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Review article

GEODETIC AND GEODYNAMIC STUDIES AT DEPARTMENT OF GEODESY AND GEODETIC ASTRONOMY WUT

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Abstract

The article presents current issues and research work conducted in the Department of Geodesy and Geodetic Astronomy at the Faculty of Geodesy and Cartography at Warsaw University of Technology. It contains the most important directions of research in the fields of physical geodesy, satellite measurement techniques, GNSS meteorology, geodynamic studies, electronic measurement techniques and terrain information systems.

Keywords: physical geodesy, satellite measurement techniques, GNSS meteorology, geodynamic studies

1. Introduction

The Department of Geodesy and Geodetic Astronomy is one of five scientific and educational units of the Faculty of Geodesy and Cartography at Warsaw University of Technology. The history of the department goes back to 1922 when the Department of Surveying I was founded under the guidance of professor Edward Warchałowski at the then Faculty of Surveying. In subsequent years, the Department of Practical Astronomy was founded, which was headed by Felicjan Kępiński (1924/1925). The activity of the Faculty was interrupted by World War II. However, Warsaw University of Technology and the Geodetic Department resumed their operation immediately after the end of the war, that is as early as in the academic year 1945/1946. The Department of Higher Geodesy was soon joined by the Department of Geodetic Astronomy and the Department of Adjustment Calculus and Geodetic Calculations. During the subsequent reorganisations, the Institute of Geodesy and Geodetic Astronomy was formed from the merger of the three departments. Finally in 2008, the Department of Geodesy and Geodetic Astronomy was created following the reorganisation of the entire university.

Research conducted by the staff of the department has included and continues to include, first of all, issues related to definition and implementation of reference systems. The scientific achievements related to the design, establishing and levelling of basic geodetic control networks made it possible for the staff to play an important role in international scientific conferences. An important role in these studies was played by long-term astrometric observations conducted in the Astro-Geodetic Observatory in Józefosław.

It should be emphasised that the research conducted in the department is part of the mainstream of international scientific work in the field of geodesy. Noteworthy is the fact that a little more than a decade after World War II – i.e. in 1959 – the department staff performed the first gravimetric measurements with stations in Antarctica. This article presents scientific work currently done by the department staff in the field of: physical geodesy (see section 2), satellite measurement techniques (see section 3), GNSS meteorology (see section 4), geodynamic studies (see section 5), electronic measurement techniques (see section 6) and terrain information systems (see section 7).

2. Physical geodesy research

One of the main areas of research conducted by the Department of Geodesy and Geodetic Astronomy includes problems in the field of physical geodesy and geodetic gravimetry in several key areas of interest: absolute and relative gravimetry, the modelling of the Earth's gravity field as well as tidal gravimetric measurements and their application in geodynamic studies.

2.1. Research on changes in the absolute value of gravity

Research on changes in the gravity with the use of absolute gravimetric measurements has been carried out by the department since the early 1990s. This is related to the experiments resulting form the research conducted by Professor Zbigniew Ząbek in relation to the construction of the first Polish ballistic gravimeter ZZG (Ząbek, 1996; Ząbek et al., 2004). This gravimeter has been used to conduct research on the variability of the gravity field at the station in Józefosław, whose contemporary analysis has been carried out in the work (Olszak, 2011), to establish the National Gravimetric Control Network (Sas-Uhrynowski, 2002) and in the international project UNIGRACE, whose aim was to unify absolute measurements performed by different types of absolute instruments.

Since 2005, the department has had a ballistic gravimeter FG-5 No. 230, which has been used for scientific projects and implementation work, such as:

a) "Study of long-term changes in the absolute intensity of the force of gravity on the major tectonic units in the territory of Poland from 2006 to 2009" headed by Prof. Marcin Barlik, as part of which geodynamic studies were started that included monitoring changes in the absolute value of intensity of the Earth's gravity force at the Astro-Geodetic Observatory of Warsaw University of Technology in Józefosław near Warsaw and four stations located on the main tectonic units in the territory of Poland (Lamkówko, Giby, Ojców and Borowiec) (Barlik et al., 2009);
b) "Unified gravimetric reference frame for Polish GNSS stations and geodynamic test fields" led by Janusz Walo, PhD (Walo, 2010). The main objective of the project was to establish a unified and accurate gravimetric reference frame throughout the country for Polish permanent GNSS stations and geodynamic test fields. In 2007 and 2008, as part of this project the absolute value of the gravitational acceleration was established at six stations located near IGS/EPN permanent stations and at seven stations located

within two geodynamic test fields: the Pieniny Test Field (3 points) and the Sudeten Network (4 points).

c) Since 2006, research has been conducted to extend the structure of the Polish gravimetric control points. The first projects were completed the network structure from the early 1990s and redefined the structure of gravimetric bases so that they could be based on absolute points (Barlik et al., 2010). The work resulted in the creation of the structure of the basic gravimetric control network of the country in accordance with the requirements set by the IAG and the establishing two calibration databases that met the accuracy and infrastructural requirements related to the application of the most accurate relative gravimeters (Barlik et al., 2008).
d) In 2011, the concept of comprehensive modernisation of the gravity control was introduced in cooperation with the Institute of Geodesy and Cartography, which involved its establishment only with absolute measurements (Krynski et al., 2013). The authorities of the Head Office of Geodesy and Cartography approved the joint project, which was presented at the end of 2001, and its implementation was commenced in 2014 (Barlik, Krynski, Olszak, Cisak, et al., 2011).
e) The work on modernisation and establishment of the fundamental gravity control network was completed in 2014. The works included: making a measurement of the absolute value of the acceleration at 21 points of the fundamental control network, re-development of the absolute observations made between 2006 and 2008 at eight points of the modernised gravity control network, the measurement of the vertical gradient at all the 29 points of the modernised basic fundamental gravity control network.

It is very important for all the research on the determination of the absolute value of the gravitational acceleration to ensure a unified gravity reference level for the obtained results and measurement consistency when measurements are made using multiple absolute gravity models or types. This is a very important element of metrological consistency assurance for the observations of the absolute value of gravitational acceleration, which determines the interpretation possibilities of this research method. The identification of the gravitational acceleration by a ballistic gravimeter FG-5 is done in SI system (Systeme International d'Unites) that is related to the laser wavelength (expressed in meters) and the clock frequency (expressed in Hertz). The value of the acceleration, obtained based on the equation of path, is determined in $\mathrm{m\,s^{-2}}$. Meeting the metrological consistency of the absolute observations performed by different ballistic instruments is conditioned by:

a) The participation in international calibration campaigns: RCAG, ECAG or ICAG (every two years);
b) The annual comparison within the local calibration campaign with an absolute gravimeter participating in the EURAMET project;
c) The annual calibration of the length standard (a helium-neon laser with iodine stabilisation) and the frequency standard (a rubidium clock);
d) Periodic (at least twice a year) local comparison campaigns consisting in simultaneous measurements of the gravitational acceleration by means of a field gravimeter A10 and gravimeter FG5 used in the measurements of the fundamental control network in observatories adapted for this very purpose – this is also a reference to linking the gravitational acceleration at base points with the gravitational acceleration at fundamental points of the gravity control network;
e) Periodic, monthly observations of the acceleration values at a selected point.

Fig. 1. Local absolute gravimeter calibration meeting in Józefosław (November 2014)

For the purposes of the project of modernisation of the base and fundamental networks, the above-mentioned requirements were achieved through:

a) the participation of the ballistic gravimeter FG5 No. 230 and gravimeter A10 No. 20 in the ICAG2011 campaign, together with all the ballistic gravimeters participating in the Euramet project;
b) the dual local comparison of the gravimeter FG5 No. 230 with the gravimeter A10 No. 20, performed in 2012 and 2013 in the Observatory in Borowa Góra during the implementation of the basic gravity control network modernisation project;
c) the calibration campaign in November 2014, which made it possible to compare the gravimeter FG5 No. 230 with gravimeter A10 No. 20 in the Observatory in Józefosław (Fig. 1) during the implementation of the fundamental gravity control network modernisation project;
d) the calibration of the time and frequency standard for gravimeter FG5, conducted in the Micro-g laboratory (USA) in July 2014;
e) the local comparison campaign performed at the Laboratory of the Table Mountain Gravity Observatory (USA) in July 2014;
f) the performance of regular gravimetric observations at a station in the Astro-Geodetic Observatory in Józefosław at monthly intervals at least (see item 2.2);
g) the participation in the local calibration campaign of the gravimeter FG5 in Wettzell and Pecný in February 2015.

This assignment, completed in cooperation with the Central Office of Measures, the Head Office of Geodesy and Cartography and the Institute of Geodesy and Cartography, introduces new technical standards in an era in which there are modern methods of implementation of control networks through absolute observations only.

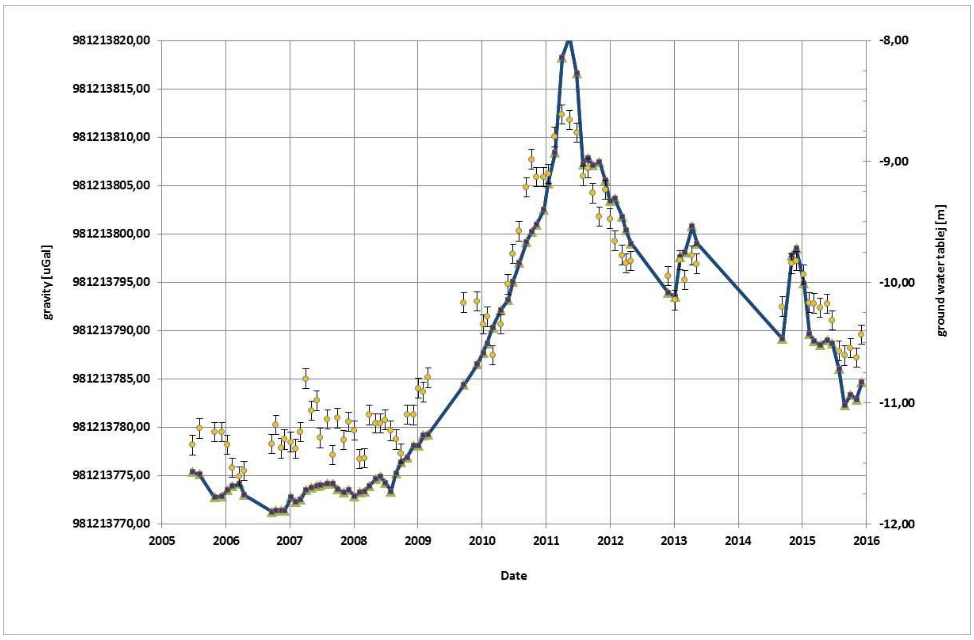

Fig. 2. The gravity values measured within 2005-2014 in Józefosław

2.2. Research on changes in the absolute value of the gravity in Józefosław

The research on changes in the absolute value of the gravitational acceleration at a point located at the Gravimetric Laboratory of the Astro-Geodetic Observatory in Józefosław has been conducted since July 2005. In 2006, the measurement pole was rebuilt so as to enable synchronous measurements with up to four meters.

The observatory has a 10-year observation series of "quasi-permanent" determinations that is conducted at approx. 1-month intervals and is unique in Poland. The determinations are made using the gravimeter FG5 No. 230 manufactured by Micro-g Solutions Inc. This instrument enables determination based on one-day observations of the intensity of gravity with the average error of $2 \times 10^{-8}\,\mathrm{m\,s^{-2}}$ (2 µGal). The gravimeter uses the free fall of the test mass (retro-reflector) in a vacuum vessel. The observations are made on the basis of the same regime for the observation session and the development of results – each observation session is performed within a daily cycle that includes at least 24 observation series. This is an extremely valuable research material of causes and interpretation of changes in the absolute value of the gravitational acceleration.

Until December 2015, nearly a hundred such observations were made, which is the longest series of observations of this type in Poland. Figure 2 shows the results since the start of the observation cycle.

In addition to absolute and relative gravimetric observations, the laboratory performs supplementary observations that monitor the change in the environmental conditions around the gravimetric stations. The elements of this type, used for the analyses related to the use of gravimetric measurements, include the measurement of ground water level (based on a piezometer reading), soil moisture around the station (measurements around the observation station by means of ML-1 Theta Probe) and atmospheric pressure.

The absolute gravimeter FG5 is used also indirectly for the interpretation of results of tidal observations conducted by the Gravimetric Laboratory with the LaCoste&Romberg spring gravimeter, model ET26 (see item 2.3). Its function within this element consists in annual synchronous measurements to determine tidal gravimeter scale (unit) calibrations (Rajner & Olszak, 2010). The calibration results show that the 24-hour session (that is about

24 hourly measurement series by means of the gravimeter FG5) is enough to get sufficient accuracy for gravimetric work.

In 2015, a detailed analysis of the impact of the selection of hydrological models was conducted based on GLDAS, WGHM and GRACE RL05. The analysis pointed to slight differences between models in terms of the magnitude of the gravitational effect (0.3 µGal) determined on their basis. The results were correlated with the observed changes in the gravitational acceleration resulting from all possible time series of changes in the absolute value of g in the territory of Poland. Thus, with the exception of the globally variable effect, it was possible to capture the changes in the acceleration resulting from the global environmental factors, pointing to their interpretation for the significance of the hydro-geological monitoring.

