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Jan Kryński

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publish semiannually peer-reviewed articles with original solutions of theoretical, experimental or applicable problems in the field of geodesy, surveying engineering, cartography, photogrammetry and related disciplines. Besides original research papers, the journal includes commissioned review papers on topical subjects and special issues arising from chosen scientific symposia or workshops.

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Preface

Wide range of activities carried on by the International Union of Geodesy and Geophysics (IUGG) and its Associations, in both organizational and research fields, is reported at IUGG General Assemblies regularly organized every 4 years. On the other hand, results of research from individual countries – IUGG members – are traditionally presented either to IUGG or to the Associations for the current IUGG General Assembly.

National Committee for the International Union of Geodesy and Geophysics, affiliated by the presidium of the Polish Academy of Sciences (PAS), is the adhering organization representing Poland to IUGG and its Associations. As such, the National Committee coordinates the flow of information in both directions between IUGG and respective Polish scientific community. For a number of decades the reports on activities on geodesy in Poland in the quadrenium were presented to the International Association of Geodesy (IAG) by the Committee on Geodesy of the Polish Academy of Sciences on the request of the Polish National Committee for IUGG.

In 2003 IAG established the Global Geodetic Observing System (GGOS). The GGOS is the component of IAG dedicated to providing the geodetic infrastructure necessary for monitoring the Earth system and for global change research. Polish research institutions providing geodetic observations in the framework of the IAG services (including GGOS) have signed in 2011 an agreement on the establishment of research network GGOS-PL integrating research activity of seven Polish observatories.

The Committee on Geodesy of PAS appointed two editors of the recent Polish National Report on Geodesy Prof. Jaroslaw Bosy and Prof. Jan Krynski entrusting them simultaneously coordination of works on the report. This report has been prepared for submission to the IAG at its General Assembly in Prague, Czech Republic, during the 26th IUGG General Assembly, 22 June – 2 July 2015. It consists a summary of research activity in geodesy performed in a period of 2011–2014 in Poland, mostly within the GGOS-PL components.

The Polish National Report on Geodesy 2011-2014 is in the form of the five peer-reviewed review papers (chapters):

1. Reference Frames and Reference Networks (Jaroslaw Bosy and Jan Krynski);
2. Gravity Field Modelling and Gravimetry (Jan Krynski);
3. Earth Rotation and Geodynamics (Aleksander Brzezinski, Janusz Bogusz, Jolanta Nastula and Wieslaw Kosek);
4. Positioning and Applications (Jerzy B. Rogowski and Paweł Wielgosz);
5. Theoretical Geodesy (Andrzej Borkowski and Wiesław Kosek);

which were developed in cooperation with the researchers from the following universities and research institutes:

- AGH University of Science and Technology in Krakow;
- Institute of Geodesy and Cartography in Warsaw;
- Military University of Technology in Warsaw;
- Space Research Centre of the Polish Academy of Sciences in Warsaw;
- University of Agriculture in Krakow;
- University of Warmia and Mazury in Olsztyn;
- Warsaw University of Technology;
- Wroclaw University of Environmental and Life Sciences.

The report is published in the Special Issue of the Geodesy and Cartography, the official journal of the Committee on Geodesy of Polish Academy of Sciences. The editors thank the authors of all articles (chapters), reviewers and all those who contributed to develop the final form of the report.

Jaroslaw Bosy and Jan Krynski

Editors of the Special Issue

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Reference frames and reference networks

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Abstract: The summary of research activities concerning reference frames and reference networks performed in Poland in a period of 2011–2014 is presented. It contains the results of research on implementation of IUGG2011 and IAU2012 resolutions on reference systems, implementation of the ETRS89 in Poland, operational work of permanent IGS/EUREF stations in Poland, operational work of ILRS laser ranging station in Poland, active GNSS station networks in Poland, maintenance of vertical control in Poland, maintenance and modernization of gravity control, and maintenance of magnetic control in Poland. The bibliography of the related works is given in references.

Keywords: reference system, reference frame, ETRS89, vertical control, gravity control, magnetic control

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1. Introduction

In July 2003 the International Association of Geodesy (IAG) has established the Global Geodetic Observing System (GGOS: http://www.ggos.org). The GGOS is the component of the IAG dedicated to providing the geodetic infrastructure necessary for monitoring the Earth' system and for global change research. In the framework of GGOS the geometric space techniques <Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), Interferometric Synthetic Aperture Radar (InSAR) and altimetry>, gravimetric space and terrestrial techniques (orbit analysis, high-low satellite-to-satellite tracking, low-low satellite-to-satellite tracking, satellite gradiometry, terrestrial and airborne gravimetry), geodetic space techniques providing Earth rotation parameters (VLBI, LLR, SLR, GPS as well as the relevant astrometric techniques and missions) and atmospheric sounding techniques (GNSS-to-LEO and GNSS to Earth) with respective models are integrated. The GGOS integrates the three basic components: the Earth's shape, the Earth's gravity field and the Earth's rotational motion.

The backbone of this integration is the existing global ground network, based on the geodetic space techniques: VLBI, SLR, GNSS and DORIS. These techniques should operate as one global entity and in one global reference frame. The global reference frame in the GGOS is a realization of the International Terrestrial Reference System (ITRS). The ITRS is a world spatial reference system co-rotating with the Earth in its diurnal motion in the space. The ITRS was adopted by the International Union of Geodesy and Geophysics (IUGG) in Vienna in 1991 (resolution No 2).

The IAG Subcommission for the European Reference Frame (EUREF) recommended in 1991 that the terrestrial reference system for Europe should be coincident with ITRS at the epoch t_0 = 1989.0 and fixed to the stable part of the Eurasian Plate. The system was named the European Terrestrial Reference System 89 (ETRS89) and it is realized now by the EUREF Permanent Network (EPN: www.epncb.oma.be).

The ETRS89 was introduced in Poland technically by the GNSS technique in the last years of the 20th century and by law in 2000. On 2 June 2008, the Head Office of Geodesy and Cartography in Poland (GUGiK) commenced operating the multifunctional precise satellite positioning system named ASG-EUPOS. The ASG-EUPOS network defines the European Terrestrial Reference System ETRS89 in Poland. A close connection between the ASG-EUPOS stations and 18 Polish EUREF Permanent Network (EPN) stations controls the realization of the ETRS89 on Polish territory.

In 2010-2011 GUGiK integrated the ASG-EUPOS with the existing geodetic networks (horizontal and vertical) using GNSS and spirit levelling. Those actions resulted in developing and then legal introduction in 2012 new technical standards: to the National Spatial Reference System (PSOP) and to establish and maintain the geodetic (horizontal and vertical), gravity and magnetic control in the country. Thus, the geodetic, gravimetric and magnetic system in Poland has been associated with the European one (previous and current). This allowed for the next step of networks integration in Poland, namely, in 2013 started integration of national geodetic control with gravimetric control. Modern geodetic, gravimetric and magnetic networks in Poland are to be fully consistent with the European system.

In 2011, following the initiative by the Section of Geodetic Networks and the Section of Earths' Dynamics of the Committee on Geodesy of the Polish Academy of Sciences, a new research network "Polish Research Network for Global Geodetic Observing System" (acronym GGOS-PL) has been established.

The paper presents the achievements of Polish research and government institutions in last four years in areas related to the implementation of global reference systems, integration of geodetic, gravimetric and magnetic observations for the realization of new and unified reference frame and reference networks in Poland.

2. Implementation of IUGG2011 and IAU2012 resolutions on reference systems

An extended research on the implementation of the new paradigm of celestial reference systems, time systems and transformations between celestial and terrestrial systems was continued at the Department of Geodesy and Geodynamics of the Institute of Geodesy and Cartography (IGiK), Warsaw. New algorithms and computing programs were subsequently developed for calculating ephemeris for the Astronomical Almanac (Rocznik Astronomiczny) of the Institute of Geodesy and Cartography (Fig. 1) starting from the Astronomical Almanac for the year 2004 that was the first Astronomical Almanac in the world that fully implemented the IAU2000 resolutions of the IAU XXIV General Assembly in Manchester in 2000 with complete description of new systems and transformations.

Following editions of the Astronomical Almanac have subsequently been updated. The 2007 edition of the Astronomical Almanac implemented a number of resolutions of the IAU XXVI General Assembly in Prague in 2006. They concern the nomenclature, re-definition of the Barycentric Celestial Reference System (BCRS) and Geocentric Celestial Reference System (GCRS) as well as re-definition of the Barycentric Dynamic Time. The 2008 edition of the Astronomical Almanac additionally implemented the resolution adopted by the IUGG XXIV General Assembly in Perugia in 2007 concerning the re-definition of the International Terrestrial Reference System (ITRS) as a specific case of the Geocentric Terrestrial Reference System (GTRS). According to the resolution of the IAU XXVI General Assembly in Prague in 2006 precessional part of the IAU2000A precession-nutation model was replaced with the

P03 starting from the 2009 edition of the Astronomical Almanac. The 2010 edition of the Astronomical Almanac, following resolutions of the IAU XXVII General Assembly in Rio de Janeiro in 2009, implemented a new set of astronomical constants named IAU2009 as well as ITRF2 as fundamental astrometric realization of ICRS (Krynski, 2011b). The resolution of IAU XXVII General Assembly in Rio de Janeiro in 2009 has been adopted by IUGG XXV General Assembly in Melbourne in 2011. The 2011, 2012, 2013 and 2014 editions the Astronomical Almanac contain all updates to the previous editions (Krynski and Sekowski, 2010, 2011, 2012, 2013). The resolution of the IAU XXVIII General Assembly in Beijing in 2012 concerning the new definition of the astronomical unit has been implemented in the Astronomical Almanac starting from 2013 edition. Works on modification of presentation methods of high precision astrometric and geodetic data in view of the latest achievements in the field of reference systems are in progress (Sekowski and Krynski, 2011).

Fig. 1. The Astronomical Almanac of the Institute of Geodesy and Cartography: 2011–2014 editions

A historical review of the fundamental reference systems and methods for implementing international celestial reference systems (ICRS), from classical astrometry to VLBI, was presented (Rogowski and Brzezinski, 2012) The role of celestial reference systems in astrometry, space and satellite geodesy was discussed, in particular the role of celestial reference frames as a realization of the inertial frame.

3. Implementation of the ETRS89 in Poland

The EUREF Permanent Network (EPN) is the basis for the realization of ETRS89 in Poland. The national and local GNSS networks are connected to the EPN and/or IGS stations for the realization the reference frame on local scale (Bosy, 2014). Based on the long term time series of the positions and velocities from regularly updated EPN solutions, the EPN stations are categorized taking into account the station quality and the length of the available observation time span (http://www.epncb.oma.be/_productsservices/coordinates/). Figure 2 shows the map of categorized stations as in 27 October 2014.

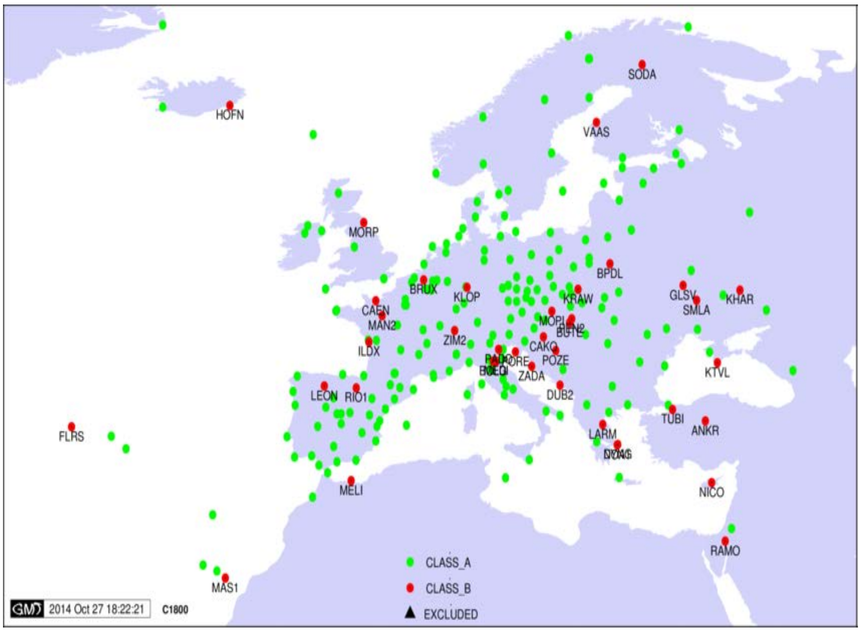

Fig. 2. Categorization of the EPN stations
(http://www.epncb.oma.be/_productsservices/coordinates/EPN_classes.php)

The class A (green colour in Fig. 2) are the stations for which positions have 1 cm accuracy at all epochs of the time span of the used observations. The class B (red colour in Fig. 2) are the stations for which positions have 1 cm accuracy at the epoch of minimal variance of each station. Only Class A stations are suitable as fiducial stations for the densifications of the ETRS89 (Bosy, 2014)

In 2012 the Head Office of Geodesy and Cartography (GUGiK) that represents surveying and mapping authority in Poland has completed tasks related to the definition of new reference frame for Poland. The frame was established basing on two extended GNSS campaigns conducted between 2008 and 2011 and their cumulative adjustments performed independently by the teams of the Space Research Centre of the Polish Academy of Sciences and the Warsaw University of Technology. Following the resolution No. 2 undertaken by the sub-committee EUREF on EUREF Symposium 2010 in Gavle, Sweden (2-5 June 2010) ETRF2000 has been approved by GUGiK as the new realization of ETRS89 in Poland. The frame named PL-ETRF2000 (epoch 2011.0) was also introduced into Polish legal act <*Regulation of Council of Ministers for National Spatial Reference System* (*pl. Rozporządzenie w sprawie Państwowego Systemu Odniesień Przestrzennych z dnia 15 października 2012 r.*)> as a primary frame for a high accuracy geodetic surveying (Fig. 3).

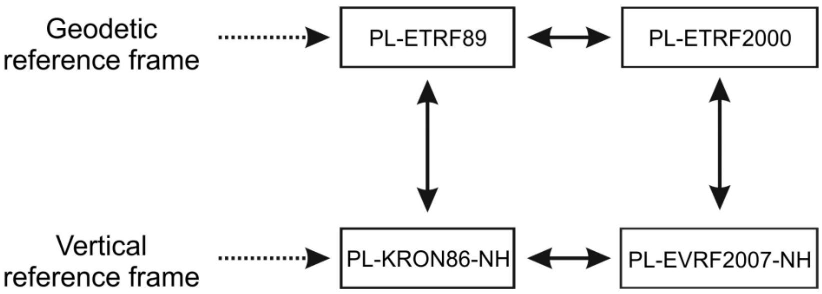

Fig. 3. Polish National Spatial Reference System

Previous realization of PL-ETRS89 called EUREF89 (Fig. 3), remains valid due to its long-term use in a field measurements (especially in cadastre). GUGiK provided a grid model and software for transformation between PL-ETRF2000 and EUREF89 reference frames (Krynski and Rogowski, 2013).

At the EUREF Symposium 2015 in Leipzig the computation was validated a second time. A new processing and an alignment to IGS08b has been performed to fulfil the EUREF densification guidelines. Totally 81 sites with a time span of 3.7 years were analysed. All stations got the class A status, which ensures 1 cm accuracy at any epoch during the entire time interval. The new solution proposed to EUREF (resolution 2) is referred as "EUREF Poland 2015".

Differences of this new solution to the previously derived solution PL-ETRF2000 (epoch 2011,0), which used in federal surveying since July 2013 showed that maximum differences do not exceed of 10 mm horizontally and 20 mm vertically (in direct comparison). In the majority horizontal differences do not exceed 5 mm. The slightly different alignment to the IGS08b caused roughly an offset in height by 8 mm.

It is planned to update the official coordinates only for sites where equipment or location changes occurred during the period of time being processed.

4. Stations in Poland involved in realization of ITRS and ETRS89 reference frames

4.1. Operational work of GNSS permanent stations in Poland

Permanent IGS and EPN GNSS stations operate in Poland since 1993. Recently 18 permanent GNSS stations (Table 1), i.e. Biala Podlaska (BPDL), Borowa Gora (BOGO, BOGI), Borowiec (BOR1), Bydgoszcz (BYDG), Gorzow Wielkopolski (GWWL), Jozefoslaw (JOZE, JOZ2), Krakow (KRAW, KRA1), Lamkowko (LAMA), Lodz (LODZ), Katowice (KATO), Redzikowo REDZ (Suwalki (SWKI), Ustrzyki Dolne (USDL), Wroclaw (WROC) and Zywiec (ZYWI) (Fig. 4) operate in Poland within the EUREF program (Krynski and Rogowski, 2011, 2012, 2013, 2014).

Fig. 4. EPN/IGS permanent GNSS stations in Poland (2014)

The stations BOGI, BOR1, JOZE, JOZ2, LAMA and WROC operate also within the IGS network (http://www.epncb.oma.be/_trackingnetwork/stations.php). A brief characteristics of those stations is given in Table 2. Products of the permanent GNSS stations in Poland, together with such stations in Europe, were the basis of the networks that are applied for both research and practical use in geodesy, surveying, precise navigation, environmental projects, etc. Data from those stations is transferred via internet to the Local Data Bank for Central Europe at Graz, Austria and to the Regional Data Bank at Frankfurt/Main, Germany.

The EPN stations at Borowa Gora (BOGI), Borowiec (BOR1), Jozefoslaw (JOZ2, JOZ3), Cracow (KRAW, KRA1), Lamkowko (LAM5), and Wroclaw (WROC) take part in the EUREF-IP project (http://igs.bkg.bund.de/root_ftp/NTRIP/streams/streamlist_euref-ip.htm) (Fig. 5, Table 3).

Four of those stations, i.e. BOGI, BOR1, JOZ2 and WROC participated also in IGS Real-time GNSS Data project. The station WROC since 2014 is also included into the IGS Multi-GNSS Experiment (MGEX) pilot project (http://igs.org/mgex).

Table 1. EPN/IGS permanent GNSS stations in Poland

Name (abbreviation)	Latitude	Longitude	Status	Receiver
Biala Podlaska (BPDL)	52º02'07"	23º07'38"	EUREF	TRIMBLE NetR5
Borowa Gora (BOGI)	52º28'30"	21º02'07"	IGS, EUREF	Javad TRE_G3T DELTA
Borowa Gora (BOGO)	52º28'33"	21º02'07"	EUREF	TPS Eurocard
Borowiec (BOR1)	52º16'37"	17º04'24"	IGS, EUREF	TRIMBLE NetRS
Bydgoszcz (BYDG)	53º08'04"	17º59'37"	EUREF	TRIMBLE NetR9
Gorzow Wielkopolski (GWWL)	52º44'17"	15º12'19"	EUREF	TRIMBLE NetR9
Jozefoslaw (JOZE)	52º05'50"	21º01'54"	IGS, EUREF	Trimble 4000 SSI
Jozefoslaw (JOZ2)	52º05'52"	21º01'56"	IGS, EUREF	LEICA GRX1200GGPRO
Katowice (KATO)	50º15'12"	19º02'08"	EUREF	TRIMBLE NetR5
Krakow (KRAW)	50º03'58"	19º55'14"	EUREF	Ashtech μZ-12
Krakow (KRA1)	50º03'58"	19º55'14"	EUREF	TRIMBLE NetR5
Lamkowko (LAMA)	53º53'33"	20º40'12"	IGS, EUREF	LEICA GRX1200+GNSS
Lodz (LODZ)	51º46'43"	19º27'34"	EUREF	TRIMBLE NetR9
Redzikowo (REDZ)	54º28'21"	17º07'03"	EUREF	TRIMBLE NetR9
Suwalki (SWKI)	54º05'55"	22º55'42"	EUREF	TRIMBLE NetR9
Ustrzyki Dolne (USDL)	49º25'58"	22º35'09"	EUREF	TRIMBLE NetR9
Wroclaw (WROC)	51º06'47"	17º03'43"	IGS, EUREF	LEICA GR 25
Zywiec (ZYWI)	49º41'12"	19º12'21"	EUREF	TRIMBLE NetR9

Table 2. Characteristics of Polish EPN stations

4 char. Station ID	Domes Number	Location/ Institution	Receiver/ Antenna	Started operating/ as EPN station	Meteo Sens./ Manufacturer	Data transfer blocks	Observations performed
BOGI	12207M003	**Borowa Gora** Inst. of Geodesy and Cartography	**Javad TRE_G3T DELTA** ASH701945C_M SNOW	**03JAN2001**/ since 265/2002 (GPS week No 1185)	**LB-710HB** LAB-EL Poland MET4A Paroscientific Inc.	24 h 1h	Ground water level Astrometry Gravity GPS/GLONASS/Galileo Geomagnetic field
BOGO	12207M002	**Borowa Gora** Inst. of Geodesy and Cartography	**TPS Eurocard** ASH700936C_M SNOW	**08JUN1996**/ since 182/1996 (GPS week No 0860)	***LB-710HB*** LAB-EL Poland	24 h 1h	Ground water level Astrometry Gravity GPS/GLONASS Geomagnetic field
BOR1	12205M002	**Borowiec** Space Research Centre, PAS	***Trimble NetRS*** AOAD/M_T NONE	**10JAN1994**/ since 365/1995 (GPS week No 0834)	**HPTL.3A** NAVI Ltd. SKPS 800/I Skye Instr. Ltd. ARG 10/STD Skye Instr Ltd.	24 h 1h	SLR GPS/GLONASS Time service

BPDL	12223M001	**Biala Podlaska** Head Office of Geodesy and Cartography	***Trimble NetR5*** TRM55971.00 TZGD	**04DEC2007**/ since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS
BYDG	12224M001	**Bydgoszcz** Head Office of Geodesy and Cartography	**Trimble NetR9** TRM59900.00 SCIS	**04DEC2007**/ since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS/Galileo/ SBAS
GWWL	12225M001	**Gorzow Wielkopolski** Head Office of Geodesy and Cartography	**Trimble NetR9** TRM59900.00 SCIS	**10DEC2007**/ since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS/Galileo /SBAS
JOZE	12204M001	**Jozefoslaw** Inst. of Geodesy and Geod. Astr., WUT	**Trimble 4000SSI** TRM14532.00 NONE	**03AUG1993**/ since 365/1995 (GPS week No 0834)	***LB-710RHMS*** LAB-EL Poland	24 h 1h	Ground water level Astrometry Gravity tidal GPS
JOZ2	12204M002	**Jozefoslaw** Inst. of Geodesy and Geod. Astr., WUT	**Leica GRX1200GGPRO** LEIAT504GG NONE	**03JAN2002**/ since 257/2003 (GPS week No 1236)	**LB-710RHMS** LAB-EL Poland MET4A Paroscientific Inc.	24 h 1h	Ground water level Gravity absolute Gravity tidal GPS/GLONASS
KATO	12219S001	**Katowice** Marsh. Off. of the Siles. Prov.	**Trimble NetR5** TRM57971.00 TZGD	3**0JAN2003**/ since 222/2003 (GPS week No 1231)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS
KRAW	12218M001	**Krakow** AGH UST	**Ashtech µZ-12** ASH701945C_M SNOW	**01JAN2003**/ since 026/2003 (GPS week No 1203)	**LB-710** LAB-EL Poland	24 h 1h	GPS
KRA1	12218M002	**Krakow** AGH UST	**Trimble NetR5** TRM57971.00 NONE	**01JAN2010**/ since 080/2010 (GPS week No 1576)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS
LAMA	12209M001	**Lamkowko** UWM	**Leica GRX1200+GNSS** LEIAT504GG LEIS	**01DEC1994**/ since 365/1995 (GPS week No 0834)	**MET4A** Paroscientific Inc.	24 h 1h	Ground water level Gravity GPS/GLONASS
LODZ	12226M001	**Lodz** Head Office of Geodesy and Cartography	**Trimble NetR9** TRM59900.00 SCIS	**03DEC2007**/ since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS/Galileo /SBAS
REDZ	12227M001	**Redzikowo** Head Office of Geodesy and Cartography	**Trimble NetR9** TRM59900.00 SCIS	**07DEC2007**/ since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS/Galileo /SBAS
SWKI	12228M001	**Suwalki** Head Office of Geodesy and Cartography	**Trimble NetR9** TRM59900.00 SCIS	**05DEC2007**/ since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS/Galileo /SBAS
USDL	12229M001	**Ustrzyki Dolne** Head Office of Geodesy and Cartography	**Trimble NetR9** TRM59900.00 SCIS	**03DEC2007**/ since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS/Galileo /SBAS
WROC	12217M001	**Wroclaw** Univ. of Env. & Life Sciences	**Leica GR 25** LEIAR25.R4 LEIT	**28NOV1996**/ since 329/1996 (GPS week No 0881)	**MET4A** Paroscientific Inc.	24 h 1h	Ground water level GPS/GLONASS/Galileo/ BeiDouQZSS/SBAS
ZYWI	12220S001	**Zywiec** Marsh. Off. of the Siles. Prov.	**Trimble NetR9** TRM59900.00 SCIS	**30JAN2003**/ since 222/2003 (GPS week No 1231)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS/Galileo/ SBAS

Table 3. Characteristics of Polish EPN stations producing real time data streams

Location	St. ID	Observations	Latitude [deg]	Longitude [deg]	Receiver	RTCM type - message types (update rate [s])
Borowa Gora	BOGI	GPS+GLO	52.48	21.04	Javad TRE_G3T DELTA	RTCM 3.0 - 1004(1), 1006(10), 1008(10), 1012(1)
Borowiec	BOR1	GPS+GLO	52.28	17.07	*TRIMBLE NetRS*	RTCM 2.3 - 1(1),3(10),18(1),19(1), 22(10)

Jozefoslaw	JOZ2	GPS+GLO	52.02	21.03	Leica GRX1200GGPro	RTCM 3.0 - 1004(1), 1006(60), 1008(60), 1012(1)
Jozefoslaw	JOZ3	GPS+GLO	52.02	21.03	Leica GRX1200GGPro	RTCM 3.0 - 1004(1),1006(15), 1008(15),1012(1),1033(15)
Krakow	KRAW	GPS	50.01	19.92	Ashtech µZ-12	RTCM 2.2 - 1(1),3(60),16(60),18(1), 19(1),22(60)
Krakow	KRA1	GPS+GLO	50.01	19.92	*TRIMBLE NetR5*	RTCM 3.0 - 1004(1), 1006(10), 1008(10), 1012(1),1013(10),1033(10)
Lamkowko	LAMA	GPS+GLO	53.89	20.67	Leica GRX1200GGPro	RTCM 3.0 - 1004(1), 1006(15), 1008(15), 1012(1), 1019, 1020, 1033(15)
Warsaw	WARS	GPS+GLO	52.00	21.00	Leica GRX1200+GNSS	RTCM 3.0 - 1004(1),1006(15), 1008(15), 1012(1)
Wroclaw	WROC	GPS+GLO	51.11	17.06	Leica GR 25	RTCM 3.0 - 1004(1),1006(15), 1008(15),1012(1),1013(15),1033(15)

Fig. 5. Polish EPN stations participating in the EUREF-IP project (2013)

Since March 2005 Ntrip Broadcaster is installed at the AGH University of Science and Technology (http://home.agh.edu.pl/~kraw/ntrip.php). The Ntrip Caster broadcasts RTCM and raw GNSS data from 17 sources, mainly from permanent station taking part in the framework of EUREF-IP project (Krynski, 2011a).

