpedient due to strong gravity effect. Flatness of the floor surface is critical as well;
- careful modeling and consideration of all visible attracting masses (walls, columns), accounting doors and window openings, as well as all height variations. All measurements have to be reduced to single effective height.

Advantages of variometric method comparing to gravimeters:

- Absolute method, all measured quantities are absolute values of second derivatives of gravity potential;
- measurements are independent from each other point to point (it's not the case for static gravimeters);
- measurements are more noise-proof because of long period of self-oscillation of the torsion balances (about 10 minutes);
- high sensitivity to very close masses (~ r-3);
- very low instrumental drift.

Disadvantages of variometers:

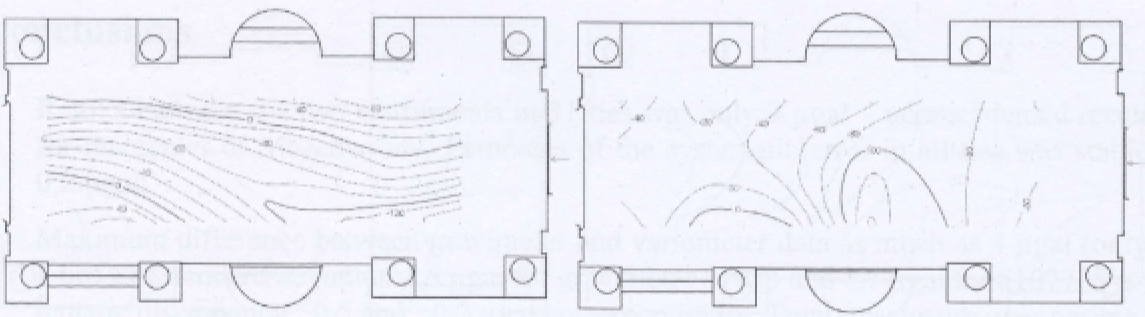
- Weight of the instruments (60 kg);
- long measurement sessions – minimum 1,5 hours per point;
- short range of visibility, because (as mentioned above), the second derivatives of potential are proportional to r^{-3}, not r^{-2} like gravity forces.

The old building of MIIGAIK appeared to provide excellent conditions for gravity measurements of both types.

The variometric survey has taken place with two instruments E-60 with intervals 1 and 2 meters. Measurement points were placed not less 1 m apart the massive walls. The largest height difference on the polygon is 40 mm. The instruments were installed without a tripod, so the effective height was 45 cm. Theory says that to obtain the two horizontal gradients three sets of azimuth of the balance system is sufficient: 0° – 120° – 240°, with the final closing measurement at 0° to ensure stability of the system.

Three profiles with 1 m interval and one profile with 2 m interval were accomplished, in total 39 points.

Horizontal gradients along the profiles achieved 180 E (18 µgal/m), gravity change Δg calculated from (1) achieved 17 µgal, average 8 µgal (Fig. 3). The redundant repeated measurements indicated error of repeatability only 2 E for horizontal gradients.

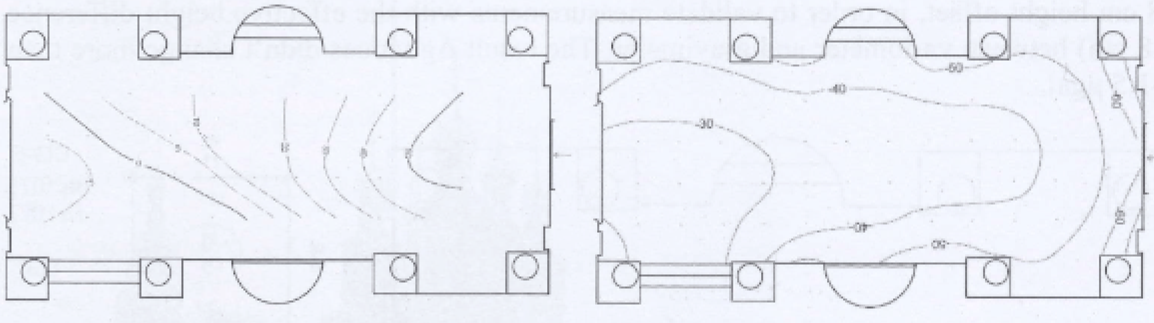


a) b)