2.3. Tidal gravimetric measurements and their application in geodynamic studies

The Gravimetric Laboratory in Józefosław has a LaCoste-Romberg spring gravimeter, model ET (serial number 26, referred to as LCR in this article). It is a special model designed for observations of the Earth tides (ET is short for Earth tides). The continuous measurement encompasses the changes in the gravitational acceleration. It is important to emphasise the obvious fact that the instrument does not differentiate between the sources of the gravitational acceleration changes, and thus registers the resultant value of the impact of all geophysical and geodynamic phenomena. Therefore, it is important to develop careful initial observations and remove discontinuities, noise and violent phenomena, such as earthquakes. For more information about this instrument, gravimetric measurements, auxiliary measurements and data cleansing, see the work (Rajner, 2009, 2010a).

The main purpose of the gravimeter is to determine Earth tides. These are various effects caused by a differential gravitational interaction of celestial bodies. Given the nature of these phenomena, the total effect can be shown as a composition of multiple simple harmonic expressions, whose arguments depend only on a few basic frequencies. These are tidal waves. These waves are grouped into bands in the area of low frequencies (fortnightly, monthly and yearly periods and constant expressions) as well as in diurnal and semi-diurnal bands and subsequent multiples of cycles per day.

In fact, Fourier harmonic analysis is of less importance in the study of tides, where the frequency of tidal waves (resulting from the astronomical phenomena) are very well known. In this case, we use the Method of Least Squares, which also makes it possible to determine amplitudes and phase shifts of tidal waves. Thus, the main result is the identification of gravimetric factors and phase delays of the main groups of tidal waves. Figure 3 shows examples of such determination and the compliance with the Wahr-Dehant terrestrial tide model. In many cases, the discrepancies from the model can be explained by the presence of different geodynamic factors (see subsequent subsections).

The analysis of observations of the Earth tides performed by means of a spring gravimeter is also used for the study of geodynamic phenomena such as:

a) The examination of the indirect impact of ocean tides. Despite a considerable distance from the oceans, Józefosław makes it possible to observe the indirect effects associated with the deformations of the Earth's crust due to the varying load on the bottom resulting from ocean tides. This effect has been examined thoroughly and the results can be found in the work Rajner (2010c). It turns out that the OTL effect is the greatest for a M_2 tidal wave and the values of this effect can be as high as one µGal. This is a small value, but this magnitude is very clear in the case of the development of long time series.

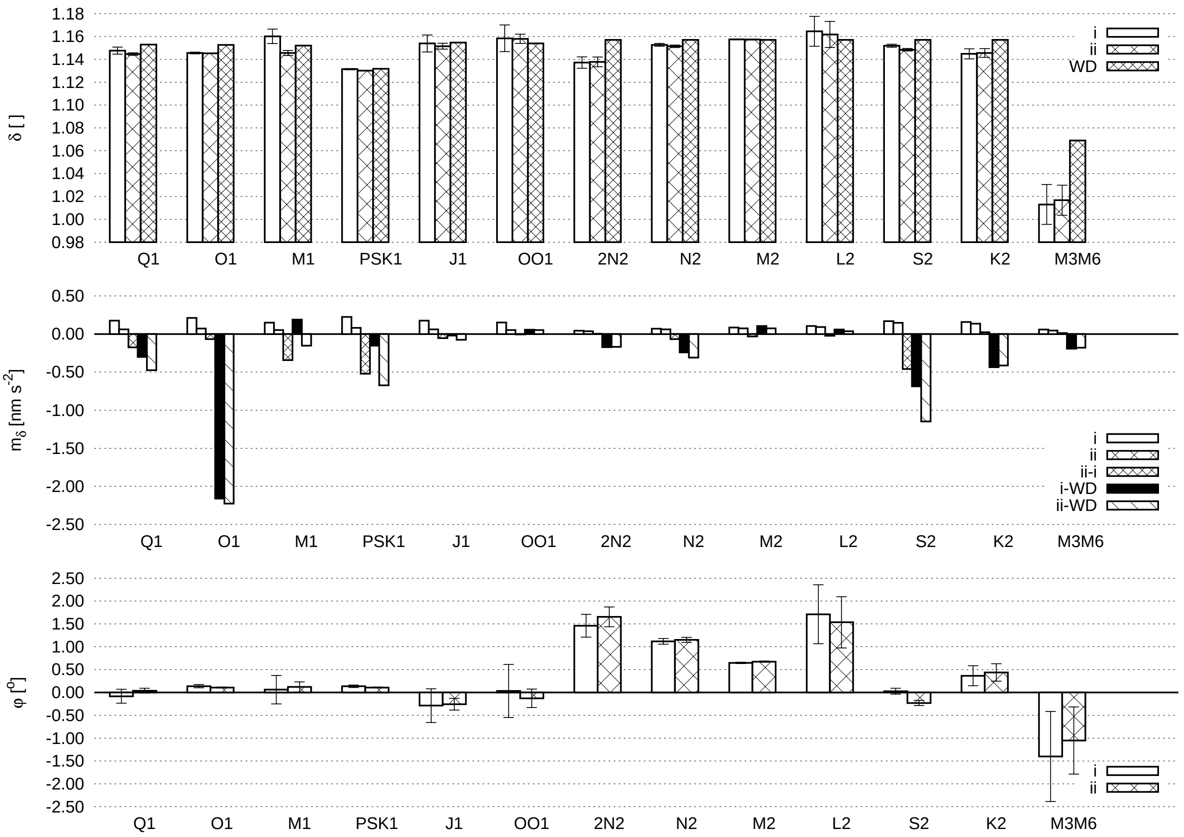

Fig. 3. Determined gravimetric factors and phases for main tidal constituent, without (i) and with (ii) barometric pressure as auxiliary data, and comparison do Wahr-Dehant (WD) tidal model

b) The determination of the period of free nutation of the Earth's core. A very interesting possibility resulting from precise determination of gravimetric factor values is the ability to determine the period and quality factor of the phenomenon of free core nutation (FCN). The presence of the liquid core causes a resonance and hence a subtle deviation in the gravimetric factors from the model values for the 24-hour tides. It should be noted that gravimetry, together with the VLBI technique, is the only method that makes it possible to examine the phenomenon described and provides an example where the geodesic methods have an advantage over seismic methods in the examination of deep layers of the Earth. Our research has been presented at the General Assembly of the European Geosciences Union (Rajner & Brzeziński, 2012). In the case of our observations, the value of the free core nutation period was 430 stellar days, which is in line with other gravimetric determinations as well as those coming from the VLBI observations. The obtained value of Q factor (approx. 1000) is much smaller than those from space observations, but it confirms the accuracy associated with the fact that gravimetric methods usually show much lower, probably underestimated Q factor values.

c) The study of the Earth's free oscillations. Another subject of gravimetric examinations that can compete with geophysical methods – mainly with low-frequency seismographs – is the free oscillations of the Earth. As a result of earthquakes, vibrations of the Earth occur with some specific frequencies that are dependent on the structure of the Earth. They are clearly visible in the seismic measurements. However, superconducting gravimeters have an advantage in the case of long-term fundamental ones. It turns out

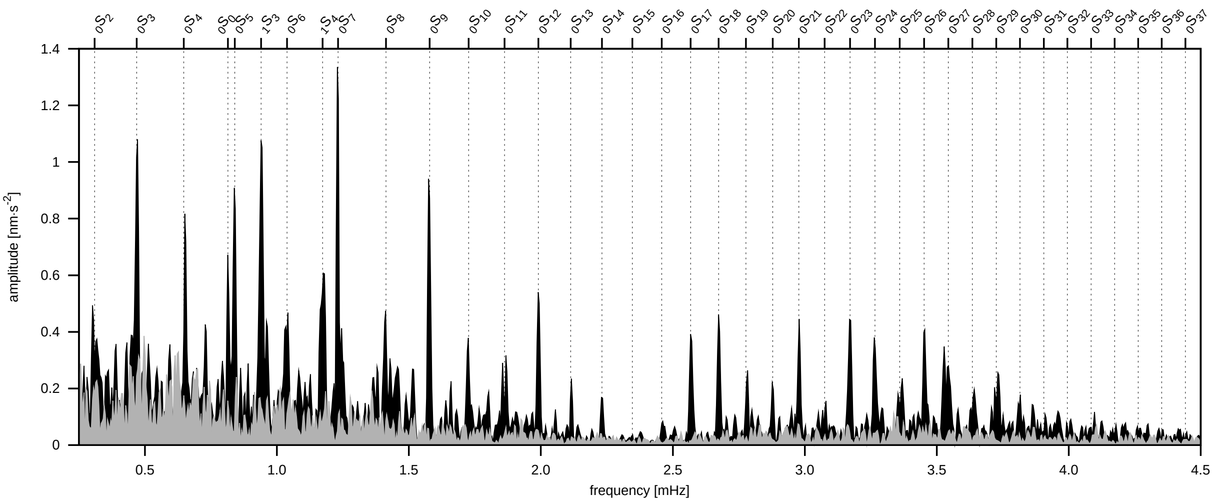

Fig. 4. Spherical normal modes determined after 2010 Chilean Earthquake, grey colors shows usual noise background

that these vibrations are also significant and clear in tidal observations using a spring gravimeter in the case of strong earthquakes. The results of our research are available in the article (Rajner & Rogowski, 2011). Figure 4 shows the identified spheroidal modes.

d) Examination of the effect of the atmosphere on changes in the gravitational acceleration. An important research problem where observations from gravimeters in Józefosław were used was the problem of determination of the effect of the atmosphere on gravity measurements. The work took into account the complex physical nature of this phenomena, the gravitational effects and those related to the indirect impact resulting from the deformation of the Earth's crust. These considerations were included in the doctoral dissertation (Rajner, 2014). The paper indicated that for the most accurate ballistic gravimeters and superconducting gravimeters, it is necessary to take into account the actual distribution of the atmospheric masses. Detailed analyses are included in the cited dissertation. However, in order to present the significance of this effect, we will note only that seasonal differences related to changes in mass distribution in the atmosphere that do not affect the surface pressure changes cause differences of 2 µGals to 3 µGals.

To sum up, one can note that despite the fact modern spring gravimeters lost some of their importance and cannot compete with the superconducting gravimetry, they still are a source of relevant information in the context of geophysical and geodynamic interpretations. In addition to the scientific works cited herein, there were several cross-section papers within the research on tidal gravimetry that gave a general overview of the possibilities and application of stationary observations using a spring gravimeter (Rajner, 2010b, 2013; Rogowski et al., 2010; Barlik, Rajner, & Olszak, 2011).

2.4. Other research using the Earth's gravity field

In addition to the works with the application of absolute gravimetric measurements, research is conducted that is related to the inclusion of geopotential models into tasks related to geoid modelling and definition of reference systems for altitude measurements. In this type of tasks, one should point out:

a) the use of geopotential models to determine system corrections in levelling;
b) levelling gravimetric networks in various tidal systems;

c) analysis of sources for obtaining gravimetric data for reduction of geodetic observations;
d) geoid (quasi-geoid) model study in the territory of Poland;
e) application of the European model of gravimetric geoid EGG08.

The most important works relate to the analyses of sources for obtaining gravimetric data for the reduction of geodetic observations – it is necessary to use the knowledge of gravity field parameters in the process of reduction of astronomical coordinates, vertical deviation, astronomical azimuth and linear measurements. Also the process of preparing the levelling network necessitates collection of such information to calculate the normal correction. Source are understood to be direct measurements, a possibility of interpolating anomalies from the existing gravimetric data sets and calculating them based on geopotential models. The study included field data, the data from the Polish Geological Institute used to interpolate anomalies and the data from the Earth Gravitational Model 2008 (EGM2008) in its full form and in the form cutted off to the 360th degree and order of the polynomial of harmonic coefficients. It was found it is possible to replace the measurement data with the data generated from the geopotential model for 90% of the area of Poland while maintaining the accuracy required by the Polish technical standards. For mountain areas, it is necessary to use the elements of the natural gravity field determined only through direct measurements (Kalinczuk, 2009; Jackiewicz, 2012).

Another important task that corresponds to the new challenges posed by the new definition of the national spatial reference system is the application of the model of the European gravimetric geoid EGG08. Along with the harmonisation of the reference level for the vertical control networks that is carried out in Poland through the implementation of the vertical reference frame PL-EVRF2007-NH, the quasi-geoid surface model should be changed to match the new reference level. The unification of the control networks, performed at the European scale, requires also a supralocal approach to the problem of reference surface modelling used for satellite levelling. At the continent scale, a model of the European Gravimetric Quasi-Geoid is being created – the current edition being from 2008 (Denker, 2013). This model is based solely on the approach of determining the figure of the Earth based on gravimetric data. Using a quasi-geoid model developed in such a way – without deformation caused by fitting it into the identified height anomalies on the satellite-levelling points – allows for functioning of the gravimetric quasi-geoid model as a tool for detection and control of the quality of the networks established by GNSS methods related to the vertical control network. Model EGG2008 was subjected to a series of comparative analyses of intervals identified at EUVN points and ASG-EUPOS network ex-centres, which form the basis for estimation of the absolute accuracy of this model in the territory of Poland. A proposal was also prepared for the application of gravimetric quasi-geoid model in the practical geodetic work in addition to the analysis of the possibility of implementing the European geoid model – such a concept that will not change or deform the gravimetric definition of the reference surface, which is valuable from the viewpoint of the independence from the satellite-levelling network errors (Piętka, 2014).