4.2. Operational work of ILRS laser ranging station in Poland

The Satellite Laser Ranging station in Astrogeodynamic Observatory of the Space Research Centre (SRC) of the Polish Academy of Sciences in Borowiec (ILRS 7811) was not operational from March 2010 due to malfunctioning of the laser. The analysis of long time series of SLR solutions for most SLR stations in the period 1983–2011 has been performed. Its use for the next ITRF solution was discussed (Schillak and Lejba, 2013). At the end of 2013 the new laser was installed (Fig. 6) in the Observatory and the return to continuous laser ranging is expected by the end of 2014.

Fig. 6. New laser at the Borowiec Observatory

Analysis of GPS and SLR data for reference frame determination and maintenance was conducted by the joint team of the Centre of Applied Geomatics, Military University of Technology (MUT) and the Astrogeodynamic Observatory in Borowiec, Space Research Centre, Polish Academy of Sciences. In particular, vectors between two close GNSS and SLR stations were investigated. Comparison of positioning solutions for the two close stations, in particular when obtained using data from different positioning techniques, allows to separate the real movement of the stations from the changes of the coordinates resulting from the factors strictly connected to one technique, e.g. processing errors or equipment malfunction. The quality of local ties plays a significant role in the realization of global reference frame, e.g. ITRF2008.

The GNSS and SLR data from the selected IGS and ILRS collocated stations (Fig. 7) from the period 1996-2012 were processed with the Bernese v.5.2 and Geodyn-II software, respectively, using the coherent processing strategy in terms of applying the same parameters and models (Szafranek and Schillak, 2012).

Fig. 7. Analysed stations with GNSS and SLR sites related using local ties

The GNSS and SLR station coordinates for each collocation station were expressed in geocentric X, Y, Z coordinates (ITRF2008 for the epoch of 2005) (Szafranek et al., 2014b). The GNSS solutions were reduced to the SLR markers positions using local ties values and then transformed to the topocentric frame N, E, U.

Due to the difficulties with the determination of reliable and precise reference point, accuracy of local ties measurements is unlikely to be less than 3 mm. In practice, however, many of the differences between the values of local ties and the respective ones calculated from the positions determined by each technique are significantly larger. They reflect the systematic shift between two types of solutions.

Figure 8a presents time series of *N*, *E*, *U* coordinates of three different instruments: GNSS GRAS station (green) and two SLR stations: 7835 (navy blue) and 7845 (blue) in Grasse, France. Unfortunately, SLR stations did not have common period of measurements, but both can be used for control of the GNSS one. Up to 2001 the good agreement in all components between both time series can be observed. In 2001 about 25 mm difference occurred between GRAS and 7835 Up components, but as the discontinuity concerns SLR coordinates it is more likely that this effect is caused by some changes at SLR station. The new SLR station 7845 launched in 2008 shows a very good agreement in all three components with the GNSS coordinates.

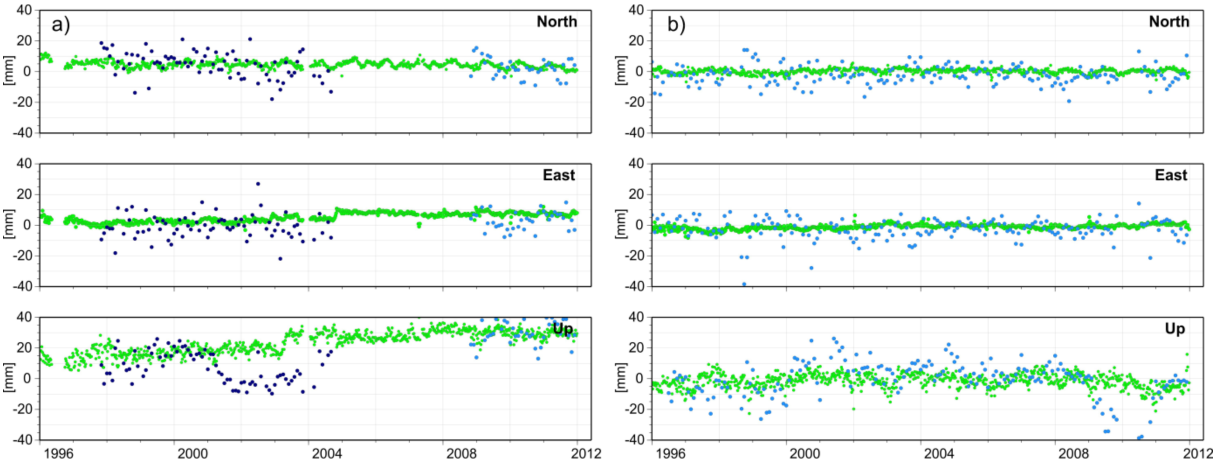

Fig. 8. Time series of *N*, *E*, *U* components of the GNSS station GRAS (green) and SLR stations 7835 (navy blue) and 7845 (blue) – on the left (a); time series of the WTZR (green) and SLR station 8834 (blue) – on the right (b)

Time series of GNSS solutions can provide information for detection of some internal problems affecting SLR station, e.g. the station Wettzell (Germany) (Fig. 8b). The agreement in both horizontal components of GNSS WTZR and SLR 8834 is observed, while some disturbances at the level of 40 mm can be noted in SLR solutions for *Up* component in 2009-2010.

The possibility of mutual control of coordinates obtained from GNSS increases with the number of collocated instruments working simultaneously. The GNSS-SLR site in Yaragadee (Australia) consists currently of GNSS YAR2 (green) and 7090 SLR stations (Fig. 9a). Up to 1998 the second GNSS station YAR1 was in operation (grey), so the coordinates of two GNSS stations can be compared. They were not fully independent instruments, as they shared the same antenna, so the reference point was the same for both YAR1 and YAR2. Anyway, some differences in coordinates occurred. The agreement in horizontal components between YAR2 and 7090 is very good for the whole time of observations, but there are some differences concerning the *Up* component especially before 2002. Both types of time series show oscillations, which in particular are clearly seen in GNSS solutions.

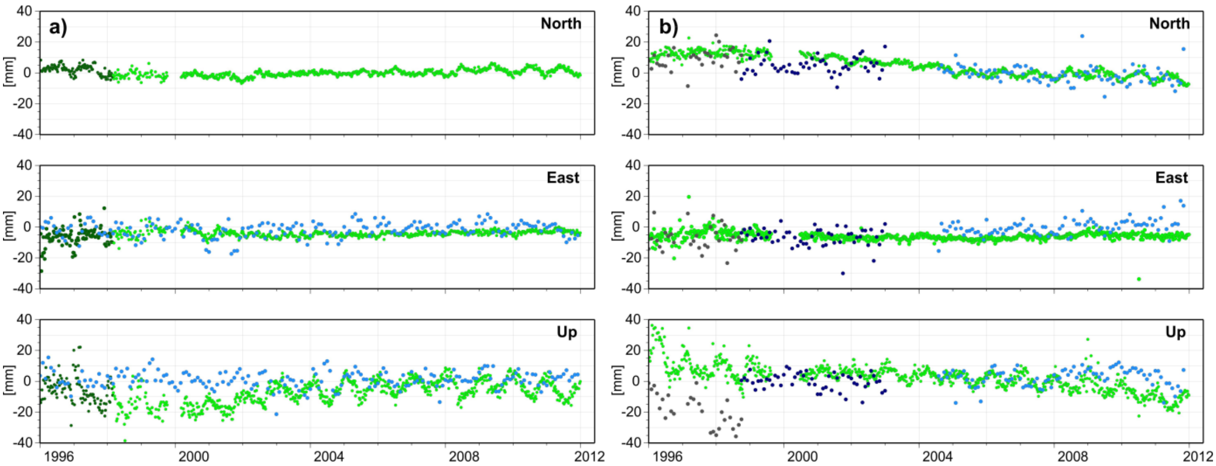

Fig. 9. Time series of *N*, *E*, *U* components of the GNSS stations YAR1 (grey) and YAR2 (green) and SLR station 7090 (blue) – on the left (a); time series of the GNSS station TIDB (green) and SLR stations 7843 (grey), 7849 (navy blue) and 7825 (blue) – on the right (b)

Another example of multi-station is at the Australian Capital Territory. The distance between 7843 and 7825 is about 36 kilometres. Time series of TIDB, 7843, 7849 and 7825 were presented in Fig. 9b. The agreement between coordinates from GNSS and all SLR stations is very good except for the *Up* component of 7843 SLR station. The disagreement can be observed when compare 7843 topocentric coordinates with all four other stations, so it rather proves the imperfection of the local tie for this station. The gap in 2003 was caused by a serious Canberra fires, which harmed Mt Stromlo site 7825. It explains some change of its *Up* component. The 7825 replaced 7849, but when comparing its coordinates to the TIDB station (not harmed by the fire) it is clearly seen that then new instrument was placed in the exact position of 7849.

Special attention was paid to the stations affected by earthquakes which can cause serious discontinuities not only in coordinates but also in stations velocities. After the earthquake the stabilization of station position can take even a few years. When two instruments operate close to each other the change in their coordinates due an earthquake to should be comparable (Sapota et al, 2014).

Detection of temporal disturbances in SLR and GNSS solutions allow to undertake proper actions. The faster the reaction the smaller data lost. The permanent change of the coordinates should be followed by new local tie determination. The analysis of time series can also be used to estimate the quality of local ties, which are crucial for the maintenance of the global reference frame. This is crucial especially for new ITRS realization.

5. Active GNSS station networks for the realization of ETRS89 in Poland

5.1. ASG-EUPOS – a multifunctional precise satellite positioning system in Poland

ASG-EUPOS (Active Geodetic Network European Position Determination System) is the Polish multifunctional augmenting system for precise positioning that consists of more than 120 permanent GNSS reference stations[1]. The system has been established by the Head Office of Geodesy and Cartography (GUGiK) in Poland and became fully operational in 2008 (www.asgeupos.pl). The ASG-EUPOS stations are evenly distributed over the country substantially densifying the EPN network (Fig. 10).

[1] The total number of stations vary due to implementation of new or exclusion of some of existing stations from the system

Fig. 10. Distribution of ASG-EUPOS permanent GNSS reference stations
(http://www.asgeupos.pl/webpg/graph/dwnld/map_en_dwnld.jpg 2014)

At the end of 2014 101 ASG-EUPOS permanent GNSS reference stations were working in Poland (53 of them were GPS/GLONASS stations and 33 prepared for Galileo signal acquisition). Other 23 reference stations located neighbouring countries were included to the common solutions of the ASG-EUPOS system. A huge modernization of equipment of all reference stations launched in 2014 is to be completed in 2017.

5.2. Validation of ETRS89 realization in Poland

ASG-EUPOS system is the official realization of the European Terrestrial Reference System (ETRS89) on the territory of Poland. The Head Office of Geodesy and Cartography (GUGiK) is responsible for managing the system while the Centre of Applied Geomatics of the Military University of Technology (CAG MUT) supports GUGiK by processing data and analysing solutions to ensure an additional control and monitoring of the system. After more than 30 months of permanent observations at ASG-EUPOS stations, it was possible to obtain reliable solutions which enabled the establishment of the European Terrestrial Reference Frame (PL-ETRF2000) in Poland (coordinates and velocities for each ASG-EUPOS site are considered official).

The results of permanent analysis of time series of ASG-EUPOS network stations coordinates in actual ITRS realization (ITRF2008) are provided by CAG MUT (http://www.cgs.wat.edu.pl) since 2008 (Bogusz et al., 2012a, 2012b; Szafranek et al., 2013a, 2014a). Figure 11 shows the horizontal residual (intraplate) velocities of ASG-EUPOS stations in ETRF2000.

The reliable determination of horizontal and vertical velocities of permanent stations is nowadays an indispensable element of the correct realization of the reference system. The horizontal and vertical velocities in the frame realizing ETRS89, e.g. ETRF2000, are required to transform coordinates between the realizations of ETRS89 and to control stability of coordinates of the national primary control network.

Currently, the ASG-EUPOS system offers precise positioning services in post-processing and real-time, and provides a homogeneous reference frame for GNSS users in Poland. There are three independent levels (Fig. 13) for the control of the stability of the ETRS89 realization in Poland (Bosy, 2014).

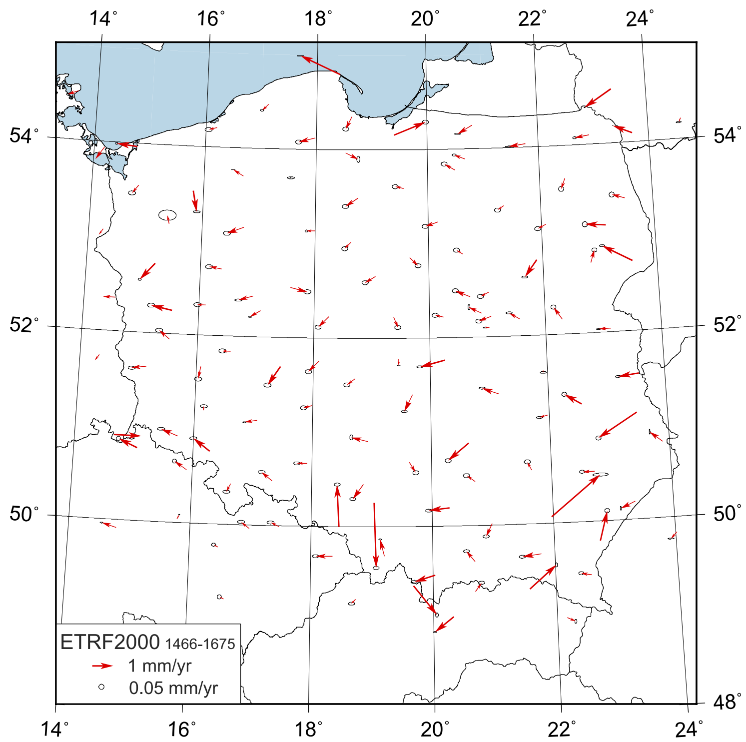

Fig. 11. Horizontal velocities of ASG-EUPOS stations in ETRF2000 determined by CAG MUT

Figure 12 shows vertical velocities of ASG-EUPOS stations in ITRF2008 and ETRF2000 (Kontny and Bogusz, 2012; Szafranek et al., 2013).

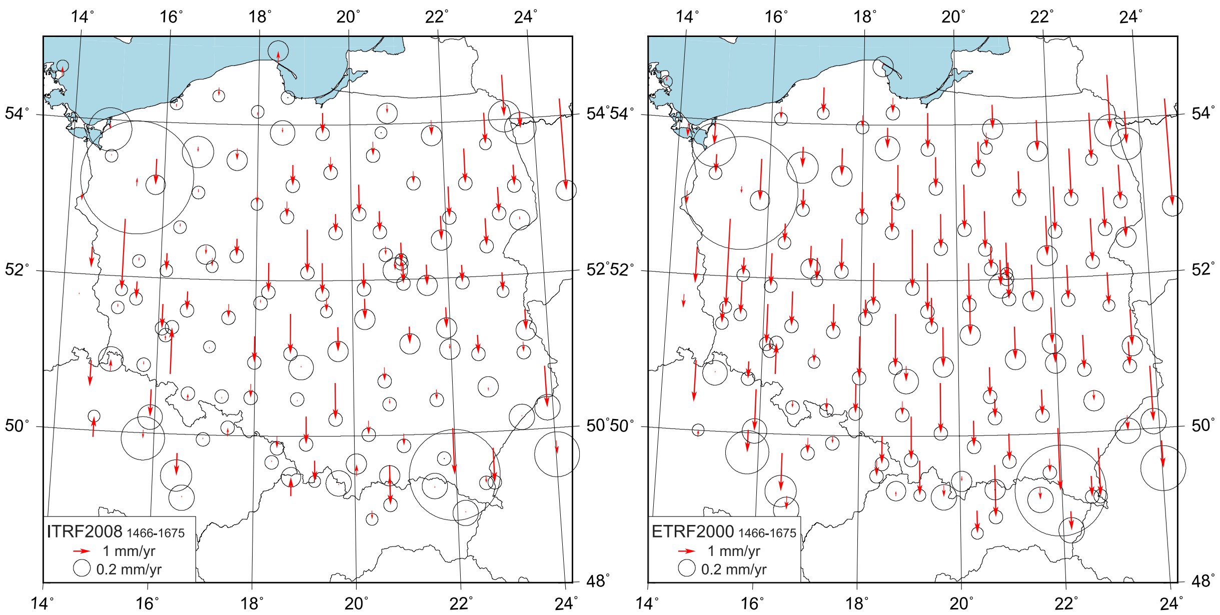

Fig. 12. Vertical velocities of ASG-EUPOS stations in ITRF2008 and ETRF2000 determined by MUT

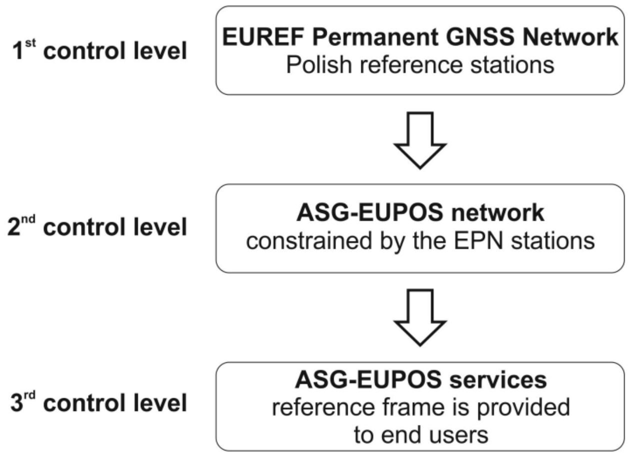

Fig. 13. ETRS89 realization and control via the ASG-EUPOS system

The first level of control is realized by the EPN Analysis Centres that provide weekly solutions for the coordinates of regularly distributed GNSS stations in Poland. The ASG-EUPOS Processing Centre calculates the network on a daily basis according to the EPN standards, using the Bernese GPS software. The same standards and software are used in a second level control of the stability of ETRS89 in Poland. The third control level is realized using the Trimble Pivot Apps software and the reference frame is provided to the end users. The ASG-EUPOS system is actually a stable and uniform realization of ETRS89 reference system in Poland (Bosy, 2014).

6. Maintenance of vertical control in Poland

The re-levelling of the 1st order vertical control in Poland which was the first step of the 4th levelling campaign in Poland started in May 1999 and was completed in June 2002. The levelling network consisting of 382 lines of 17 516 km with 16 226 benchmarks has been adjusted as a free-network with one fixed point Warszawa-Wola in Kronstadt2006 system. Normal height of that point was obtained using the constraint of zeroing mean difference between heights in Kronstadt2006 system and the respective ones in Kronstadt86 at secular stations of the network. Those differences at secular stations vary from –19 mm in Northern Poland to 22 mm in Southern Poland (Krynski, 2011a). The continuation of the 4th levelling campaign in Poland was spirit levelling of 2nd order levelling network consisting of 17 930 km of levelling lines with 25 868 benchmarks. Its last stage was the modernization of 2nd order levelling network in Silesia region that started in 2011 and was completed in 2012. The whole network was adjusted in 2012 in Kronstadt2006 datum (Krynski and Rogowski, 2012, 2013).

In 2013 the final adjustment of the 4th levelling campaign in Poland was completed. Also, 63 EUVN and EUVN DA points as well as 71 eccentric points of ASG-EUPOS network permanent stations were included into adjustment. All heights were reduced to zero tidal system.

The final adjustment of 1st and 2nd order network was performed in PL-EVRF2007-NH using 49 stable EUVN points as datum points. The PL-EVRF2007-NH vertical datum is the new vertical datum in Poland since 1 January 2014. The accuracy of levelling was estimated as 0.74 mm/km, standard deviation of the height of a single benchmark is 3.5 mm and its maximum error is 7.5 mm (at the state border).

The relationship between geodetic and vertical reference frame realizations of the Polish National Spatial Reference System (Fig. 5) is shown in Figure 14.

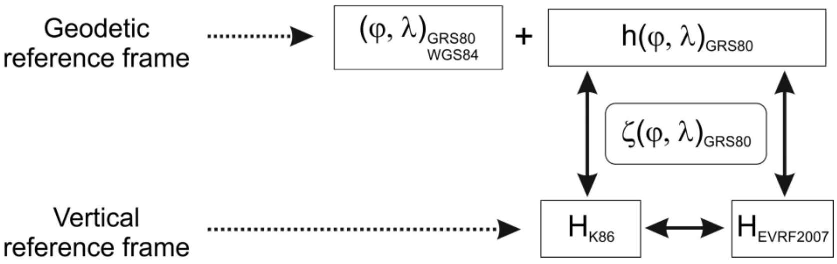

Fig. 14. The relationship between geodetic and vertical reference frame realizations of Polish National Spatial Reference System

The element common for all components of the *Polish National Spatial Reference System* is the GRS80 ellipsoid (Fig. 14). The coordinates (φ, λ) in the geodetic reference system (PL-ETRF89 or PL-ETRF2000) refer to the GRS80 ellipsoid. Quasigeoid heights $\zeta(\varphi, \lambda)_{GRS80}$ and ellipsoidal heights $h(\varphi, \lambda)_{GRS80}$ are also referred to the GRS80 ellipsoid (Fig. 11) what indirectly links normal heights (H$_{K86}$ - PL-KRON86-NH or H$_{EVRF2007}$ - PL-EVRF2007-NH). with that ellipsoid. The Head Office of Geodesy and Cartography (GUGiK) provides a grid of quasigeoid heights $\zeta(\varphi, \lambda)_{GRS80}$ and the software for transformation between PL-ETRF89 or PL-ETRF2000 and PL-KRON86-NH or PL-EVRF2007-NH. The models and software are available by on the web site of GUGiK (http://www.gugik.gov.pl/bip/informacja-publiczna/modele-danych2).

The differences between the heights in PL-EVRF2007-NH and PL-KRON86-NH datums are presented in Figure 15 (Krynski and Rogowski, 2014).

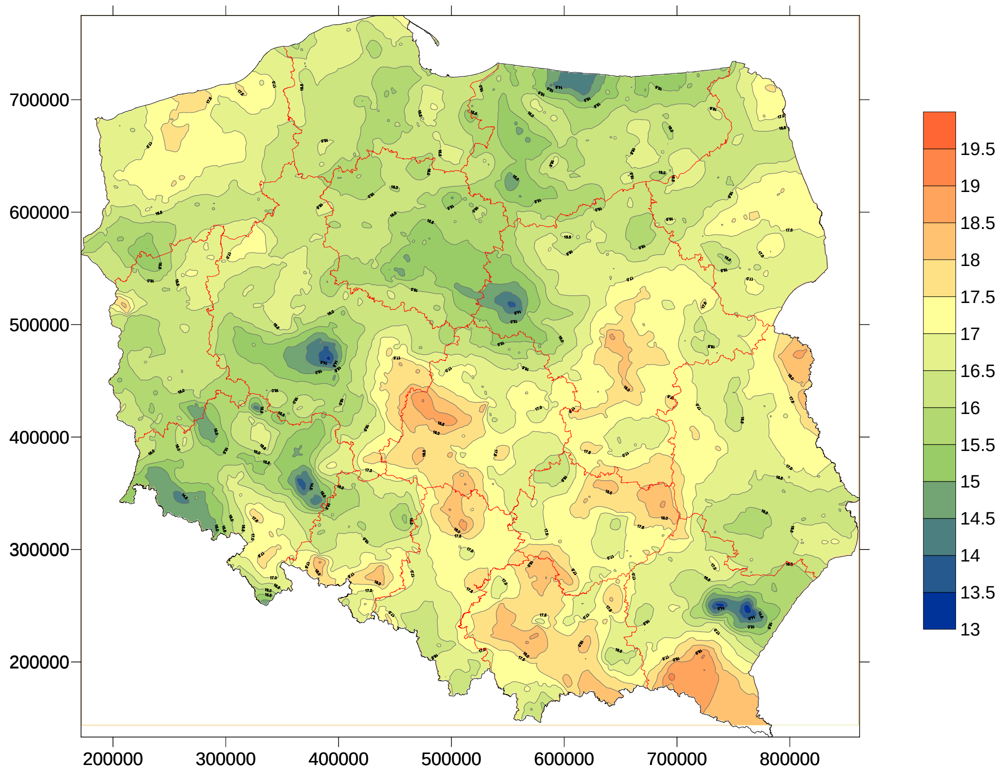

Fig. 15. Differences of heights between vertical datums PL-EVRF2007-NH and PL-KRON86-NH [cm]

Two vertical reference frames are in use at present in Poland (Fig. 5.4): the PL-KRON86-NH which can officially be used until 31 December 2019 and the PL-EVRF2007-NH which is fully compliant with EVRF2007-NH (http://www.dziennikustaw.gov.pl/du/2012/1247/1).

