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On a lasting role of geodynamics in modern vertical and gravity reference systems

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Abstract. Both definition and realization of vertical reference systems require gravity. Relation between height changes and gravity changes is well known in geodynamics on local, regional, and global scale. Consideration of time as additional dimension is needed in the modern vertical and gravity reference systems as well as in processing both levelling and gravity data.

Classical vertical and gravity reference systems are briefly presented followed by the discussion of the need of advanced modification of both systems. Geodynamic aspects in creating modern vertical and gravity reference systems were discussed. The role of geodynamics in the realization of vertical and gravity reference systems was presented with emphasizing the key role of metrology.

Keywords: vertical reference system, gravity reference system, geodynamics, metrology

1 Introduction

Mutual relation between heights and gravity is specified in fundamentals of physical geodesy. In the theory of height systems as well as in the realization of vertical system gravity is an important component. Similarly, gravity systems are referred to heights. Relation between height changes and gravity changes is well known in geodynamics. Interpretation of observed height changes in terms of geodynamic effects, like vertical crustal movements, without respective data on gravity changes may lead to false conclusions.

Similarly, reported in the literature changes of gravity, e.g. gravity changes monitored quasi-permanently (Barlik *et al.*, 2009a, 2009b, 2010) to be reliably interpreted in terms of geodynamics require respective information on height changes.

Results of repeatable levelling campaigns indicated the need of attributing an epoch to each campaign as well as of referring levelling observations to time scale to eliminate tidal deformation effects. Results of space missions, especially geopotential models developed from GRACE mission data show seasonal variations of gravity field on local, regional and global scale. Such variations can also be monitored with repeatable high precision terrestrial absolute gravity measurements. Consideration of time as additional dimension is thus needed in the modern vertical and gravity reference systems as well as in processing both levelling and gravity data.

It should be noted that measuring techniques used in practical engineering surveys, that traditionally were purely 2D techniques, are no longer independent on those used in 3D geodesy. Global satellite navigation systems GNSS are commonly used for positioning and more and more also for heighting. Replacement of static reference frames with the kinematic ones that are sensitive on geodynamics affects no longer only geodetic surveying but also practical engineering surveys. Thus, the point that geodynamics might only be the subject of research is clearly outdated.

2 Characteristics of classical vertical and gravity reference systems

2.1 Classical vertical reference system

Classical vertical reference system is realized by the vertical control network. Heights of the benchmarks of the network are determined in the process of least squares adjustment of spirit levelling observations. They are usually expressed in the official height system of the country, i.e. normal, orthometric, etc., related to reference height, commonly called sea surface, determined from tide gauge data. The vertical control network is expected to be homogeneous in terms of uniform metric. Therefore, the surveying instruments applied, i.e. sets of precise levels with precise levelling rods need to be calibrated; calibration should be done in highly specialized laboratories. Metrology is thus an extremely important component of establishing and then maintaining vertical reference frame.

The reference surface of the classical vertical reference frame as determined using spirit levelling data is of discrete form. It can be a levelling geoid or quasigeoid when the height system used is orthometric or normal, respectively.

Measuring campaigns of precise spirit levelling at the vertical control network were periodically repeated. In Poland, for example, such campaigns were conducted every 20 years; differences of heights of the benchmarks were reaching the level of a dozen centimetres. The obtained height changes may be interpreted in terms of vertical deformation of the Earth crust.

No gravity was required to be determined at each benchmark of the Polish vertical control network. However, gravity data were needed to compute height system corrections to transform measured height differences into heights of the official height system; in Poland such corrections reached the level of 2 cm for a levelling line. Gravity data were also needed to calculate tidal correction; in Poland they did not exceed 1.5 mm for a levelling line of 50 km length in average.

The classical vertical reference system is static. Consideration of time that linked vertical reference system with geodynamics was reduced to attributing the epoch to the system, which has not been frequently applied, and to calculate tidal corrections.

2.2 Classical reference system for gravity

Classical reference system for gravity is realized by the gravity control network. Gravity of the network stations are determined in the process of least squares adjustment of relative gravity observations. The gravity level of the system is determined by a link to one or more stations where absolute gravity measurements were conducted. The gravity control network is expected to be homogeneous in terms of uniform metric. Therefore, the surveying instruments applied, i.e. static gravimeters need to be calibrated; it is usually done on properly maintained gravimetric calibration baselines. Thus, also in establishing and maintaining creating gravity reference frame metrology is an extremely important component.

The classical reference system for gravity in Poland is static.

There was no necessity to precisely determine heights of the points of the gravity control network; the example is the Polish Fundamental Gravimetric Control Network (POGK'99) - as a gravity control which points were not levelled using precise spirit levelling.

3 Decline of classical vertical and gravity reference systems

3.1 Decline of classical vertical reference system

There are numerous factors indicating the decline of classical vertical reference system. To keep classical vertical reference frame well maintained requires its re-measurements. The levelling campaigns on the scale of the average size country like Poland, take usually many years, what results in low precise determination of the epoch of reference surface (classical levelling geoid/quasigeoid), and they are extremely expensive. Thus, the campaigns are not being repeated with sufficient frequency. It results in large time spans between consecutive levelling campaigns.