3. Research on satellite measurement techniques

The research on satellite measurement techniques conducted by the Department of Geodesy and Geodesic Astronomy focuses on the problems related to the development of observations as part of the EPN network Analysis Centre, the improvement of the GNSS positioning algorithms and the testing of GNSS measuring sets.

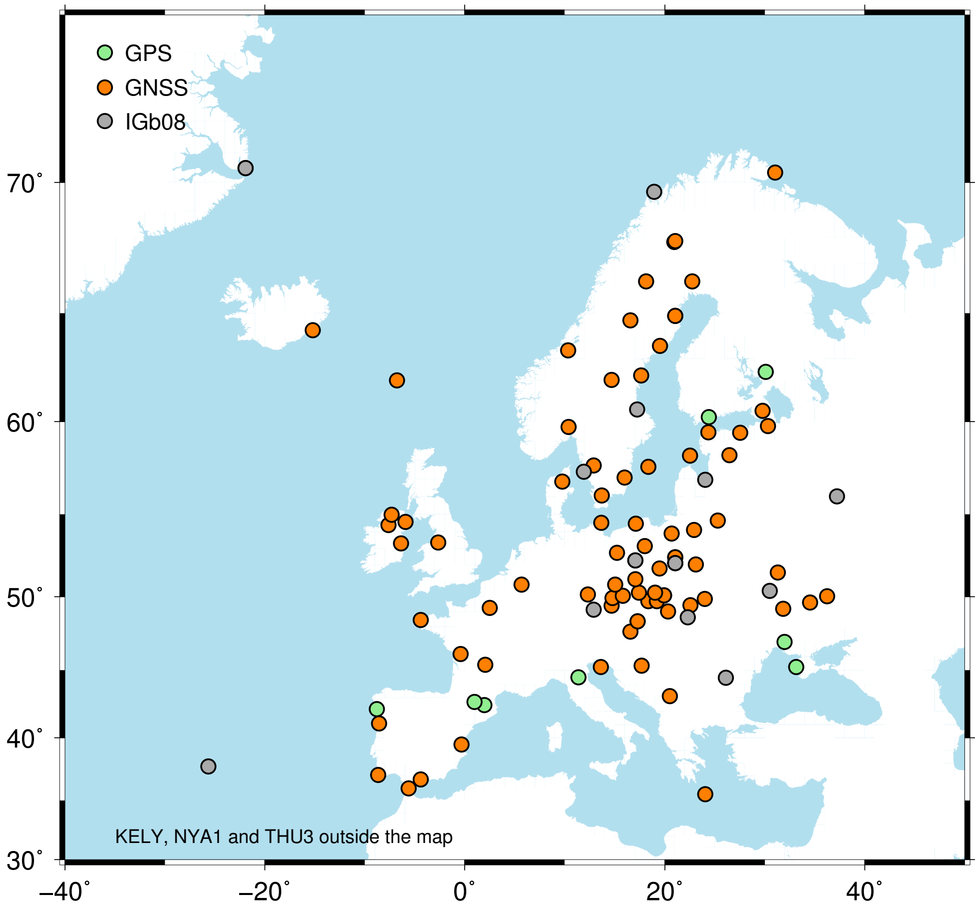

Fig. 5. EPN subnetwork processed by WUT AC at the end of 2015

3.1. GNSS data processing at WUT EPN Analysis Centre

Since 1996, Department of Geodesy and Geodetic Astronomy of the Warsaw University of Technology (WUT) has been processing GNSS data as the EUREF Analysis Centre. EUREF is a regional reference frame subcomission for Europe which is part of the Commision 1 „Reference frames" of the International Association of Geodesy. EUREF deals with the definition, realization and maintenance of European geodetic reference frames, e.g. ETRS89. ETRS89 is realized and maintained through the EUREF Permanent Network (EPN), a network of about 280 continuously operating GNSS reference stations. GNSS data collected by EPN stations are regularly processed by 16 EPN Analysis Centres (AC) and each AC processes a different subnetwork of stations. Station position solutions of the EPN ACs are combined into one official EUREF solution by the Analysis Combination Centre (ACC). Since 2014, the EPN ACC tasks have been done by the consortium of the Military University of Technology and the Warsaw University of Technology.

WUT analysis centre contributes to EUREF with final (weekly and daily) and rapid (daily) GNSS solutions of its subnetwork (Liwosz, 2015a). Final solutions (station positions and troposphere) are generated every week using final products of the International GNSS Service (IGS) during data processing, while rapid solutions (station positions only) are generated every day in a fully automated process using IGS rapid products. GNSS data are processed using Bernese GNSS Software 5.2 (Dach et al., 2015). WUT subnetwork currently consists of about 100 EPN stations (Fig. 5) and almost 90% of stations track both GPS and GLONASS satellites. WUT solutions, i.e., station coordinates in SINEX format and zenith tropospheric delays, are available from the EPN data centers: BKG (`ftp://igs.bkg.bund.`

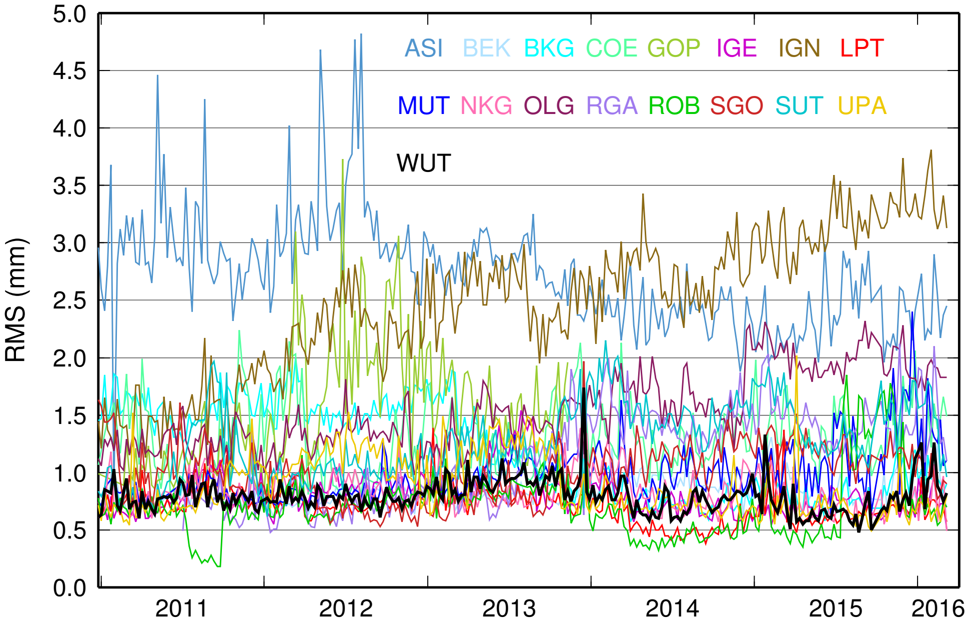

Fig. 6. RMS of position residuals after Helmert transformation between each EPN AC weekly solution and the combined weekly solution. Thicker black line shows RMS values for WUT analysis centre

`de/EUREF/products`) and EPN (`ftp.epncb.oma.be/epncb/product/clusters`). Figure 6 shows RMS values of the position residuals after Helmert transformation between all EPN AC weekly solutions, and the combined weekly solution generated by the EPN ACC during last five years; RMS values for WUT analysis centre are shown by a thick black line.

Apart from above regular contributions, in years 2010-2011 WUT also participated in EPN Reprocessing 1 project, which aimed at reanalysing of all historical EPN GNSS data (1996-2006) in a consistent way using latest models and processing strategies (Liwosz et al., 2010).

In addition, WUT AC has been testing new analysis options and their effect on GNSS results of the regional network. This includes, e.g., testing the effect of using GLONASS-specific receiver antenna calibrations for GLONASS observations (Liwosz, 2013), inclusion of non-tidal loading effects, or the usage of Vienna Mapping Function versus Global Mapping Function for troposphere modelling (Liwosz, 2015a, 2015b).

Other activities of the WUT analysis centre include collaboration with Polish Head Office of Geodesy and Cartography (GUGiK). In 2011 WUT processed observations of Polish national GNSS reference network and created a new realization of ETRS89 for Poland called PL-ETRF2000 (Liwosz & Rogowski, 2012). The final solution included about 700 permanent and epoch GPS points, which were observed in two measurement campaigns (in 2008 and in 2010/2011). In 2015, WUT AC together with GUGiK reprocessed continuous 3.7-year GNSS data (2011.3-2015.0) from Polish national GNSS network (called ASG-EUPOS) and created an updated realization of ETRS89 for Poland (Liwosz & Ryczywolski, 2015; Ryczywolski & Liwosz, 2015). The new solution was accepted as Class A standard by EUREF Technical Working Group on EUREF Symposium in Leipzig ("EUREF 2015 Resolutions," 2015).

3.2. Stochastic modelling of GNSS observations

One of the research issues undertaken as part of the scientific work conducted by the Department of Geodesy and Geodetic Astronomy included studies related to the improvement of mathematical model for determining positions based on Global Navigation Satellite Systems (GNSS). This model consists of a deterministic description, which defines the functional relationships between the GNSS observations and unknown parameters, and a stochastic description, which defines the assumptions about the observation accuracy characteristics (observation precision and correlations). The functional description of the GNSS positioning models over the last few decades has been the subject of detailed study and its mathematical definition and resolution algorithm have been accurately defined and described in the literature, depending on the method of parametrisation of observations (Geometry-Based and Geometry-Free Models), taking into account the effect of measurement errors related primarily to signal propagation in the atmosphere (Fixed, Float and Weighted Models) and the method of forming the observations in the form of their differences (Zero, Single and Double Difference Models). The stochastic description of GNSS positioning models is much harder to define and requires further refinement. Its correct definition is crucial for both the accuracy of the estimated parameters in the positioning model (the unknown position, the tropospheric delay parameters) and for the assessment of the confidence level of the results of this estimation. Of particular importance in this regard is the process of resolution of the carrier phase ambiguity, which consists of two stages: ambiguity estimation and its validation. The stochastic model is very important in this process because it defines the shape and size of the search space at the ambiguity estimation stage and affects the level of significance and the strength of the validation test and is used for the definition of the parameters describing the quality of the ambiguity resolution (e.g. Ambiguity Dilution of Precision or Ambiguity Success Rate). The most important research areas in the field of improvement of stochastic models focus on realizing the description of the precision of different types of GNSS observations and taking into account the physical correlations between the observations and the ways to incorporate the characteristics into the positioning algorithm. Estimation of the accuracy and correlations of the GNSS observations depending on the type of receiver was subject of research related to testing the GNSS measuring sets (see item 3.3).

Based on the determined observation precision parameters, a stochastic model of GNSS observations was developed for Network RTK positioning, defined as *Network-Based Stochastic Model* (NBSM) (Prochniewicz, 2013; Prochniewicz, 2014; Prochniewicz et al., 2016). This model is dedicated, in particular, to instantaneous positioning, which is based solely on a single observation epoch. In addition to observation measurement noise, this model takes into account residual errors, which are not included in the deterministic model. These errors reflect the accuracy of the ionospheric and geometric network correction terms and are determined together with the corrections as an estimation of the variance in the network solution. The inclusion of the accuracy characteristics of the corrections into the stochastic model results in creation of a weighted model. Schematically, the NBSM model can be presented by the formula:

$$\mathrm{D}\left\{\mathbf{l}\right\} = \mathbf{C}_{\mathbf{l}} + \mathbf{C}_{\delta}, \tag{1}$$

where: $\mathbf{C}_{\mathbf{l}}$ means variance-covariance matrix of the observation vector $\mathbf{l}$ and $\mathbf{C}_{\delta}$ means a matrix containing estimates of variance of the correction for each observation; $\mathrm{D}\{*\}$ means dispersion operator. Detailed form of the formula 1 for Network RTK instantaneous positioning model using double differences of dual-frequency GPS observations and ionospheric and geometric network corrections was presented in Prochniewicz (2014).