In practice, however, Kronstadt60 vertical reference system is still in use in many places in Poland and the transformation of heights to PL-KRON86-NH is done locally. The results of the analyses of local transformations between Kronstadt60 and Kronstadt86 (PL-KRON86-NH) in the area of Krakow's district using polynomial regression (Fig. 16) (Ligas and Banasik, 2012) and a continuation of this study with the use of kriging approach (Ligas and Kulczycki, 2014). have been published. Differences between heights the those systems within the study area vary from 2.5 cm to 5.5 cm. They have been modelled using a polynomial regression model. The model uncertainty has been estimated at the level of 1–4 mm; it depends on the location (Fig. 13). The uncertainty of the newly predicted heights (benchmarks that were not used in model developing) measured by confidence intervals was estimated at the level of 5–8 mm.

Since the horizontal position of benchmarks was determined with the accuracy of several tens of meters it was necessary to estimate how much it affects the transformation function itself. It was shown that even for the largest error in benchmark position of 500 m that effect does not exceed 0.04 mm, thus it is negligible (Ligas and Banasik, 2012).

The results obtained in cross validation and true validation prove that the kriging based approach to local height transformation turned out to be slightly more effective than the polynomial regression model (Ligas and Banasik, 2012) in terms of prediction capability (Ligas and Kulczycki, 2014).

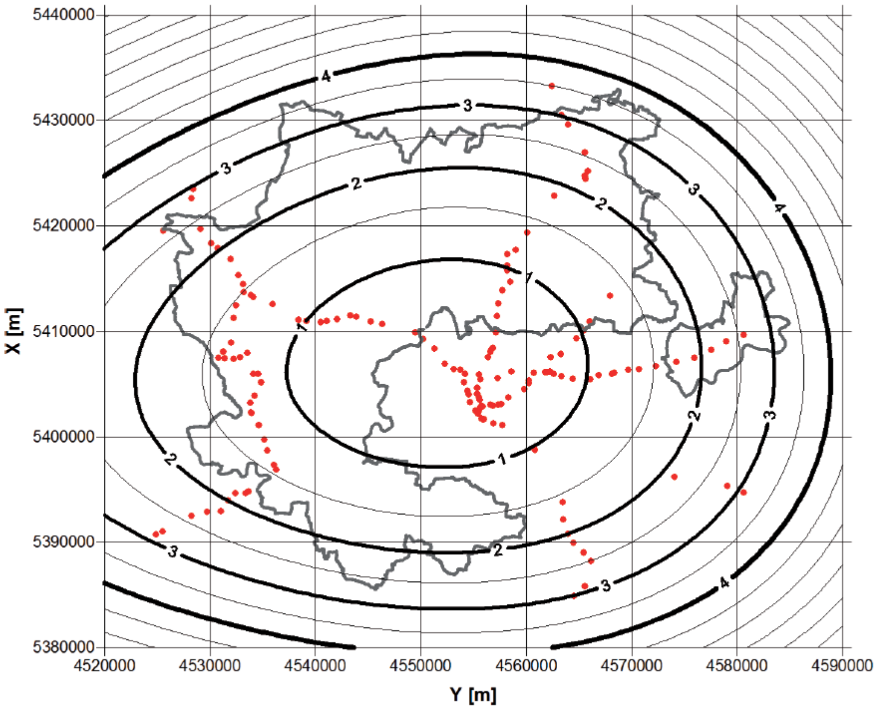

Fig. 16. Half of the confidence interval for the quadratic transformation function (confidence level of 0.95) [mm]

The unification of Kronstadt86 local vertical datum with global vertical datum was discussed (Lyszkowicz et al., 2014). Gravity potential differences ΔW between the Kronstadt86 datum and the global vertical datum were computed using ellipsoidal heights from GNSS, normal heights from the levelling campaign and height anomalies from the EGM08 model. The obtained results indicate that there are substantial differences in the estimated value of ΔW, computed from three GPS/levelling networks: POLREF, EUVN-DA and ASG-EUPOS. It has been shown that the best fitted value of ΔW for Poland is 0.43 m^2/s^2.

7. Maintenance and modernization of gravity control

Activities concerning the maintenance and modernization of national gravity control were extensively performed in Poland. The team of the Institute of Geodesy and Cartography, Warsaw, participated in the modernization of national gravity control in Finland, Sweden, Norway and Denmark where the absolute gravity was measured with the use of the Polish A10-020 free-fall gravimeter at the points of 1st order gravity networks.

7.1. Maintenance and modernization of gravity control in Poland

The Polish Gravity Control Network POGK98, established in 1993–1998, consisted of 351 field gravity stations surveyed with the use of LaCoste&Romberg (LCR) gravimeters and 12 absolute gravity stations. Those stations were monumented with concrete pillars of size of 80×80×100 cm. The network was then maintained, gradually densified and systematically modernized by the joint team of the Institute of Geodesy and Cartography (IGiK), Warsaw, and the Warsaw University of Technology (WUT) with the financial support of the Head Office of Geodesy and Cartography (Krynski, 2011a). In particular, four gravimetric calibration baselines, including two vertical calibration baselines became available with two absolute gravity stations established with the FG5-221 of the Finnish Geodetic Institute (FGI) (Krynski et al., 2013).

The need for re-adjustment of the modernized gravity network extended by new stations, discrepancies between POGK98 and newly determined gravity (Fig. 17) and finding 25% of POGK98 stations destroyed indicated the weakness of the existing gravity control in Poland. Taking it into consideration as well as recognizing the role of geodynamics in modern vertical and gravity reference systems (Krynski and Barlik, 2012), and simultaneously noting the development of technologies of absolute gravity survey, in particular availability of absolute gravimeters - the FG5-230 of WUT as well as the A10-020 of IGiK, and the experience gained in the gravity control re-survey with the use of FG5-230 and A10-020, the concept of the establishment of new gravity control in Poland has been developed (Krynski et al., 2012).

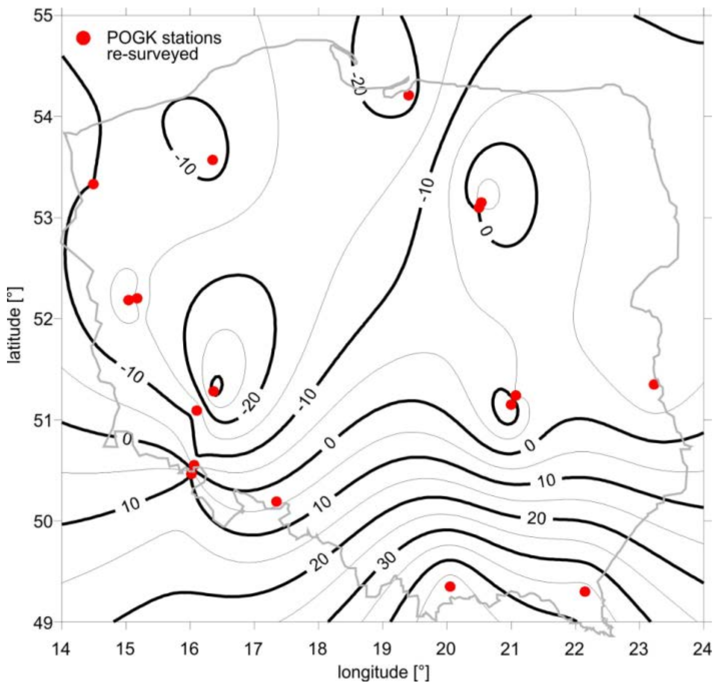

Fig. 17. Difference d*g* between gravity measured in 2007-2008 on chosen POGK stations and the corresponding one in POGK98 system [μGal]

Research on modern vertical gravity reference systems was conducted at IGiK (Dykowski 2012; Krynski, 2012a, 2012b). Accuracy and reliability of the A10 absolute gravimeter was extensively investigated (Krynski et al., 2014). Suitability of the A10-020 absolute gravimeter for the establishment of new gravity control in Poland has been tested (Dykowski et al., 2012).

The project of the new gravity control in Poland developed in 2011 by the team of IGiK and WUT has been accepted in early 2012 by the Head Office of Geodesy and Cartography (Barlik et al., 2011). Gravity stations are classified into two groups of two accuracy levels. First group consists of 28 fundamental stations (one in 15 000 km^2) the existing absolute gravity stations located in buildings, and surveyed possibly in one epoch (one year) with the use of FG5-type gravimeters with an uncertainty level of gravity determined not exceeding 0.004 mGal. Second group consists of 168 field stations (Fig. 18) – called base stations (one in 1850 km^2), surveyed within the extensive campaigns with the use of portable A10-type gravimeters with an uncertainty level of gravity determined not exceeding 0.010 mGal (Dykowski and Krynski, 2014).

Base stations include chosen existing POGK98 points (78), POLREF (22) and EUVN (4) stations, as well as eccentric stations of the Active Geodetic Network (ASG-EUPOS) of permanent GNSS reference stations (57) (Fig. 19) (Krynski and Dykowski, 2013).

Methodology and measurement schemes for both gravimeters FG5 and A10 as well as the technology for precise vertical gravity gradient determinations in the new gravity control have been developed and tested. Special stands for the determination of vertical gravity gradient at fundamental stations and base stations manufactured at the Institute of Geodesy and Cartography and at the Warsaw University of Technology (Fig. 20) were tested (Dykowski, 2012; Krynski et al., 2013).

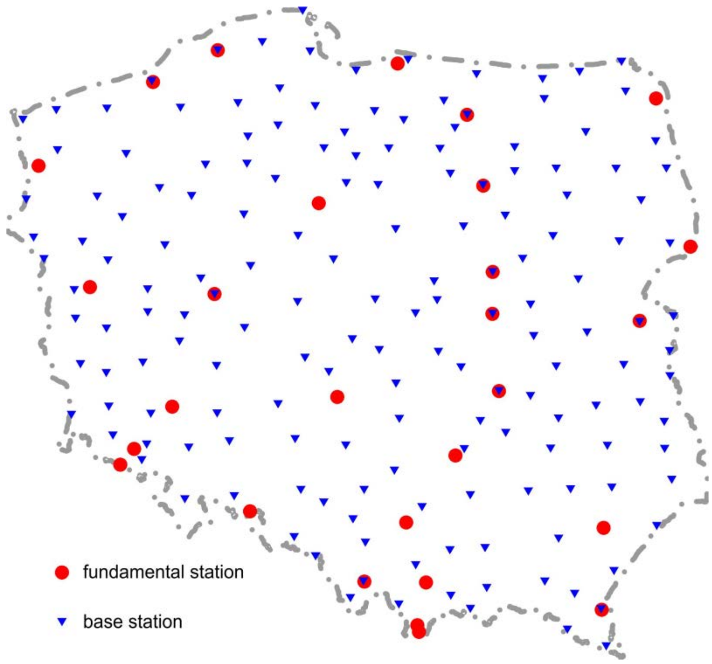

Fig. 18. Stations of new gravity control in Poland

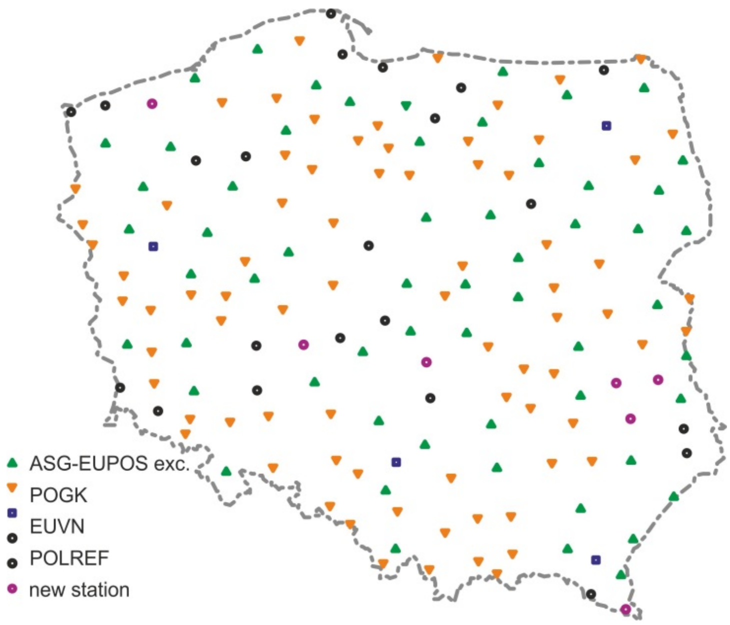

Fig. 19. Base stations of the new gravity control in Poland

Fig. 20. The stand constructed by WUT (left) and IGiK (right) for vertical gravity gradient determination at field station and laboratory station, respectively

The realization of the project of a new gravity control PBOG14 started in 2012. The team of the Institute of Geodesy and Cartography, Warsaw, conducted absolute gravity measurements with the A10-020 as well as vertical gravity gradient measurements on 168 base stations in 2012-2013 (Fig. 19) (Krynski and Rogowski, 2013, 2014). Quality of the new gravity control in Poland was preliminarily assessed. Gravity in POGK98 on 77 stations common for POGK98 and PBOG14 was compared with the respective ones of PBOG14 (Fig. 21). The mean difference and the standard deviation are 12.3 μGal and 18.6 μGal, respectively (Krynski and Dykowski, 2014).

Alongside the establishment of the base stations of the gravity control, multiple additional activities were performed to assure and provide a reliable gravity reference level. These activities concerned regular gravity measurements on monthly basis with the A10-020 on the test network at Borowa Gora Geodetic–Geophysical Observatory (Dykowski et al., 2013a), calibrations of metrological parameters of the A10-020 gravimeter (Sekowski et al., 2012) and scale factor calibrations of LCR gravimeters, participation with the A10-020 in the international (ECAG2011, ICAG2013) and regional comparison campaigns of absolute gravimeters and local comparisons with the FG5-230. Careful analysis of the data gathered throughout the project resulted in the estimation of the Total Uncertainty budget for the A10-

020 gravimeter on each of 168 base stations. It provides a reliable quality assessment of the new gravity control in Poland (Krynski and Dykowski, 2014).

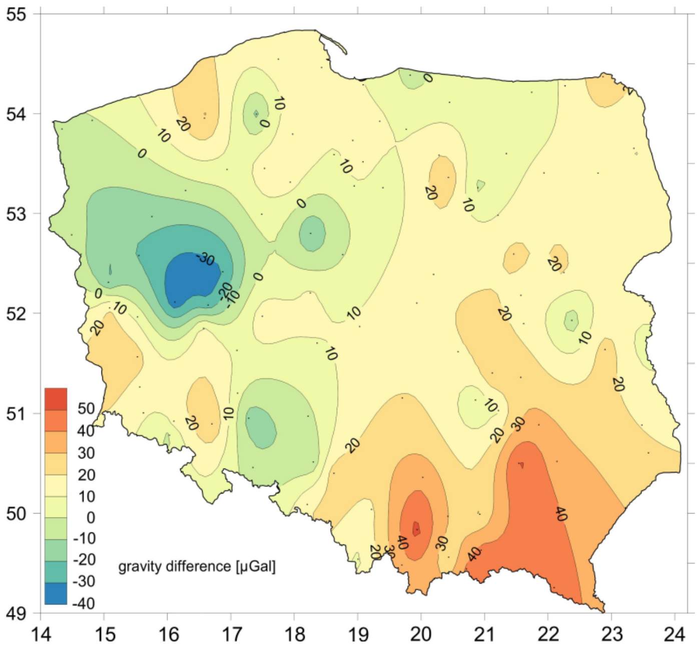

Fig. 21. Differences between PBOG14 and POGK98

Absolute gravity measurements with the FG5-230 as well as vertical gravity gradient measurements on 28 fundamental stations as well as the survey of their ties with eccentric stations - one of which for each fundamental station is the base station of PBOG14 – using relative gravity measurements were conducted in 2014. The final analysis of the results of all gravimetric measurements carried out in 2012-2014m is expected to be done in 2015.

7.2. Maintenance of gravity control in Fennoscandia

After re-measuring the First Order Gravity Network of Finland with the A10-020 gravimeter by the team of IGiK in four campaigns in 2009 and 2010 (Krynski and Rogowski, 2011; Krynski, 2011a) the observations were gradually processed. In 2011, 2012 and 2013 the A10-020 has further been successfully used to re-survey gravity control in Sweden, Norway and Denmark (Krynski and Rogowski, 2012, 2013, 2014).

Consecutive results of renovation of the Finnish First Order Gravity Network (Mäkinen et al., 2012a) and of gravity change in Finland 1962-2010 from the comparison of legacy relative measurements with new measurements made with the A10-020 were published and presented at international scientific conferences (Mäkinen et al., 2011, 2012b, 2013).

8. Maintenance of magnetic control in Poland

The magnetic repeat station network in Poland, established in 1955, consists of 19 field stations (Fig. 22) and is maintained by the Institute of Geodesy and Cartography, Warsaw.

Three components of magnetic field vector were surveyed at first every 2÷4 years at each network station. Starting from 1970, the survey is performed every 2 years. Data from two Polish magnetic observatories – Belsk and Hel and from Ukrainian magnetic observatory - Lvov are also used for the determination of secular variations of the Earth magnetic field in Poland. There are also operating two permanent magnetic stations: Borowa Gora of the Institute of Geodesy and Cartography (Jedrzejewska, 2013), and Suwalki of the Institute of Geophysics of the Polish Academy of Sciences (Welker, 2013a).

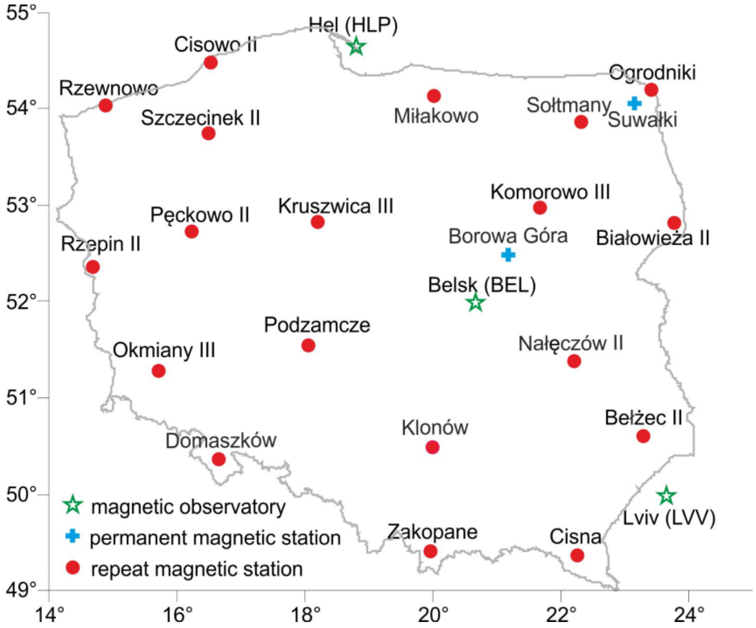

Fig. 22. Polish magnetic repeat station network

Data acquired at the magnetic repeat stations together with data from are used to calculate components of the geomagnetic intensity vector at those stations (Welker, 2013b). The results are regularly provided to the magnetic database of the Institute of Geodesy and Cartography, Warsaw, as well as to World Data Centre for Geomagnetism in Edinburgh, UK.

Polish magnetic repeat station network is getting improved continuously (Welker, 2011; Welker et al., 2013) according to the European standards defined by **MagNetE (Magnetic Network of Europe) of IAGA (International Association of Geomagnetism and Aeronomy).** The list of the Polish magnetic repeat stations surveyed in the years 2011–2014 is given in Table 4.

Table 4. Polish magnetic repeat stations measured in the period 2011–2014

Station name	Latitude [° ' "]	Longitude [° ' "]	2011	2012	2013	2014
Cisowo II	54 26 20	16 27 39		×		×
Ogrodniki	54 08 22	23 27 06		×		
Milakowo	54 01 12	20 05 20		×		×
Rzewnowo II	53 54 20	14 58 34			×	
Soltmany	53 42 03	22 24 07		×		
Szczecinek II	53 36 36	16 34 50		×		
Komorowo III	52 50 16	21 46 18		×		×
Bialowieza II	52 42 32	23 51 04		×		×
Kruszwica	52 40 25	18 18 30			×	
Peckowo II	52 35 40	16 19 20			×	
Rzepin II	52 15 35	14 44 31			×	
Podzamcze	51 24 16	18 09 05	×		×	×
Naleczow II	51 14 15	22 11 12			×	

Okmiany III	51 07 33	15 44 26			×	
Belzec II	50 27 33	23 20 30	×		×	
Klonow	50 20 37	20 09 59	×		×	×
Domaszkow	50 13 20	16 40 05			×	×
Zakopane	49 17 22	20 01 51			×	
Cisna	49 12 44	22 19 39	×		×	

Following the rules of MagNetE Polish magnetic repeat stations are surveyed every 2–4 years (Table 4). During each survey the station marks are controlled and in case of necessity the marks are corrected. In the case of damage of the station or in the case when the station demands are no longer fulfilled, it is displaced to the other site; at the new location a special procedure is applied to secure the continuity of observations.

10. Summary and conclusions

In the years 2011–2014 the global reference system ITRS and the regional ETRS89 were introduced legally and practically in Poland. The satellite-observing infrastructure (GNSS and SLR) operates within the IAG services and has been integrated into the GGOS-PL network. The research in this area has shown that the implementation of a uniform system ETRS89 is the basis for the integration of other Earth observation techniques with high spatial and temporal resolution (including real-time applications).

The ETRS89 was also introduced into Polish legal act *Regulation of Council of Ministers for National Spatial Reference System* (PSOP) and is the basis for the integration of geodetic, vertical, gravimetric and magnetic networks in Poland. The PSOP legal regulation introduced for the use of new vertical reference system EVRF2007, results of research helped refine models of quasigeoid heights $\zeta(\varphi, \lambda)_{GRS80}$ and their software implementations for end users.

The integration process in last four years allowed the development of methods and applications for transformation between the PSOP elements (geodetic – 3D, horizontal – 2D and vertical – 1D) and its epoch realizations.

Advance research in gravimetry in Poland, in particular in absolute gravity survey, resulted in the establishment of the new gravity control in Poland according to recent international standards, which is one of most modern worldwide. The tool for the transformation of gravity from the previous gravity system to the new one has also been provided.

Magnetic system in Poland is continuously maintained. Considering strong variability of geomagnetic field, magnetic control in Poland is regularly re-surveyed providing actual parameters describing secular variations of that field.

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Gravity field modelling and gravimetry

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Abstract: The summary of research activities concerning gravity field modelling and gravimetric works performed in Poland in the period of 2011–2014 is presented. It contains the results of research on geoid modelling in Poland and other countries, evaluation of global geopotential models, determination of temporal variations of the gravity field with the use of data from satellite gravity space missions, absolute gravity surveys for the maintenance and modernization of the gravity control in Poland and overseas, metrological aspects in gravimetry, maintenance of gravimetric calibration baselines, and investigations of the non-tidal gravity changes. The bibliography of the related works is given in references.

Keywords: gravity field, geoid, quasigeoid, absolute gravity, gravimetry, global geopotential model, height anomaly

1. Introduction

Substantial progress in gravity field modelling and gravimetry is observed in last decades. They are traditional areas of research activities in Poland. The extensive information on those activities has been presented in consecutive quadrennial Polish National Reports on Geodesy for IUGG and in the annual National Reports to the IAG Sub-commission for EUREF. In a period of 2011–2014, researchers from the following research centres: Centre of Geodesy and Geodynamics, Institute of Geodesy and Cartography in Warsaw (IGiK); Department of Geodesy and Geodetic Astronomy, Warsaw University of Technology (WUT); Department of Planetary Geodesy, Space Research Centre, Polish Academy of Sciences in Warsaw (SRC); Department of Surveying Engineering, University of Warmia and Mazury in Olsztyn (UWM); and the Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences (UPWr), Centre of Applied Geomatics, Military University of Technology in Warsaw (MUT) were involved in gravity field modelling and gravimetric works. Most of the results of their research were presented on international conferences; some were published in the international journals. In particular, a historical review of gravimetry for geodesy and geodynamics has been elaborated (Krynski, 2012b).

Application of the method of local quasigeoid modelling based on the geophysical technique of gravity data inversion using non-reduced surface gravity data and GNSS/levelling height anomalies (GGI method) was investigated in UPWr and verified on tree test areas in Poland. An extensive research on evaluation of GOCE-based global geopotential models (GGMs) has been conducted by the team of IGiK. Terrestrial gravity data as well as GNSS/levelling data from the territory of Poland due to high quality are found suitable for accuracy evaluation of not only most recently developed geoid models but also of GGMs. In particular, an attempt was made to use absolute gravity data for the evaluation of GGMs. Also the use of GOCE-based GGMs in the process of geoid determination in Poland and in Sudan was investigated in IGiK. Some achievements in the field of geoid determination in the area of Poland in the last two decades were summarized and performance of new geoid model for Brunei was analysed by the researches from UWM and UPWr.

Temporal variations of gravity field were the subject of research in three research centres in Poland. Investigations conducted in IGiK concentrated on the estimate of geoid height variations in different regions of Europe and their modelling. Researches from SRC and UWM investigated the use of Wiener-Kolomogorov and ANS filters for filtering GRACE and analysed time series of equivalent water thickness in southern Poland.

Main activities in gravimetry were focused on the use of absolute gravity surveys for the maintenance of the national gravity control. The experience gained during the re-survey gravity control in Finland with the A10-020 gravimeter of IGiK were used in the projects on modernization of gravity control in Denmark, Norway, and Sweden and finally the establishment of new gravity control in Poland. Special attention was paid to metrological aspects of absolute gravimetry, in particular reliability and repeatability of gravity determination with the A10-020 gravimeter as well as total uncertainty budget for that gravimeter.

Very important component of research in gravimetry in Poland concerned the analysis of the absolute gravity measurements regularly performed with the A10-020 on the stations of the test network in Borowa Gora Geodetic-Geophysical Observatory (IGiK) and with the FG5-230 in the Astrogeodetic Observatory in Jozefoslaw (WUT). Absolute gravity determinations in the Geodynamic Laboratory in Ksiaz (SRC) were also analysed. Wavelet decomposition in the Earth's gravity field investigation was a subject of study by the joint team of MUT and SRC.

