3. GRAVITY FIELD MODELLING AND GRAVIMETRY

3.1. INTRODUCTION

This part of the Polish National Report on Geodesy is the quadrennial report of gravimetric works performed in Poland in a period from 1999 to 2002. It summarises investigations such as national gravity surveys, absolute and relative gravity measurements, non-tidal gravity changes monitoring, data handling and mapping, theoretical research on gravity field and modelling geoid and quasi-geoid for Poland, etc. Those activities were conducted mainly at the following research centres listed in an alphabetic order:

- Department of Geodesy and Geodynamics, Institute of Geodesy and Cartography in Warsaw;
- Department of Mining Surveying and Environmental Engineering, University of Mining and Metallurgy in Cracow;
- Department of Planetary Geodesy, Space Research Centre, Polish Academy of Sciences in Warsaw;
- Institute of Geodesy, University of Warmia and Mazury in Olsztyn;
- Institute of Geodesy and Geodetic Astronomy, Warsaw University of Technology.

The content of the chapter is based on the material prepared by Marcin Barlik, Jozef Beluch, Jan Krynski, Adam Lyszkowicz and Andrzej Sas-Uhrynowski.

The bibliography of the related works is given in references.

3.2. ABSOLUTE GRAVITY DETERMINATION

Study on portable ballistic gravimeter TBG was further advanced at the Institute of Geodesy and Cartography, Warsaw. Methods of estimation of calibration accuracy of the TBG were discussed (Zanimonskiy et al., 1999). The series of experiments conducted with low-cost TBG-95 portable gravimeter was used to the determination of optimal strategy of measurements that leads to gravity determination at the accuracy level of 10 μGal. It concerns a maximum internal auto-control together with a necessary external control. In particular, it has been demonstrated that the auto-seismic effect in rise-and-fall gravimeters can be reduced to the level of that in free-fall gravimeters by improving instrument's rigidity and implementing randomisation of disturbances (Zanimonskiy et al., 2000). The pressure level of 10^{-6} Torr in the ballistic chamber is usually considered as a basic requirement in the precise absolute gravimeters. The problem with the higher-pressure level in the ballistic chamber was investigated. It was shown that gravity can be determined with rise-and-fall instrument with 10 μGal accuracy by taking the measurements at different levels of residual pressure, e.g. between 0.1 Torr and 0.01 Torr, and at different parts of trajectory of rising and falling test-body. Thus the increase of residual pressure by 4 orders of magnitude may result in degrading gravity determination by one order of magnitude only. Some components of the strategy developed when experimenting with portable ballistic gravimeter are usable in improving absolute gravity survey of higher level of accuracy (Zanimonskiy et al., 2002).

The absolute rise and fall ZZG gravimeter, constructed at the Institute of Geodesy and Geodetic Astronomy of the Warsaw University of Technology, was used in 1999-2002 for absolute gravity survey at some stations of the Polish national gravimetric network.

It was also used as one of the absolute gravimeters in the international campaigns (Poland, Slovakia, Czech Republic, Hungary, Germany) (Zabek et al., 2002) as well as in the project on the establishment of the Polish-Slovak latitudinal gravimetric baseline Warsaw-Niedzica-Poprad-Modra Piesky (Bratislava). Periodic gravity variations at the Jozefoslaw Astro-Geodetic Observatory were investigated with use of repeated gravity measurements with ZZG gravimeter (Pachuta et al., 2001; Robertson et al., 2001).