Fig. 3a, b: Horizontal gradients of gravity W_{xz} (3a) and W_{yz} (3b) from variometer E-60, contour value 20 E

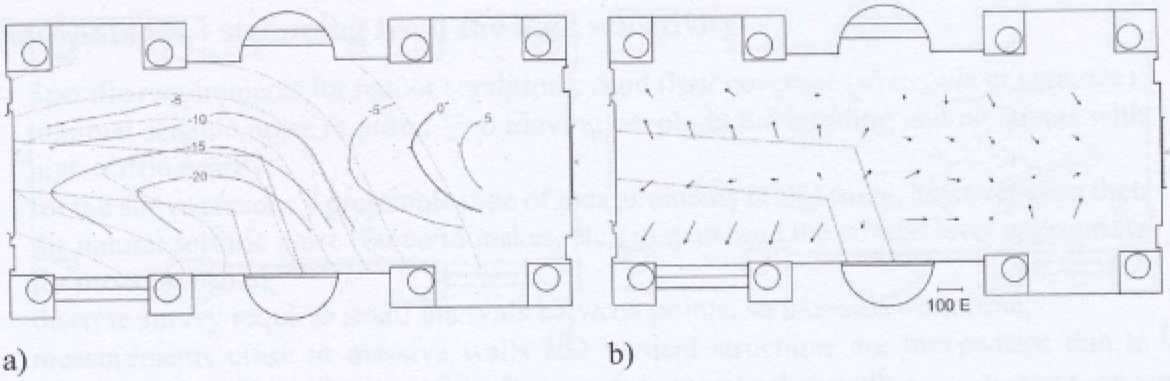
The survey show that the gravity increase is monotonous and reaches 75 µgal from one side to another (Fig. 4a). After accounting for redundant measurements and accuracy estimation the general picture of Δg was obtained (Fig. 4a). After that corrections for attraction of visible masses were implemented. The model included 11 rectangular blocks 1-2 m of thickness with brick density $\delta = 1{,}7$ gr/cm^3, door and window openings were taken into account (Fig. 4b). On the last step regional trend 60 E along North-South direction (long side of the the vestibule) was subtracted. This specific regional trend is an influence of well-known phenomena "Moscow attraction anomaly".

Finally the local gravity anomaly became clearly visible (Fig. 5a). Its size up to 30 µgal comply the expected gravity effect of the corridor. Vectors of residual horizontal gradients with values up to 100 E are divergent and indicate the presence of linear-extended object (Fig. 5b).



a) b)

Fig. 4a, b: Gravity change (4a), contour 5 µgal, attraction of walls (4b), contour value 10 µgal



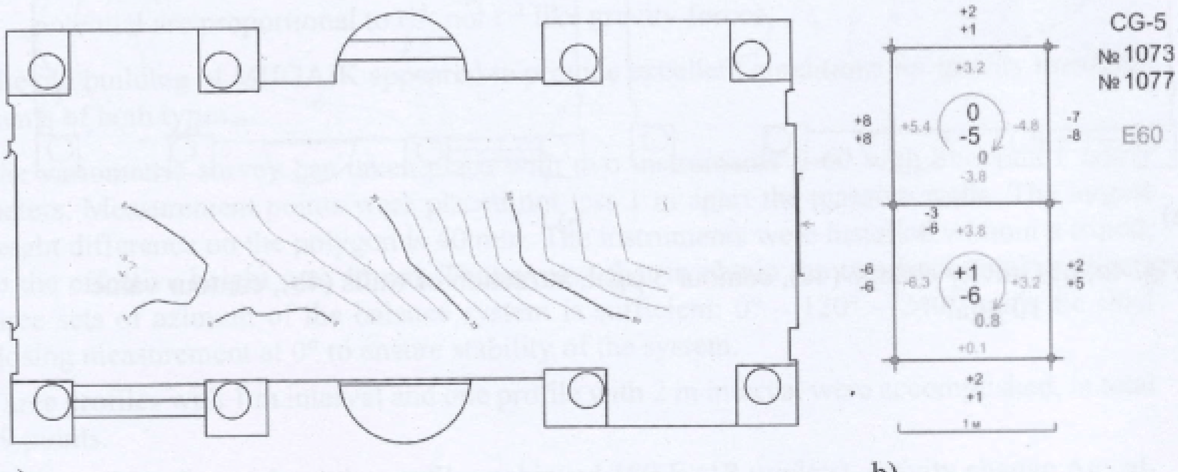
a) b)