Some results of research on gravity field modelling and gravimetric works performed in Poland in a period of 2011–2014 are presented.

2. Geoid/quasigeoid modelling and study of the gravity field in Poland

2.1. Evaluation of GOCE-based GGMs

Since the mid of 2010, global geopotential models (GGMs) based on GOCE mission data became available. They became the subject of the intensive study of the team of the Institute of Geodesy and Cartography, Warsaw. The area of Poland has been selected as a case study area of GGMs. It seems specifically suitable for the accuracy assessment of GOCE-based GGMs due to the availability of high-precision quasigeoid model (accuracy below 2 cm) (e.g. Krynski, 2007) and homogeneously distributed high-precision GNSS/levelling data as well as accurate and dense terrestrial gravity data.

GOCE-derived GGMs were evaluated in terms of height anomalies and gravity anomalies over Poland with the use of the respective functionals calculated from the EGM08 geopotential model as well as height anomalies at 184 stations of high precision GPS/levelling control traverse. Analysis of first three releases of GOCE-based GGMs indicated an improvement of the consecutive releases of GOCE gravity field models. It also showed that their fit with the EGM08 in terms of height anomalies and gravity anomalies measured with a standard deviation is below 10 cm, and 3 mGal, respectively (Godah and Krynski, 2011). Accuracy assessment of the 3rd release of GOCE-based GGMs over the area of Poland using the EGM08 and GPS/levelling height anomalies was continued showing its high quality (Godah and Krynski, 2012). The investigation of 3rd release GOCE-based GGMs which were developed using 12 months of effective GOCE data (1st release was based on 2 months data, and 2nd release was based on 8 months data), demonstrates that the differences between corresponding height anomalies along the control traverse exhibit a distinct periodic pattern with wavelength in the range of 183-188 km after the projection onto a parallel (Fig. 1). This pattern may indicate the suitability of using GPS/levelling control traverse for practical study of GOCE-based GGMs spatial resolution.

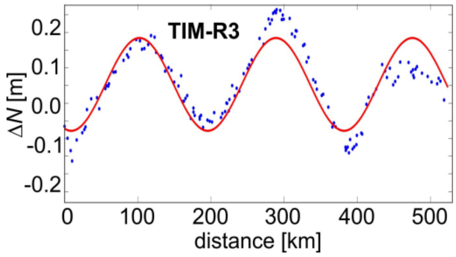

Fig. 1. Periodic pattern of the distribution of differences between the height anomalies from TIM-R3 and the corresponding ones from GPS/levelling at the control traverse

Further analysis concerning the accuracy evaluation of one GOCE-only GGM, four GOCE/GRACE satellite-only GGMs, and one GOCE/GRACE GGM combined with terrestrial gravity data showed an extremely good agreement of those models with the EGM08 (Table 1). It also demonstrated the potentiality of using the high-precision and high-resolution GPS/levelling control traverse for the evaluation of GGMs (Godah and Krynski, 2013a).

Table 1. Differences between height anomalies and gravity anomalies obtained from GOCE-based GGMs and the corresponding ones calculated from the EGM08 (N_{max} = 200)

Model	$\zeta_{GOCE} - \zeta_{EGM08}$ [m]				$\Delta g_{GOCE} - \Delta g_{EGM08}$ [mGal]			
	min	max	mean	std dev.	min	max	mean	std dev.
DIR-R3	–0.281	–0.006	–0.159	0.051	–3.433	4.215	0.076	1.381
TIM-R3	–0.114	0.123	0.005	0.046	–3.011	3.356	0.033	1.225
GOCO-03S	–0.100	0.109	0.000	0.044	–2.897	3.057	–0.004	1.184
DGM-1s	–0.441	–0.111	–0.300	0.066	–3.836	5.143	0.036	1.794
EIGEN-06s	–0.384	0.017	–0.159	0.064	–5.994	4.813	0.098	1.780
EIGEN-06c	–0.299	–0.034	–0.162	0.042	–3.504	3.212	0.017	1.041

New developments in processing GOCE data resulted in new releases of GOCE-based GGMs. The fits of height anomalies obtained from 4th release GOCE-based GGMs developed using 12 months of effective GOCE data, to GNSS/levelling data were investigated and compared with the respective ones of 3rd release GOCE-based GGMs and the EGM08 (Table 2).

The fit of 4th release GOCE-based GGMs truncated to d/o 200 and extended with the EGM08 coefficients to GNSS/levelling data ranges from 2.7 to 3.9 cm in terms of standard deviation of height anomalies differences. It exhibits clear improvement (60–70%) with respect to the corresponding results obtained from the previous 3rd release of GOCE-based GGMs. TIM-R4 GGM was found adequate for modelling the long-wavelength component (e.g. up to d/o 200) of the geoid over the area with high performance of the EGM08 such as the area of Poland. It has also been shown that 4th release GOCE-based GGMs will considerably improve the determination of height anomalies in the areas where the EGM08 performs poorly, such as e.g. Africa, South America and South-East Asia. An accuracy of 2.1–3.3 cm of height anomalies obtained from 4th release GOCE-based GGMs at maximum d/o 200 could be expected at any place on the Earth, except the poles and their adjacent areas that were not flown over by the GOCE satellite (Godah et al., 2014a).

Table 2. Statistics of height anomalies differences between those obtained from GNSS/levelling data and the corresponding ones determined from the EGM08 (up to d/o 2190) as well as 3rd release and 4th release GOCE-based GGMs (truncated at 200 d/o) extended with the EGM08 (from d/o 201 to 2190) [m]

GNSS/levelling sites	Statistics	EGM08	TIM-R3	DIR-R3	TIM-R4	DIR-R4
POLREF 315 sites	min	0.007	–0.160	–0.177	–0.036	–0.035
	max	0.170	0.352	0.329	0.207	0.209
	mean	0.100	0.089	0.090	0.093	0.095
	std dev.	0.027	0.084	0.091	0.037	0.039
EUVN 58 sites	min	0.019	–0.071	–0.126	–0.007	0.025
	max	0.173	0.256	0.278	0.168	0.191
	mean	0.092	0.089	0.095	0.088	0.090
	std dev.	0.028	0.079	0.085	0.036	0.039
Control traverse (1st+2nd order) 184 sites	min	0.027	–0.172	–0.212	–0.025	–0.023
	max	0.126	0.284	0.282	0.122	0.136
	mean	0.075	0.090	0.088	0.055	0.057
	std dev.	0.022	0.101	0.105	0.030	0.036
Control traverse (1st order) 44 sites	min	0.043	–0.126	–0.103	0.006	0.020
	max	0.126	0.269	0.248	0.122	0.136
	mean	0.087	0.060	0.066	0.064	0.067
	std dev.	0.019	0.112	0.107	0.027	0.032

The last, release 5 GOCE-based GGMs: DIR-R5 and TIM-R5, were also validated over the area of Poland. GNSS/levelling data were employed to evaluate height anomalies obtained from 5th release GOCE-based GGMs. In addition, gravity anomalies from 5th release GOCE-based GGMs were validated using the corresponding ones obtained from a high accuracy (i.e. beneath below 10 μGal) absolute gravity data at almost 170 stations homogenously distributed over the area of Poland obtained with the absolute gravimeter A10-020 within the last two years (Fig. 2). The spectral enhancement method was used to overcome the spectral band inconsistency problem between the GGMs and the ground truth based data. The fit of the EGM08 and 5th release GOCE-based GGMs in terms of gravity anomalies, measured with a standard deviation is 1.71 mGal, and 1.75-1.80 mGal, respectively (Godah et al., 2014c).

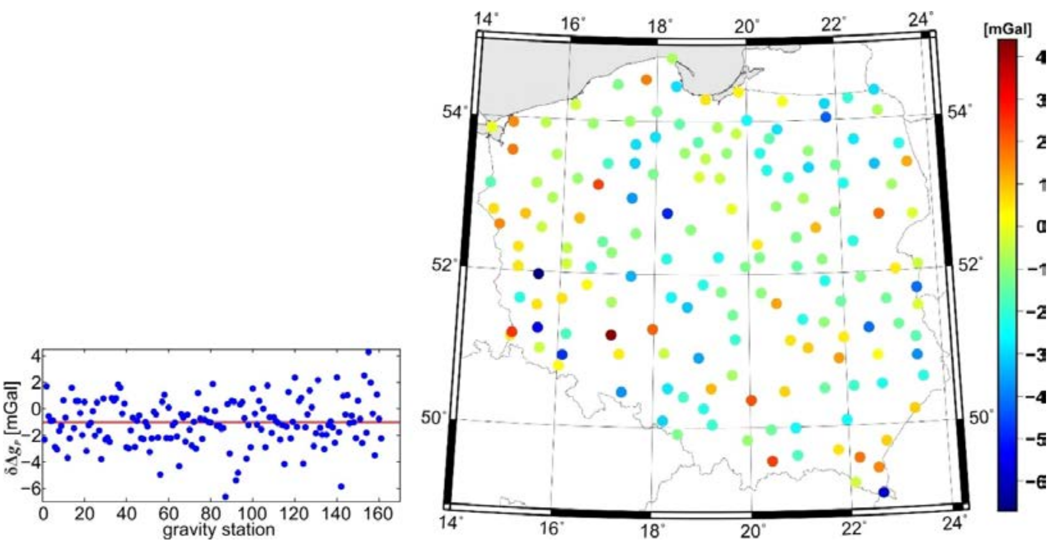

Fig. 2. GOCE-based GGM TIM-R5 vs. absolute gravity data

The results of studies on GOCE-based GGMs conducted over the area of Poland have efficiently been applied for the assessment of the GOCE GGMs over the area of Sudan. In particular, the 3rd release GOCE-based GGMs were compared in Sudan with the terrestrial gravity and GNSS/levelling data. The GOCE-derived free-air gravity anomalies and height were found consistent with the respective terrestrial ones within the range from 4.9 to 5.6 mGal, and 64 cm, respectively (Godah and Krynski, 2013b).

The team of the Institute of Geodesy and Cartography, Warsaw, participated with the ballistic A10-020 gravimeter in re-survey of gravity control in Norway in 2011. The results of absolute gravity survey with the A10-020 in Norway in 2011 were used for the validation of GOCE-based GGMs in Southern Norway (Pettersen et al., 2012a, 2012b).

2.2. Geoid modelling

The quality of a gravimetric geoid model depends on the quality of the gravity data used as well as on the quality of the GGM applied for modelling low frequency component of the gravity field. 3rd release GOCE-based GGMs, evaluated over Poland with the use of high-resolution and high accuracy terrestrial data, were applied to evaluate quality of terrestrial free-air gravity anomalies and height anomalies from GNSS/levelling data in Sudan. The GOCE-derived free-air gravity anomalies were compared with the respective ones from the terrestrial database using two different approaches. In the first approach high frequency gravity signals (e.g. 201 to 2190 d/o) were recovered with the use of the EGM08, and in the second approach a low pass filtering was implemented to remove those signals. It has been shown that the use of a low pass filtering provides better results for all investigated GOCE-based GGMs. The consistency of GOCE-derived free-air gravity anomalies with the respective terrestrial ones are within the range from 4.9 to 5.6 mGal. It was also shown that GOCE-based GGMs fit better in Sudan to terrestrial data than the EGM08. The results of the comparison of height anomalies from GOCE-based GGMs with the corresponding ones from GNSS/levelling data suggest the standard deviation of the vertical datum in Sudan at the level of 64 cm. This estimate, however, might not be fully representative due to very limited number of GPS/levelling heights used and their inhomogeneous distribution (Godah and Krynski, 2013b).

The use of 3rd release and 4th release GOCE-based GGMs for modelling the gravimetric quasigeoid for Poland was investigated. Two highly accurate gravimetric quasigeoid models were developed over the area of Poland using high resolution Faye gravity anomalies with the use of remove-compute-restore strategy and least squares collocation method. In the first model named $QGM_{Tim\text{-}R4+Terr}$, the GOCE-based GGM was used as a reference geopotential model, and in the second one named $QGM_{EGM08+Terr}$ – the EGM08. The models were evaluated with GNSS/levelling data and their accuracy performance was assessed (Table 3).

Table 3. Statistics of differences between height anomalies obtained from GNSS/levelling data and the corresponding ones obtained from combined gravimetric quasigeoid models [m]

Statistics	$\zeta_{GNSS/levelling} - \zeta_{TIM\text{–}R4+Terr}$				$\zeta_{GNSS/levelling} - \zeta_{EGM08+Terr}$			
	POLREF	EUVN	Control traverse		POLREF	EUVN	Control traverse	
	315 sites	58 sites	44 sites (1st order)	184 sites (1st+2nd order)	315 sites	58 sites	44 sites (1st order)	184 sites (1st+2nd order)
Min	0.023	0.057	0.065	0.040	0.020	0.047	0.069	0.037
Max	0.215	0.224	0.152	0.153	0.231	0.215	0.146	0.153
Mean	0.113	0.107	0.109	0.098	0.114	0.106	0.105	0.095
Std dev.	0.028	0.033	0.021	0.024	0.029	0.031	0.019	0.021

The analysis of the accuracy of height anomalies obtained from the resulting gravimetric quasigeoid models indicates that for the area of Poland the gravimetric quasigeoid model based on the TIM-R4 GGM is slightly worse than the one based on the EGM08. It also reveals that the GOCE data cannot improve the modelling of the gravimetric quasigeoid for the areas with high performance of the EGM08, e.g. Poland, but such areas could be suitable to evaluate GOCE-based GGMs, in particular to estimate the accuracy of height anomalies obtained from those models. On the other hand, when 1-2 cm accuracy of geoid at d/o 200 obtained from GOCE mission is achieved, the GOCE-based GGMs might be considered in such areas as an independent tool to assess regional/local geoid/quasigeoid models as well as to detect outliers among GNSS/levelling data (Godah et al., 2014a).

Contribution of GOCE mission data to modelling regional gravimetric geoid in two areas with highly different terrestrial data availability, i.e. Poland and Sudan, was investigated. On the basis of the combination of 4th release GOCE-based GGMs and local terrestrial gravity data, the gravimetric geoid models for the area of Poland as well as for the area of Sudan were developed using the least squares collocation method. The models were evaluated using GNSS/levelling data. The results for Poland and Sudan are given in Tables 4 and 5, respectively.

Table 4. Standard deviations of differences between height anomalies from gravimetric quasigeoid models in Poland developed using TIM-R4 or EGM08 with terrestrial gravity data and the corresponding ones obtained from GNSS/levelling data [m]

GNSS/levelling	TIM-R4	EGM08
POLREF 315 sites	0.028	0.029
EUVN 58 sites	0.033	0.031
Control traverse (1st+2nd order) 184 sites	0.024	0.021
Control traverse (1storder) 44 sites	0.021	0.019

Table 5. Statistics of differences between geoid heights from gravimetric geoid model in Sudan and the corresponding ones obtained from GNSS/levelling data at 19 stations [m]

Min	0.096
Max	2.066
Mean	0.920
Std dev.	0.644

It has been shown that GOCE-based GGMs can substantially improve local gravimetric geoid models in the areas of lacking uniform terrestrial gravity data coverage, e.g. a sub-region of East Africa. GNSS/levelling data available in Sudan does not allow for the evaluation of the gravimetric geoid models at a few centimetre accuracy level; the use of GOCE-based GGMs is recommended for GNSS heighting in Sudan (Godah et al., 2014b).

The determination of accurate geoid model remains an important challenge for geodetic research in Sudan. For the area of Sudan a new gravimetric geoid model SUD-GM2014 has been determined using TIM-R4 GOCE-based GGM, available terrestrial mean free-air gravity anomalies and the high-resolution Shuttle SRTM30 global digital terrain model. The computations of the SUD-GM2014 were performed using remove-compute-restore procedure and the least squares collocation method. The residual terrain modelling reduction method was applied to estimate the topography effect on the geoid. The resulting gravimetric geoid model has been evaluated using geoid heights at 19 GNSS/levelling points distributed over the country. The fit of the SUD-GM2014 to the available GNSS/levelling data in terms of the standard deviation of geoid heights differences is 64 cm. Large mean of geoid heights differences (up to 90 cm) are observed, which might imply serious problem within the vertical datum in Sudan. Therefore, re-establishment the levelling networks and uniform the vertical datum for the area of Sudan is essentially needed The use of GOCE-based GGMs for modelling the gravimetric geoid can play a significant role in the unification of the height system for the area of Sudan. Since GOCE-based GGMs provide geoid heights with the accuracy of 10 – 20 cm (Godah et al., 2014b), the SUD-GM2014 gravimetric geoid model or the geoid model computed from GOCE-based GGMs only is recommended as reference for GNSS heighting in Sudan (Godah and Krynski, 2014).

The review of some achievements of Adam Lyszkowicz in the field of geoid determination in the area of Poland using various data sets, and various methods, starting from 1992, has been presented by the author. Special attention has been paid on the evaluation of geoid models developed and the gravity field functionals calculated from the various global geopotential models. Also the need of fitting of computed geoid models to the national vertical reference system was stated. In conclusion the author stated that the present accuracy of gravimetric geoid/quasigeoid models in Poland is 1.4 cm, and accuracy of the geoid computed from the EGM08 is 2.4 cm. He also estimated accuracy of gravity anomalies and deflections of the vertical obtained from the EGM08 as equal to 2.5 mGal, and 0.6" – 0.7", respectively (Lyszkowicz, 2012).

A new gravimetric geoid model has been developed for Brunei with the use of terrestrial and airborne gravity data as well as altimetry data. The computation of the model was performed using the least squares collocation method and remove-compute-restore procedure with the EGM08 global geopotential model. The estimated accuracy of the gravimetric geoid for the territory of Brunei is at the level of 0.3 m. The geoid model developed shows poor quality of the existing GPS/levelling data in Brunei (Table 6) that indicates poor quality of local vertical datum (Lyszkowicz et al., 2014).

Table 6. Statistics of differences between geoid heights from gravimetric geoid model in Brunei and the corresponding ones obtained from GNSS/levelling data at 86 stations [m]

Min	-43.80
Max	-36.94
Mean	-40.41
Std dev.	1.58

The GGI method relies on developing a local model of disturbing potential (anomalous potential) T in the outer space. The basic input data used in the calculations are: GNSS/levelling height anomalies and non-reduced gravity data (gravity disturbances or free-air gravity anomalies referred to the terrain surface). The calculation is performed in four steps. In the first one that includes preliminary calculations, the GNSS/levelling height anomalies are converted using the Bruns' theorem to disturbing potential. Next, the local model of disturbing potential in external space is developed. Important elements of this model are discrete density distribution models of topographic masses and disturbing masses occurring between the geoid and the level of compensation. Once the model parameters are determined, disturbing potential is calculated in the new points on terrain surface which finally is converted to a height anomaly using again the Bruns' theorem.

Three examples of detailed local quasigeoid models calculated for three test areas of different size in Poland (3900 km^2, 23 000 km^2, 117 000 km^2) and of different density of the gravity data coverage demonstrated the capacity of the method. For each test area three quasigeoid models were calculated: one without using a GGM, and the others with the use of the EGM96 and the EGM08, respectively. The results obtained indicate that the method is suitable for developing high accuracy local quasigeoid models (the accuracy obtained was at the level of accuracy of GNSS/levelling test data) (Trojanowicz, 2012a).

One of the main problems occurring in the application of the GGI method is to determine the density model weighting matrix that controls the inversion process. The results of test calculations provide the optimum range of constant coefficients that allow defining the model weighting matrix. The optimum values of coefficients have been designated for the different sizes of zones of constant density and for the approaches: without using a GGM, and with the use of the EGM96 and the EGM08 (Trojanowicz, 2012b).

2.3. Temporal variations of the gravity field from GRACE data

Time variations of the gravity field obtained from the series of geopotential models developed from GRACE (Gravity Recovery and Climate Experiment) data can be interpreted in terms of geoid heights and mass time variations with unprecedented temporal resolution. The series of filtered monthly solutions of geopotential models developed from GRACE data and GLDAS (Global Land Data Assimilation System) hydrological models were used in the analysis. Variations of hydrology and geoid heights at the continental part of Europe and selected 14 subareas (Fig. 3) were estimated with a spatial resolution of 0.5º × 0.5º for the period August 2002 – June 2010.

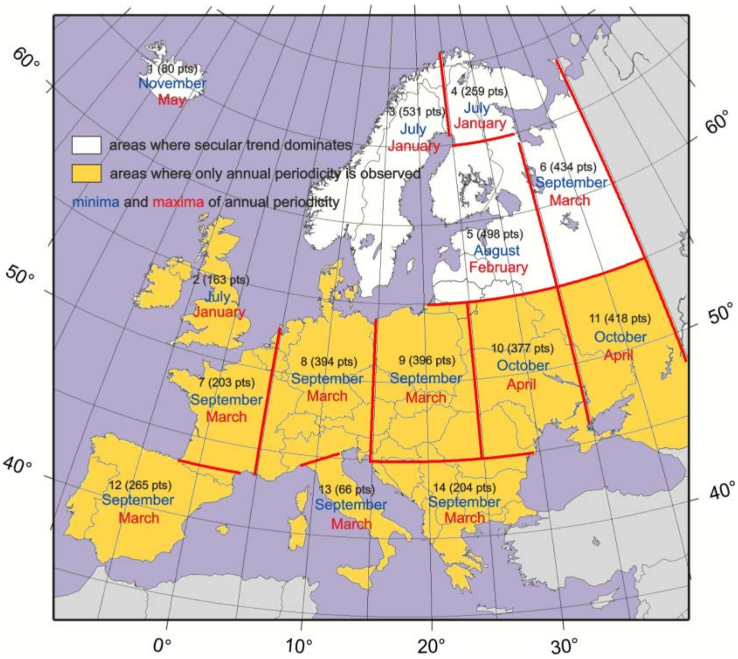

Fig. 3. The subareas of Europe with the number of points used to determine the average representative for each subarea (in brackets) as well as a trend and annual periodicity of equivalent water height variations (indicated months where minima and maxima occur)

Variations in mass distribution obtained from geopotential models were compared with the respective results obtained from hydrological data (Fig. 4).

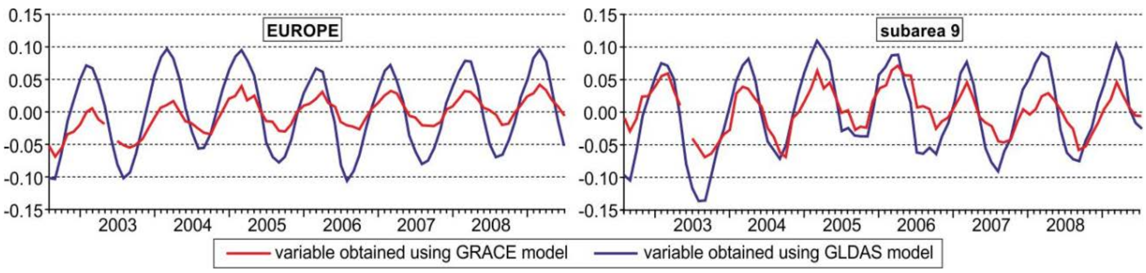

Fig. 4. Equivalent water heights variation obtained using GRACE and GLDAS models [m]

Annual periodicity of hydrology and geoid height variations with minima in September and maxima in March is observed for the area of Europe. The linear trend is also present in the signal. It dominates the signal in Northern Europe (Norway, Sweden, Finland) where a secular trend due to Post Glacial Rebound is observed. In the subareas of Central Europe only an annual periodicity appears. Results obtained using GRACE data show high correlation with the results calculated using GLDAS hydrological models (Krynski et al., 2014a).

It has been shown that the temporal variations of the gravity field over Europe obtained from GRACE data in terms of the geoid height can efficiently be modelled. Models of geoid height changes consisting of the seasonal term with the period of 12 months, and a trend in the form of 2nd order polynomial (trend and seasonal variations) were developed for the area of Europe and for 14 subareas. Optimum model for Europe and the subarea 9 (Fig. 3) against the observed variation of geoid height is presented in Figure 5. To verify those models values of geoid height changes calculated using GRACE data over the period July 2010 – October 2010 were compared with the respective once based on the models developed.

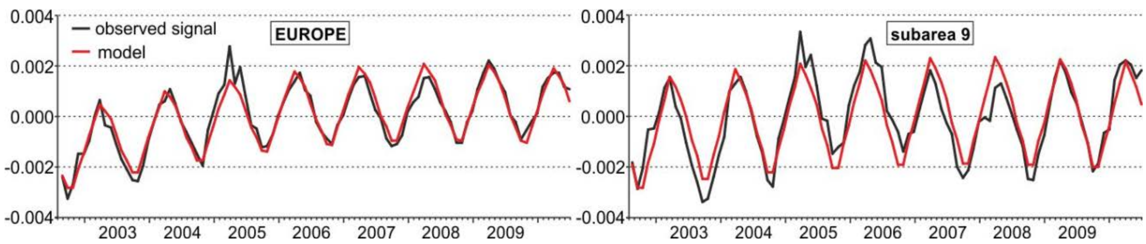

Fig. 5. Optimum model against the observed variation of geoid height[m]

Estimated averaged variations of geoid heights in the period 2002 – 2010 in the subarea covering Poland are within 7 mm. In reality variations larger than 1 cm should be expected (Kloch-Glowka et al., 2012).

It was indicated that the concept of static geoid as a reference surface in precise heighting, with the use of contemporary global positioning techniques becomes outdated. Thus there is a growing need for kinematic models of the gravimetric geoid. It would require the continuation of the GRACE-type space missions (Krynski et al., 2012).

Models of the geoid height variations developed for Europe and its 14 subareas on the basis of GRACE data from the period August 2002 – June 2010 were used to predict the geoid height variations for the next four months, i.e. July – October 2010. The predicted values were then compared with the respective ones obtained from the GRACE data. For Europe the correlation coefficient equals to 0.93 (Krynski et al., 2012, 2014a).