ZZG gravimeter took part in gravity measurements conducted in the framework of EU/CEI project UNIGRACE (Unification of Gravity Systems in Central and Eastern Europe) (Sledzinski et al., 1999; Reinhart et al., 1999). The project was launched in 1997 as multipurpose interdisciplinary project and concluded in 2002. It consisted in establishing the absolute gravity stations covering the area from the Baltic Sea to Adriatic and the Black Sea and forming the frame for connection of all national gravimetric networks and providing the unified precise gravity frame in Central and Eastern Europe joined with the network of the Western Europe. The main aim of the Project UNIGRACE is to provide a reference gravity frame indispensable for unification of gravity systems existing in Central and Eastern European countries and for the definition of a unique height system. It contributes considerably to the determination of the geoid in Europe and for sea level variation studies. Ten absolute gravity intra-plate and seven tide gauge stations were measured in 12 countries: Austria, Bulgaria, Croatia, Czech Republic, Finland, Germany, Hungary, Italy, Poland, Romania, Slovakia, Slovenia. The gravity surveys were made by five absolute gravimeters from Austria, Finland, France, Germany and Poland (Zabek and Pachuta, 2000a; Robertson et al., 2001). Two observation campaigns of the UNIGRACE project have been successfully conducted in 1998/1999 and 2000/2001.
The project was realised under the umbrella of the Central European Initiative CEI WG Science and Technology Section C "Geodesy" and was financially supported by the European Commission from the INCO COPERNICUS Programme. The analyses of the precise gravity data of UNIGRACE campaigns indicate that there are considerable changes of the gravity at some absolute gravity stations. Those changes cannot be interpreted in terms of station displacements ground water level variations or atmospheric effects. Further investigation of the gravity time changes will be carried out.

3.3. NATIONAL SURVEYS OF GRAVITY

The new gravity control network for Poland was established in 1993-1998 (Sas-Uhrynowski et al., 1999a; Sas, 1999; Siporski, 1999; Sas-Uhrynowski et al., 2000). It contains 12 absolute gravity stations, at which 21 absolute gravity measurements, using 5 various ballistic gravimeters: FG5 No.101, FG5 No.107, JILAg-5, ZZG and IMGC, have been performed (Sas-Uhrynowski and Cisak, 2001). The first four gravimeters were applied for absolute gravity measurements in 1994-1998 at the station Borowa Gora. Borowa Gora station was accepted as the fundamental station of the network. Several results obtained have varied from the others even up to 30 μGal. Therefore the verification of the absolute measurements results was necessary. The verification was carried out by comparison of gravity differences (Δg) between the pairs of stations, obtained from absolute and relative measurements. Relative measurements were conducted between the absolute gravity stations by means of long-link method (150-350 km), using 4 LaCoste&Romberg gravimeters. The results of relative gravity measurements on 25 long spans have been used for the verification. The location spans against the gravity network is shown in Fig. 3.1.