The proposed model was verified by comparing the results of Network RTK instantaneous positioning model using the NBSM model with the standard model (Ionosphere-Fixed Troposphere Fixed). Test fields were selected so as to verify the proposed model in different measurement conditions: for baselines with a medium (approx. 30 km) and considerable (approx. 55 km) length and for networks with a small (approx. 80 m) and great (approx. 500 m) height difference. The observations were made during strong ionospheric activity, which further complicates precise positioning. Spatial modelling of ionospheric and geometric errors used the Ordinary Kriging Method (OKR), which was based on the approximation of the empirical variogram with the Gaussian model. The estimation of the corrections and their variance was performed separately for the DD ionospheric and geometric errors, independently for each epoch and each satellite. The results of the resolution of the positioning model were compared based on the obtained results of integer ambiguity estimation, its validation using statistical tests and the position estimation accuracy. Based on the test results, it can be concluded that the use of the NBSM stochastic model in the Network RTK instantaneous positioning increases the number of correct ambiguity resolutions (AR) compared to the Fixed model by 1-8% to the level of 90-99%. The NBSM model also allows for more effective validation of ambiguity, i.e. the use of smaller critical values for the test while minimizing the Type II errors. This makes it possible to increase the AR success rate by approx. 3-15%. It is also very clear improvement in the position estimation accuracy. The use of the NBSM model helps to reduce the positioning error by approx. 20-30% for horizontal components and by approx. 15-25% for vertical components. Figure 7 shows results of the Network RTK instantaneous positioning for a sample test baseline with the length of approx. 46 km. The graphs show the resultant positioning error (in relation to a known/true value) for the two models being compared (the upper graph – Fixed model, the lower graph – Weighted model with NBSM). The asterisk designates resolutions for which an failure ambiguity resolution was reached and the dot designates a correct ambiguity resolution. On this basis, it can be concluded that both the number of failure resolutions and the positioning error for the correct resolutions is significantly reduced in the case of the application of the NBSM model. Detailed test results are presented in the works (Prochniewicz, 2013; Prochniewicz, 2014; Prochniewicz et al., 2016).

3.3. Research on testing the GNSS equipment

More and more frequently nowadays, GNSS receivers should undergo basic and periodic technical examinations that are confirmed by a certificate of conformity in accordance with the legal requirements. Such tests are carried out in authorised laboratories before the start of the measurements, after their completion and in case there is suspicion that the technical parameters of the instruments have been changed.

GNSS instrument compliance tests are not specified and defined in the Polish legislation. One can only resort to the use of ISO standards, but these do not cover all aspects of GNSS receiver and antenna testing. The basic assumption of GNSS instrument testing should be the adoption of the principle that they are carried out in laboratories that are adapted to this purpose and on specially prepared testing fields. The laboratory part of the tests should be performed in accordance with a procedure including the appropriate GNSS signal generators (simulators) (Szpunar et al., 2012). Constellation simulators are devices that generate GPS/Glonass/Galileo/EGNOS (L1 and C/A) signals and reproduce measurement environment in the laboratory (see Fig. 8). Depending on the device, they can simulate a signal delay, Doppler effect, movement of the satellites, the atmospheric impact and various models of antennas – most commonly on the basis of actual navigation files. Such devices make it possible to programme measurement scenarios for the assessment of the positioning precision.

It is possible to develop scheduled test measurement scenarios and define the coordinates that should be determined by the test receiver. Depending on the operating parameters,

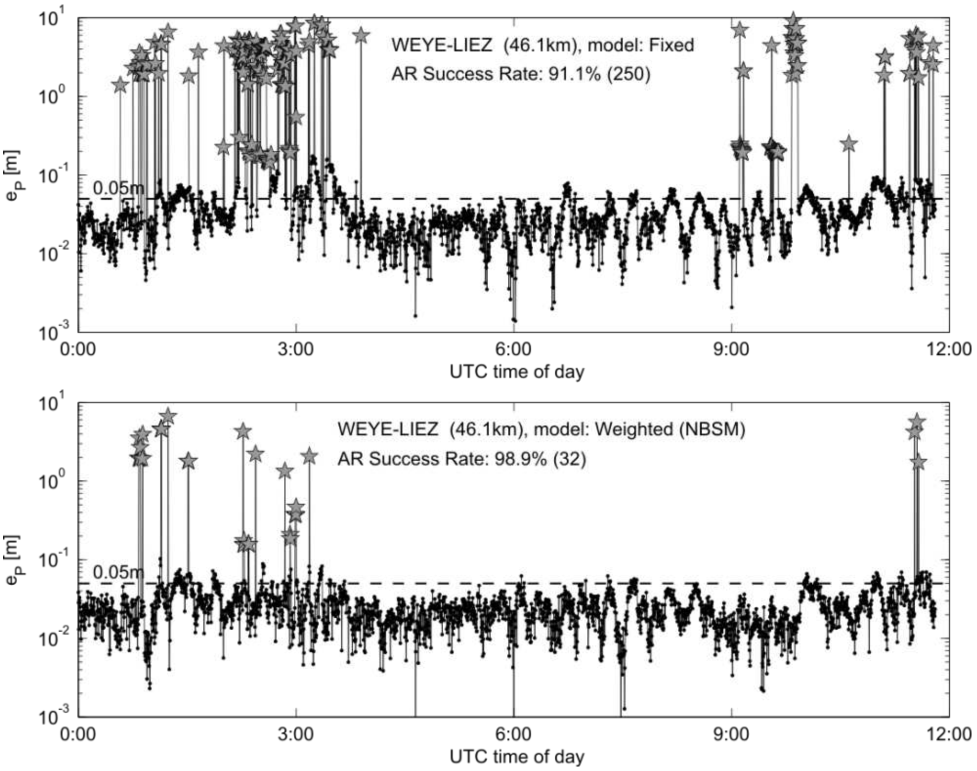

Fig. 7. Position errors of user station for the test baseline WEYE-LIEZ: Fixed Model (top), Weighted Model (bottom) (Prochniewicz, 2014)

one can simulate the signal from virtually any current GNSS system satellite as well as from the satellite augmentation systems (EGNOS).

GNSS receiver laboratory tests make it possible to define the stochastic characteristics: i.e. the precision of different types of observations and the correlations between them. Determination of individual variances and covariances allows to build a stochastic model of observations in the form of a variance-covariance matrix (VC). Depending on the GNSS positioning model and the type of the receiver, various elements of the matrix are included. Figure 9 shows sample non-zero elements of the variance-covariance matrix for the undifferentiated dual-frequency phase (L_1, L_2) and code (P_1, P_2) GNSS observations for four satellites (i, j, k, l) for two epochs (t_m, t_n). The blue colour represents the variance of the observations while the cross and temporal correlations are denoted by red and green, respectively. Depending on the types of receivers, these elements may have significant values that can be estimated on the basis of e.g. laboratory tests using the observation of the zero-baseline (Dróżdż & Szpunar, 2012) or GNSS signal generator.

The tests conducted in the Department of Geodesy and Geodetic Astronomy concerned the determination of individual elements of the VC matrix for the instantaneous kinematic positioning model, which is based only on a single observation epoch. For such a model, the temporal correlation is ignored. Observations for a pair of receivers made for the zero-baseline test allow to assess the measurement noise of individual types of observations based on residues of the double differences of these observations.

Figure 10 shows sample measurement noise for L1 phase observations and P1 code observations identified for two receivers (Leica GX1230GG and Trimble 4700). On the basis of this noise, variance and covariance was determined for observations grouped in five-degrees intervals, depending on the satellite elevation. Assuming identical noise values

Fig. 8. GNSS Signal Generator GSG 5 (source: `http://spectracom.com/`)

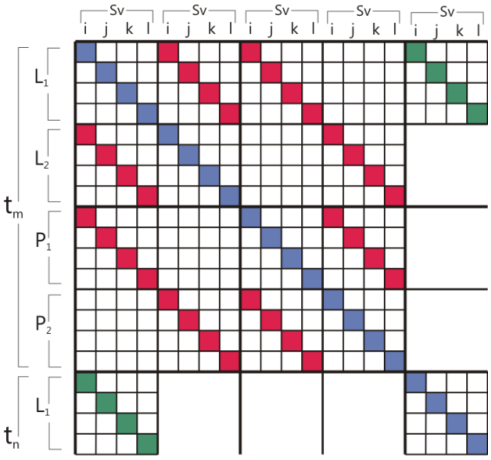

Fig. 9. Non-zero elements of the variance-covariance matrix for undiferenced GNSS observations (blue – variance, red – cross-correlation, green – time correlation)

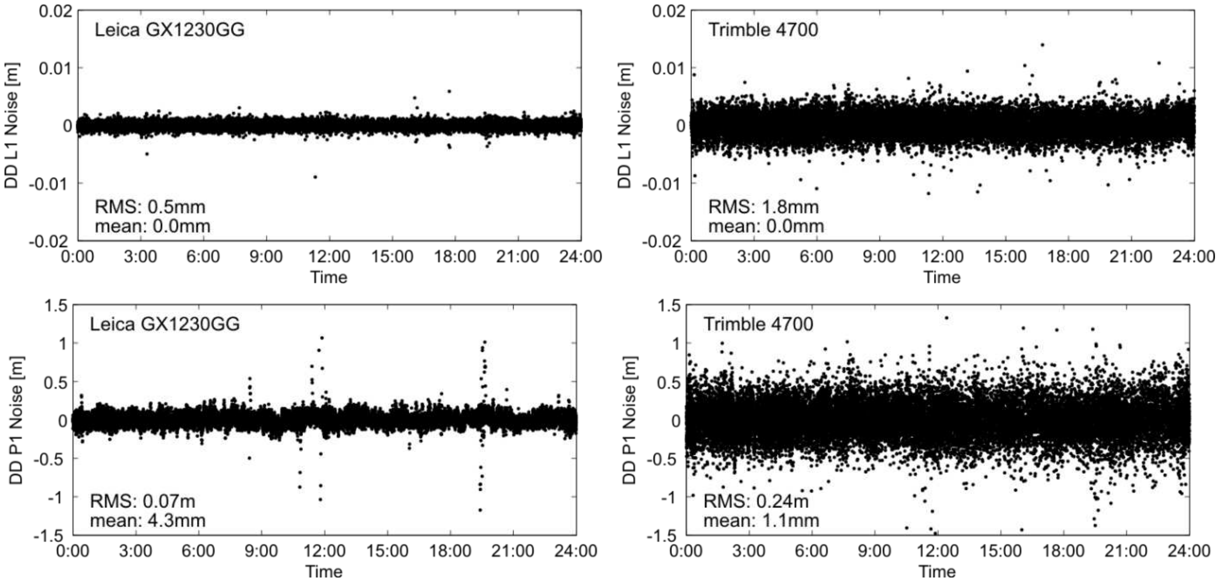

Fig. 10. GPS signal noise of DD phase for L1 (top) and code for P1 (bottom) observations for two tested receivers: Leica GX1230GG (left) and Trimble 4700 (right)

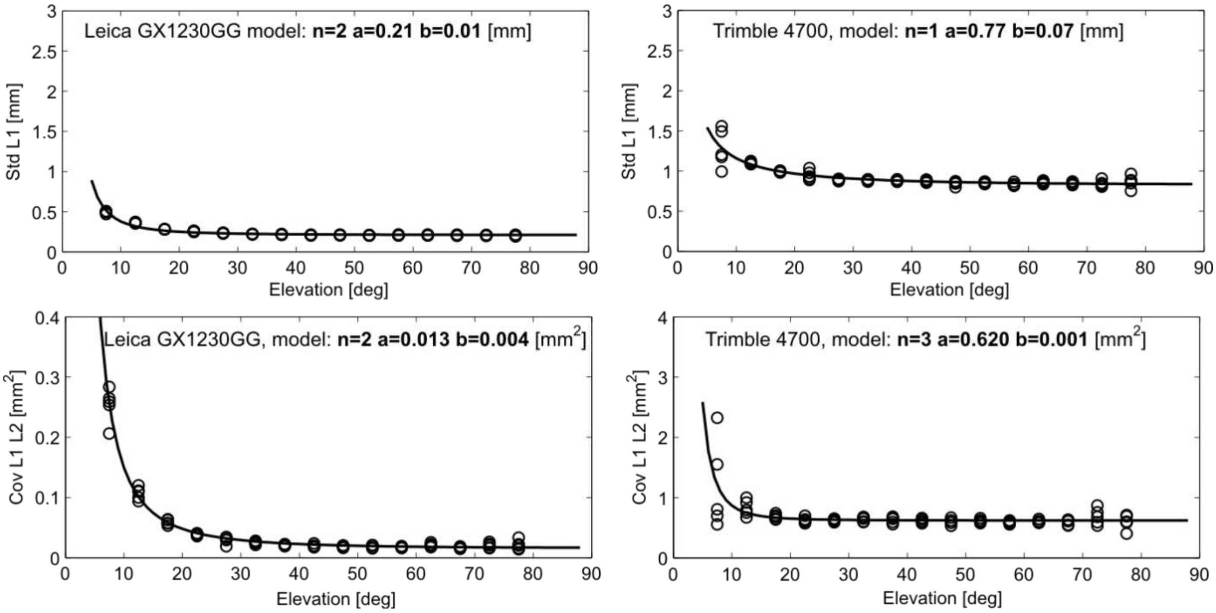

Fig. 11. Empirical stochastic models for L1 standard deviation (top) and L1/L2 covariance (bottom) for two tested receivers: Leica GX1230GG (left) and Trimble 4700 (right)

for the two receivers, empirical functions of the standard deviation (σ) and covariance for undifferentiated observations based on satellite elevation were established.

