Gravimetry for geodesy and geodynamics – brief historical review

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Abstract. For last two centuries the role of gravity measurements in geodesy was continuously growing with the development of physical geodesy, growing needs for precise geodetic products and progress in technology. A very condensed historical review of gravimetric surveys with their uncertainty characteristics is given in the paper. It starts with single gravity measurements using simple pendulum through the application of reversible pendulum up to four-pendulum apparatus. Superiority of relative gravity survey over absolute gravity survey using pendulum has been highlighted. Further, the development of static spring gravimeters is briefly presented followed by precise ballistic gravimeters that provide more accurate gravity than relative gravity survey and become a valuable tool for geodynamic research. The concept of superconducting gravimeter and its role in geodynamic research is highlighted. Special emphasis is given to the portable free-fall gravimeter A10 designed for field survey. Also the achievements in the direction of developing atomic absolute gravimeters are briefly mentioned.

The evolution of the concept and realization of the gravity control is discussed on the background of the progress in gravimetry, paying special attention on its scale and gravity level. It is illustrated with some examples of evolving Polish national gravity control. Finally an attempt to formulate the concept of modern gravity control is presented.

Keywords: gravimetry, pendulum, gravimeter, geodesy, geodynamics

1 Introduction

Development of theoretical foundation of geodesy following the progress in physics as well as growing technological possibilities of gravity measurements placed gravimetry among fundamental geodetic surveying techniques. Gravity measurements started to be of larger interest for geodesy when they reached the uncertainty level of $10^{-5}\,g$, i.e. $10^{-4}\,m \cdot\ s^{-2} = 10\,mGal$. Such measurements were first conducted in 1792 by Borda and Cassini with the use of a $3.8\,m$ wire pendulum with a platinum ball (Torge, 1989). Gravity was calculated on the basis of precisely measured oscillation time and the length of pendulum. For next 150 years gravity data was provided for geodesy by pendulum measurements. Its role in geodesy was continuously growing. By the end of 19^{th} century the results of gravity survey were already used for reduction of geodetic and astronomic observations to the sea level, calculation of corrections to precise geometric levelling, interpolation of the deflections of the vertical, and the determination of the shape of the Earth as well as the external gravity field. Growing need for gravity data resulted in the development of gravimetry.

The paper gives a brief review of major steps in developing gravity measurement techniques, gravity reference systems and the concepts of gravity control illustrated with the examples of gravity control in Poland.

2 Gravimetry based on pendulum measurements

The important step forward in acquiring gravity data was the development of the principle of reversible pendulum. First such pendulum of 1 m length dedicated for field use was constructed by Kater in 1818. Initially the apparatus provided absolute gravity at 35 *mGal* uncertainty level but constructional improvements of reversible pendulum over the decades resulted in better quality of gravity determination (Torge, 1989).

First gravimetric measurements were conducted on single points, mainly within experimental projects on local scale. More intensive gravity survey was performed within the project "Mitteleuropäische Gradmessung" initiated in 1862. Up to the year 1884 absolute gravity was measured at as many as 122 points with the mobile reversible pendulum of 1 m and 0.5 m length with uncertainty of 10 $mGal$. Distribution of those points was, however, very inhomogeneous, even on the territory of Central Europe (Torge, 1989).

The experiments with the determination of gravity using pendulum conducted in the first half of 19^{th} century showed that relative gravity survey is more accurate than the absolute gravity survey. The uncertainty of gravity difference reached the level of 5 $mGal$. Since then relative gravity surveys dominated in geodetic gravimetry for almost 150 years. Relative gravity measurements have been intensified at the end of 19^{th} century with the use of brass pendulum of 25 cm length. The number of gravity points in 1912 exceeded 2000.

Relative gravity measurement, similarly to relative height measurement, requires absolute reference level determined with sufficiently high accuracy. First gravity reference level called Vienna Gravity System, based on gravity value determined using pendulum by Oppolzer in Vienna, was established in 1891 (Fajklewicz, 2007). After a series of gravity measurements (1898 – 1904) in Potsdam conducted by Kühnen and Furtwängler with the use of improved reversible pendulum, the absolute gravity determined was considered as most accurate in the world. It became the basis of a new fundamental gravity system introduced in 1909 as Potsdam Gravity System, which lasted as such until 1971.