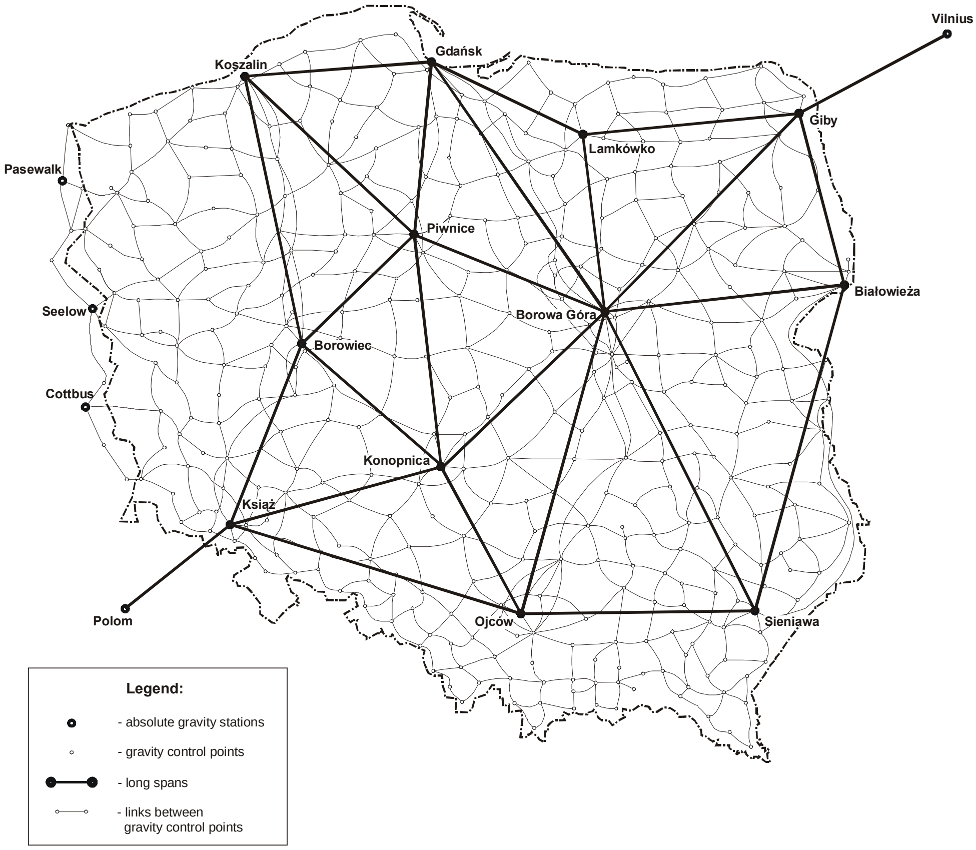

Fig. 3.1. Polish national gravity control network '99

The measurements at long spans have been conducted using simultaneously three LCR gravimeters. Each span was measured according to the A-B-A scheme, in three subsequent days. Twelve values of gravity, determined at 10 stations have been verified positively. They were obtained with JILAg-5 and both FG5 gravimeters. Both gravity and gravity differences were then adjusted. The rms errors of adjusted gravity did not exceed 4 μGal. The adjusted gravity values have been accepted as the national gravity standard of the zero order (Siporski et al., 2000; Sas-Uhrynowski, 2002). Then, the gravity differences at 685 links in a new gravity network have been adjusted, providing gravity values for 354 network stations. Gravity at those stations define a national gravity standard for practical use (Krynski et al., 2002). After adjustment, the rms of gravity at 97 % points does not exceed 10μGal. Mäkinen repeated the absolute gravity measurements at the station Borowa Gora in 2000, using the JILAg-5 gravimeter. The result obtained differs from the one of 1995 by 3μGal.

Each of 348 stations of POLREF network (a densification of EUREF-POL network that provides the ETRF reference for geodetic and surveying and mapping applications in Poland) as well as each of 554 stations of the military geodetic control WSSG was tied with two stations of the gravity control network using three LCR gravimeters. The measurements have been carried out twice, according to A-B B-A scheme. Gravity for each geodetic control point was individually adjusted. The similar gravity measurements and adjustments have been conducted to tie 33 stations of the Polish Geodynamic Network to the national gravity control.

The Institute of Geodesy and Cartography participated in 1998-2000 in establishing the Lithuanian Gravity Control Network. The Lithuanian gravity network has been tied with the

Polish one. The Polish team has measured gravity using four LCR gravimeters following the strategy applied in surveying Polish gravity control (Sas-Uhrynowski et al., 2002a).

The Institute of Geodesy and Cartography continued the co-operation with the Ukrainian Institute of Metrology in absolute gravity measurements, gravimetric metrology (Zanimonskiy et al., 1999a; Zanimonskiy et al., 1999b; Sas-Uhrynowski and Zanimonskiy, 1999a; 1999b), and terrain ballistic gravimeter (TBG) construction (Sas-Uhrynowski et al., 2001b).

The geodynamic profile about 230 km long, was established across the T-T zone in the South-East of Poland. The gravity and magnetic measurements have been carried out at six stations of the profile in three subsequent years. The results and the preliminary interpretation have been published (Krolikowski and Sas-Uhrynowski, 1999).

Within the framework of the geodynamic investigation projects, the regular gravity measurements on sub-monthly intervals at Borowa Gora Geophysical Observatory have been conducted (Zanimonskiy et al., 2000).

The original technology of calibration of static gravimeters by tilting method developed at the Institute of Geodesy and Geodetic Astronomy of the Warsaw University of Technology was applied for calibration of precise gravimeters for Polish enterprises that deal with geophysical prospecting (Pachuta et al., 2001; Sledzinski et al., 2001).