The phenomenon of flooding with the use of GRACE data was investigated. Equivalent water thickness (EWT) was determined using interpolation in places in southern Poland where flooding occurred in 2010. EWT time series were analysed and the results were verified with WGHM and NOAA hydrological models showing good mutual agreement. It has been shown that GRACE data can be used for testing the feasibility of predicting flood events in Poland. The preliminary tests performed using geological, forestry cover and soil type maps indicated the need for the extension of the analysis of EWT by taking into account issues related to meteorology, geology and soil science. The possibility of using GRACE data to implement the tasks arising from Directive 2007/60/EC of the European Parliament and of the Council on the assessment and management of flood risk was demonstrated (Birylo and Nastula, 2013a).

The research on the use of two isotropic filters: Gaussian, and CNES/GRGS, as well as two anisotropic filters: Wiener-Kolomogorov, and ANS for filtering GRACE data was conducted. Correlation, amplitude ratio, signal modification, and EWT maps were investigated. Best results in terms of correlation and amplitude ratio were obtained using ANS filter, while in terms of signal modification – with Gaussian filter (Birylo and Nastula, 2013b).

3. Absolute gravity surveys

3.1. Absolute gravity surveys for the maintenance of national gravity control in Poland

The use of portable ballistic gravimeter A10-020 for modernization of the Polish Gravity Control was investigated (Dykowski et al., 2012a). A set of recommendations and procedures have been developed. They were implemented during the establishment of new gravity control in Poland in 2012-2014 (Krynski and Dykowski, 2014b).

Research on modern vertical gravity reference systems (Krynski, 2012a, 2012b) and on the vertical gravity gradient determination for the needs of contemporary absolute gravity measurements (Dykowski, 2012a) was conducted at IGiK. In particular the structure of contemporary gravity control, the role of absolute gravity determinations, survey strategy and metrological problems were widely discussed. The results of the research as well as the experience gained during re-survey of gravity control in Finland with the A10-020 gravimeter were substantial in the project and the practical survey of new gravity control in Poland (Barlik et al., 2011b).

3.2. Absolute gravity surveys for the maintenance of national gravity control in Denmark, Norway, Finland, and Sweden

In the framework of the scientific cooperation between the Institute of Geodesy and Cartography, Warsaw, and the Finnish Geodetic Institute, 51 field sites of the Finnish gravity network (FOGN) were surveyed with the A10-020 gravimeter of the IGiK in 2009 and 2010 (Krynski, 2011; Krynski and Rogowski, 2011). First results of gravity change in Finland 1962-2010 from the comparison of legacy relative measurements with new measurements made with the A10-020 were obtained (Mäkinen et al., 2011).

Similar scientific cooperation concerning re-survey of national gravity control was later established between the Institute of Geodesy and Cartography, Warsaw, and the respective institutions in Denmark (National Space Institute, Technical University of Denmark, Copenhagen), Norway (Norwegian Mapping Authority, Oslo), and Sweden (Lantmäteriet, Geodesy Department, Gävle). The consecutive survey campaigns with the A10-020 gravimeter were conducted in Denmark in 2011, Norway in 2011 and in Sweden in 2011-2013 (Fig. 6) (Krynski and Rogowski, 2012, 2013, 2014).

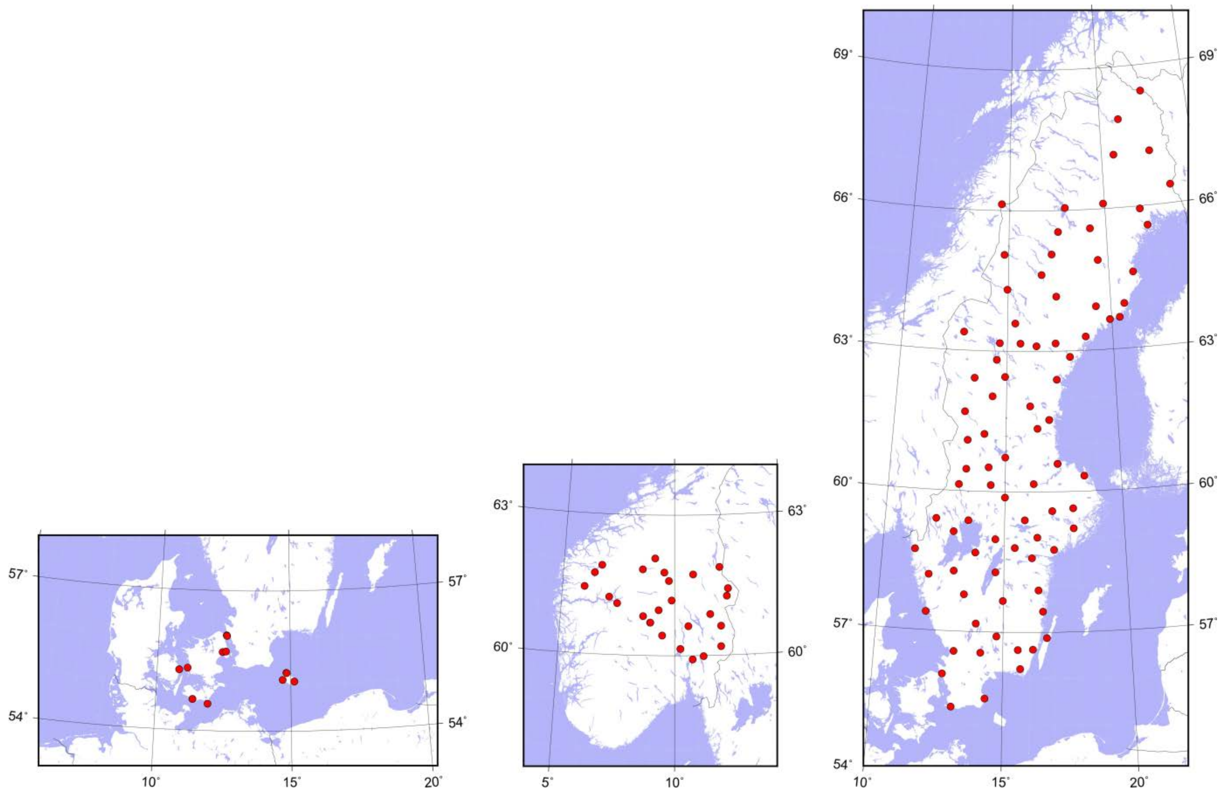

Fig. 6. Stations of gravity control networks of Denmark, Norway, and Sweden, and surveyed with the A10-020 in 2011−2013

3.3. Absolute gravity surveys for geodynamic research

Three field campaigns: in Pieniny Klippen Belt, in Sudeten Mts., and at Ksiaz Underground Geodynamic Laboratory have been conducted in 2011 for geodynamic purposes using the FG5-230 ballistic gravimeter (Krynski and Rogowski, 2012).

3.4. Metrological aspects in gravimetry

To maintain gravity control, in particular to ensure its standard in terms of gravity level and gravity unit, the free-fall gravimeters employed should regularly participate in the international absolute gravimeter comparison campaigns, and the relative gravimeters used should be respectively calibrated. Regular calibration of laser and frequency standard of free-fall gravimeters is also required. The A10-020 ballistic gravimeter of IGiK participated in 8th International Comparison of Absolute Gravimeters ICAG 2009 in Paris in 2009 (Fig. 7) (Jiang et al., 2012) as well as in 9th International Comparison of Absolute Gravimeters ICAG 2013 in Walferdange in 2013 (Krynski and Dykowski, 2014a).

Both Polish absolute gravimeters, i.e. FG5-230 of WUT and A10-020 of IGiK took part in the European calibration campaign ECAG 2011 in Walferdange, Luxemburg (Francis et al., 2013). The final results of the European Comparison Campaign of Absolute Gravimeters ECAG 2011 in Walferdange in Luxemburg proved high quality performance of the A10-020 gravimeter (Fig. 8) (Francis et al., 2012).

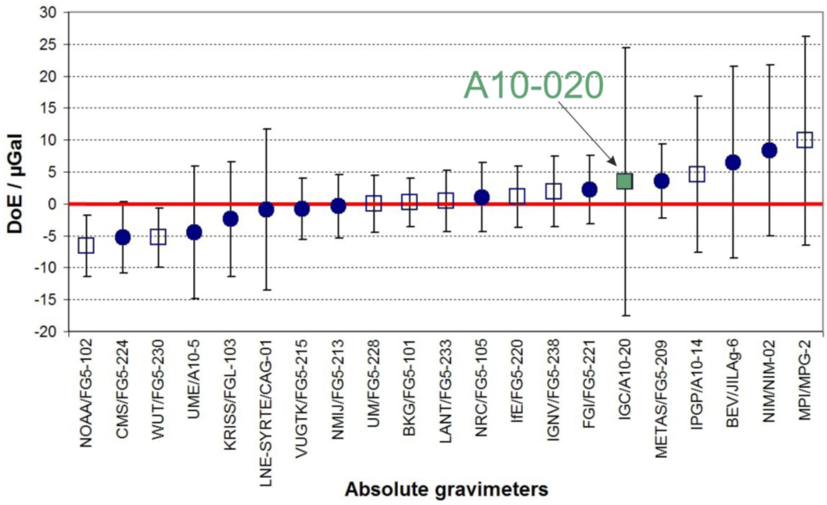

Fig. 7. Results of ICAG 2009 in Paris

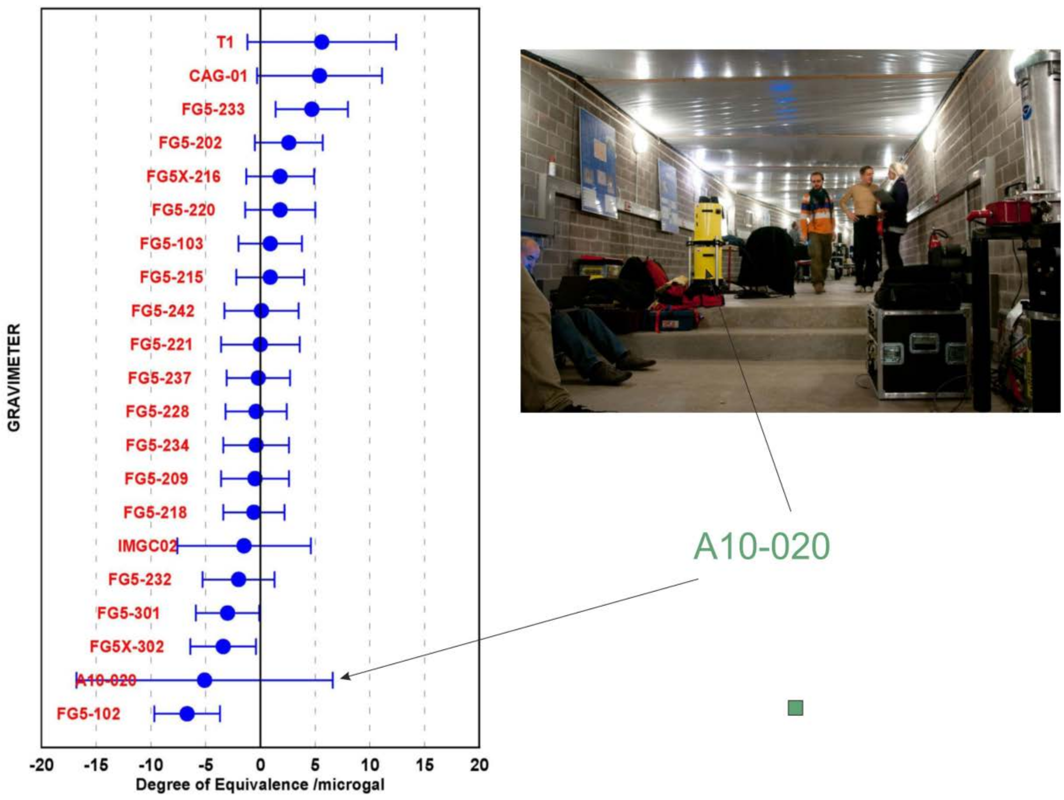

Fig. 8. Results of ECAG 2011 in Walferdange

The effects of laser and clock stability and meteorological conditions on gravity surveyed with the A10-020 free-fall gravimeter were investigated. First results were obtained from the analysis of time series of regular, monthly measurements conducted with the A10-020 at the Borowa Gora Geodetic-Geophysical Observatory for over two years at two laboratory test sites and one field station. The analysis has been performed in terms of internal consistency and compliance with the previous gravity measurements performed with a few other absolute gravimeters (mainly FG5). The results of a number of calibrations of both, the rubidium oscillator and the polarization-stabilized laser interferometer of the A10-020 were considered in the analysis (Sekowski et al., 2012). Also accuracy and reliability of the A10-020 absolute gravimeter were estimated using time series of gravity determinations on the stations of the test network in Borowa Gora Geodetic-Geophysical Observatory (Krynski et al., 2014b).

Next, stability of metrological parameters and performance of the A10-020 free-fall gravimeter were investigated. It has been shown that calibrations of those parameters is a necessity to obtain proper gravity values with the A10 gravimeter (Dykowski et al., 2012b). The research on metrological aspects of gravity determinations with the A10-020 gravimeter was particularly extensive during the establishment of a new gravity control in Poland in 2012-2014 (Krynski et al., 2013; Krynski and Dykowski, 2013, 2014b). Long-term stability of the laser lock frequencies and clock frequency are shown in Figures 9 and 10, respectively (Dykowski et al., 2013a).

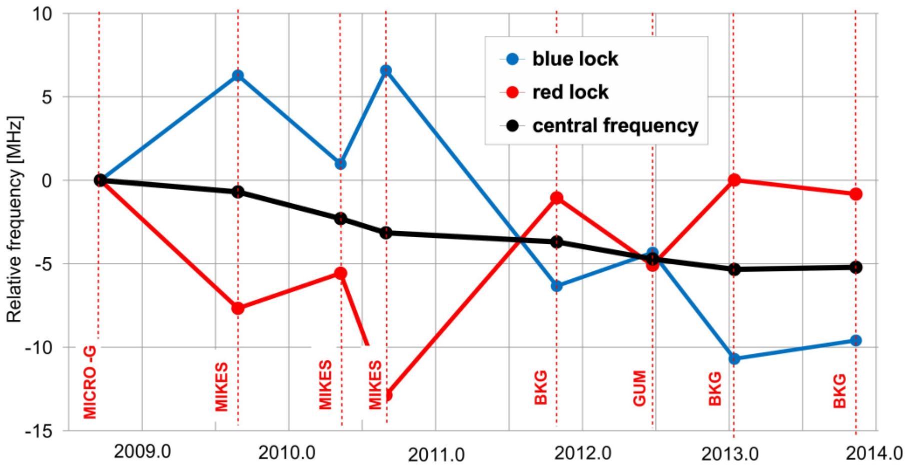

Fig. 9. Long-term stability of the laser lock frequencies of the A10-020

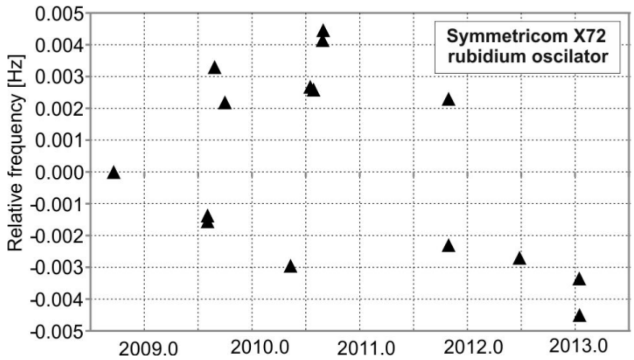

Fig. 10. Long-term stability of the clock frequency of the A10-020

The comprehensive study on the estimation of total uncertainty budget for the A10-020 gravimeter was conducted. As the A10 gravimeter is used in both laboratory and field conditions two uncertainty estimates were considered. In addition, the sensitivity of the A10 gravimeter with respect to local hydrology has been discussed. The total uncertainty evaluations improved from the 10.8 µGal to 5.5 µGal. The most significant change in the uncertainty estimates was observed in the system uncertainty. On one hand the estimates for the laser and clock uncertainties were larger than the manufacturer suggested. Yet, on the other hand the most dominant component of 10 µGal (system model uncertainty) has been replaced with the long term standard deviation of results at Borowa Gora Observatory. Values of 3.5 µGal (lab conditions) and 4.8 µGal (field conditions) had a profound influence on the total uncertainty estimate (Dykowski et al., 2013a).

The research on the use of the A10 gravimeter for calibration of spring gravimeters was conducted at IGiK. First results of the calibration with the use of the A10-020 provided scale factors with an accuracy close to 1% which is sufficient for the use of spring gravimeters for vertical gravity gradient determination (Dykowski 2012b).

3.5. Environmental effects in absolute gravity determination

All disturbing environmental and instrumental effects must be removed from absolute gravity measurements to make them useful for geodynamics research. Those, that can easily be modelled, e.g. tide, polar motion, ocean tidal loading, are routinely removed when processing measurements. Significant gravity variation is associated with changes of ground water on global scale. This effect was investigated for Lower Silesia region. Seasonal gravity changes can reach up to 2 μGal peak-to-peak amplitude. Using absolute gravity data acquired with the FG5-230 gravimeter it has been shown that neglecting this effect can cause serious misinterpretation in terms of secular gravity changes. This is specifically emphasized when only sparse data of a few year time span are used (Rajner et al., 2012).

4. Maintenance of gravimetric calibration baselines in Poland

Two modernised gravimetric calibration baselines – the Central and the Western one – are fully based on absolute gravity stations that are up to 100 km apart from each other; gravity differences between the stations range from 40 to 120 mGal. Also two vertical gravimetric calibration baselines in Tatra Mountains and in Sudeten Mountains (Krynski, 2011) are regularly maintained. The spans of the Central Gravimetric Calibration Baseline are regularly, at least once a year, surveyed with a set of LaCoste&Romberg spring gravimeters of IGiK. At the end of 2014, new gravity measurements were performed with the FG5-230 of WUT at the all stations of the Central Gravimetric Calibration Baseline, Vertical Gravimetric Calibration Baseline in Tatra Mountains and some stations of the Western Gravimetric Calibration Baseline.

5. Investigations of non-tidal gravity changes

5.1. Absolute gravity surveys in gravimetric laboratories

Absolute gravity surveys in Borowa Gora

Since September 2008 absolute gravity measurements were conducted on monthly basis with the A10-020 gravimeter on the test network (two laboratory stations and one field station) of the Borowa Gora Geodetic-Geophysical Observatory of the Institute of Geodesy and Cartography (IGiK). The results obtained are regularly presented in annual National Reports of Poland to EUREF (Krynski and Rogowski, 2011, 2012, 2013, 2014) as well as in other publications (e.g. Krynski, 2011; Dykowski et al., 2013b). The statistics of the performed measurements at the laboratory stations A-BG and BG-G2 as well as for field station 156 of the test network are given in Table 7.

Table 7. Statistics of repeated absolute gravity determinations with the A10-020 on the stations of the local test gravity network in the Borowa Gora Geodetic-Geophysical Observatory [μGal]

Statistics	A-BG	BG-G2	156
Std dev.	4.3	5.9	5.8
Max-Min	15.2	24.0	29.8

A series of gravity determined at the laboratory station A-BG of the test network is shown in Figure 11.

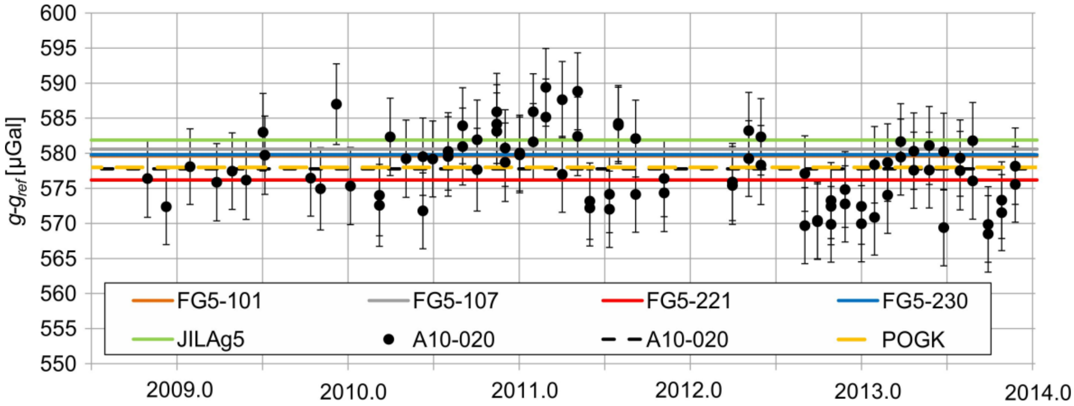

Fig. 11. Results of absolute gravity measurements with A10-020 at Borowa Gora

The A10-020 proved to be a reliable instrument also in terms of difficult weather conditions. Good agreement of the measurements taken with the A10-020 in Borowa Gora with the GLDAS/Noah corrections for hydrological conditions (for monthly solutions) was observed (Krynski and Dykowski, 2014a).

Absolute gravity surveys in Jozefoslaw

Absolute gravity measurements were carried out since 2005 on regular basis with the use of FG5-230 gravimeter in the Astrogeodetic Observatory in Jozefoslaw of the Warsaw University of Technology (WUT) (Fig. 12) (Krynski and Rogowski, 2011, 2012, 2013, 2014).

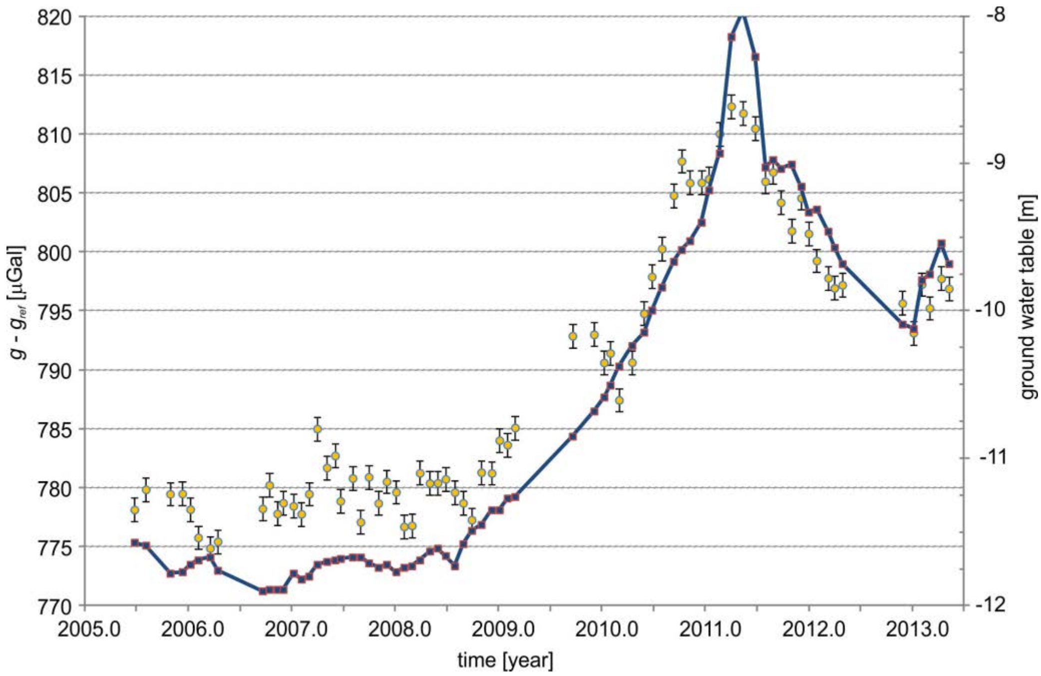

Fig. 12. Results of absolute gravity measurements with FG5-230 at Jozefoslaw (100 cm height) vs. ground water table

The results of more than 3 years of absolute gravity survey in the Astrogeodetic Observatory in Jozefoslaw together with continuous records from the spring gravimeter were analysed (Barlik et al., 2011a), in particular in terms of environmental influence on gravity measurements (Fig. 13). The impact of atmosphere and hydrosphere on global and local scale was investigated.

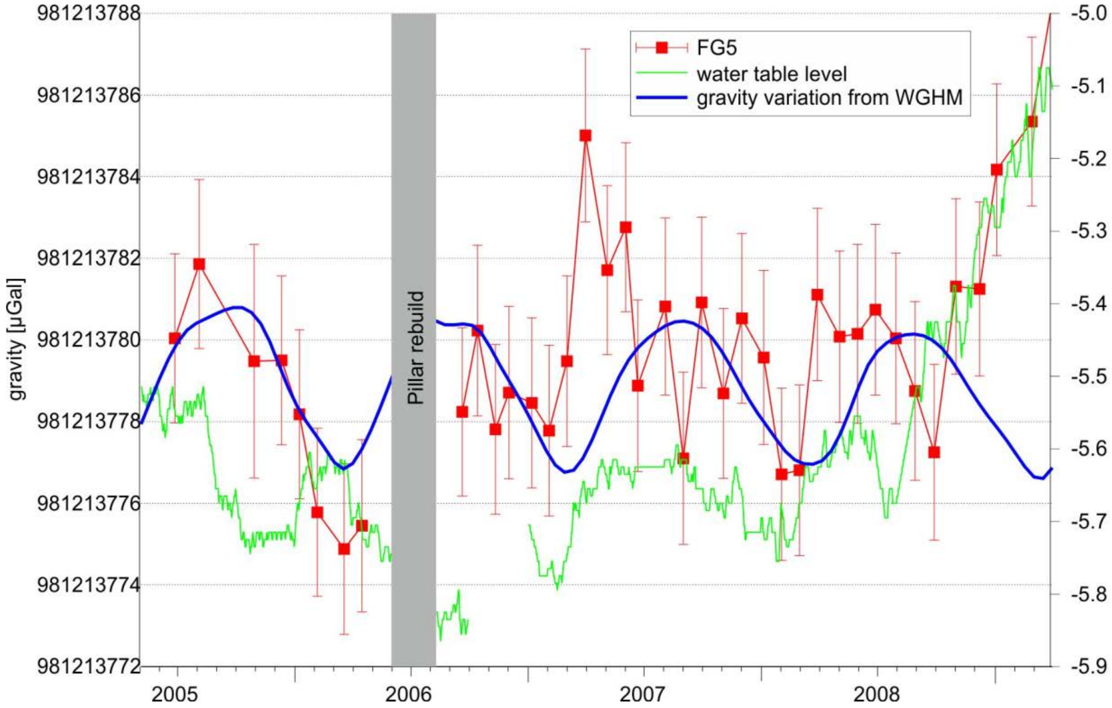

Fig. 13. Gravity measurements with the FG5-230 compared to gravity change due to continental water storage and local water table level variation

Absolute gravity surveys in Ksiaz

Absolute gravity was determined in the Geodynamic Laboratory (LG) of the Space Research Centre of the Polish Academy of Science in Ksiaz with the FG5-221 of the Finnish Geodetic Institute in April 2007 and then with FG5-230 of WUT twice in 2007 (June and November), once in April 2008 and once in June 2011. The results obtained indicated the existence of small variations of gravity at the level of 1 µGal with maxima in spring, and minima in the autumn. Very small amplitude of observed gravity variations in LG suggests that the observed gravity variations are caused only by global hydrology changes that exhibit maxima and minima in spring, and autumn, respectively, and annual amplitude of 1.5 µGal. This proves high degree of „independence" of gravimetric measurements in LG from local environmental factors such as ground water level variations, ground humidity, impact of snow cover, etc. Relative gravity measurements performed with LaCoste&Romberg G-648 gravimeter simultaneously with absolute gravity measurements are used to improve local tidal model in Ksiaz (Kaczorowski et al., 2012).