Figure 11 shows an example of the empirical function of the standard deviation for L1 and covariance L1/L2 for the two tested receivers, determined as an average of five 24-hour observation sessions.

A disadvantage of the zero-baseline test is the need to use two receivers at the same time. This makes it necessary to make assumptions about the error ratio of the two receivers or use a reference receiver. The application of a signal generator allows to use only one receiver to generate double-differences of observation by double registration of the same signal with the same receiver. Such an approach was tested using the Pendulum GSG-5 generator and two receivers: Leica GX1230GG and Hemisphere OEM P306. Due to the fact that the generator being used enabled only observation of L1 and P1, the test only determined the standard deviation of the receivers being tested. Table 1 shows a summary of test results for the three receivers as part of the following tests: zero-baseline (Leica GX1230GG, Trimble 4700) and GNSS signal generator (Leica GX1230GG, Hemisphere OEM P306). It shows the standard deviation of individual observations and error ratio for code and phase observations for a given frequency. In addition, the table also shows the correlation coefficient for various types of observations. On the basis of this table, it can be seen that the standard deviation magnitudes are heavily dependent on the type of receiver and reach very different values ranging from 0.21 mm to 1.4 mm for phase observations and 0.01 to 0.14 for code observations. Also, the correlation coefficients have very different values, depending on the type of receiver. On the basis of the tests, it can be concluded that the cross-correlation P1/P2 and L1/P1 can be neglected for Leica GX1230GG receiver and that they should be taken into account for Trimble 4700 receiver. The results of these tests show that the adoption of standard fixed observation error values and the negligence of the correlation may cause significant errors in estimation of the accuracy characteristics of the observations. The empirical models determined on the basis of laboratory tests allow for accurate estimation of the characteristics, which is a critical step in the process of comprehensive GNSS receiver testing.

Tab. 1. Stochastic properties of tested GPS receivers

Observables		Leica GX1230GG	Trimble 4700	Hemisphere OEM P306
Standard deviation	L1 [mm]	0.21/0.27	0.90	0.44
	L2 [mm]	0.39	1.40	
	P1 [m]	0.03/0.01	0.12	0.13
	P2 [m]	0.02	0.14	
σ_P/σ_L	P1/L1	150/30	130	300
	P2/L2	50	100	
Correlation factor	L1/L2	0.20-0.26	0.40-0.75	
	P1/P2	0.00	0.16-0.22	
	L1/P1	0.02-0.06	0.12-0.15	
	L2/P2	−0.10-0.00	0.11-0.13	

Fig. 12. Points of GNSS field calibration test baseline at WUT Józefosław Observatory

Testing on the field calibration baseline is the second important step in the GNSS receiver testing procedure. A sample procedure for the assessment of the precision of GNSS-RTK positioning is defined in ISO 17123-8 Part 8 "GNSS field measurement systems in real time kinematic (RTK)". Figure 12 shows a test field on the premises of the Astro-Geodetic Observatory of the Department of Geodesy and Cartography in Józefosław. The test baseline consists of four columns on which GNSS antennas with forced centring can be installed. This makes it possible to clearly and consistently reproduce the position of the antennas during the testing procedure.

A complete measurement procedure was conducted on the basis of the above-mentioned ISO standard. Leica GX1230GG receivers were tested. Each receiver made measurements in three 5-cycle series using the NAWGEO service. The results obtained after the development in the form of a 5-mm error of the horizontal coordinates qualifies the tested instruments for use in practical field measurements.

4. GNSS Meteorology

Important area of research by the Department of Geodesy and Geodetic Astronomy and WUT AC (Warsaw University of Technology EPN Analysis Centre) is a standard ZTD (zenith

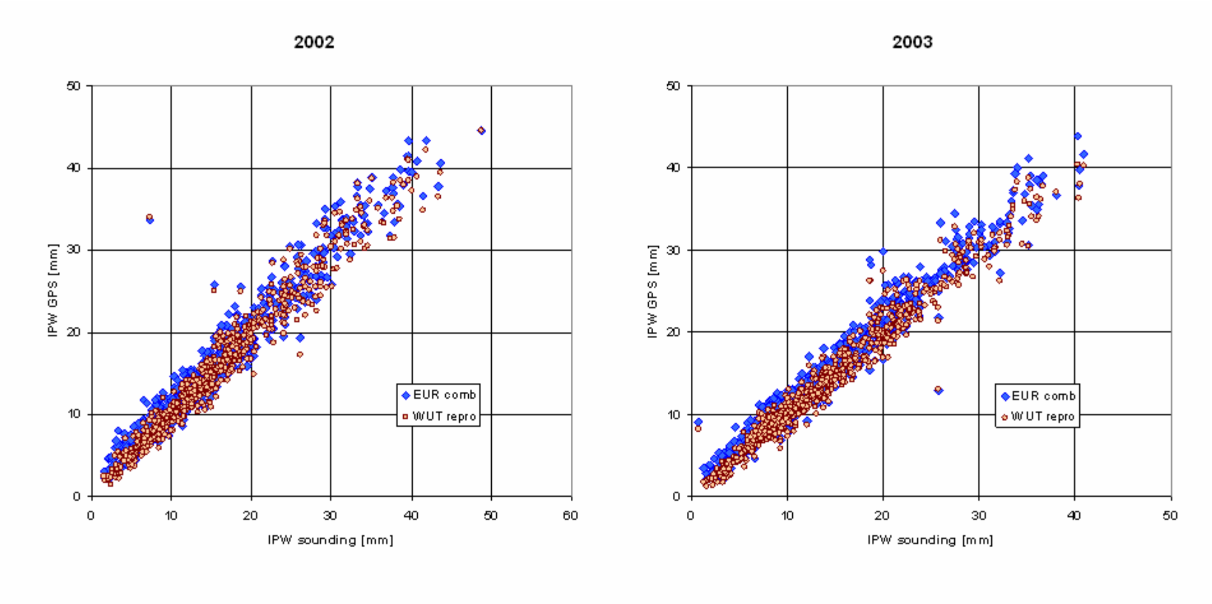

Fig. 13. Legionowo radiosounding IPW vs. GPS JOZE in 2002 and 2003: dark points - original EPN combination, bright points – WUT LAC reprocessing

tropospheric delay) estimation, monitoring of the results and research on IPW time series derived from our solutions, IGS tropospheric product and EPN combination.

WUT AC ZTD solution is of good quality: discrepancies in relation to EPN combined product 0.1 mm to 0.2 mm bias (one of the best conformities in EPN processing). IPW values coming from GPS (WUT and WUT LAC reprocessing) are tested with three meteorological water vapour data sources: radiosoundings, sun photometer (CIMEL, Central Geophysical Observatory PAS, Belsk) and numerical weather prediction models (treated as meteorological database). Both CIMEL-318 sunphotometer and radiosounding confirms that WUT LAC reprocessing ZTD values (in the years prior to 2006) are much less biased (Kruczyk and Liwosz, 2012; see Figure 13).

IPW (integrated precipitable water i.e. columnar water vapour) is investigated as valuable meteorological and climatologic parameter (Kruczyk, 2014). Tropospheric delay estimates (tropospheric product) on selected EPN and IGS permanent stations (recalculated to IPW) exhibit large information potential for meteorology and climate research. Long time series of integrated precipitable water (IPW) averaged hourly, daily and monthly can serve as climate indicators. As IPW is mostly influenced by global circulation, not surface processes, correlations of IPW with basic meteorological surface parameters (on annual and monthly basis) for different regions (see Fig. 14).

Simple charts of IPW/temperature which can be treated as climatologic diagrams were suggested and investigated. Some of these charts have been analysed with some climatologic insight - IPW clearly represents diversity of world climates (see Fig. 16).

The value of GPS IPW as a geophysical tool is investigated, especially as climatological parameter. Sinusoidal model and the more composite varieties has been adjusted to the multi-year series (LS method) of IPW (daily averaged) for diverse set of EPN and IGS stations. We search for climate change signal in the residuals or trend adjusted in composite model. In case of EPN solutions only the use of ZTDs after reprocessing is strongly recommend (Kruczyk & Liwosz, 2012). Long time series of integrated precipitable water (calculated from tropospheric delay estimates) on IGS permanent stations averaged daily can serve as change climate indicators (Kruczyk, 2015b). The seasonal model of IPW change has

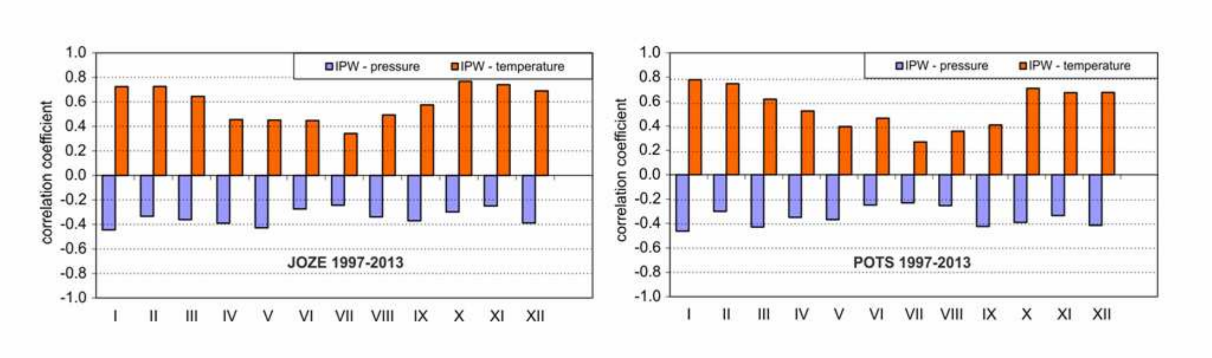

Fig. 14. Monthly correlation coefficients (IPW-temperature and IPW-atmospheric pressure) for JOZE (Jozefoslaw) and POTS (Potsdam, Germany)

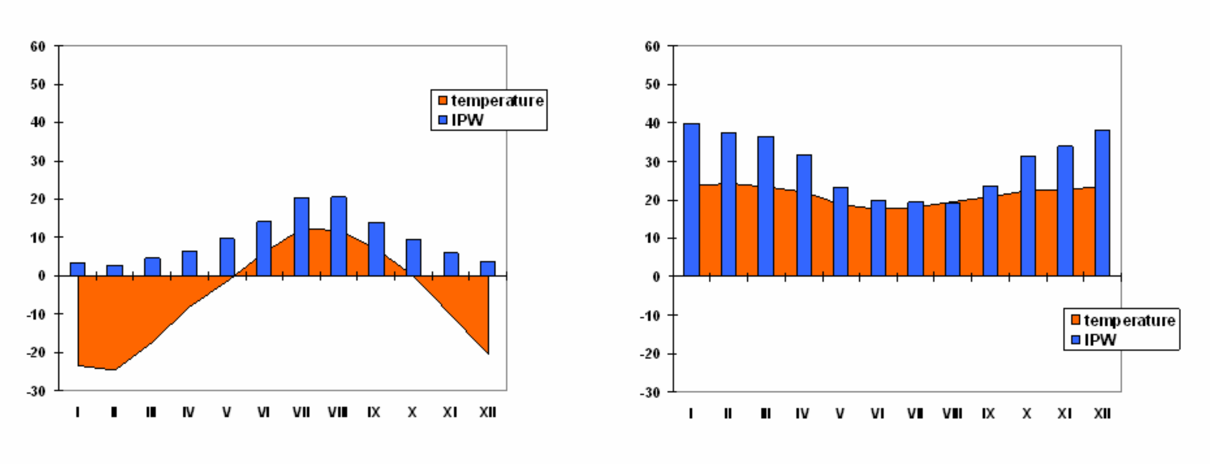

Fig. 15. Climatologic chart temperature [^{o}C] vs. IPW [mm] for northern and southern hemisphere: CHUR (Churchill, Manitoba, Canada) and CHPI (Cachoeira Paulista, Sao Paulo, Brazil); IGS tropospheric product, multi-year series

been adjusted to the multi-year series by the least square method. Different modes have been applied: sinusoidal and composite (two or more oscillations), trend fitting together with seasonal model or to residuals. Information potential of IPW for climate research depends on series length and homogeneity. To fit linear trend to long IPW series the seasonal model of 1-4 oscillations is also included (Fig. 17).

Usually it is enough to model seasonal changes by annual and semi-annual oscillation as confirms analysis of periodogram (Fig. 18). The exact method does not influence considerably the value of linear trend. The IPW trend value is mostly influenced by series length, completeness and data (also meteorological) overall quality.