3.4. INVESTIGATIONS OF THE NON-TIDAL GRAVITY CHANGES

Periodic gravity surveys are carried out four times a year on the meridian baselines of the observatory of Jozefoslaw to investigate the time variations of the vertical (Barlik, 2000b). Data is interpreted with astronomical latitude and hydrological observations (Pachuta and Barlik, 2000). Gravimetric measurements on geodynamical traverses and networks are performed in the framework of different research projects, e.g. PIENINY, SUDETES (Barlik and Cacon, 2000; Barlik, 2000d), and GRYBOW (Barlik, 2000a) using LCR, SCINTREX CG-3M and Worden – Master gravimeters.

3.5. GEOID AND STUDY ON THE GRAVITY FIELD IN POLAND

Since 1993, Polish GPS users have available the models of quasigeoid for determination normal heights. The availability of additional gravity data to the Department of Planetary Geodesy made possible the to compute a new quasigeoid model for Poland named Quasi97b. The comparison of that model with GPS/levelling geoid heights has shown discrepancies in long to medium wavelengths. Therefore the empirical corrector surface was developed that relates the Quasi97 model to the reference system of GPS and levelling heights (Lyszkowicz, 2000). The advantage of such quasigeoid model is that it will support direct conversion between the ellipsoidal reference system and normal vertical datum, even if their reference are not consistent.

The gravimetric geoid recently computed in Department of Planetary Geodesy includes a number of short wavelength components. They are as expressed as high gradient bands or broad gradient zones on the map of geoid. The analysis showed that these bands and zones coincide more or less with seismically detected faults or fracture zones that dissect consolidated basement of Poland.

Gravity data in Poland was investigated using spectral analysis with the view of refining geoid estimation methods. The analysis was based on estimates of empirical covariance function and degree variances derived from local gravity observations. Models for the variance of geoid undulations are derived for test areas. Finally the resolution of gravity data required for a centimetre to decimetre accuracy level of geoid is estimated separately for marine, flat and mountainous areas (Lyszkowicz, 2002).

The project on the cm geoid in Poland, granted in 2002 to the Institute of Geodesy and Cartography, Warsaw, by Polish State Committee for Scientific Research, came into operational stage. Several research groups are involved in the project, namely Chair of Engineering Surveying, University of Warmia and Mazury in Olsztyn; Chair of Photogrammetry and Cartography, University of Warmia and Mazury in Olsztyn; Chair of Satellite Geodesy and Navigation, University of Warmia and Mazury in Olsztyn; Institute of Geodesy, University of Warmia and Mazury in Olsztyn; Institute of Geodesy and Cartography, Warsaw; Institute of Geodesy and Geodetic Astronomy, Warsaw University of Technology; State Institute of Geology, Warsaw.

In the first step of the project a qualitative and quantitative analysis of all available data, i.e. gravity data (terrestrial, sea-borne and air-borne), deflections of the vertical, GPS/levelling, altimetry, tide gauge, topographic data (DTM), crust density. Some supplementary control surveys will be conducted. The independent geoid models, i.e. gravimetric, astro-geodetic, GPS/levelling, using the uniformed data will be computed and their internal accuracy will be estimated. Finally a geoid model based on a combination of gravimetric, astro-geodetic, GPS/levelling data will be derived (Krynski, 2001). The project is in progress. Its completion is expected by the end of 2005.

Sensitivity and stability of recent gravimeters allow for detecting gravity variations with periods from a few hours to a few weeks. The method of spectral analysis with synchronous detecting using tidal model as a basic signal was developed for determining regular gravity variations of amplitudes up to the level of a few microgals that are correlated with tidal variations and station-dependent (Krynski and Zanimonskiy, 2000).