Technical development in the beginning of 20^{th} century (invar or quartz pendulum, time signals, vacuum chamber, and later photographic data recording) enabled to measure relative gravity at the uncertainty level of $10^{-6}\,g$, i.e. $10^{-5}\,m \cdot s^{-2} = 1\,mGal$. It has been initiated by improving the Sterneck pendulum in 1887 (Torge, 1989). New pendulum apparatus consisting first of two, then three and finally of four pendulums, enabled to further increase the number of points with measured gravity. The relative gravity measurements were conducted between national fundamental gravity stations and the absolute gravity station in Potsdam.

In particular, in 1926 – 1930 three gravity points in Poland: Krakow, Poznan and Warsaw were surveyed and linked with Potsdam by relative pendulum measurements (Królikowski, 2006). For next couple of decades those points were used as fundamental for gravity survey in Poland.

3 Gravimetry based on measurements using static gravimeters

Although the observation time with the use of pendulum required for the relative gravity survey has been shortened at a station from 12h – 24h at the end of 19^{th} century to 1h – 6h in 1930., gravity survey with pendulum remained expensive and time consuming. Revolutionary change in the efficiency of relative gravity survey brought in 1930. first static spring gravimeters. They were based on the principle of compensating gravity force acting on the test mass by a measurable counteracting force bringing to an equilibrium. Observation time with those gravimeters has been reduced to 10 – 30 minutes at the point. Uncertainty of relative gravity determination with first static gravimeters was in the range of $2 - 5\,\mu m \cdot s^{-2} = 0.2 - 0.5\,mGal$. Their construction was, however, continuously improved (e.g. quartz spring); uncertainty of spring gravimeters soon reached the level of $10^{-7}\,g$, i.e. $10^{-6}\,m \cdot s^{-2} = 0.1\,mGal$. Further developments around 1950, in particular applying temperature stabilization, resulted in the increase of the precision of relative gravity survey by an order of magnitude, i.e. to the level of $10^{-8}\,g$. Many types of gravimeters were developed during next few decades. Few of them, e.g. Worden or LaCoste&Romberg astatized gravimeters lasted with only minor improvements for next 50 years. Uncertainty of relative gravity determination with those gravimeters was about $0.1 - 0.5\,\mu m \cdot s^{-2} = 0.01 - 0.05\,mGal$.

Measurement of gravity with a static gravimeter requires the conversion of a gravimeter reading, which refers to a scale of the gravimeter, to gravity units. It is done in the process of calibration of the gravimeter.

Until the beginning of last decade of 20^{th} century relative gravity survey exhibited higher precision then absolute gravity survey.

4 First gravity control networks

With rapidly increasing number of gravimeters the number of points with gravity determined had increased considerably. In the middle of 20^{th} century there were already more then 10 000 gravity points available.

First gravity control networks were established in the end of 19^{th} and beginning of 20^{th} century as the reference for gravimetric survey. They consisted of the monumented stations at which gravity referred to the epoch was determined and its accuracy was evaluated. Solid monumentation of gravity control networks points was required to ensure their long-term survival. Periodic re-survey of those points is needed to maintain the network; it also provides a unique material for investigating geodynamic processes. The gravity control networks were based on relative pendulum measurements and tied to absolute gravity determined with the use of pendulum, e.g. to Potsdam Gravity value. Those networks were then densified with gravity points surveyed using more efficient static gravimeters. With the development of precise spring gravimeters, only the measurements using static gravimeters became the basis of gravity networks. As before, the tie to the absolute gravity ensured gravity level of the gravity control. The gravity unit was determined in the calibration of relative gravimeters to ensure the appropriate scale of gravity network. Most reliable and adequate method for calibration of gravimeters was found to use gravimetric calibration baselines. Such baselines became an integral part of national gravity control networks.