5.2. Variations of the gravity record from SG data

Application of wavelet decomposition using the regular orthogonal symmetric Meyer wavelet to processing superconducting gravimeter (SG) data from Wettzell and Bad Homburg participating in the Global Geodynamics Project (GGP) was investigated. The wavelet transform enables the investigation of the temporal changes of the oscillation amplitudes or the decomposition of the time series for the analysis of the required frequencies. Data from an earthquake period recorded at various locations and a quiet period with no seismic disturbances were analysed. The decomposition was followed by the Fast Fourier Transform for signal frequency components and then by correlation analyses of corresponding frequency components for all sensor combinations, for the quiet and the earthquake periods separately. Low frequency components as well as combinations between two sensors at the same site for the quiet days characterise by high correlation coefficients. For the time of the earthquake, the Wettzell site data proved strong correlation for all frequency components, while the Bad Homburg site data showed an unexpected decrease of correlation for the majority of frequency components. It has been proven that wavelet decomposition is a suitable method for data interpolation, especially from the time of earthquakes. Moreover, it is a very useful tool for filtering the data and removing noise (Bogusz et al., 2013).

6. Summary and conclusions

Research on gravity field modelling in research centres in Poland concentrated on the evaluation of GOCE-derived global geopotential models, geoid modelling and temporal variations of the gravity field.

High quality terrestrial data from Poland allowed for reliable evaluation of GOCE-based GGMs. Special role of uniformly distributed absolute gravity data in such evaluation was indicated. The results obtained showed the usefulness of GOCE-based GGMs for developing reference surface for heights, in particular in the regions with insufficient terrestrial data. Analysis of geoid models developed for the area of Poland (accuracy at the level of 2 cm) and the area of Sudan with the use of GOCE-based GGMs indicated that those global geopotential models can be recommended as best reference surface for GNSS heighting in Sudan. Some practical conclusions were drawn when studying the application of the method of local quasigeoid modelling based on gravity data inversion. GRACE data was found useful for determining temporal variations of the gravity field in Europe. Equivalent water heights variation obtained using GRACE models are correlated with those from hydrological models. Geoid height variations have been estimated for subareas of Europe. It also was shown that they reliably be modelled by a seasonal term and a trend in the form of the 2nd order polynomial. It was highlighted that the concept of static geoid as a reference surface in precise heighting, with the use of contemporary global positioning techniques becomes outdated. There is thus a growing need for kinematic models of gravimetric geoid.

An extensive study of the A10-020 ballistic gravimeter showed its usefulness for the maintenance and modernization of gravity control. Absolute gravity surveys with the A10-020 gravimeter were successfully conducted on the stations of gravity control in Denmark, Norway, Finland, Poland and Sweden. Also accuracy and reliability as well as total uncertainty of the A10-020 in both laboratory and field conditions were estimated using time series of gravity determinations in Borowa Gora Geodetic-Geophysical Observatory which is essential for the evaluation of the quality of gravity control. Absolute gravity measurements carried out on regular basis with the use of FG5-230 gravimeter in the Astrogeodetic Observatory in Jozefoslaw were analysed in terms of environmental influence on gravity measurements. Non-tidal gravity changes were also investigated with the use of repeatable absolute gravity measurements with the FG5-230 in Pieniny Klippen Belt, in Sudeten Mts. and at Geodynamic Laboratory in Ksiaz.

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Earth rotation and geodynamics

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Abstract: This paper presents the summary of research activities carried out in Poland in 2011-2014 in the field of Earth rotation and geodynamics by several Polish research institutions. It contains a summary of works on Earth rotation, including evaluation and prediction of its parameters and analysis of the related excitation data as well as research on associated geodynamic phenomena such as geocentre motion, global sea level change and hydrological processes. The second part of the paper deals with monitoring of geodynamic phenomena. It contains analysis of geodynamic networks of local, and regional scale using space (GNSS and SLR) techniques, Earth tides monitoring with gravimeters and water-tube hydrostatic clinometer, and the determination of secular variation of the Earth' magnetic field.

Keywords: Earth rotation, GNSS, SLR, tidal investigations, Earth magnetic field

1. Introduction

The research concerning Earth rotation and geodynamics performed in Poland in a period of 2011-2014 was conducted mainly in the following research institutions, listed in an alphabetic order: Borowiec Astrogeodynamic Observatory, Space Research Centre of the Polish Academy of Sciences in Borowiec (BOR); Department of Applied Geomatics, Military University of Technology in Warsaw (MUT); Department of Geodesy, University of Agriculture in Krakow (UAK); Department of Geodesy and Geodetic Astronomy, Warsaw University of Technology (WUT); Department of Geodesy and Geodynamics, Institute of Geodesy and Cartography in Warsaw (IGiK); Department of Geodesy and Geoinformatics, Wroclaw University of Technology (PWr); Department of Photogrammetry and Remote Sensing, University of Warmia and Mazury in Olsztyn (UWM1); Department of Planetary Geodesy, Space Research Centre of the Polish Academy of Sciences in Warsaw (SRC); Department of Satellite Geodesy and Navigation, University of Warmia and Mazury in

Olsztyn (UWM2); Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences (UPWr); Institute of Geography and Regional Development, University of Wroclaw (UWr); Polish Geological Institute – National Research Institute in Warsaw (PIG).

Earth rotation is considered as one of three pillars of modern geodesy, besides the geokinematics and gravity field. The Earth orientation parameters (EOP) which are determined on the regular basis from the observations of space geodesy techniques, are sensitive to the global mass and angular momentum exchanges between the solid Earth and its fluid envelopes, the atmosphere, the oceans, the land hydrosphere, the cryosphere and the core. Hence, the analysis of the observed EOP and of the related geophysical parameters is important for understanding the global processes in the system Earth. Modelling and predicting Earth orientation parameters are also essential for the realization of global reference systems, the International Terrestrial Reference System (ITRS) and the International Celestial Reference System (ICRS), and of relations between these systems (Rogowski and Brzezinski, 2012). The investigations on Earth rotation started in Poland in late 1970's. They were conducted mostly by the researchers of the SRC, concentrating on the theory and interpretation of the Earth rotation and geophysical excitation data. In the last years, several scientists from other research institutions (UAK, UWr, WUT) became involved in those investigations. Also the scope of research has been extended on the associated geodynamic phenomena, such as geocenter motion, global sea level change and hydrological processes.

Since 1980's the monitoring of the geodynamic phenomena became possible using space-based techniques. The models of the tectonic plate movement are described by means of the permanent station velocities. The results of research on velocities determined from Satellite Laser Ranging (SLR) as well as Global Positioning System (GPS) are presented in this review paper. The permanent observations were carried out on the EUREF Permanent Network (EPN), the ASG-EUPOS network, which a multifunctional active geodetic network in Poland, and on the geodynamic network in the Sudety Mts. (GEOSUD, S-W Poland), established in 1996 with some subsequent extensions. A very important element of geodynamic research concerns tidal observations. Such observations are carried out in Poland since early 1970's with spring gravimeters (gravimetric tides), horizontal pendulums and water tiltmeter (clinometric tides). Currently, tidal observations are carried out in two Polish observatories – Borowa Gora (IGiK) and Ksiaz (SRC). Long-term research on secular variations of the geomagnetic field in Europe was continued at IGiK with the use of the geomagnetic data obtained from the European observatories.

2. Earth rotation

In a period of 2011–2014 investigations concerning Earth rotation have been carried out in Poland by the researchers of SRC, UAK, and WUT. Additional research on associated geodynamic phenomena, the geocentre motion, sea level change and modelling of hydrological processes, has been conducted at UAK and UWr. Polish researchers working on Earth rotation participated in the activities of the international scientific organizations (International Association of Geodesy – IAG, International Astronomical Union – IAU, International Earth Rotation and Reference Systems Service - IERS) and of their commissions and working groups. They were also active in the organization of national and international meetings devoted to the Earth rotation topics. Results of their research have been reported at the international conferences, workshops, and published in the scientific journals. Short summaries of the most important results and achievements together with the list of related publications are presented below.

2.1. Theory of Earth rotation

Modelling subdiurnal variations of Earth rotation: The diurnal and subdiurnal signals in Earth rotation despite the small size are important for understanding the high frequency global dynamics of the solid Earth and the overlying fluid layers. The research concerning such signals is also important for validation of the high resolution determinations of Earth orientation parameters and of the procedures applied for data reduction. The so-called complex demodulation (CD) technique applied by Brzezinski and his co-workers since the middle of 1990's, has been shown to be a powerful method for modelling subdiurnal signals in Earth rotation, particularly the irregular or quasi-harmonic variations which need to be monitored in the time domain and studied using the time domain methods. Complex demodulation is a method of extracting high frequency signals from time series. The output "image" of the signal is a low-frequency time series which is easy to handle in analysis (Fig. 1). Detailed description of the CD technique and its application for the Earth rotation studies was given by Brzezinski (2012). The paper begins with general introduction of the method and its properties, and then gives description of its application for modelling diurnal and subdiurnal components of polar motion and UT1, and of the corresponding excitation functions. Finally, the dynamical equations derived can be used for direct comparison of the signals demodulated from the Earth rotation to the geophysical excitation data.

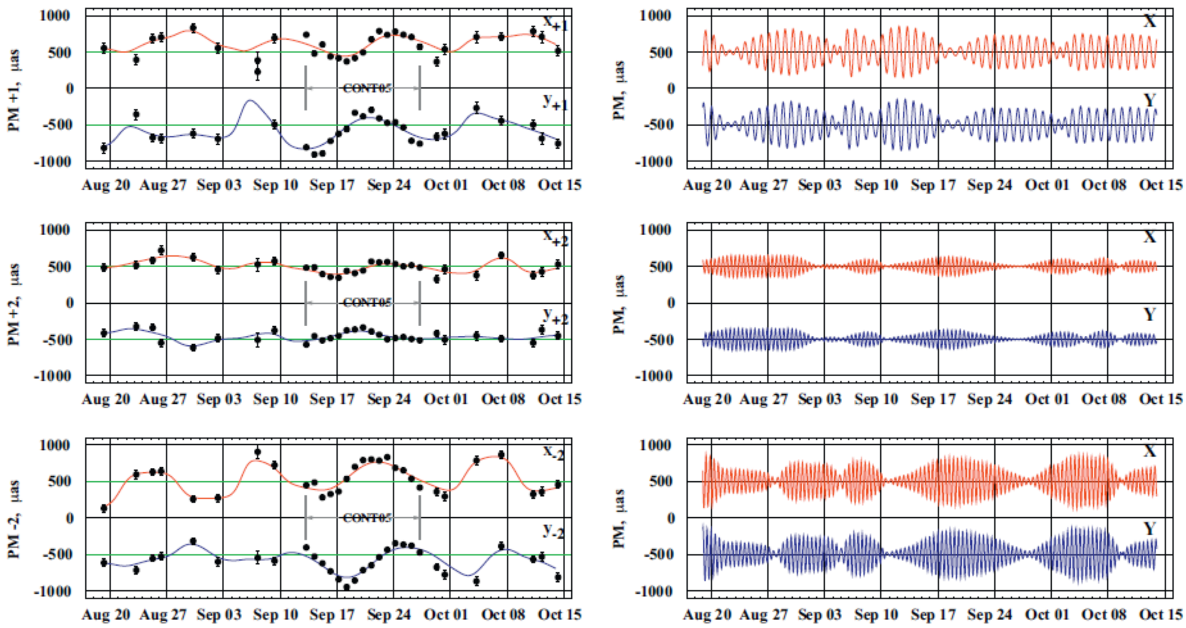

Fig. 1. From the top to bottom: prograde diurnal, prograde semidiurnal and retrograde semidiurnal components of polar motion (PM) demodulated from VLBI data. Shown are the raw estimates with error bars together with smoothed and interpolated curves (left), and the reconstructed corresponding high-frequency variations in PM (right). For the reason of visibility, the *x* and *y* components of demodulated and reconstructed series have been shifted in the vertical direction by adding (*x*) or subtracting (*y*) of 500 µas. Period of analysis 1984.0-2006.2, period shown 15 August – 15 October 2005 (Brzezinski, 2012)

A successful application of the CD technique for analysis of the Very Long Baseline Interferometry (VLBI) observations has been done in cooperation with researchers from the Institute of Geodesy and Geophysics of the Vienna University of Technology (Böhm et al., 2012). The features of complex demodulation were used in an extended parameterization of polar motion and universal time which was implemented into a dedicated version of the Vienna VLBI Software VieVS. The functionality of the approach was evaluated by comparing the three sets of amplitudes and phases of harmonic variations at tidal periods (diurnal/semidiurnal): 1) derived from demodulated Earth rotation parameters (ERP; this is

the subset of EOP including only polar motion components and UT1/LOD), 2) estimated from hourly resolved VLBI ERP time series and 3) taken from a recently published VLBI ERP model, to the terms of the conventional model for ocean tidal effects in Earth rotation recommended by the IERS. The three sets of tidal terms derived from VLBI observations extensively agree among each other within the 3σ level of the demodulation approach, which is below 6 microarcseconds (μas) for polar motion and universal time. They also coincide in terms of differences to the IERS model, where significant deviations primarily for several major tidal terms are apparent. An additional spectral analysis of the demodulated ERP series of the ter- and quarterdiurnal frequency bands did not reveal any significant signal structure; see (Brzezinski and Böhm, 2012) for details. The CD technique applied in VLBI parameter estimation could be demonstrated a suitable procedure for the reliable reproduction of high frequency Earth rotation components and thus represents a qualified tool for future studies of irregular geophysical signals in ERP measured by space geodetic techniques.
Nearly diurnal variations in the atmospheric and nontidal oceanic angular momenta (Atmospheric Angular Momentum – AAM, Oceanic Angular Momentum – OAM) contribute at measurable level to all components of Earth rotation. The estimated contributions to nutation have amplitudes over 0.1 milliarcsecond (mas), while in case of polar motion and UT1 the amplitudes are up to 0.04 mas. However, there are still significant discrepancies between the contributions estimated from different geophysical models as well as between those derived from geophysical models and geodetic data. Brzezinski (2011) used a new consistent set of 20-year time series of AAM and OAM based on the ERA-Interim reanalysis fields and the corresponding simulation from the ocean model for circulation and tides (OMCT), to extract the diurnal component and to estimate their influence on Earth rotation. The results were compared to the earlier estimates using the AAM series from the National Center for Environmental Prediction / National Center for Atmospheric Research (NCEP-NCAR) reanalysis model and the OAM series from the barotropic ocean model, derived by Brzezinski, Ponte and Ali in 2004. The estimated geophysical contributions were also compared to the available results derived from the space geodetic observations of Earth rotation.

Modelling free oscillations in Earth rotation: There are two important eigenmodes in the equatorial component of Earth rotation: the Chandler wobble (CW) and the free core nutation (FCN). Studying rotational eigenmodes of the Earth is an important scientific task. First, their parameters, the resonant period T and the quality factor Q, depend on the internal constitution of the planet and on its rheological properties. Second, by tracking the associated free motions of the pole one can gain much knowledge about global-scale processes taking place within the Earth and in its outer fluid layers. Finally, a good understanding of the eigenmodes is necessary for modelling and prediction of the time variations in polar motion and nutation.

The 14-months Chandler wobble is a free motion of the pole excited by geophysical processes. Several recent studies demonstrated that the combination of atmospheric and oceanic excitations contains enough power at the Chandler frequency and is significantly coherent with the observed free wobble. The paper (Brzezinski et al., 2011) was an extension of earlier studies by Brzezinski and co-authors using the same method of analysis but other available estimates of atmospheric and oceanic excitation of polar motion. The authors tried to assess the role of land hydrology in the excitation balance by taking into account the Hydrological Angular Momentum (HAM) estimates. The results obtained (Table 2.1) generally confirmed earlier conclusions concerning the atmospheric and oceanic excitation. Adding the hydrological excitation was found to increase slightly the CW excitation power, while the improvement of coherence depended on the geophysical models under consideration. The research on the free CW had been continued by Brzezinski and Rajner (2014) who estimated the CW parameters T and Q based on the stochastic models of polar motion and geophysical excitation data. They applied the Kalman deconvolution filter developed by Brzezinski in 1992. This filter can be used to analyse either the polar motion data alone, or simultaneously the polar motion and the excitation data, in order to estimate the unknown residual excitation. By imposing the minimum variance constraint upon the estimated unknown excitation they could find the best value of the resonant parameters T and Q. The CW parameters estimated from different sets of polar motion and geophysical excitation data were compared to each other as well as to the earlier results derived by the alternative algorithms.

Tab. 2.1. Comparison of the observed (C04) and modelled (combination ECCO2: AAM – NCEP-NCAR reanalysis, OAM – data-assimilating model ECCO, kf066b run, HAM – NCEP-water, time span 1993.0–2009.0) excitations of polar motion. Complex correlation and coherence coefficients are shown as magnitude and argument, power spectral density (PSD) unit is mas^2/cpy (Brzezinski et al., 2011)

Geophysical excitation vs. C04	Correlation overall	Coherence at Chandler freq.	PSD at Chandler freq. mod./obs.
A-pressIB			6.9/42.6
A-wind			3.1/42.6
A	0.574 −3°	0.663 12°	11.9/42.6
O-mass			10.4/42.6
O-motion			3.6/42.6
A+O	0.847 −4°	0.805 −2°	44.4/42.6
H			3.0/42.6
A+O+H	0.842 −5°	0.800 −9°	49.1/42.6

(Brzezinski et al., 2014) studied the excitation of the observed FCN signal by diurnal variation of the atmospheric and oceanic angular momenta, using AAM time series based on three different atmospheric reanalysis models, NCEP-NCAR, ERA-40, and ERA-interim, combined with OAM data from the ocean model OMCT. Comparison with the VLBI nutation data (Fig. 2) showed that the excitation based on the ERA-Interim model is not reliable at the diurnal retrograde frequencies. The spectral analysis of other excitation data sets confirmed the earlier conclusion that the mass term of excitation contains sufficient power to explain the observed amplitude of the FCN oscillation. The coherence analysis of geodetic and geophysical excitations was not conclusive, presumably because the signal-to-noise ratio in AAM and OAM data was too low in the vicinity of the FCN frequency.

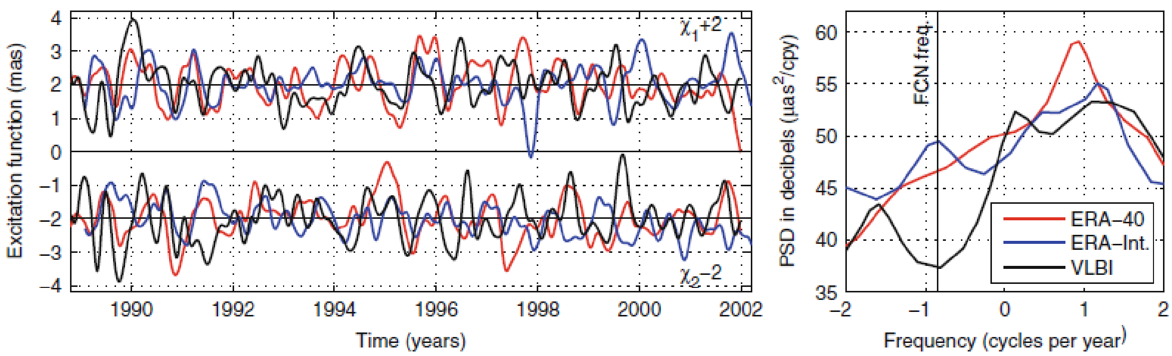

Fig. 2. Comparison of the geodetic excitation of nutation (black) to the combination of atmospheric and oceanic excitations, model ERA-40 (red) and ERA-interim (blue) (Brzezinski et al., 2014)

Earth rotation observed by ring laser: The ring laser gyroscope (RLG) is a promising emerging technology for direct and continuously measured variations in Earth rotation. A single instrument is capable to determine the polar motion of the instantaneous rotation pole (IRP), in contrast to the space geodetic techniques which report the terrestrial motion of the conventional Celestial Intermediate Pole (CIP). Among several instruments which have been developed so far, the most accurate for monitoring high frequency polar motion is the G ring laser gyroscope in Wettzell, Germany. Considerable progress has been attained in the analysis and interpretation of the ring laser measurements recently. Brzezinski has been continued in a period of 2011-2014 his research on the interpretation of the RLG data (Tian et al., 2011).

2.2. Analysis of polar motion observations and of the related excitation data

Comparison of geophysical, gravimetric and geodetic excitations of polar motion: The contribution of Earth' hydrology to polar motion is usually evaluated from the continental water storage predicted by models. In order to validate their predictions, the modelled hydrological excitation can be compared to geodetic observations after removing atmospheric and oceanic effects. However, previous studies have shown large disagreements, mainly due to the lack of global measurements of related hydrological parameters. At present, it is possible to estimate the excitation functions of polar motion χ_1 and χ_2 due to the global hydrology from the observations of the Gravity Recovery and Climate Experiment (GRACE) mission. Data processing of GRACE observations has been carried out by several centres of analysis around the world. Seoane et al. (2011) focused on the GRACE solution computed by the Groupe de Recherche de Géodésie Spatiale (GRGS). The prominent annual variations observed by GRACE were in better agreement with geodetic observations than the models estimates (Fig. 3)**.**

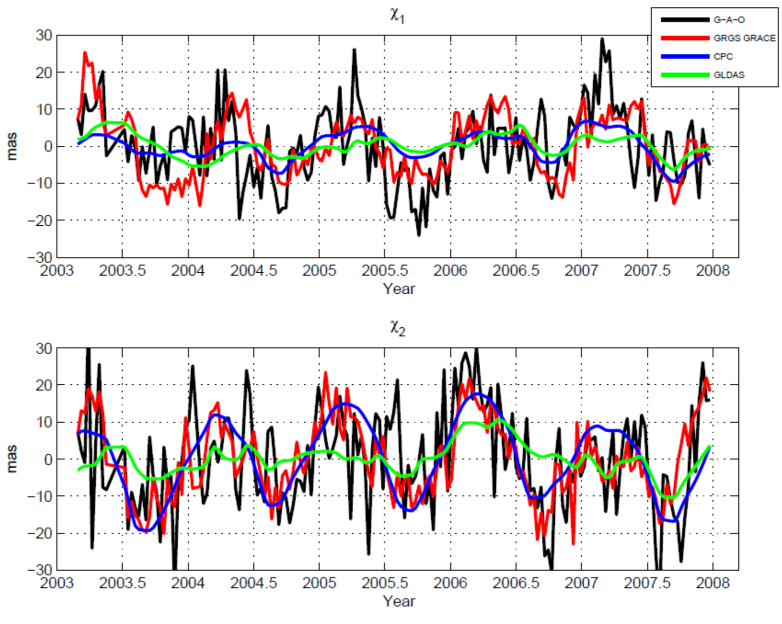

Fig. 3. Hydrological excitation functions computed from: geodetic observations (G-A-O), atmospheric and oceanic effects are removed; GRACE gravity field processed by GRGS; CPC hydrological model; and GLDAS hydrological model (Seoane et al., 2011)

The main contribution to the annual signals came from the monsoon climates at the low latitudes regions (latitudes <30°N). Their influences on the annual oscillation estimated from the models and from the GRACE observations were in a very good agreement. The study showed that the effect of the high latitudes regions (latitudes ≥30°N) can not be neglected. The principal areas of snow cover and continental climates were found at these latitudes. When comparing the contributions of the high latitudes regions predicted by the hydrological models to those observed by GRACE, the authors noticed the significant discrepancies, particularly at the annual band. At the inter-annual scales, GRACE observations confirmed the significant influence of the hydrology. Finally, the authors remarked that GRACE observations show the possible influence of water storage variation in exciting polar motion around the frequency of 3 cycles per year. They expected that improvements in the GRACE data processing and larger series of gravity field solutions would help the hydrological models to provide an adequate predictions and upgrade the global annual budget of the polar motion excitation.

Nastula et al. (2011a, 2011b) and Nastula (2014) compared contributions to polar motion excitation determined separately from each of three kinds of geophysical data: atmospheric pressure, equivalent water height estimated from hydrological models, and harmonic coefficients of the Earth' gravity field obtained from GRACE experiment. Hydrological excitation function which is expressed by HAM, has been estimated from models of global hydrology, based on the observed distribution of surface water, snow, ice, and soil moisture. The authors used global models of land hydrosphere as well as of atmosphere and oceans, with the excitation of polar motion expressed by HAM, AAM and OAM, respectively. All those geophysical excitation functions were compared with the observed geodetic excitation function of polar motion (Geodetic Angular Momentum – GAM). The spectra and the time-variable spectra of the following excitation functions of polar motion: GAM, AAM+OAM, AAM+OAM+HAM, GAM-AAM-OAM residual geodetic excitation function, and HAM were computed too. Phasor diagrams of the seasonal components of polar motion excitation functions, of all HAM functions as well as of two GRACE solutions: Center for Space Research (CSR), Centre National d'Etudes Spatiales / Groupe de Recherche de Géodésie Spatiale (CNES/GRGS) were determined. Results showed that different models of HAM differ significantly in amplitudes and phases. None of the HAM estimates closed the budget of the geophysical excitation of polar motion.