3.6. GRAVITY IN APPLIED SURVEYING

The concept of combining two surveying techniques for detecting mining extraction effects was elaborated in the Department of Mining Surveying and Environmental Engineering, University of Mining and Metallurgy in Cracow (Szczerbowski, 2001). It suggests the essential relationship between gravity anomalies and subsidence. The presented model is based on presumed correlation between the excavation geometry and the geometry of dilatancy of deformed space in rock massif. The geometric parameters describing size and location of excavation are in fact common factors for considered functions. The model of density changes was presumed. The purpose of the approach presented is to create a model of deformation based on gravimetric and positioning methods. Combination of a group of scientific methods is useful for

- getting more valuable parameters of excavation as a result of so called back analysis in the case abandoned extraction or uncontrolled solution mining,
- expansion of old anthropogenic or natural (resulted from suffosion or karst processes) excavations,
- monitoring of the stability of areas influenced by mining excavations,
- better prediction of surface damage.

References

Barlik M., (2000a): *On the contribution of the vertical gravity gradient anomalies to the separation between geoid and Molodensky's quasigeoid (basing on the example of the geodetic test field near Grybow)*, Reports on Geodesy, IG&GA WUT, No 2(50), 2000.

Barlik M., (2000b): *Determination of the separation between geoid and quasigeoid using vertical gravity gradient observations along the gravimetric baseline in the meridian of astro-geodetic Observatory of Warsaw University of Technology at Jozefoslaw*, Reports on Geodesy, IG&GA WUT, No 2(50), 2000.

Barlik M., (2000c): *Investigation of the local covariance function of vertical gravity gradient anomalies*, Reports on Geodesy, IG&GA WUT, No 2(50), 2000.

Barlik M., Cacon S., (2000): *Gravity changes observed in the Polish Part of Eastern Sudety Mountains and Fore-Sudetic Block in period 1992 – 1998*, EGRSE - International Journal of Exploration Geophysics, Remote Sensing and Environment, VI.2, Brno, 2000.

Barlik M., (2000d): *Gravimetric investigations of geodynamic phenomena in the East Sudety Mts. and Fore - Sudetic Block*, Reports on Geodesy, IG&GA WUT, No 7(53), 2000.

Krolikowski C., Sas-Uhrynowski A., (1999): *Zmiany czasowe sily ciezkosci i pola magnetycznego Ziemi w SE Polsce*, Przeglad Geologiczny, Vol. 47, No 1, pp. 79-86.

Krynski J., Sas-Uhrynowski A., Siporski L., (2002): *Verification of the Absolute Gravity Measurements in Poland*, Instrumentation and Metrology in Gravimetry Workshop, 28-30 October 2002, "Institut de Europe", Castle of Muensbach, Luxembourg (in press).

Krynski J., Zanimonskiy Y., (2000): *Regular Gravity Variations from the Analysis of Short Time Series of Data* (in Polish), Zeszyty Naukowe Akademii Rolniczej we Wroclawiu Nr 394, Geodezja i Urzadzenia Rolne XVII, Wydzial Melioracji i Inzynierii Srodowiska, Wroclaw, 2000, pp. 253-263.

Krynski, J., (2001): *Polish Geoid Project*, Presented at the NKG Working Group Meeting on Geoid, Satellite Geodesy and Geodynamics, 8-10 October, 2001, Hønefoss, Norway.

Lyszkowicz A., (2000): *Improvement of the Quasigeoid model in Poland by GPS and levelling data*, Artificial Satellites, Journal of Planetary Geodesy, Vol. 35, No 1, pp. 3-8.

Lyszkowicz A., (2002): *The analysis of gravity field data in view of sub decimetre geoid in Poland*, Proceeding of the 3rd Meeting of the International Gravity and Geoid Commission of IAG, August 26-30, 2002, Tessaloniki, Greece, Springer Verlag, IAG Symposia, (in press).

Pachuta A., Barlik M., (2000): *Corrections to the gravity and vertical gradient of gravity resulting from water level changes in artificial reservoirs*, Reports on Geodesy, IG&GA WUT, No 6(52), 2000.

Pachuta A., Barlik M., Walo J., (2001): *Computer Aided Calibration of the Static Gravity Meters*, Reports on Geodesy, IG&GA WUT, No 2(57), Warsaw, 2001.