4.1 Gravity control network in Poland – an example

First gravity control network in Poland has been established in 1955 – 1962. Gravity measurements were performed using Askania Gs11 gravimeters. Properly monumented 18 1^{st} order gravity control points were surveyed in 1955 – 1957 using air transport, while 144 2^{nd} order gravity control points with no monumentation were surveyed in 1957 – 1962 using surface transport (Fig. 1) (Krynski, 2007).

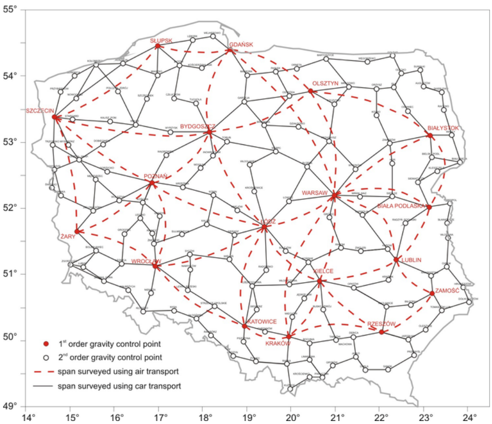

Figure 1. *First gravity control network in Poland*

Figure 2. *International Gravimetric Polygon*

Gravity level of the adjusted network was determined by a tie to Warsaw-Okecie point of the international gravity network in Potsdam Gravity System. The scale of the network was ensured by the calibration of Askania Gs11 gravimeters on the calibration baseline maintained using four-pendulum apparatus.

Following the growing requirements of geodesy and then geodynamics, gravity control network in Poland was improved in next few decades. First, it has been densified in 1962 – 1964 by adding 20 new 2^{nd} order points and 122 intermediate points of 2^{nd} order, as well as a number of relative measurements and new gravimetric ties to Potsdam and Prague. Its further improvement took place within the framework of the project on unification of standard and scale of gravity control networks in Central and East European countries. International Gravimetric Polygon consisting of 19 points (Fig. 2) was established in 1968. Polish gravity control network after re-adjustment was further referred to Potsdam Gravity System (Krynski, 2007).

5 Gravimetric survey in 1950 – 1970

Besides the increase of precision of relative gravity surveys the advent of absolute gravimeters measuring gravity on the basis of free-fall is observed in the middle of 20th century. Although first stationary absolute gravimeters – free-fall gravimeter constructed in 1951 by Sakuma at BIPM Sévres, France and rise and fall gravimeter constructed by Cook in 1965 at the National Physical Laboratory, Teddington, UK – provided gravity at the uncertainty level of $10^{-7}\,g$, which was an order of magnitude worse than contemporary thermostatic spring gravimeters, they were consequently improved following the technological development, in particular in electronics, measuring time and distance, and in material sciences. Many laboratories took then the challenge to develop stationary absolute gravimeters, e.g. VNIM Leningrad in 1954 – 1959, BIPM Sévres in 1957 – 1958, NCR Ottawa in 1958 – 1959, PPL Princeton in 1962, NBS Gaithersburd, MD in 1965, NRLM Kakioka in 1965 – 1967, BIPM Sévres in 1967 – 1983, PTB Braunschweig in 1969, DANW Berlin in 1969 – 1970, NSL Sydney in 1970. First mobile free-fall gravimeter was constructed in 1968 – 1969 by Hammond and Faller at the Wesleyan University, Connecticut, USA (Torge, 1989). It measured gravity at the same uncertainty level as the existing, cumbersome stationary absolute gravimeters.

Growing number of gravity measurements indicated urgent need for establishing new gravity system of world-wide range. Absolute gravity measurements conducted in 1930. by the National Bureau of Standards, Washington D. C., and by National Physical Laboratory, Teddington, UK, with the use of upgraded reversible pendulum with uncertainty of $10\,\mu m \cdot s^{-2} = 1\,mGal$ showed that the gravity value being the basis of the Potsdam Gravity System in affected by the bias of about 14 $mGal$ in (Torge, 1989). All gravity values referred to Potsdam should thus have been lowered by 14 $mGal$. Finding the bias in the Potsdam Gravity System as well as the progress with free-fall gravimeters in 1960. accelerated the establishment the first global gravity network.