Analysis of the geodetic residuals: Differences between geodetic excitation function of polar motion GAM and joint atmospheric plus oceanic excitation functions (AAM, OAM) were computed (Nastula et al., 2011a; Kolaczek et al., 2012). The geodetic residuals computed for different models of AAM and OAM differ from one model to the other. Standard deviations of the geodetic residuals had maxima at the level exceeding a dozen mas. In the case of geodetic residuals computed with the same OAM models, differences were at the level of several mas. Comparison of geodetic residuals determined using different global ocean models showed significant differences among them. Comparison of these geodetic residuals and global hydrological and gravimetric excitation functions of polar motion showed that amplitudes of HAM variations are smaller than the variations of geodetic residuals. Therefore, the estimated time series of HAM have not enough energy to close the agreement between geodetic and geophysical excitations.

Regional excitation functions of polar motion: Nastula and Salstein (2012) estimated hydrological polar motion excitation functions over land areas regionally from hydrological models and from GRACE geopotential models. The hydrological models included equivalent water heights fields determined from groundwater, soil moisture and snow estimates on continents. They considered land data from the Climate Prediction Center (CPC) hydrological model and from the surface modelling system named Global Land Data Assimilation System (GLDAS), both providing monthly estimates. They also used satellite gravity data, expressed in terms of the GRACE RL04 Equivalent Water Thickness (EWT) from CSR. The mass effects of the ocean and the atmosphere as well as postglacial rebound were removed, so in this way hydrological excitation of polar motion could be estimated from the gravity data. Monthly resolution of the data restricted the analysis to seasonal signals only. Large hydrological variability in EWT occured in the lower latitude Southeast Asia, South Asia, and the South American Amazon regions; it remains significant in polar excitation even after multiplication by polar motion transfer functions, except the very low latitudes (Fig. 4). Differences between models and GRACE-related values were still considerable; they need to be reconciled to form the best estimates of hydrological variability. Additionally, variations from the atmosphere were determined over land areas from NCEP/NCAR reanalyses; they are noted to be strongly dependent on variability over the high topography regions of Eurasia and North America.

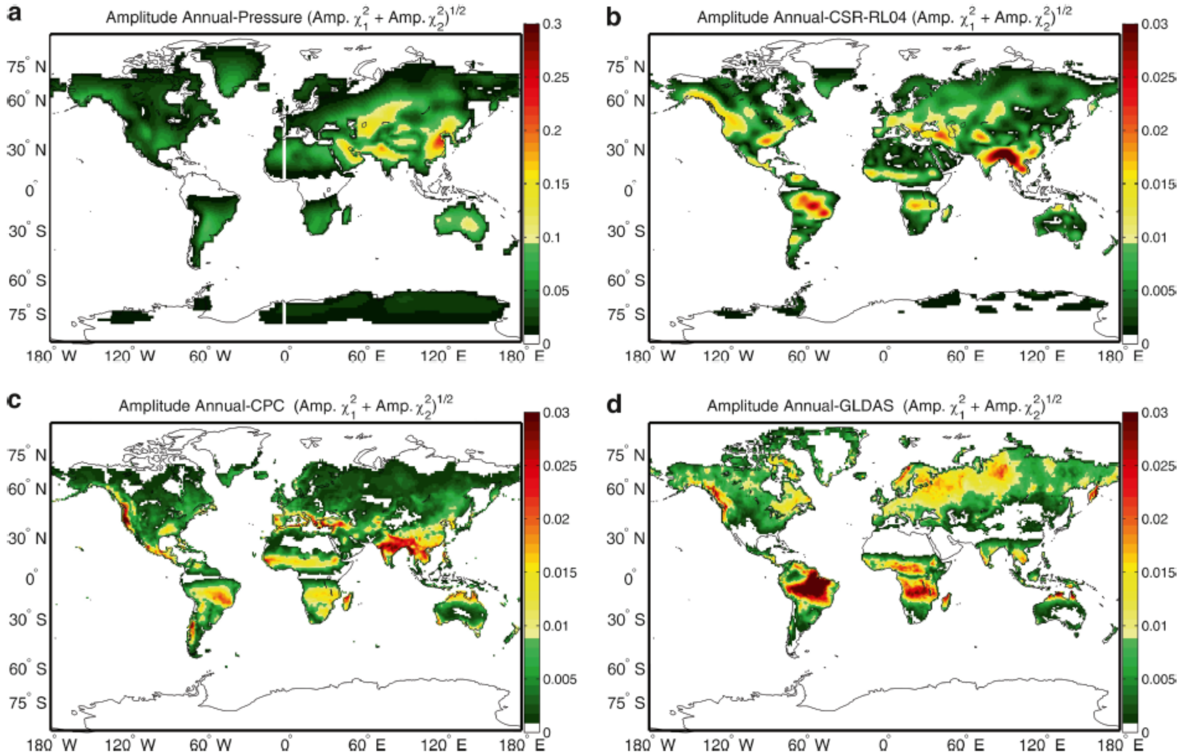

Fig. 4. Maps of amplitudes of the annual oscillation of complex-valued components of polar motion excitation functions: (a) atmospheric pressure polar motion excitation function, in 2.5° × 2.5° grids; (b) gravimetric polar motion excitation function, from GRACE CSR RL04 solution in 1°×1° grids; from hydrological polar motion excitation function in 1°×1° grids from two models (c) CPC, (d) GLDAS (units – mas) (Nastula and Salstein, 2012)

Regional values of the oceanic excitation functions of polar motion were computed from the bottom pressure and oceanic current fields from the ECCO/JPL data-assimilating model kf080 for the period 1993–2009 (Nastula et al., 2012). The influence of different geographic regions of the ocean on the excitation of polar motion determined by calculating correlations and covariances between these regional excitations and either the global non-atmospheric excitation or the global oceanic excitation. The non-atmospheric excitations estimated by subtracting the atmospheric signal from the excitation computed from geodetic observations of polar motion; the global oceanic excitation function is equivalent to the sum of the oceanic excitation function computed in every grid point. Using the oceanic bottom-pressure and current fields from the ECCO/JPL model kf080 the authors have explored the way in which different oceanic regions are responsible for non-atmospheric excitation of polar motion in two spectral bands, the annual and around the Chandler period. To quantify the relation between oceanic regional and global excitation functions, either geodetic non-atmospheric or oceanic, they computed covariance magnitude, coherence magnitude and phase shift between regional and global excitation values, using a Fourier transform band pass filter (FTBPF) applied to excitation functions expressed in terms of complex valued series $\chi = \chi_1 + i\chi_2$ (Fig. 5). The comparative analysis showed that the southern Indian Ocean and the South Pacific Ocean are important regions for non-atmospheric polar motion excitation. The maximum of variability over southern Indian Ocean was especially important in the case of the annual oscillation. The Atlantic Ocean makes less significant contribution to the non-atmospheric polar motion excitation than the Pacific and Indian Ocean in both spectral ranges considered. There is a high covariance of the signals generated over Inland seas like the Mediterranean and the Sea of Japan with the global signals.

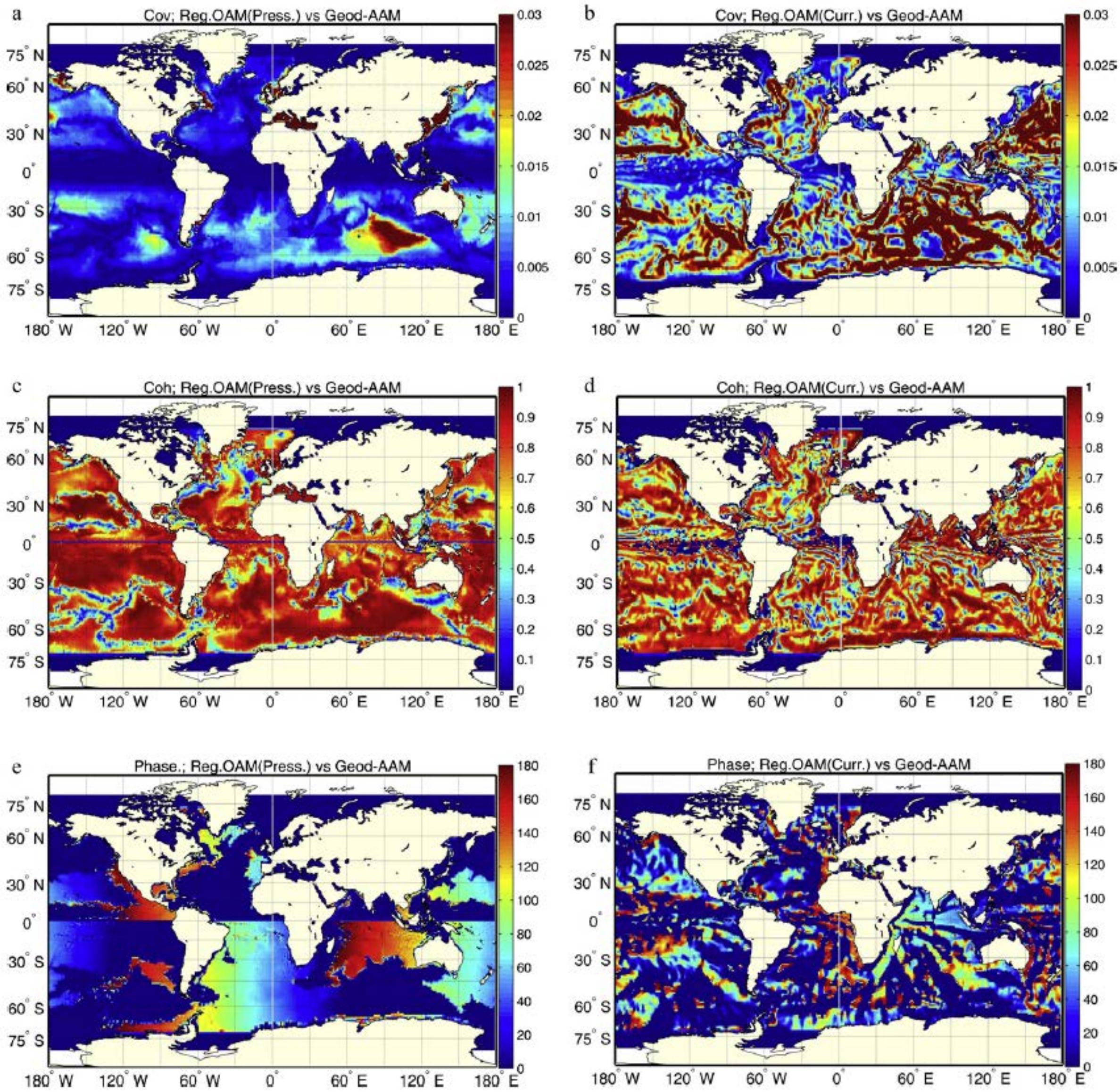

Fig. 5. Maps of (a, b) magnitude of covariances, (c, d) magnitude of coherence (e, f) and phase between prograde components of signals in the band around the Chandler oscillation of regional OAM (left panels pressure, right panels currents) and of global non-atmospheric geodetic excitation function (Nastula et al., 2012)

Nastula et al. (2014) compared regional contributions to polar motion excitations determined separately from each of three kinds of geophysical data: atmospheric pressure, oceanic bottom pressure and land hydrology estimated from the GRACE satellite mission. Their key results of this fractional covariance study in the case of annual term were: (l) atmospheric pressure – strong variability over the high topography regions of Eurasia and North America, (2) ocean bottom pressure – strong variability in regions such as the southern Indian Ocean, (3) land hydrology – the prominent annual signals are situated in the Amazon, Central and South of Africa, North of

Australia, India and Indochina. For the Chandler frequency band they found: (1) atmospheric pressure – two maxima in the variability one over the North European Plain, with the centre over the western side of the Central Russian Upland, and the other one over North Asia with the centre over Siberia and two secondary maxima, one over east coast of US and the other one south of the southern tip of South America, (2) ocean bottom pressure – south eastern Pacific, southern Indian Ocean, and North Atlantic dominate, (3) land – hydrology maxima were scattered above land areas.

Local Equivalent Water Thickness determination as a source of data for flood phenomenon observation: GRACE data was filtered and presented in the form of EWT with a temporal resolution of one month on 0.5°×0.5° grid for the whole territory of Poland (Birylo and Nastula, 2012b, 2012c). EWT on 0.5°×0.5° grid were determined from two global models of the land hydrosphere, WGHM and NOAA with temporal resolution of one month. EWT were then interpolated with linear interpolation method (Nearest Neighbour method) in four locations flood inundated in 2010 (Wilkow, Wroclaw, Wloclawek, Krakow). The biggest EWT changes occured in the southern Poland in March, and the lowest in the beginning of autumn. In addition, the results showed a significant increase of EWT in March 2010, and two, three times more than the average of EWT (0.06 mm) in the months of flood 2010, i.e. in May and June 2010. In March, the average EWT in the southern Poland was about 0.06 mm, while in 2010 it was twice larger. In the coming months, the EWT level felt usually to 0.02 mm, and in 2010, its state was 0.05 mm. Based on analyses performed in the study, the authors concluded that the GRACE data could be used to test the feasibility of predicting flood events in Poland.

GRACE signal filtering: The effect of filtering the GRACE data on the estimated maps of EWT was analyzed (Birylo and Nastula, 2012a). The authors carried out four tests of filters, which included correlation, amplitude ratio and signal modification and EWT maps generation. The best results in the four tests were achieved when using ANS filter. Analysis of amplitude ratio showed that low degree harmonics of the gravity field lead to up to 28% reduction of the signal strength for the Gauss filter, and better results can be achieved by adapting longer filtering radius and inclusion harmonics of 118±10 degree and order. The CNES/GRGS and Wiener-Kolmogorov filters indicated 6% reduction of GRACE signal strength, and the ANS filter performed with 0% signal loss. The greatest signal modification was observed when using the Wiener-Kolomogorov filter (0.06÷6.87), and the best results were obtained for the Gauss filter (even 0.00) – the longer filtering radius, the more uniform modification. Using the CNES/GRGS filter led to modification rates of 0.02÷0.03, and using the ANS filter it ranged from 0.18 to 0.31. The same spatial range (–0.2÷0.2 cm) was found for the Gauss filter, Wiener–Kolomogorov filter, and ANS filter, but for the CNES/GRGS filter, the vertical spatial distribution was within the range (–1÷1) cm.

2.3. Prediction of Earth orientation parameters and the related geophysical parameters

Wavelet based techniques allow to perform a time-frequency comparison of the geodetic (computed from pole coordinates data) and fluid excitation functions (Kosek et al., 2011a). These two functions became the most similar when the fluid excitation function was composed of the atmospheric, ocean and land hydrology excitation functions. Higher order semblance function revealed that addition of hydrology angular momentum to the sum of atmospheric and oceanic ones improves the phase agreement between the geodetic and fluid excitation functions in the annual frequency band. The wavelet based semblance filtering enabled the determination of the common signals in both excitation functions. Increase in the threshold value in the semblance filtering of the geodetic and fluid excitation functions increased the correlation coefficients values between the filtered common oscillations.

In October 2010 the US Naval Observatory in Washington together with the Space Research Centre in Warsaw initiated the Earth Orientation Parameters Combination of Prediction Pilot Project (EOPCPPP) to compute EOP predictions on an operational basis (Kosek et al., 2011b). The pole coordinate data predictions from different prediction contributors and ensemble predictions computed by the U.S. Naval Observatory were studied to determine the statistical properties of polar motion forecasts by analysing second, third (skewness) and fourth (kurtosis) statistical moments about the mean value. It was found that prediction errors of pole coordinates data do not satisfy normal distribution. The skewness values for different participants showed that the probability distribution becomes more asymmetric when the prediction length increases. The kurtosis values usually decreases with the prediction length, which means that the probability distribution becomes more flat and has larger tails than a normal distribution.

Kosek (2012) found that short-term prediction errors of pole coordinates data were caused by wideband short period oscillations in joint atmospheric-ocean excitation functions. Some large prediction errors of pole coordinates data in 1981–1982 were caused by wideband oscillations in ocean excitation functions while in 2006–2007 they were caused by wideband oscillations in joint atmospheric-oceanic excitation functions (Fig. 6). It had been shown that the combination of the prediction methods treating separately deterministic and stochastic part of the EOP can provide the best accuracy of the prediction. The recommended prediction method for pole coordinates data is the least-squares (LS) and autoregressive (AR) combination and the Kalman filter is recommended for the prediction of UT1–UTC data. Short term prediction errors of the EOP data are not caused by variable amplitudes and phases of the most energetic oscillations in these data because they are much smaller when the data are smoothed by removing the frequency components computed using the discrete wavelet transform band pass filter.

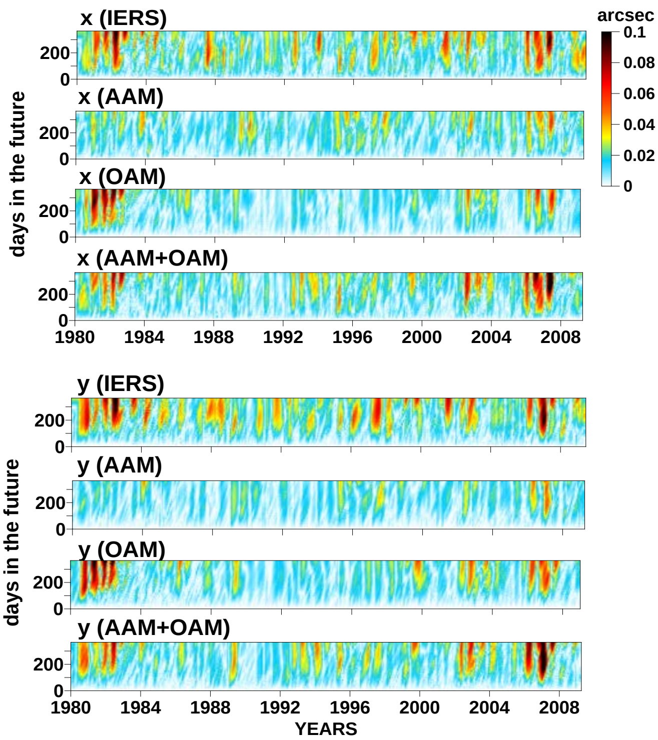

Fig. 6. The LS+AR prediction errors of IERS pole coordinates data and of pole coordinates model data computed from AAM, OAM and AAM+OAM excitation functions. (Kosek, 2012)

To forecast the IERS UT1–UTC, which is necessary for real-time transformation between the terrestrial and celestial reference frames, the combination of LS extrapolation of a polynomial-harmonic model with the multivariate autoregressive (MAR) prediction technique had been proposed (Niedzielski and Kosek, 2012b). The method uses the bivariate time series comprising length of day data corrected for tidal effects and the axial component of AAM data. The superior performance of the MAR prediction in comparison to the AR one was observed, in particular during El Niño and La Niña events. The mean prediction error of the UT1–UTC data for the LS+MAR combination is usually smaller than for the LS+AR one, and the proposed method is recommended to improve longer term forecasts of these data.

2.4. Research on associated geodynamic phenomena

2.4.1. Geocenter motion

The spectra-temporal wavelet semblance with the application of the modified Morlet wavelet function enables computation of correlation coefficients between the centre of mass time series determined by Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), Global Navigation Satellite Systems (GNSS) and Satellite Laser Ranging (SLR) techniques as a function of time and frequency (Kosek et al., 2014). The highest positive semblance values occur in the *XY* equatorial plane for the retrograde annual oscillation in the GNSS and SLR data as well as prograde annual oscillation between DORIS and other two techniques. The spectra-temporal semblance functions in *YZ* plane between the centre of mass time series of SLR and other two techniques show annual prograde oscillation. The wavelet-based semblance filtering with application of the Shannon wavelet functions enabled computation of common signals in the time series of geocenter motion. The most energetic part of this signal is the retrograde annual oscillation in the equatorial plane with amplitude of 2-3 mm and this oscillation is out of phase between DORIS and two other techniques. These common signals constructed using lower frequency components enable determination of the smoothed geocenter time series model (Fig. 7).

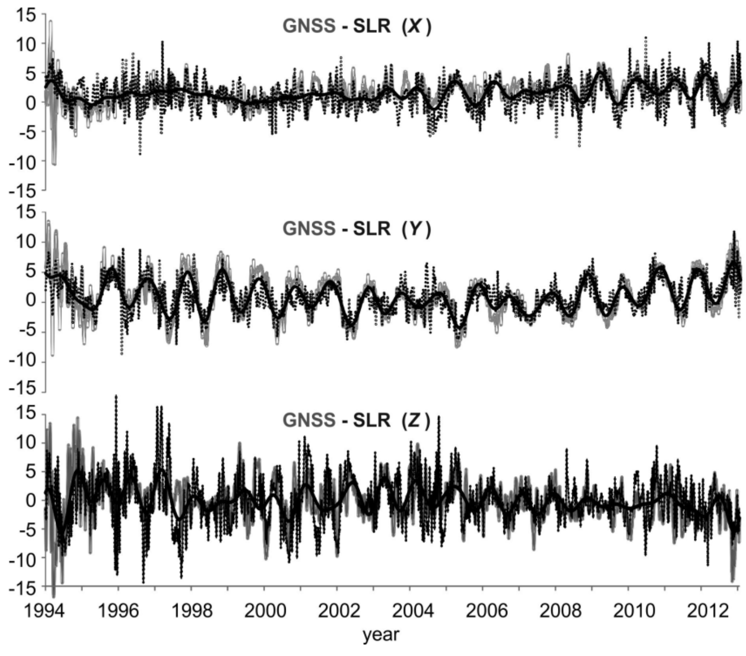

Fig. 7. The model centre of mass time series (bold) computed as the average of the GNSS (gray) and SLR (dotted) common oscillations composed of only 6 lower frequency components together with the filtered oscillations (Kosek et al., 2014)

2.4.2. Sea level change

Niedzielski (2011b) showed the results of analysis focusing on optimal orders of autoregressive models determined for sea level anomaly (SLA) residuals. Memory of stochastic processes – those that govern irregular sea level residuals at various locations – is rather weekly organized in space. In the vicinity of Indonesia, and in certain areas of the central and eastern equatorial Pacific Ocean, there exists a poorly organized concentration of grid cells in which sea level residuals are described by high-order models. Associated with this is an investigation into the El Niño-Southern Oscillation (ENSO) impact on sea level change in the equatorial Pacific. Niedzielski and Kosek (2011a) compiled their results and provided a comprehensive characterization of how ENSO influences sea level modelling experiments. Now, sea level change studies are migrating towards processing time series offered by the Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) repository. Near-real time and delayed time data are to be analyzed, modelled and predicted. The near-real time system and service for sea level prediction, known also as Prognocean was designed, implemented and based at the University of Wroclaw. Initially, gridded daily SLA data, known also as MSLA, obtained courtesy of AVISO repository are predicted for 1, 7 and 14 days in the future. Along with predictions, Root Mean Squared Error (RMSE) of predictions is computed in near-real time so that the users are able to evaluate the performance of the system and service. The following prediction methods were implemented: 1) extrapolation of a polynomial-harmonic model built for deterministic components and the combination of this method with 2) autoregressive prediction of residuals, 3) threshold autoregressive model and 4) multivariate autoregressive model (Niedzielski and Mizinski, 2013).

The sea level anomalies based on satellite altimetry data available from AVISO website were analysed (Kosek et al., 2013). The time-frequency analysis based on the Fourier Transform filter of these data enables to detect ocean regions where the signal in sea level change is not linear. It has been found that the annual oscillation in these data is not linear, has a broadband character, and it is mostly responsible for the increase of short-term prediction errors of sea level anomaly data. It creates oscillations with frequencies being an integer multiplicity of the annual frequency. Thus, amplitude maxima of all these shorter period oscillations are located almost in geographic regions of the annual oscillation amplitude maxima. The increase of the prediction errors of sea level anomaly data is mostly caused by variable amplitudes and phases of the broadband annual oscillation. Swierczynska et al. (2014) demonstrated that the asymmetry between El Niño and La Niña events recorded in sea level variation occurs only during extreme episodes of ENSO. They also explained that the asymmetry is controlled by certain regular cycles with time-variable amplitudes.

The stochastic low-order autoregressive moving average (ARMA) and generalized autoregressive conditional heteroscedastic (GARCH) models were used to model irregular sea level fluctuations in the least-squares residuals of the sea level anomaly data (Niedzielski and Kosek, 2011b). The authors found that AR and ARMA models are adequate, with a successful fit to these residuals in some patchy bits of the equatorial Pacific. In contrast, GARCH models have been shown to be rather inaccurate, specifically in the vicinity of the tropical Pacific, in the North Pacific and in the equatorial Indian Ocean. The pattern of the Tropical Instability Waves (TIWs) called also Legeckis waves has been observed in the statistics of AR and ARMA model residuals indicating that the dynamics of these waves cannot be detected by the linear stochastic processes. It was shown that it is rather difficult to unequivocally recommend particular models for the forecasting capable to describe the nonlinear sea level anomalies present in the equatorial Pacific and the tropical Indian Ocean.

Niedzielski and Kosek (2012a) reviewed statistical properties of sea level fluctuations observed by TOPEX/Poseidon and Jason-1 altimetry missions, both on global and regional scales, as well as different temporal domains including long-, medium-, and short-term components of sea level fluctuations. It was shown that ENSO-driven signal in sea level change extends from east towards central Pacific, as indicated by unexpectedly coherent spatial patters of a few statistical measures (Fig. 8). The authors found that there is a zone in central Pacific where skewness of sea level variability is approximately equal to 0 and kurtosis is equal to 3. In addition, the standard deviation of sea level variation is lower in such areas. The zone in question may be interpreted as the boundary of ENSO-driven fluctuations of sea level.