Reinhart E., Richter B., Wilmes H., Sledzinski J., Marson I., Erker E., Ruess D., Mäkinen J., (1999): *UNIGRACE (Unification of Gravity Systems in Central and Eastern Europe). Preliminary results of the absolute gravity campaign 1998*, Reports on Geodesy, IG&GA WUT, No 4 (45), 1999.

Robertson L., Zabek Z., Pachuta A., et al., (2001): *Results from the Fifth International Comparison of Absolute Gravimeters*, ICAG97, Metrologia, 38/2001.

Rotanova N., Odincov S., Sas-Uhrynowski A., Welker E., (2000): *The magnetic anomaly field over Poland and adjacent regions by using MAGSAT satellite data*, Acta Geoph. Polonica, 2000, Vol. XLVII, No 2, pp. 224-240.

Sas A., (1999): *Analiza porownawcza nowej podstawowej osnowy grawimetrycznej kraju (POGK 97) z osnowa z lat 60*, Proceedings of the Institute of Geodesy and Cartography, t. XLVI, z. 98, pp. 51-58.

Sas-Uhrynowski A., Cisak M., Sas A., Siporski L., (1999a): *Zmodernizowana podstawowa osnowa grawimetryczna kraju (POGK 97)*, Proceedings of the Institute of Geodesy and Cartography, t. XLVI, z. 98, pp 41- 49.

Sas-Uhrynowski A., Welker E., Kasyanenko L., Demina I., (1999b): *Magnetic Maps of the Baltic Sea*, Technika Poszukiwan Geologicznych – Geosynoptyka i Geotermia, PAN, No 1, Proceedings of the 7th International Meeting of the Working Group – Neogeodynamica Baltica, UNESCO/IGCP Project No 346, Poland, pp. 94-95.

Sas-Uhrynowski A., Zanimonskiy Y., (1999a): *Field tests of the portable absolute gravimeter for remote application*, Proceedings of the Antarctic Geodesy Symposium 1999, Warsaw, SCAR Reports.

Sas-Uhrynowski A., Zanimonskiy Y., (1999b): *Relative and absolute gravimeters in large areas*, Proceedings of XXII IUGG General Assembly, Birmingham, Session JSG 14 /E/19-A3.

Sas-Uhrynowski A., Cisak M., Mroczek S., Sas A., Siporski L., (2000): *A new gravimetric control network for Poland*, Proceedings of the 6th Geodetic Millenium Meeting Poland-Italy, University of Mining and Metallurgy, Faculty of Mining Surveying and Environmental Engineering, Krakow, Poland, 29 June – 1 July 2000, Special Issue of Reports on Geodesy, Inst. of Geodesy and Geodetic Astronomy, Warsaw U. of Tech., No. 8(54), 2000, pp. 55-60.

Sas-Uhrynowski A., Cisak M., (2001): *Absolutne pomiary grawimetryczne w Polsce*, Proceedings of the Institute of Geodesy and Cartography, t. XLVIII, z. 103, pp. 193-216.

Sas-Uhrynowski A., Mroczek S., Karataev H., Karagodina O., (2001a): *Reflection of the recent depth tectonophysical processes in dynamics of the gravity and magnetic fields within Belarus*, Paper I. *Structure of the geophysical network for gravity field variation monitoring*, LITHOSPHERE, Institute of Geological Sciences of the Belarussian National Academy of Sciences, No 1(14), pp. 120-130.

Sas-Uhrynowski A., Zanimonskiy Y., Kostin A., (2001b): *Badanie i udoskonalenie polowego grawimetru balistycznego TBG*, Proceedings of the Institute of Geodesy and Cartography, t. XLVIII, z. 103, pp.83-114.

Sas-Uhrynowski A., (2002*): Absolute gravity measurements in Poland*, Proceedings of the Institute of Geodesy and Cartography, Monographic Series No 3, pp. 7-65.

Sas-Uhrynowski A., Mroczek S., Sas A., Petroskevicius P., Obuchowski R., Rimkus D., (2002a). *Establishment of Lithuanian National Gravimetric First Order Network*, Vilnius Gediminas Technical University, Geodesy and Cartography, Vol. XXVIII, No 3, pp. 75-82.