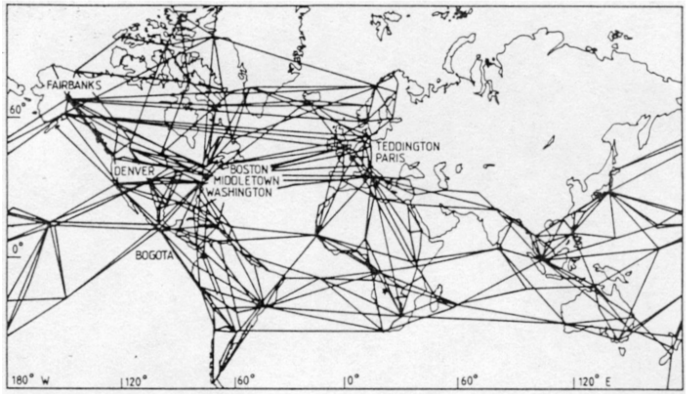

Figure 3. *International Gravity Standardization Net 1971*

6 Global gravity network igsn71

Global gravity network, called International Gravity Standardization Net 1971 (IGSN71), was established as a result of international cooperation over two decades, coordinated by the International Association of Geodesy (IAG) of the International Union of Geodesy and Geophysics (IUGG). The network consisted of 1854 gravity points. Gravity level of IGSN71 was defined by 10 absolute gravity measurements conducted on 8 stations, 8 measurements with Hammond and Faller mobile free-fall gravimeter, and 2 measurements with stationary instruments by Sakuma in Sévres, and by Cook in Teddington, respectively (Fig. 3) at the uncertainty level of $0.1 - 1.0\,\mu m \cdot s^{-2} = 0.01 - 0.1\,mGal$ (Torge, 1989).

Recent 1200 relative pendulum measurements performed at the uncertainty level of $2 - 4\,\mu m \cdot s^{-2} = 0.2 - 0.4\,mGal$ additionally controlled the scale of the IGSN71. Moreover, approximately 12 000 relative gravimetric measurements of long spans contributed to the strength of the network while about 11 700 eccentric relative gravity surveys ensured local links. The uncertainty of those measurements was within the range of $0.2 - 2.0\,\mu m \cdot s^{-2} = 0.02 - 0.2 mGal$.

Following the resolution of the XV IUGG General Assembly in Moscow in 1971 the IGSN71 replaced the Potsdam Gravity System

(PGS). It was recommended to apply the correction of $-14\ mGal$ to the gravity, i.e. $g_{IGSN71} = g_{PGS} - 14\ mGal$ (Krynski, 2007).

In Poland, the implementation of IGSN71 was conducted with simultaneous improving of the scale of the gravity control network using the data from the International Gravimetric Polygon (Fig. 2) of 1968 as well as established later the National Gravimetric Polygon. First, gravity at 15 stations of those polygons, considered as reference, was transformed from PGS to IGSN71 as follows: $g_{IGSN71} = g_{PGS} - 14.000\ mGal$. Then, all observed gravity differences in the gravity control network corrected due to the change of the gravity unit in the network: $\Delta g_{IGSN71} = \Delta g_{PGS} \cdot (1 - 3.8 \cdot 10^{-4})$ have been adjusted to fixed gravity at 15 reference stations (Krynski, 2007).

7 Progress in absolute gravity survey in 1975-2000

In the last decades of 20th century an extensive progress in the development of mobile ballistic gravimeters is observed. Numerous laboratories, e.g. IMGC Torino since 1976, IAE Novosybirsk since 1976, ERI Tokyo since 1976, AFGL Hanscomb, Mass. in 1978 – 1981, NIM Beijing since 1979, Jaeger S. A. Levallois-Perret, since 1980, JILA Boulder, Co since 1981, ILO Mizusawa since 1982, IGGP San Diego since 1984 (Torge, 1989), and WUT Warsaw in 1993, attempted to employ the newest technology achievements to the construction of the gravimeters. Most of them were based on the free-fall principle. Their accuracy ranged within $0.1 - 0.5\,\mu m \cdot s^{-2} = 0.01 - 0.051\,mGal$. Some of those gravimeters were used only locally.