GNSS technology of heighting becomes more and more competitive to spirit levelling. The technology is worldwide available, commonly used, extremely efficient, and inexpensive. Its use for heighting requires precise knowledge of the reference surface in arbitrary point at the observation epoch. Time variations of reference surface can recently be monitored using space gravity missions as well as time series of astrometric observations. Seasonal variations of geoid heights reach the level of a few centimetres; variations of geoid heights in Poland do not exceed 1 cm (Kloch-Główka *et al.*, 2011). Seasonal variations of the direction of the plumb line (variations of the deflection of the vertical) can reach the level of 0.2-0.3 arcsec (Krynski and Zanimonskiy, 2011).

The reference surface (geoid/quasigeoid) can recently be determined at the very high level of precision (in Poland 1.7-3.0 cm (Krynski, 2007; Krynski and Kloch, 2009)) and its time variations can easily be monitored with the use of the data from space gravity missions as well as from terrestrial gravity data. It indicates the growing role of gravimetry in developing and maintaining vertical reference system. Gravimetric geoid/quasigeoid should thus replace spirit levelling geoid/quasigeoid as the reference surface for heights. Such replacement is in progress e.g. in a new vertical reference system under development for North America. Geodynamics become thus an important component of the realization of recent vertical reference systems.

3.2 Decline of classical reference system for gravity

The decline of classical gravity reference system is first of all due to the development of ballistic gravimeters and growing availability of absolute gravity measurements. Contemporary ballistic gravimeters provide gravity with considerably better accuracy than static relative gravimeters. Moreover, new high precision ballistic gravimeters designed for field survey, like A-10 gravimeter, may practically eliminate relative gravity survey from the realization of gravity reference system. They assure higher precision and reliability of the gravity reference system fulfilling recent requirements. They also assure extremely quick and inexpensive maintenance of the gravity control. Consideration of time as additional dimension is critical in the realisation of gravity reference system.

4 Geodynamics versus vertical and gravity reference systems

One of the main natural objectives of geodynamics is the recognition of the tendency of horizontal and vertical motion of tectonic plates. There is also a distinctive practical objective of geodynamics. It focuses on maintaining coordinates and gravity value at control points at possibly actual level, and requires monitoring of both vertical and gravity reference systems.

Due to high precision of contemporary surveying techniques the geodynamic signal in the observations used to determinr heights as well as gravity cannot be any longer neglected, i.e. treated as random effect that might apparently be filtered out. Consideration of time variation of the gravity field resulting in variations of the reference surface (geoid/quasigeoid), direction of the plumb line as well as gravity reference level is necessary.

Raw observations acquired with the use of global observation techniques of positioning and gravity field modelling are referred to the instantaneous reference system that varies with time. Its time variations should be known in order to eliminate the bias and be able to refer observations to the official reference system in which the final result is expected to be determined.

To maintain contemporary vertical and gravity reference systems both heights and gravity need to be periodically re-surveyed and the variations of both should carefully be monitored. Only precise monitoring of height and gravity variations can result in reliable separation of vertical movements from sea level changes, what is crucial for the determination of reference surface for heights.

5 Geodynamics and metrology in realization of vertical and gravity reference systems

Geodynamics became inseparable with the realization of contemporary reference systems. Increasing need for monitoring variations of reference surface for vertical reference system (geoid/quasigeoid) not only on global scale, but also on regional and local scales is observed. There is also a need for monitoring variations of the direction of the plumb line, which is the reference for orientation of vertical axis of majority of terrestrial surveying instruments.

Realization of reference systems requires extremely careful consideration of tidal effects. Precision of computed tidal corrections must correspond to high precision of contemporary measurements as well as fulfil the accuracy requirements of the final product. In many countries, including Poland, tidal models are insufficient. Coefficients of elasticity of the Earth crust in the model are in such case not sufficiently representative due to small number of tidal stations as well as their distribution.

It is necessary to maintain gravity in the gravity control at possibly actual level. It can be assured by repeatable absolute gravity measurements at the number of fundamental stations as well as base stations of the gravity control. The role of metrology in realizing and maintaining vertical reference frame is well known and does not need to be highlighted here. It should, however, be emphasised that metrology plays the key-role in maintaining gravity control, i.e. assurance of standards of ballistic gravimeters, but also control and assurance of reliability of gravity determined when no network adjustment is possible.

6 Conclusions

Geodynamics became an inseparable component of contemporary geodesy. Its role is particularly important in definition and maintaining reference systems for heights and gravity. Due to time variations of gravity field the gravity needs frequent re-surveying and always be brought up to date. Their reliability strongly depends on fulfilling metrological procedures. Monitoring time variations of the gravity field provides actual data of required quality not only for calculating appropriate corrections to the spirit levelling observations but also for defining and maintaining reference surface for heights as well as corrections to "precise" GNSS heighting.

The role of metrology in the realization of reference systems is beyond any discussion, especially when traditional observation techniques based on relative surveys are applied. When using, however, techniques providing absolute determination of quantities needed, as it takes place in case of ballistic gravimeters, metrological procedures cannot be limited to the calibration of measuring units (time and distance in case of free-fall gravimeters). In such case the instruments (ballistic gravimeters) should be periodically intercompared with other instruments of at least the same class in comparison campaigns of regional as well as of international scale. Last such international comparison campaign gathering 26 absolute gravimeters was conducted in November 2011 in Walferdange, Luxembourg.

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