Fig. 5a, b: Results of variometric survey. 5a – dark lines – measured gravity, contour value 5 μgal, light lines – calculated gravity effect of the underground masses, contour value 5 μgal. Strait lines indicate the corridor layout. 5b – vectors of horizontal gradients from variometer data.

Computed misclosure of Δg values along sides of 1 x 1 m squares is a reliable quality indicator of the solution (Fig. 6b). The average misclosure of all squares was 0.5 μgal, and only twice it has slightly exceeded 1 μgal. The total misclosure over the perimeter of 22 sections was 0.6 μgal. This allows the variometric method to be used as a reference standard polygon for testing static gravimeters, such as SCINTREX CG-5.

Selected subset of 27 points with 1 m interval (31 gravimeter ties) was measured with two SCINTREX gravimeters (s. n. 1073 and s. n. 1077), sequent one after another. The measurements took place during evening time, each series contained 5 minutes of 1-second readings with averaging over 1 minute. Scatter of minute averages in general didn't exceed 1-3 μgal, rarely 4-5 μgal.

Since the effective height of gravimeter is 27 cm, 6 additional gravimeter ties were done with 18 cm height offset, in order to validate measurements with the effective height difference (18 cm) between variometer and gravimeter. The result Δg values didn't change more than 1-1,5 μgal.



a) b)

Fig. 6a, b: 6a – Gravity change measured with gravimeters SCINTREX CG-5, contour value 5 μgal. 6b – Δg misclosures along squares (example): variometric (light digits) and gravimetric (dark digits) for each of the instruments.

Conclusions

1. R. m. s between the two instruments in 31 ties was only 2 µgal – unprecedented result for the center of Moscow city. Estimates of the systematic error in all ties was stable 0,2 µgal;

2. Maximum difference between gravimeter and variometer data as much as 4 µgal (only 1 tie) and standard deviation 1,6 µgal for gravimeter #1073 and 1,7 µgal for #1077. Systematic discrepancy −0,5 and −0,2 µgal correspondingly. Total misclosure over perimeter of the site (22 ties) was 1 µgal for #1073 and zero for #1077;

3. These values are significantly less than the declared nominal characteristics of the gravimeters SCINTREX CG-5 (5 µgal), so gravimeters of this type can be applied for similar task under the same conditions;

4. Gravity variometers can be used for creation local metrological polygon.

Another variometric survey was done inside an old church of late XVII century (Fig. 7a), in order to check hypothesis about passages under the floor. Because of intensive traffic outside all measurements were made in late midnight. The walls of the church (0,9 – 1,5 m thick) didn't allow to get closer 1,5 meters to them. The interval between survey points was 2 meters, in total 22 points were measured.

After routine numeric integration of horizontal gradients, correction for attraction of the walls (up to 70 µgal, the model contained 17 blocks) and corrections for height irregularities were added, local trend (20 E) was subtracted.

The residual local horizontal gradients (up to 30 E) and gravity anomaly values (up to 2,5 µgal only, Fig. 7b) show no evidence of any anomaly masses under the floor of the church.

Fig. 7a