Few of them, however, e.g. GABL manufactured in Novosibirsk in 1976, IMGC produced first in 1976 and then continuously improved, JILA constructed in Boulder in 1980 and then improved in 1986 as a series of 6 JILAg gravimeters participated in the international projects and were involved in extended measurements in numerous regions of the world. In 1993 the team of AXIS Instruments Company in Boulder, Colorado, lead by Faller, experienced in developing JILA gravimeters, manufactured a mobile FG5 gravimeter designed to operate in laboratory conditions, that provides gravity with uncertainty at the level of $10^{-9}\,g$, i.e. $0.01\,\mu m \cdot s^{-2} = 1\,\mu Gal$. The series of FG5 dominated soon the market of ballistic gravimeters.

8 Gravity control networks of the end of 20th century

With the FG5 the absolute gravity survey became more precise than the relative survey. It caused the change in the concept of the gravity control network. The network should be based on possible large number of absolute gravity points. To ensure the gravity standard the performance of absolute gravimeters should be mutually compared. Gravity level of the network is obtained by transferring international gravity level by means of using ballistic gravimeters which participated in the international comparison campaigns of absolute gravimeters. The densification of the gravity control network should be done with the use of static gravimeters. Gravimetric calibration baselines which become an integral part of the gravity control network should be based on high precision absolute gravity points.

8.1 Gravity control network in Poland in 1990. – an example

Most of points of the new gravity control network established in 1994 – 1996 in Poland were monumented already in 1970. The network was based on 12 absolute gravity points surveyed with a few free-fall gravimeters: two FG5 (Germany, USA), JILAg-5 (Finland), IMGC (Italy), and ZZG of WUT (Poland), that all participated in the comparison campaigns of absolute gravimeters in BIPM in Sévres. All 363 points of the network (Fig. 4) were surveyed with LCR gravimeters calibrated at the gravimetric calibration baseline. The adjusted network forms a POGK97 gravity system. Standard deviation of adjusted gravity at the network point equals $0.1\,\mu m \cdot s^{-2} = 10\,\mu Gal$ what corresponds to the uncertainty level of $10^{-8}\,g$ (Krynski *et al.*, 2003).

In 2006 – 2008 the first stage of modernization of the gravity control network in Poland was conducted. It concerned the

Figure 4. *Polish gravity control network* POGK97

increase of the number of absolute points surveyed with the FG5-230, modernisation of two gravimetric calibration baselines and establishment of two new vertical gravimetric calibration baselines in Tatra and Sudeten Mountains (Fig. 5) (Krynski and Rogowski, 2008).

9 Superconducting gravimeters

Superconducting gravimeter (SG) represents the new generation of relative gravimeters.

It uses the principle of superconductivity in metals in extremely low temperatures that assures constant electromagnetic field. Such a field keeps a superconductive test body in equilibrium. The displacements of the test body from its zero position due to gravity changes are electrostatically compensated and measured.

First SG manufactured by GWR Instruments Inc., San Diego, at the end of 1960. were cumbersome and their maintenance was very expensive. Recent SGs, e.g. iGrav^{TM} SG meter are mobile and economic. They are also extremely stable; their long-term drift does not exceed $10^{-10}\, m \cdot s^{-2}/year$. Uncertainty of SGs reaches the level of $10^{-11}\, g$, i.e. $10^{-10}\, m \cdot s^{-2} = 0.01\, \mu Gal$.

Figure 5. *Polish gravity control network modernised in 2006-2008*

Both, accuracy and stability of SGs makes them extremely useful in geodynamics and in geodesy. In geodynamics they are used to investigate long-period tidal effects, to monitor polar motion, and to monitor tectonic processes, e.g. those preceding the earthquakes.