The next field of research is to asses areological techniques of water vapour retrieval in polar regions. Three independent techniques to obtain integrated precipitable water (GPS solution, radiosounding and CIMEL sunphotometer) have been tested in case of dedicated GPS measurements by Polish Polar Station in Hornsund Fjord at four points in Greenland (Kruczyk & Liwosz, 2015; Kruczyk, 2015a). CIMEL sunphotometer IPW and IPW values derived from standard solutions of IGS and EPN (combined solution) show relatively good agreement but also some biases of 2 % to 7 %. IPW bias shows seasonal dependence (especially in case of Thule) what signals some systematic deficiencies in solar photometry as IPW retrieval technique. (Fig. 19). Probable cause to this phenomenon is a change of

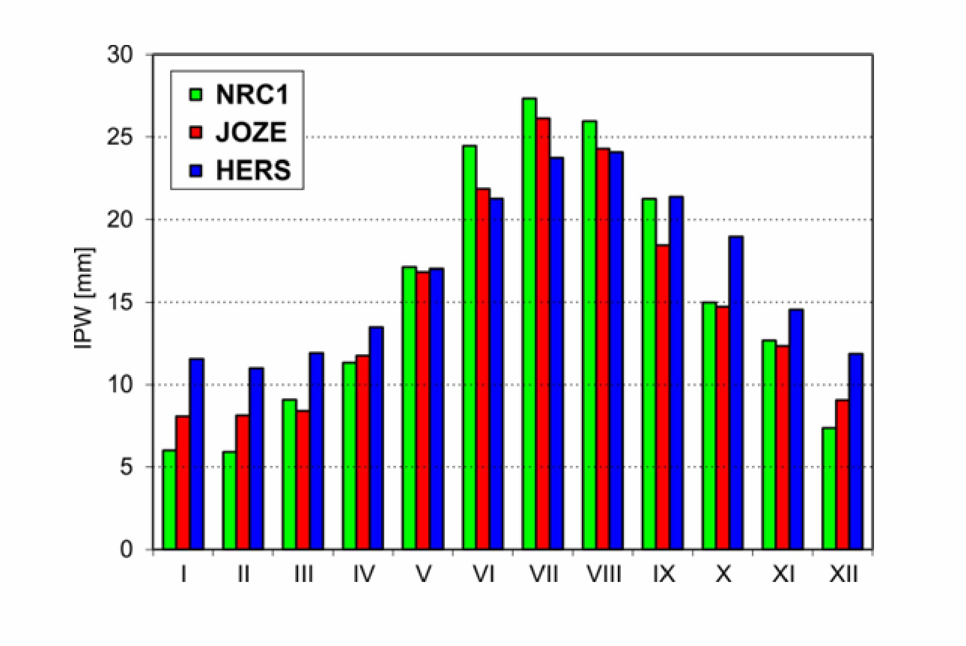

Fig. 16. IPW monthly averages for three IGS stations in temperate climate zone of the Northern Hemisphere: NRC1 (Ottawa, Canada) is definitely continental, HERS (Hailsham, Susex, UK) definitely oceanic, JOZE (Jozefoslaw) falls in between

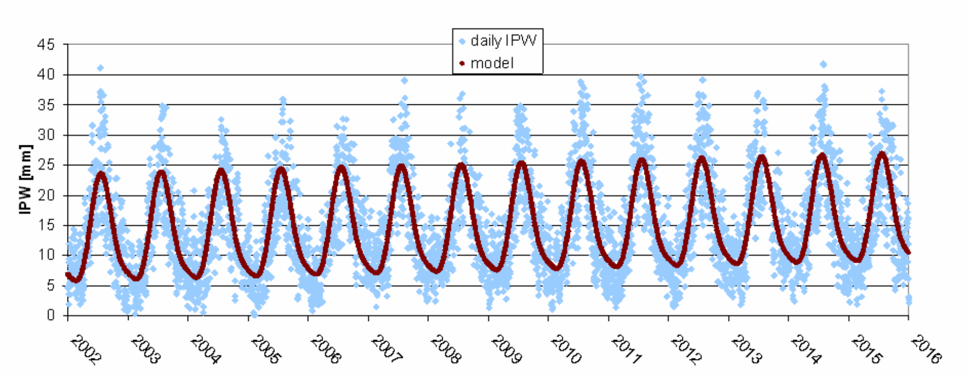

Fig. 17. IPW for JOZE (Józefosław) and linear model with 2 oscillations (annual and 1/2-year) applied to 2002-2015 period, IGS tropospheric solution, IPW trend in this case is evident: 0.25 mm/year

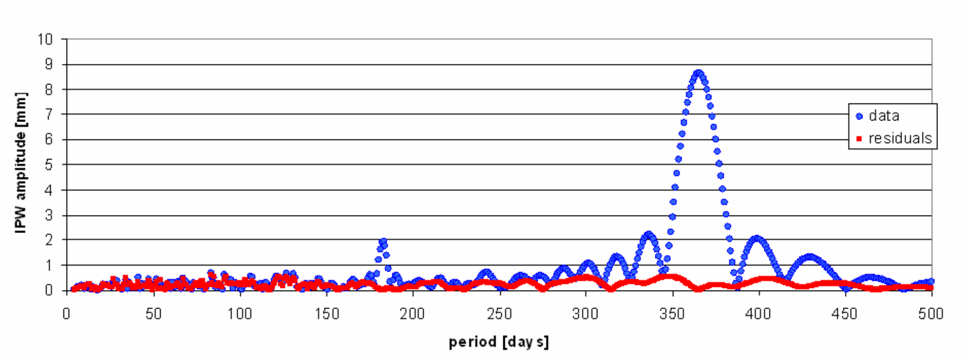

Fig. 18. Periodogram of IPW series and residuals after subtracting annual and semiannual oscillations for JOZE (Józefosław), multi-year series: 1997-2013

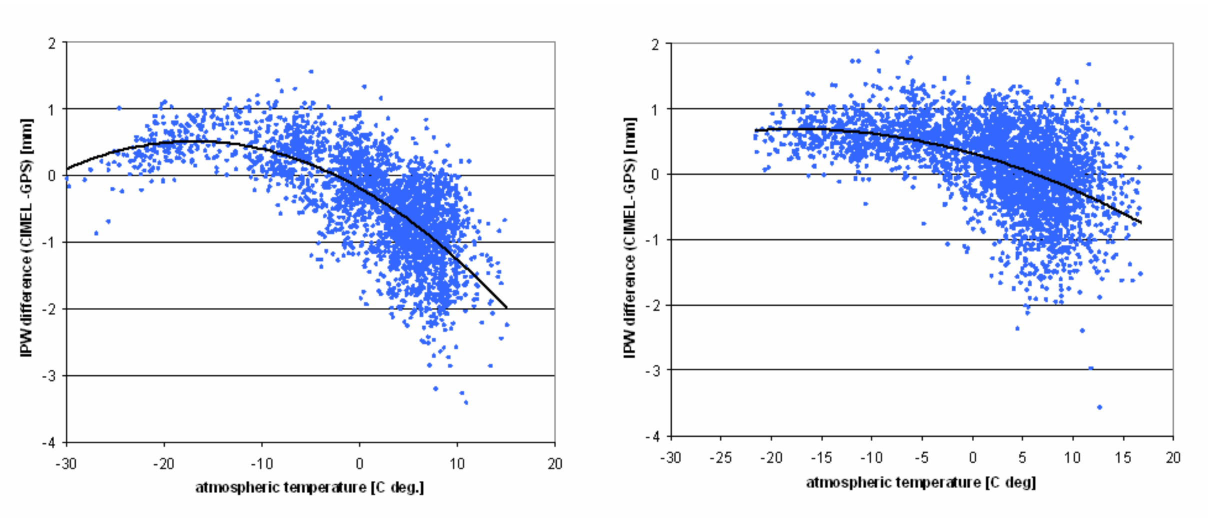

Fig. 19. IPW difference (CIMEL-GPS) for Thule-THU2 for 2009–2011 and Ittoqqortoormiit - Scoresbysund (SCOR), , for 2012–2014 as a function of atmospheric temperature, IGS tropospheric solution

optical filter characteristics in sunphotometer working in extreme polar conditions. Averaged IPW difference for RAOB (radiosounding observation) – GPS is relatively small and show no dependence on temperature. The attempt to compare aerological techniques (CIMEL and RAOB) brings similar temperature – IPW difference dependence.

Another field of research is also the study on IPW and ZTD time series derived from both GNSS and NWP numerical weather prediction models. Some detailed experiences in dealing with operational numerical prediction models treated as a source of IPW and ZTD needed for GNSS tropospheric products quality assessment have been gained (Kruczyk & Mazur, 2013). Authors used operational numerical prediction model COSMO-LM (maintained by Polish Institute of Meteorology and Water Management) in two different resolution versions: 14 km and 2.8 km and global model GFS (operated by NOAA NCEP). Both input fields and first prognosis steps of operational numerical prediction models were processed as IPW source for comparisons and analyses. comparisons and analyses. Diversity of factors concern precise derivation of IPW and ZTD from model grid e.g.: interpolation of data in space, numerical integration in zenith direction, correction for model topography, physical equations chosen for humidity parameters conversions etc. Analysed results of many comparisons lead to some clues about key factors in such calculations. Greatest attention is paid to input fields (and first prognosis steps) of operational numerical weather prediction model COSMO-LM (maintained by Polish Institute of Meteorology and Water Management). Comparisons were made of different static solutions (mainly IGS and EPN) and IPW/ZTD calculated from numerical weather prediction model grid in several tested modes. tested modes. IGS and EPN zenith tropospheric delay (ZTD) recalculated to precipitable water (IPW) show good conformity in relation to COSMO model data. COSMO reveal positive IPW bias of about 1 mm - model is ‘too wet’ (see Fig. 19). Many factors affect both procedure of IPW derivation from COSMO model and calculation of IPW from tropospheric delay: most crucial is height adjustment, but even minor ones like water vapour density formula or barometric equation can affect IPWV on submilimeter level.

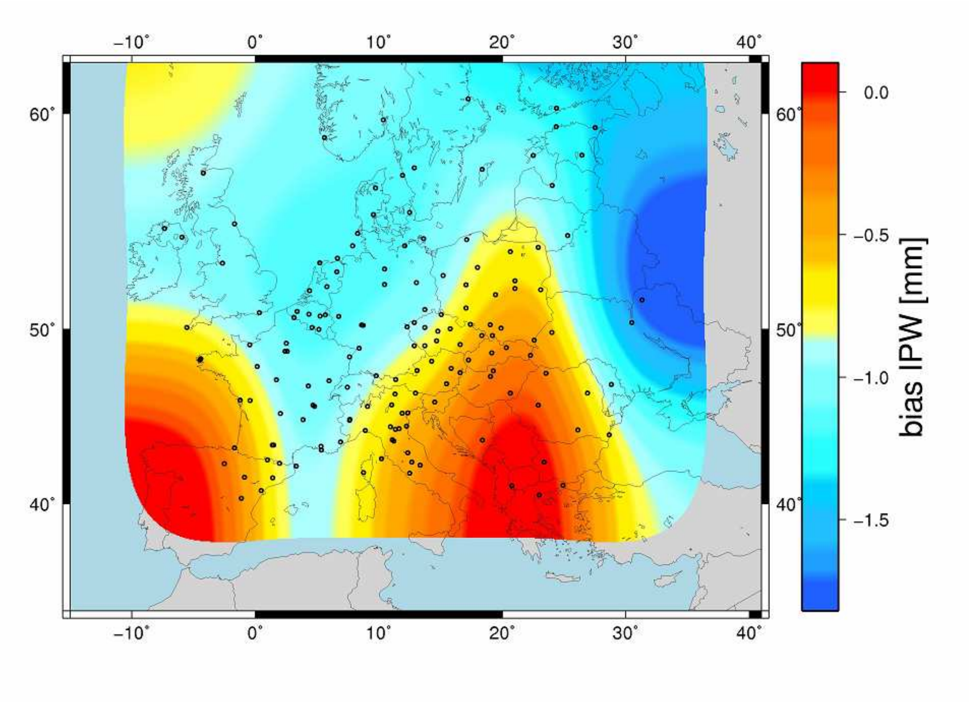

Fig. 20. IPW difference (GNSS EUR tropospheric combination - COSMO-LM_14; annual average) map for 2011, meteo from COSMO model GNSS networks provide us with vertically integrated humidity information (precipitable water) which can feed COSMO model (nudge water vapour content in right direction) in network much denser then radiosoundings

5. Geodynamics

5.1. Variation of Earth rotation - modeling and observation of high frequency effect

The main tasks of modern geodesy is research concerning the shape, gravity and rotation of the Earth (Plag & Pearlman, 2009). Unprecedented progress could be achieved in this field during the last decades thanks to development of the space geodetic techniques, Very Long Baseline Interferometry - VLBI, Satellite and Lunar Laser Ranging - SLR, LLR, Global Navigation Satellite Systems - GNSS, which replaced classical methods of the optical astrometry. The accuracy and time resolution of space geodetic observations enabled studies of different geodynamic phenomena which were known earlier only from the theoretical predictions. The Department of Geodesy and Geodetic Astronomy of WUT has been conducting since about 10 years research on Earth rotation, focusing on high frequency (diurnal and subdiurnal) variations of Earth rotation parameters. Of particular interest are applications of the observations by the Ring Laser Gyroscope - RLG, relatively new geodetic technique measuring inertial rotations locally and in real time without the need for an external reference system.