Siporski L., (1999): *Wyrownanie wynikow pomiarow nowej podstawowej osnowy grawimetrycznej kraju (POGK 97)*, Proceedings of the Institute of Geodesy and Cartography, t. XLVI, z. 98, pp. 59-64.

Siporski L., Mroczek S., Sas A., Sas-Uhrynowski A., (2000): *Krajowy wzorzec grawimetryczny 99*, Zeszyty Naukowe Akademii Rolniczej we Wroclawiu Nr 394, Geodezja i Urzadzenia Rolne XVII, Wydzial Melioracji i Inzynierii Srodowiska, Wroclaw, 2000, pp. 359-370.

Sledzinski J., Zabek Z., Barlik M., Pachuta A., (1999): *UNIGRACE National Progress Report of Poland*, Reports on Geodesy, No 2(43) 1999.

Sledzinski J., Barlik M., Kalinowska-Sledzinska B., (2001): *The metrologic services offered by the Institute of Geodesy and Geodetic Astronomy of the Warsaw University of Technology*, Proceedings of the Conference „Metrology in Geodesy", Department of Theoretical Geodesy of the Slovak University of Technology, Bratislava, 6 June 2001.

Szczerbowski Z., (2001): *Surface deformation and gravity changes - relationship conditions of exploited rock mass*, Instytut Gospodarki Surowcami Mineralnymi i Energia PAN, Biblioteka Szkoly Eksploatacji Podziemnej, Seria z Perlikiem, No 4, Krakow, pp. 3–107.

Zabek Z., Pachuta A., (2000a): *Absolute measurements with Polish ballistic gravimeter*, Workshop on High Precision Gravity Measurements with Application to Geodynamics and Second GGP Workshop, Walferdange, Luxembourg, 24-26 March 1999, Ed. by B. Ducarme and J. Barthelemy, Luxembourg, 2000.

Zabek Z., Pachuta A., (2000b): *Time variations of the gravity at the UNIGRACE station Jozefoslaw*, Reports on Geodesy, IG&GA WUT, No 6(52), 2000.

Zabek Z., Kielek W., Knap T., (2002): *Long Period Earth Gravity Changes at Main Tectonic Units of Poland's Territory*, Reports on Geodesy, IG&GA WUT, No 1(61), 2002.

Zanimonskiy Y., Sas-Uhrynowski A., Siporski L., (1999a): *Gosudarstvennaia gravimietritcheskaia set – nacionalnyi etalon uskorenia sily tiazhesti*, Proceedings of the 2nd International Scientific-Technical Conference "Metrology – 99", Kharkov Institute of Metrology, Kharkov, Ukraine, 5-7 September 1999, pp. 214-216.

Zanimonskiy Y., Krynski J., Sas-Uhrynowski A., Cisak J., (1999b): *Estimation of Calibration Accuracy of the Portable Ballistic Gravimeter* (in Russian), Proceedings of the 2nd International Scientific-Technical Conference "Metrology – 99", Kharkov Institute of Metrology, Kharkov, Ukraine, 5-7 September 1999, pp. 217-222.

Zanimonskiy Y., Krynski J., Sas-Uhrynowski A., Cisak J., (2000): *First Results of Regular Gravity Measurements on Sub-Monthly Intervals at Borowa Gora Geodetic-Geophysical Observatory*, Proceedings of the Workshop on High Precision Gravity Measurements with Application to Geodynamics and Second Global Geodynamic Project Workshop, March 24-26, 1999, Luxemburg, Cahiers du Centre Europeen de Geodynamique et de Seismologie, Vol. 17, pp. 239-246.

Zanimonskiy Y.M., Krynski J., Nagornyi V.D., Sas-Uhrynowski A., (2002): *On the Optimal Measuring Strategy for Ballistic Gravimeter*, Proceedings of the Instrumentation and Metrology in Gravimetry Workshop, 28-30 October 2002, "Institut de Europe", Castle of Muensbach, Luxembourg (in press).