In geodesy they are used to control absolute gravimeters and to calibrate satellite gravity missions.

10 Needs for gravity determination at the beginning of XXI century

Increase of accuracy an efficiency of gravimetric measurements, especially in terms of absolute gravity determination substantially extended applications of gravity in geodesy and located precise gravity measurements among fundamental surveying techniques for geodynamics. Gravity is recently needed not only for

- reduction of geodetic and astronomic observations to the sea level,
- calculation of corrections to precise spirit levelling,
- interpolation of the deflections of the vertical,

- determination of the shape of the Earth,

as it took place for last 200 years, but also for

- Earth gravity field modelling, including geoid,
- Earth tides monitoring and modelling,
- determination of vertical crustal movement,
- calibration of space gravity missions,
- monitoring of temporal variations of the Earth gravity field,
- monitoring of polar motion,
- maintenance of integrated geodetic networks, e.g. European Combined Geodetic Network ECGN.

Fulfilling those needs requires

- establishment of sufficiently dense network of absolute gravity points,
- periodic re-survey of those points with absolute gravimeters every few years,
- participation in the comparison campaigns of absolute gravimeters,
- establishment and maintenance of a respective number of gravity stations continuously recording gravity,
- establishment and maintenance of appropriate gravimetric calibration baselines,
- continuous research to ensure appropriate gravimetric standards for geodesy and geodynamics.

11 The A10 absolute gravimeter for field survey

Works of Faller's team in the Micro-g LaCoste, Colorado, on incorporation of newest technology in the construction of free-fall gravimeters resulted in 2003 in the construction of the first portable ballistic gravimeter A10. Its accuracy is at the level of a few microgals that corresponds to uncertainty within the range of 10^{-8}g – 10^{-9}g. Although the A10 in terms of accuracy is comparable with best contemporary relative gravimeters the fact that it provides absolute gravity makes it superior. When using the A10 for the determination of gravity there is neither a need of long traverses of relative gravity survey nor a need of a link to gravity control; the results of survey can practically be obtained immediately in the field. Also no errors of gravity network propagate on the gravity determined with the A10. The big advantage of the A10 is the possibility of its use for field survey as well as its efficiency, i.e. 1 hour survey at a point is sufficient, while the survey with e.g. FG5 requires at least 24 hours. Gravity survey with the A10 is not only inexpensive but it is easy to repeat frequently, and, what is very important, it can be performed in practically one epoch on the large number stations.

By the end of 2011 there were about 25 A10 gravimeters manufactured. One of them, the A10-020, is since 2008 extensively investigated in terms of its operability, accuracy and repeatability by the team of the Institute of Geodesy and Cartography, Warsaw (Krynski and Roguski, 2009; Sekowski *et al.*, 2011) and used for the geodynamic research and modernisation of gravity control (e.g. Krynski *et al.*, 2010). The experience gained with the A10-020 indicates the urgent need to modify the concept of gravity control and modernise the existing gravity control networks. It also proves the usefulness of the A10 for monitoring geodynamic processes (Krynski and Sekowski, 2010).

12 Atomic absolute gravimeters

Both, research and results of experiments conducted in last years indicate that new generation of absolute gravimeters will also be based on free-fall principle, except a cloud of about 107 cold Rb atoms will be used instead of test body. During a free-fall a cloud of atoms crosses over three laser beams that first split the cloud onto two streams and then sets them together what causes interference. The phase shift between two arms of the interferometer, which is proportional to gravity is determined from the state of atoms on the output of the interferometer.

First stationary absolute cold atom gravimeter has been manufactured by SYRTE, Observatoire de Paris. It took part already in two comparison campaigns of absolute gravimeters: ICAG2009 in Sévres and ECAG2011 in Walferdange. Its internal accuracy is at the level of 10^{-9}g, i.e. $0.01\,\mu m \cdot s^{-2} = 1\,\mu Gal$.