5.1.1. General description

A common feature of the high frequency variations in Earth rotation is their small size. The total peak-to-peak size is only up to about 1 milliarcsecond (mas) corresponding to 3 cm at the Earth surface. Such variations could not be observed by the methods of optical astrometry and early space geodetic measurements, because the observations were not sufficiently accurate and their sampling interval was significantly longer than 1 day. Hence all earlier predictions were purely theoretical based on the knowledge about the shape

and internal constitution of the Earth. Almost all observational evidence of diurnal and subdiurnal variations in Earth rotation has been gathered during the last two decades. The high resolution observations of Earth orientation are still under development. For instance, one purpose of the VGOS (formerly VLBI 2010) system is continuous measurement of the Earth Orientation Parameters (EOP). We believe that combining the RLG observations with the VLBI measurements can help to achieve this task.
Despite the small size, the diurnal and subdiurnal signals in Earth rotation are important for understanding the high frequency global dynamics of the solid Earth and the overlying fluid layers. The research on them is also important for validation of the underlying theories and of the high resolution determinations of Earth rotation parameters including the procedures applied for data reduction. Let us start from a short systematic review of the high frequency signals in Earth rotation; for more detailed description see (Brzeziński, 2009):

1. Astronomical variation. The responsible physical mechanism is the lunisolar torque exerted upon the rotating Earth. The main corresponding effect in Earth rotation is the astronomical precession-nutation expressed by the conventional model, currently the IAU 2006/2000 model (Petit & Luzum, 2010), and the so-called celestial pole offsets observed by VLBI. A minor part of the astronomical variation, called subdiurnal nutation or libration, is the prograde diurnal variation in polar motion (amplitude up to 50 microarcseconds - μas), and semidiurnal variation in Universal Time (UT1, amplitude up to 75 μas).
2. Ocean tide contribution. The underlying physical mechanism is the influence of the gravitationally-forced ocean tides with diurnal and semidiurnal periods, upon the rotating Earth via the angular momentum exchange. The ocean tides contribute to all three components of Earth rotation, including precession-nutation, polar motion and UT1. In case of polar motion and UT1 this is dominant effect in the diurnal and semidiurnal frequency bands. In case of polar motion the ocean tide influence consists of semidiurnal and prograde diurnal variation with amplitudes up to 330 μas and 150 μas, respectively, while in case of UT1 the ocean tide influence appears as semidiurnal and diurnal variations with amplitudes up to 260 μas and 240 μas, respectively.
3. Diurnal atmospheric tides. The diurnal cycle in solar heating give rise to variations in the atmospheric angular momentum - AAM with main components S_1, S_2 of periods 24 and 12 hours, and their sidelobes due to seasonal modulations. These harmonic components are superimposed on the background variation of stochastic character. Similar effect can be seen in the non-tidal ocean angular momentum - OAM due to the ocean response to the atmospheric forcing. All diurnal and semidiurnal harmonics of AAM and OAM expressing the atmospheric thermal tides are added to the harmonics with the same frequencies but produced by the gravitational ocen tides. With exception of S_1, in all cases the ocean tide contributions are significantly larger than the corresponding thermal effects expressed by AAM and OAM.

5.1.2. Earth rotation observed by ring laser

As stated above, our current research focuses on the applications of the Ring Laser Gyroscope for monitoring variations in Earth rotation. The RLG is a promising, emerging technology for direct and continuous measurement of changes in Earth rotation (Schreiber et al., 2009; Tian, 2013). A single RLG instrument is capable to determine a certain combination of the the components of the instantaneous rotation vector. This is in contrast

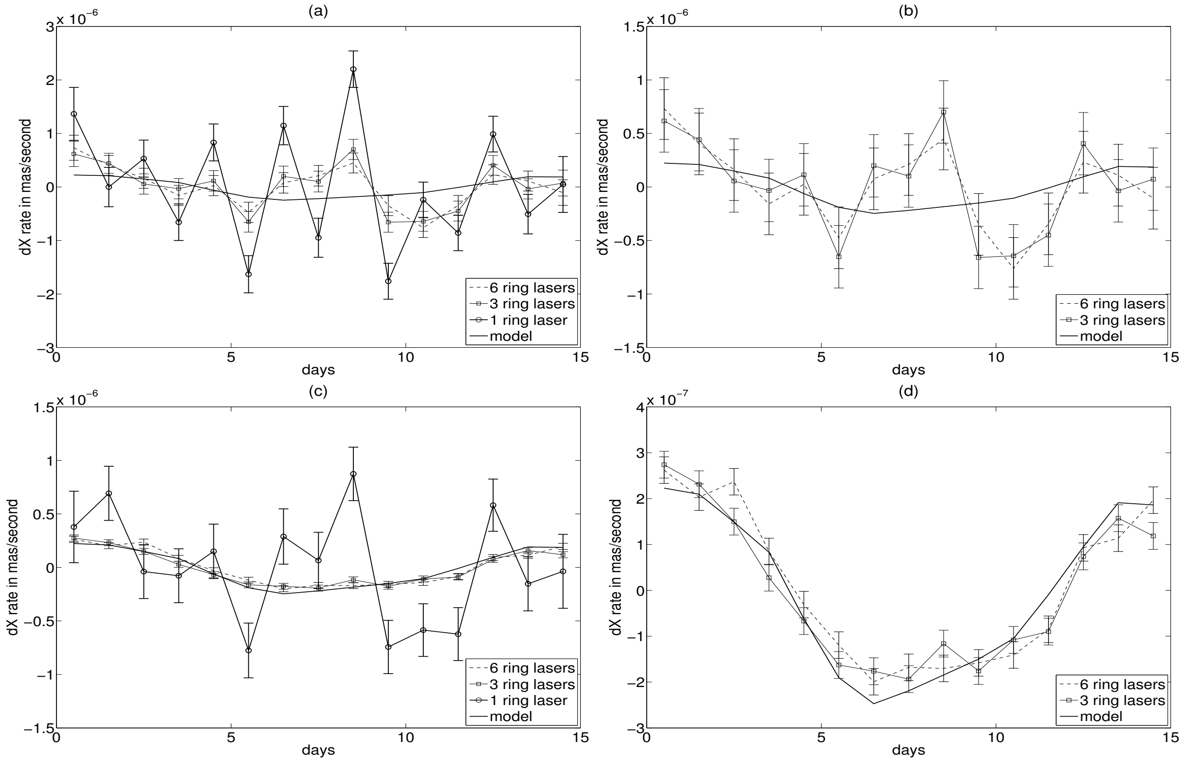

Fig. 21. Nutation rates from VLBI and RLG combined solution. Plots (a) and (b) show results for an assumed RLG accuracy level of 10-9 and (c) and (d) for 10-10. Note the different scales on vertical axes. From (Tercjak et al., 2015)

to the space geodetic techniques which report the terrestrial and celestial motions of the conventional Celestial Intermediate Pole and the rotation angle around this pole (IERS Conventions, 2010). The advantage of this technique is its ground character and relatively low cost of construction and operation (Schreiber et al., 2009). Although the technique still needs enhancement by constructing additional instruments over the world (Nilsson et al., 2012), the RLG observations can be treated as an important supplement of space geodetic techniques in the research concerning Earth rotation. Its potential has been already investigated and proven by e.g. Schreiber et al., 2004; Cerveira et al., 2009; Schreiber et al., 2009 or Nilsson et al., 2012. Apart from that also a possibility of estimation the nutation rates from combination of RLG with VLBI data have been studied by Tercjak et al., 2015. In that study we have shown that estimation of nutation rates from the RLG observations is possible only under certain restrictive assumption. One of such assumption is improvement of the relative level of accuracy to at least 10^{-10} (Fig. 21), while the current level reaches 10^{-8} with possible improvement to 10^{-9} (Schreiber & Wells, 2013).

Now of our great interest is the issue concerning possibility of monitoring diurnal and subdiurnal signals in polar motion and UT1, especially geophysical contributions which are irregular and cannot be represented by harmonic models. We have already presented preliminary results at the last General Assembly of the International Union of Geodesy and Geophysics in Prague (Tercjak & Brzeziński, 2015). We examined in that work how the known modelled signals in Earth rotation parameters translate into the Sagnac frequency observed by a ring laser like the one at the Wettzell Geodetic Observatory. Further investigation of the subject concerns global and local diurnal and subdiurnal effects impacting orientation of the instrument. We consider influence of both tidal and non-tidal effects, including atmosphere loading. The investigation is in progress.

To conclude this report we should say that though the investigations on the usage of the RLG for monitoring changes in Earth rotation have been carried out for about 15 years, nevertheless it is still relatively new subject and our Department has a chance to contribute to the development of this technique.

5.2. Geodynamic studies in the Pieniny Klippen Belt

The geodynamic studies in the Pieniny Klippen Belt (PKB) have been carried out since the early 1960. (Czarnecka, 1988, 1992). In the period between 1978 and 1995, they were conducted by the research staff of the then Institute of Geodesy and Geodetic Astronomy at Warsaw University of Technology (Ząbek et al., 1988, 1993; Margański, 1997). As part of these studies, ten elevation observation epochs were performed using the precision levelling method on the vertical network, along with precision measurements of distances in the horizontal network and measurements of differences in the intensity of gravity. Moreover, in the 1990s absolute gravimetric measurements were made at one station and GPS satellite measurements were performed in collaboration with the Slovak University of Technology in Bratislava.

In 2001 – after a six-year break – research on the Pieniny geodynamic traverse was resumed. In the meantime, a dam was built on the Dunajec River in the area of the Niedzica castle and an artificial lake (Czorsztyn Reservoir) and the lower reservoir in Sromowce Wyżne were formed. Thus, a new important element appeared in the studies, which was related to the impact of movements of the earth's crust on the safety of the operation of the dam. As part of a new research project, the vertical, and horizontal and gravimetric control networks were measured and geophysical studies i.e. shallow seismic probing and electric resistivity profiling, were resumed. Detailed results of the work performed in that period can be found in the monograph edited by Czarnecki (2004). After completion of the project, the scope of work was limited to annual GNSS satellite measurements on the horizontal network points and gravimetric measurements at selected absolute stations.

Since 2004, horizontal movement of the geodynamic units were determined at the GNSS network points. This network consists of 15 GNSS stations, including 6 stabilised stations within PKB region, 5 stations within the Magura (MN) nappe and 4 stations within the Podhale flysch (PF) (see Fig. – left). The whole test field is complemented by 4 GNSS stations located in the area of the Tatra Mountains.

The GNSS measurements have been made at horizontal network points annually at the beginning of September in accordance with a unified observation scheme since 2004. The duration of the observation session for the four base points (NIWK and WDZA within PM and KACI and SPSV within FP) is 72 hours. For the other points, the session duration ranges from 6 to 12 hours. In 2015, reprocessing of the GNSS observations was performed for the entire network using the Bernese GNSS Software 5.2. The measurements have been developed in 24-hour sessions based on double observation differences for all independent vectors. The diagram of development of the observations was consistent with the standard procedure for the development of the GNSS regional network contained within the Process Control Program Files `RNXSNX.PCF` of the Bernese GNSS Software 5.2 (Dach et al., 2015).

Based on the coordinates of the GNSS network stations, horizontal velocity vectors of the geodynamic network points were determined for the measurement epoch. On their basis, linear trends were determined for the changes in coordinate components in the topocentric system for the north-south and east-west directions. Residual values of the linear trends were determined following the deduction of the velocity of the Eurasian plate determined

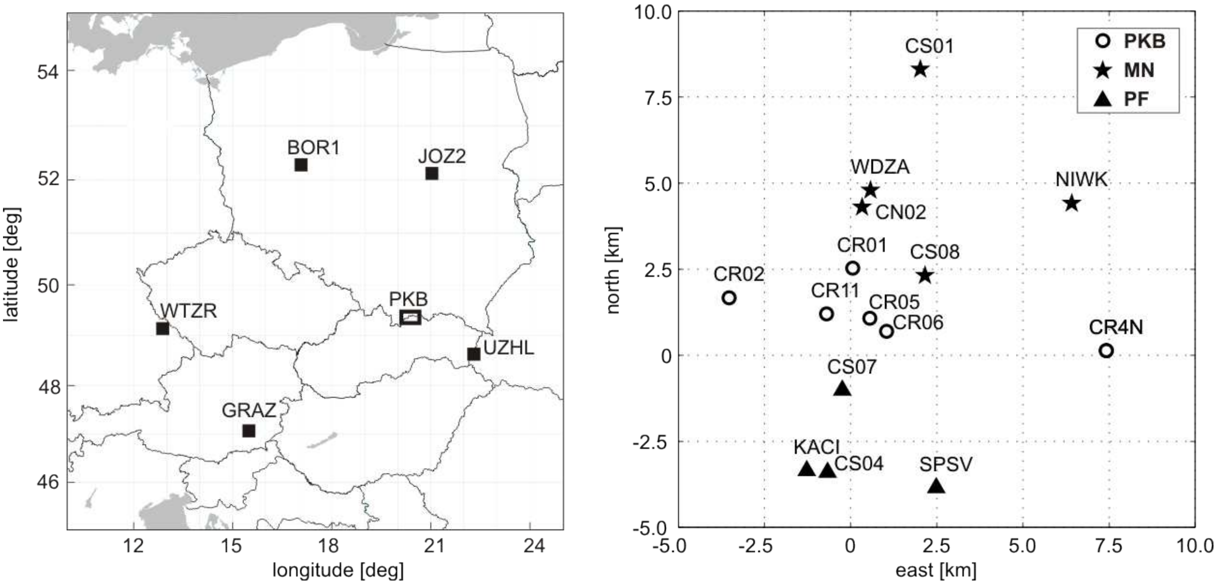

Fig. 22. Map of datum definition sites (left) and points of PKB geodynamic test field (right)

Tab. 2. Summary of residual horizontal velocity

				Residual velocity [mm/year]							
unit	station	North	East	unit	station	North	East	unit	station	North	East
PKB	CR01	0.1	–0.2	MN	NIWK	–0.8	0.4	PF	KACI	–0.2	0.6
	CR02	–0.2	–0.3		WDZ	–0.3	0.5		CS04	–0.9	–0.2
	CR4N	–0.3	2.5		CN02	0.0	0.5		CS07	–0.9	–2.2
	CR05	–1.1	–0.4		CS01	0.2	1.2		SPSV	0.0	0.2
	CR06	0.4	0.2		CS08	–0.8	0.0		**Mean**	–0.5	–0.4
	CR11	–1.1	1.8		**Mean**	–0.3	0.5				
	Mean	–0.4	0.6								

on the basis of the plate geodetic model ITRF2008-PMM (Altamimi et al., 2012). Table 2 contains a breakdown of the station residual velocities for individual points and the average velocity for three tectonic units.