In a few laboratories, including SYRTE, Observatoire de Paris, there are also advanced works on a mobile high-precision absolute gravimeter based on atom interferometry. The level of the internal acuracy of, for example, the Girafon gravimeter developed in ONERA, Palaiseau, is $3 \cdot 10^{-9}\,g$, i.e. $0.03\,\mu m \cdot s^{-2} = 3\,\mu Gal$, while of the gravimeter developed in AG Optische Metrologie, Humboldt Universität zu Berlin, is almost an order of magnitude better, i.e. $4 \cdot 10^{-10}\,g$, i.e. $0.004\,\mu m \cdot s^{-2} = 4\,\mu Gal$.

It should be noted that mobile atomic absolute gravimeters brake the canon of absolute gravity surveys to be static. The atomic technology allows to measure absolute gravity in motion as precisely as in a static mode. Thus the atomic absolute gravimeters can be used in shipborne an airborne gravimetry as well as in satellite gravity missions which will further revolutionize gravimetry.

13 On the concept of modern gravity control in a medium size country

Modern gravity control should fulfil the needs of contemporary geodesy and geodynamics considering temporal variations of the gravity field. Its concept should take into account and incorporate recent technological development, accuracy and reliability requirements, as well as assurance of its efficient maintenance.

The modern gravity control should thus consist of gravity stations surveyed only with the use of ballistic gravimeters. The stations could be classified into two groups. First group, consisting of fundamental stations located in buildings, would be surveyed possibly in one epoch with the stationary FG5-type gravimeters. The second group – let us call them base stations – would be surveyed within the extensive campaigns with portable A10-type gravimeters. The uncertainty level of gravity determined at fundamental stations would be $0.002 - 0.004\,mGal$ while – at base stations $0.004 - 0.008\,mGal$. The average distribution of fundamental stations is suggested one station in 10000 km^2, while base stations – one station in 1600 km^2. Location of the stations of the gravity control should fulfil the requirements ensuring appropriate quality of absolute gravity measurements and possibly ensure long-term lasting. All gravity control stations need a solid monumentation ensuring stability required for absolute gravity measurements and their repeatability.

Modern gravity control is not a network any longer. The spans between its stations are not expected to be surveyed with static gravimeters. Therefore, no traditional network adjustment is performed since no functional link of the gravity control stations by measurements exists. The role of the adjustment is somehow replaced by employing adequate tools of metrology (Krynski and Barlik, 2011). The gravity level of the gravity control will be determined by using ballistic gravimeters that participated in the international absolute gravity comparison campaigns. In addition, both FG5-type and A10-type gravimeters should participate in appropriate regional comparison campaigns of absolute gravimeters as well as in more frequent local comparison campaigns of only those gravimeters that are used to establish the gravity control.

To keep its standard gravity control must be regularly re-surveyed every few years. Besides, in the area covered with gravity control it would be beneficial to run a number of stations continuously recording gravity, equipped preferably with SGs.

The role of relative gravity survey in the establishment of modern gravity control becomes limited to the determination of vertical gravity gradient. This is, however, very important component of the gravity control that is used for the transfer of gravity from the height of the measurement with one ballistic gravimeter to the other as well as to the ground mark. An error in vertical gradient propagates very strongly on the transfer of gravity from one height to another. It easily extends the precision of contemporary ballistic gravimeters. Therefore an advanced technology and strategy of determining vertical gravity gradient is strongly recommended.

14 Summary and conclusions

Due to technological development reflected in precision and reliability of gravity survey the role of gravimetry in geodesy and geodynamics has continuously been growing, in particular in last hundred years. Simultaneously, the concepts and realization of reference system for gravity as well as national gravity control changed considerably. Recent availability of precise and reliable absolute gravimeters ensuring efficient gravity measurements in both, laboratory and field conditions, high precision superconducting gravimeters as well as space gravity missions provide unprecedented information on gravity field of the Earth in terms of accuracy and resolution as well as its temporal variations. Further development of gravimetry and its applicability for geodesy and geodynamics is expected in next decades.

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