Based on the average velocities of the units, it can be said that their mutual position over 11 years is stable and shows no significant changes. The three tested units are characterised by negative velocities for the northern component at a similar level of –0.3 mm/year to –0.5 mm/year. For the eastern component, only the southern PF unit is characterised by a negative velocity, which may indicate the presence of local inner tidal movements between PKB and PF in this direction.

The absolute gravimetric measurements were first made in the Pieniny Klippen Belt in October 1993 and used a meter constructed by Ząbek in 1994. In 2008, three points of the traverse were included in the unified gravimetric reference system created for Polish geodynamic traverses (Walo, 2010). The first point was stabilised in Łącko (MN) and the second one – in Kacwin (PF). In the PKB area, one already existing point in Niedzica was selected, where measurements with a ZZG absolute ballistic gravimeter had been made (Ząbek et al., 1993).

From 2008 to 2015, three observation sessions were performed with the gravimeter FG-5 No. 230. A typical observation session consisted of a 24 observation series. The final acceleration value is the average of the observation series, which takes into account the following corrections: lithosphere tide correction (Wenzel tidal potential catalogue), tide corrections including the movement of sea masses (FES2004 model), barometric correction, the correction due to the location of the pole and the value of the gradient of the gravitational acceleration. The effect shown in table 3 take into account the results of the absolute gravimeter calibration, presented as part of ICAG2011 (Francis et al., 2013).

The analysis of the absolute observations made after 2008 indicates small changes in the values between the epochs. The analysis of the results indicates a high degree of independence of the station in Kacwin to changes in the local hydrological conditions. This station is characterised by the smallest changes in acceleration and their values correspond to the impact of global hydrology. Other stations are characterised by larger changes in acceleration, whose basis is geodynamic in nature or results from their local hydrological effect.

The results of the geodynamic studies confirm that the Pieniny Klippen Belt demonstrates a small neotectonic activity, which manifests itself primarily through clearly noticeable altitude changes. Clear changes of gravity in two geological complexes were documented, as well. Horizontal point movements are small and do not show a clear trend in terms of their value and direction. Only for the eastern component, the Podhale Flysch (PF) is characterised by a negative velocity, which may indicate the presence of local movements between PKB and PF. Confirmation of this fact, however, requires subsequent measurement epochs in the future.

6. Electronic measurement techniques

The problems in the field of electronic measurement techniques that are the subject of research conducted by the department have included the problems related to geodesic metrology and geodetic instrument testing. As part of the research, terrestrial laser scanners testing procedures were analysed.

The laser scanning technology is one of the fastest developing measuring techniques at the turn of the 20th and 21st century. It found widespread use in many fields, including but by no means limited to geodesy, forestry, architecture, archaeology and forensics (Pieniak M.,Świerczyńska E.,2013b). Laser scanners were built by extending the functionalities of electronic total stations commonly used in geodesy. These modifications enabled acquisition and fast automatic registration of large amounts of data (x, y, z, intensity, RGB). Due to varied use of scanners – and thus different working conditions and development scales – they are characterised by different parameter ranges.

For a geodesist using an TLS terrestrial laser scanner on specific civil engineering structures, an important piece of information is the information on accuracy with which it is able to acquire measurement data and whether the instrument meets the manufacturer's accuracy parameters (Pieniak & Świerczyńska, 2013). It must be kept in mind that all

Tab. 3. The gravity measurements results on absolute points after 2008

Epoch	measurement site Łącko	 Niedzica	 Kacwin
2008.15	980 892 800.4 µGal	980 855 669.2 µGal	980 843 150.6 µGal
2011.25		980 855 662.0 µGal	980 843 152.1 µGal
2015.25	980 892 791.7 µGal	980 855 666.9 µGal	980 843 150.6 µGal

Fig. 23. Position of scanner relative to interferometric comparator

scanners, just like all geodesic instruments, are burdened with instrument errors. In addition, the technical specification of individual instruments is often scarce. Different manufacturers provide precision parameters contained within in different ways – often without detailed information on the method of their determination. The parameters are often values achievable in laboratory conditions but are difficult or even impossible to achieve in reality and dependent both on weather conditions and the calibration method. The task of testing terrestrial laser scanners is difficult. They are characterised by similar but nevertheless differing design and functioning, different prism/mirror/tile rotation range, different types and frequencies of laser beams, weather resistance, tightness and even such small but important factors like the lack of a positioner and the limited reproducibility of measurements (it is only possible to increase the point cloud density). The problem of testing terrestrial scanners is an issue raised by a number of research centres, with the first publications appearing as early as in 2000 (Lichti et al., 2000a, 2000b). The development scanner testing methodology will enable to design and construct modern test fields for testing, determining, comparing and monitoring scanner accuracy parameters.

Work is being currently done by the International Organisation for Standardisation (ISO) on the ninth and the tenth part of the international standard ISO 17123, which concerns testing procedures for terrestrial laser scanners (ISO 17123-9) and non-prism measurements (ISO 17123-10). The standard is supposed to enable easy and comprehensive procedure for conducting field testing and result analysis. The purpose of the standards being created is to determine the structure of test fields and – on their basis – to provide geodetic equipment testing procedures. It is not the aim of the standard to evaluate the technical capabilities of the instrument or acceptance procedures performed for their application but to increase the credibility of the measurement results that are depend on the reproducibility and repeatability of the test with a simultaneous analysis of potential sources of measurement errors. The standard means to define both simplified procedures (enabling verification of the obtained value within tolerance limits) and full procedures (enabling determination of the highest accuracy achievable by the instrument) for the accuracy testing procedure for a given piece of equipment. The task of the standard is to define how to carry out tests in field conditions with special emphasis on meteorological conditions used in determining the atmospheric correction and in the laboratory conditions. The choice of the procedure in question depends on project specialist requirements and technical requirements of the procedure itself.

Tab. 4. Obtained angle measurement accuraccy of Z+F Imager5006h compared to literature values (Kosmala & Książek, 2014)

accuracy [°]	control points (m 1 mm)				GUM	brochure
	superhigh	high	middle	preview	superhigh	
horizontal	0.009	0.009	0.010	0.094	0.003	0.007
vertical	0.011	0.013	0.012	0.075	0.004	0.007

Due to the dynamic and versatile application of TLS scanners in engineering work and the related necessity to carry out research on their testing, an idea arose at the WUT Department of Geodesy and Geodetic Astronomy to build its own test fields. With reference to test fields in Poland and abroad, a concept is being created for the construction of laboratory and field test fields located in the Computing Centre of the Warsaw University of Technology in Józefosław. A fully-equipped laboratory test field will be built there for testing modern geodetic instruments based on international experiences. The centre has large premises that provide conditions for the construction of the field which makes it possible to check and test instruments – also in field conditions. For the purpose of the concept, cooperation was undertaken with the Central Office of Measures in Warsaw and research is being conducted on the requirements of the test field being constructed. Tables 4 and 5 present selected results of Z+F Imager5006h scanner tests conducted on a WUT linear geodesic database and an interferometric comparator with a 50 m measurement range at the laboratory in the Central Office of Measures (see Fig. 23).

Table 4 presents the accuracy of angle measurement based on the intended measurement control assumed at Warsaw University of Technology and the data from the measurements from COM straightness interferometer. Table 5 shows the obtained scanner angular resolutions.

It should be kept in mind that some parameters, such as angular resolution, provided by the manufacturer are achievable only in a narrow operating range of the scanner, while others are omitted by (collimation error) although they must be taken into account in the analysis of accuracy carried out by a geodesist. For detailed information about the calibration range, method and results, see Kosmala and Książek (2014).

The measurement laboratory being designed creates opportunities to accelerate checks and analyses and increase their accuracy. It will support research teams doing work in the field of geodetic instrument testing and checking as well as original procedures and algorithms for testing the laser scanner measurement accuracy, orientation and optimisation of applications.

Tab. 5. Obtained angle resolution of Z+F Imager5006h compared to literature values (Kosmala & Książek, 2014)

mode [°]	measurements				brochure
	superhigh	high	middle	preview	superhigh
horizontal	0.0161	0.0320	0.0670	0.2762	0.0018
vertical	0.0161	0.0320	0.0670	0.2762	0.0018

7. Research in the field of geoinformatics

Since 1992 in the Institute of Geodesy and Geodetic Astronomy and now the Department of Geodesy and Geodetic Astronomy, intensive research in the field of acquisition and processing of spatial data was carried out, which was generally referred to as the subject of spatial information systems. Significant were also activities in the field of educational programmes that applied to said subject. Now that the Internet, web services and quick methods of acquiring spatial data have appeared, a term “geoinformatics” was coined, which has a much broader meaning than the spatial information systems.

Currently, the geoinformatics team deals with the analysis of the existing data models and creation of new ones that are used to reflect the reality as well as the design and construction of network services with the purpose of improving the access to spatial data. One of the most important spatial data reference registers is the address numbering (the so-called record of localities, streets and addresses). The distributed method of maintaining this register by municipalities ensures that the information is acquired at source but, on the other hand, poses technological and organisational challenges, which need to be taken into consideration for the effective functioning of the register in Poland. Action in the field of legislation also needs to be taken to improve the functioning of the address numbering (Izdebski & Malinowski, 2013). The article (Izdebski & Malinowski, 2015) presents the current state of the address numbering in Poland, together with the identification of challenges, problems and barriers to overcome and basic areas of application within the scope of citizens’ activities, functioning of self-government and central institutions and unusual applications that are being created as the address numbering is becoming more and more popular as the basic spatial reference register.

In the area of the design of network services aimed at improving the use of spatial data, attention should be drawn to the proposal of solutions for the development of a standard for two services that are important for the functioning of spatial data, i.e.:

- ULA – Address Location Service
- ULDK – Cadastral Parcel Location Service

Details of the services are described in a publication (Izdebski, 2014) and it is clear from a practical point of view that the standard is already being used in many district and regional mapping networks.

Other activities pertain to the problems of automation of the process of dealing with geodetic works in the light of the applicable legal regulations. One of the issues being analysed was the revised rules for maintaining the base map (Bielecka & Izdebski, 2014; Izdebski, 2015b) and the study of the possibility of raising the level of automation in the functioning of the national geodetic and cartographic resource and determination of the rules for parametrisation of the resource innovativeness level (Izdebski, 2015a).

The issue of SLAM (simultaneous localisation and mapping), in general, relates to the creation of a map of an unknown environment and locating the tracking agent within it at the same time. Adding 3D to this term means mapping and tracking is done in three dimensions. The aim of the research is to analyse the possibility of using simple and cheap consumer class sensors (e.g. Kinect 3D sensor or a single inspection camera) and a portable computing device (laptops, computing boards, such as Raspberry Pi, and smart-phones) for solving the tasks of automated sensor localisation in rooms (3D Self-Localisation).

8. Summary

Modern studies conducted in the field of geodesy, which has lied on the border between basic research and applied research from its very beginning, necessitates establishing cooperation between scientists from different disciplines in order to conduct interdisciplinary research work. The article presents the most important scope of research conducted by the Department of Geodesy and Geodetic Astronomy. It should be emphasised that the staff of the Department are engaged in a wide variety of research subjects – from basic problems related to the Earth's and the Earth's crust geodynamics, to gravity field modelling, to research with the use of satellite navigation systems, to clearly application-oriented work on the terrain information systems. The results presented in the article put the research conducted by the department in the mainstream of international geodesy. Thanks to the multi-threaded activity of the staff and its expertise and experience, the department is rapidly becoming a place of cooperation among national and international research teams.

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