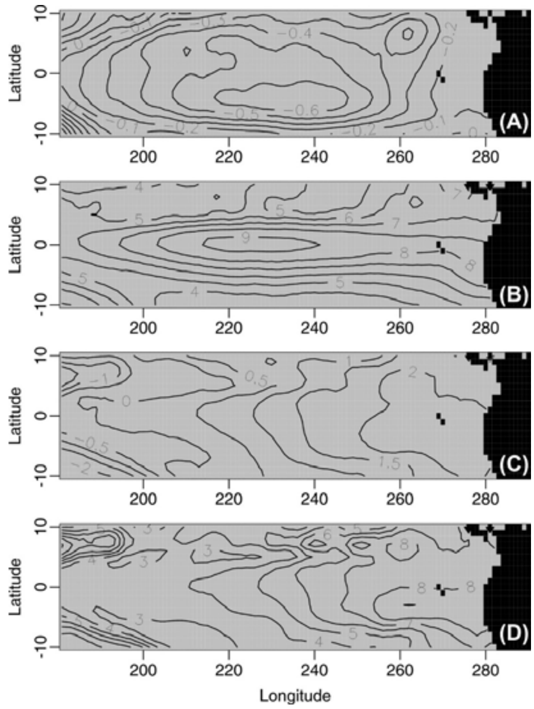

Fig. 8. Maps showing sea level change statistics: rate in cm per year (A), standard deviation in cm (B), skewness (C), and kurtosis (D) (Niedzielski and Kosek, 2012a)

The Cox-Stuart statistical test was used to estimate a minimum time span of the global mean sea level time series from TOPEX/Poseidon, Jason-1 and Jason-2 satellite altimetry which is sufficient to detect a statistically significant trend as well as to detect a significant acceleration in these data (Niedzielski and Kosek, 2011a). Considering the set of significance levels equal to 0.002, 0.004, ..., 0.1, the test was applied to compute the probability of trend detection in the global mean sea level time series in 1993–2010. It was found that whether these data were corrected for the Global Isostatic Adjustment (GIA) or not, the statistically significant trend can be detected with the probability close to 1 when these time series length is approximately equal to 2.99 and 3.09 years, respectively. Assuming available altimetry global mean sea level data it was impossible to detect any acceleration in sea level rise with the probability close to 1.

Niedzielski (2014) presented a review of ENSO and selected environmental consequences at a range of spatial scales. The fundamentals of ENSO were summarized in a descriptive way, and the key facts from the history of ENSO research as well as with recent developments in understanding the oscillation were given. Subsequently, a potential initial driving force that begins the warm ENSO episode was discussed, and the inference was limited to the Quasi-Biennial Oscillation which may be controlled by solar forcing. Later, the insight into the ENSO history was provided, with a scrutiny about the most recent phenomena and the ENSO variability over the geological time. Three environmental consequences of ENSO: irregular fluctuations of the EOPs, climatic and hydrologic teleconnections that allow migration of the ENSO signal to remote regions of the Earth (the teleconnections are explained using the specific European example), and sea level change in the equatorial Pacific and Indian Oceans were discussed. Those examples explain that ENSO is a phenomenon that impacts the dynamics of the entire Earth and controls some geophysical and environmental parameters of the atmosphere and hydrosphere on regional and local scales.

2.4.3. Hydrological processes

The aforementioned didactic paper by Niedzielski (2011b) also included topics related to hydrological processes and their characterization. A complete series of maps that complement previous work by Sen and Niedzielski from 2010 was published and discussed to illustrate a combination of time series and the Geographic Information System (GIS) methods. In particular, a moment-based characterization of discharge data at a given outlet is combined with a GIS-based description of basin topography.

Recent investigations confirm meaningful but weak teleconnections between ENSO and hydrology in some European regions. In particular, it holds for Polish riverflows in winter and early spring as inferred from integrating numerous geodetic, geophysical and hydrologic time series. Niedzielski (2011a) examined whether such remote teleconnections may affect hydrologic forecasting. On the basis of cross-correlation and wavelet analyses it was found that there is a weak but significant link between ENSO and surface hydrology in SW Poland. It was inferred that ENSO episodes may be among a few factors affecting winter and early spring discharges of rivers in SW Poland and may have a (probably limited) impact on snow-melt flood generation.

The new HydroProg system is now experimentally implemented at the University of Wroclaw for the upper Nysa Klodzka and its selected water gauge in Klodzko Valley. The aim of this system is real time prediction of water level in Odra River as well as warning of the potential hazard, its type and location.

3. Monitoring of geodynamic phenomena

3.1. Permanent GNSS observations

Determination of strain. Analysis of time series based on data from permanent GNSS stations allows to study the precision of station velocity determination as well as crustal deformation due to hydrological loading. Bogusz et al. (2013b) presented the results of testing of various methods of permanent stations' velocity residua interpolation on a regular grid, which constitutes a continuous model of the velocity field in the territory of Poland. Absolute velocities expressed in the ITRF2005 and the intraplate velocities related to the Northwest University Velocity (NUVEL) and Actual Plate Kinematic Model (APKIM) tectonic plate motions models at over 300 permanent reference stations of the EUREF Permanent Network (EPN) and Polish Active Geodetic Network (ASG-EUPOS) covering the area of Europe were investigated. Based on the velocities of permanent EPN stations, the map of the continuous velocity field was developed by interpolating velocities using the Kriging method with the nugget effect (Fig. 9).

Robustness of geodetically-defined kinematic model describing recent geodynamics was tested using numerical finite element modelling of stress and strain distribution in Central Europe (Bogusz et al., 2011). Simplified mechanical model of the lithosphere was developed using geological and geophysical data including tectonically defined discontinuities. The results of model predictions (Fig. 10) were evaluated by comparison with measured present-day stress and strain.

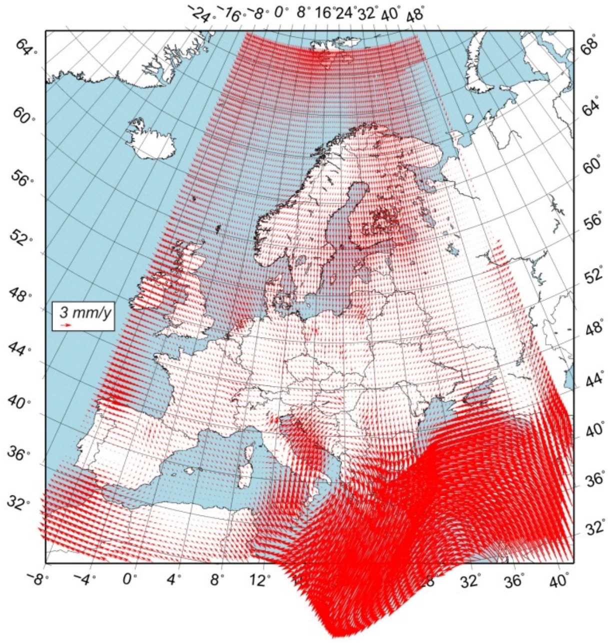

Fig. 9. The continuous intraplate velocity field for Europe with the use of APKIM2005 (IGN) model

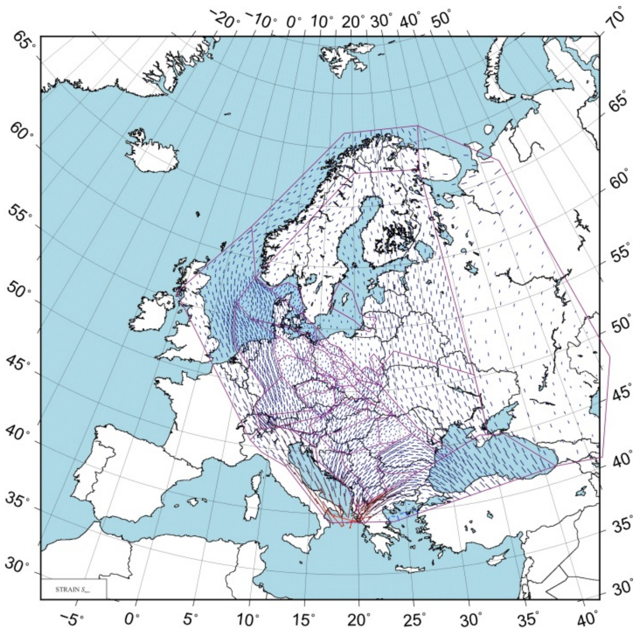

Fig. 10. Strain directions (S_{MAX}) obtained using Finite Element Method modelling

Residual time series of solutions obtained by the routine GNNS data processing (ETRF2000) were analyzed to test the models used and to find error sources that could possibly affect solutions by decreasing their reliability (in the terms of precision). There are many doubts regarding proper antennas' placement – as they are mostly installed on the roofs of the buildings. The use of data from such sites for the purpose of geodynamic study, like intra-plate velocity or strain estimations was questioned. Bogusz et al. (2012b) presented the usefulness of ASG-EUPOS time series for the determination of the regional velocity field. Calculations were performed using robust estimation instead of the least squares method due to its disadvantages, e.g. the small robustness for the large errors (stand-off values) that significantly affect estimated parameters. The velocity field was developed using the observations from the newly established (2008) ASG-EUPOS system. The intraplate velocities (IPV) were determined using geological model NUVEL-1A NNR and geological-geodetic APKIM2005 model (Bogusz and Figurski, 2012). They were compared with those obtained using geodetic techniques (ITRF global velocities and the European Terrestrial Reference Frame – ETRF ones) and large discrepancies between available models were highlighted. Due to the observed ambiguities the authors recommended the use of the absolute (ITRF) velocities and proposed the method of their verification (Bogusz et al., 2013a). Selection of the criteria qualifying insufficiently stable points to be eliminated from further computations is of a great importance for the final solution of the deformation field. In the area of Poland, which is a tectonically stable region, the strain should not exceed 3 to 4 nanostrains/year. The disturbances resulting from insufficient stability of the ASG-EUPOS stations affect significantly the computations of the deformation field. The GRID_STRAIN software that runs under the MATLAB® environment helped to achieve the continuous strain field model after the final data verification (Fig. 11).

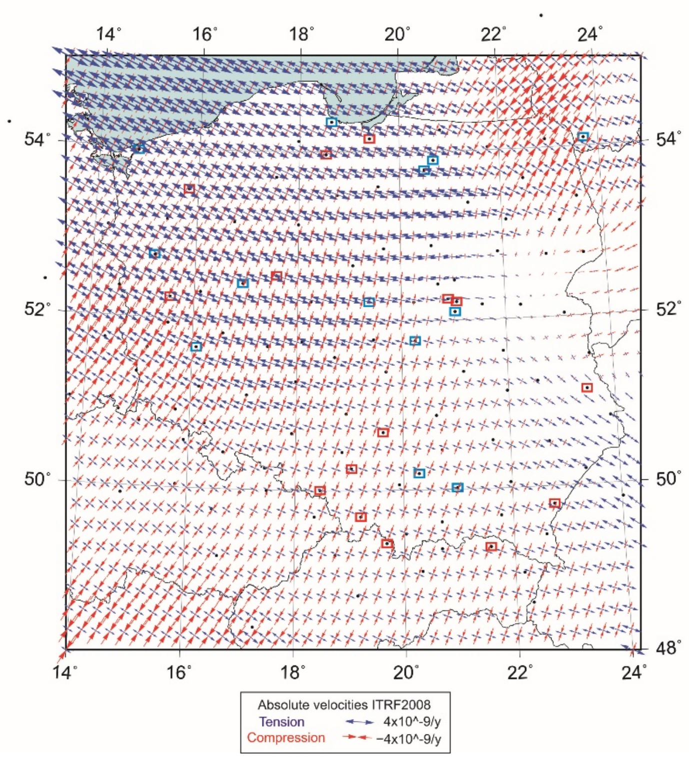

Fig. 11. Continuous strain field after the final data verification (the excluded stations are also marked to show what influence they had on the appearance of the strain field) (Bogusz et al., 2013a)

Periodic oscillations observed on several sites are probably related to the real effects from atmosphere or continental hydrosphere. Rajner (2012) analysed the temporal and spatial range of the Earth' tides, ocean tidal loading, atmospheric radiation tides loading, polar motion and its oceanic indirect effect and the non-tidal ocean loading with pointing on their magnitudes and possible effects on high precision positioning with space geodetic techniques. The author studied these effects for Jozefoslaw station of WUT.

Rajner and Liwosz (2011) described the large-scale crustal deformation due to hydrological surface loads computed basing on WaterGAP Hydrological Model with Green's functions. They focused on its influence on seasonal variation of GPS-estimated heights using the Precise Point Positioning (PPP) method. They analysed time series for 4 stations from the area of Poland. A good agreement in both amplitude and phase with 10 mm of peak to peak was found for hydrological surface loads and GPS heights. The authors developed a simple model for Poland that may help to reduce the seasonal signal in GPS solutions.

Satellite data from the ASG-EUPOS stations enable also the determination of the model of vertical crustal movements for the territory of Poland. The high credibility of levelling data is evaluated by a number of control procedures and statistical evaluation before and after adjustment, as well as during the measurement activities. Kowalczyk et al. (2014a) used daily height differences from 35 ASG-EUPOS stations determined in the EPN Local Analysis Centre at the Military University of Technology (MUT LAC) using Bernese v.5.0 software. The vectors between permanent stations for calculating the height differences were chosen with the use of Delaunay triangulation. The standard deviations of height differences vary from 3.0 mm to over 6.2 mm. The average misclosure equals ~0.3 mm/year, while the maximum misclosure is equal to ~1.0 mm/year.

The correlation between two models of vertical crustal movements was determined using two methods: absolute and relative (Kowalczyk et al., 2014b). On the basis of the obtained results the qualitative and quantitative possibility of the use of data from GNSS permanent stations for developing a kinematic model of vertical crustal movements was discussed (Fig. 12).

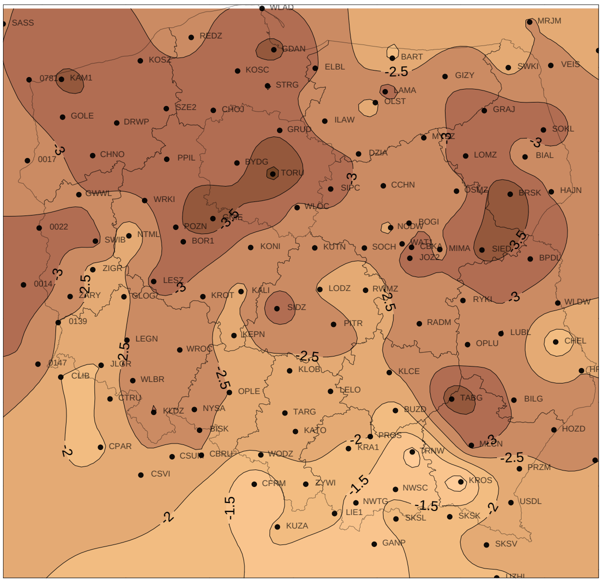

Fig. 12. Developed model of vertical crustal movements [mm/y] (Kowalczyk et al., 2014b)

The GPS time series autocorrelations can be identified both in the deterministic and stochastic part of the data. Their existence in the deterministic part of GPS time series is identified as a trend (interpreted as station’s velocity) and seasonal components (annual and semi-annual). The autocorrelation in the stochastic part of GPS time series was proven in the form of its power-law long-range dependencies with the use of numerous of methods. The use of locally weighted scatterplot smoothing (LOESS) was tested in the autocorrelation analyses (Bogusz et al., 2014a). It was shown that the trend-related behaviour is best modelled by both smoothing parameter and polynomial of degree 1. The 2nd degree polynomial with smoothing parameter close to 0.1 fits seasonal components quite well. For all of the LOESS modelled curves, the autocorrelation function (ACF) was calculated for different types of modelled phenomena. The goodness of fit of the linear regression line into topocentric components of velocity determination was investigated for the selected ASG-EUPOS and EPN stations (Bogusz et al., 2014b). The coefficient of determination R^2 close to 1 proves the well fitted LS line into the time series, while its lower values reflect the effect of unremoved (or improperly removed) outliers, offsets and seasonal components. This clearly demonstrates how the determination of the velocity of permanent GNSS stations can suffer from the incorrect data pre-analysis.

3.2. Permanent SLR observations

Due to serious failures of the laser module and telescope system the Borowiec SLR station (SOD 78113802) is offline since 25 March 2010. At the beginning of 2014 new telescope optic was replaced including primary and secondary mirror of the telescope (Cassegrain system) and special dielectric mirrors transferring laser pulse from laser unit to the telescope. Additionally, two laser modules were installed, the standard unit used for laser observations of all ILRS satellites and high-energy module dedicated to laser observations of space debris. First attempts towards observations of all ILRS objects were carried out in October 2014.

Alothman and Schillak (2014) presented a new SLR-derived velocity for the Arabian plate motion, based on data from 1996 to 2009 from SLR station at Riyadh. They calculated satellite arcs in ITRF2008 using SLR observations from about 20 ILRS stations with the GEODYN-II software. The velocity of Riyadh station was determined by fitting the linear regression line into time series of position changes. The 3D velocity determined equals 42.9±0.2 mm/year with North, East and Up components of 29.1±0.2, 31.6±0.2, and 1.9±0.3 mm/year, respectively. It is similar to the one from NNR NUVEL1A geological model.

Lejba and Schillak (2011) determined the positions and velocities of four SLR stations: Yarragadee (7090), Greenbelt (7105), Graz (7839) and Herstmonceux (7840) in ITRF2005 from 5-year observations of low orbiting (LEO) satellites (Fig. 13) using GEODYN-II software and compared the results with the respective ones derived from processing LAGEOS-1/LAGEOS-2 observations. The authors showed that the stability of station coordinates obtained from LEO satellites is in general worse (17.8 mm) than those from LAGEOS (7.6 mm). The velocities of analyzed stations were determined with the accuracy of 1 mm/year, and 0.5 mm/year when using observations of LEO satellites, and LAGEOS satellites, respectively.

Szafranek and Schillak (2012) presented the models, parameters and assumptions made for homogenous reprocessing of SLR and GNSS data from 1996-2011 in the NAPEOS software. The paper was related to the recommendation of the Global Geodetic Observing System (GGOS), which stated that the same models and parameters from IERS Conventions 2010 should be used in both processing strategies.

Strong earthquakes and tsunamis affected many stations being the core of the ITRF by position discontinuities, which caused their temporal uselessness as the reference. As a consequence, the decrease of the quality of the network geometry also occurs. The Earth crust stresses and post-seismic relaxation damages occurring near the Earth surface can be mentioned as the main reasons of coordinates change. After the earthquake the shape of time series of station coordinates can be described by curve line with dumping amplitudes (so-called “post-seismic decay”). The impact of earthquakes on the stability of time series on the selected GNSS and SLR co-located sites was investigated (Szafranek et al., 2014). GNSS and SLR data from selected co-located sites were processed to investigate the optimal method of post-seismic decays determination as well as to determine the time necessary for each station to attain the stability again.

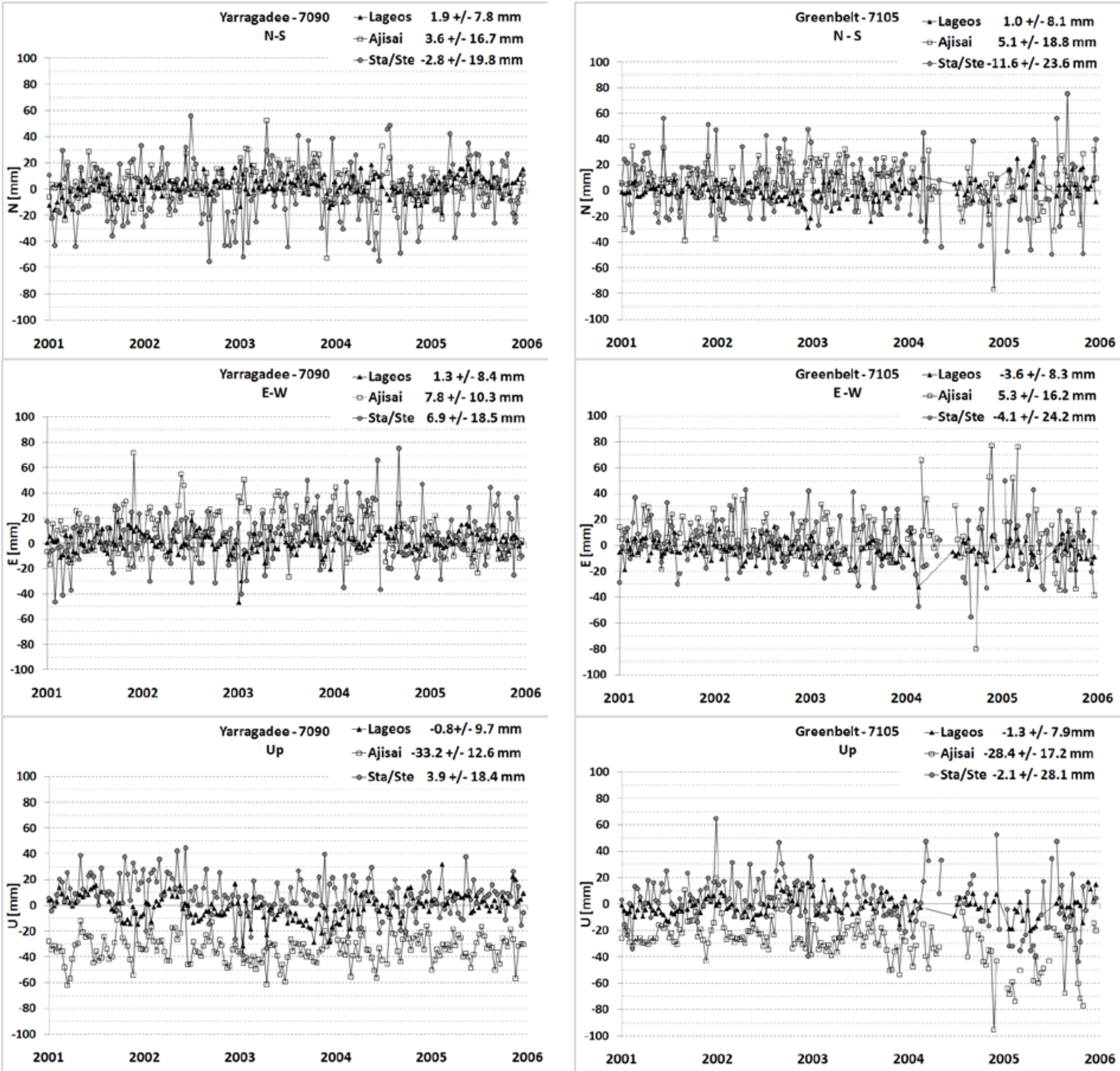

Fig. 13. Yarragadee (West Australia) and Greenbelt (MD, USA) positions (N, E, U) from Starlette/Stella, Ajisai and LAGEOS-1/LAGEOS-2 satellites in reference to ITRF2005 for epoch 2000.0 (Lejba and Schillak, 2011)

3.3. Local geodynamic networks

The geodynamic network of the Sudety Mts. (GEOSUD) was established in Poland in 1996. Simultaneously, the geodynamic network EAST SUDETEN was built on the Czech side of the border in 1997 and in 2001 it was extended for sites towards west (the WEST SUDETEN network). Since 1997 annual GPS campaigns have been performed on both networks.

Kaplon et al. (2014) focused on the results of uniform reprocessing of all measurements from the geodynamic network of the Sudety Mts. from 1997-2012. The earlier GPS observations were processed few times using the Bernese software applying different models for EOP, satellite ephemeris, pole motions, ocean loadings and antenna calibrations. The authors reprocessed the whole data set homogenously and obtained ITRF2008 coordinates and velocities have been compared with respective EPN and ASG-EUPOS solutions. The determined velocities (Fig. 14) reflected the complexity of geological structures of the examined area, where individual Sudetic and Moravo-Silesian blocks of the Bohemian Massif are affected by active dynamics of the West Carpathians and Alpine orogene structures.

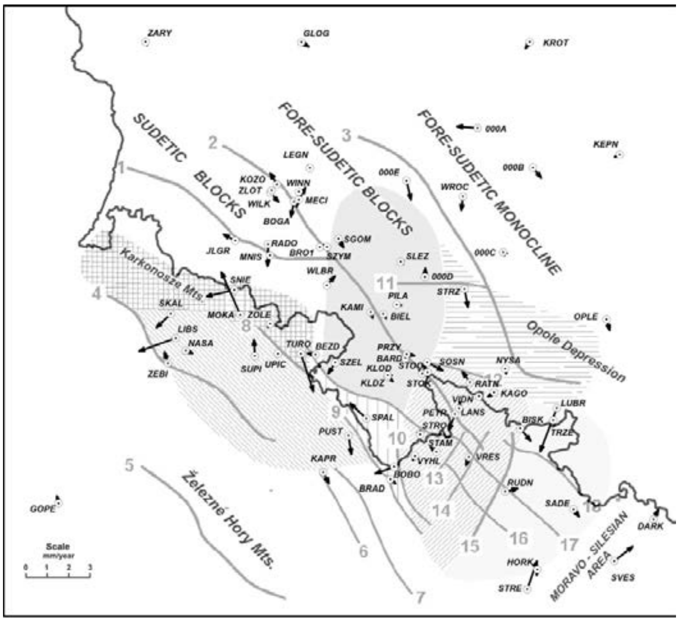

Fig. 14. Vectors of horizontal intraplate velocities (ITRF2008 reduced with ITRF2008 plate-motion model) (Kaplon et al., 2014)

Grzempowski et al. (2012) investigated the changes in the elevation of benchmarks of precise levelling lines between 1956-1999 and compared them with GPS solutions from 2008–2010 in the framework of geodynamic studies on Wroclaw Plain, situated in the SE part of Central European Subsidence Zone (CESZ). On the basis of levelling data, the authors found out the subsidence of Wroclaw Basin that increases the basin margins. Consideration of GPS data lead to the detection of the compressive strain in the axial part of the CESZ southwest of Wroclaw along W-E direction and in Opole depression along NNW-SSE direction. The extensional strain was shown to occur at the southern CESZ margin, along the W-E direction in the uplifted part of the Fore-Sudetic Block and at the northern margin of this zone, along W-E and NW-SE directions (Fig. 15).

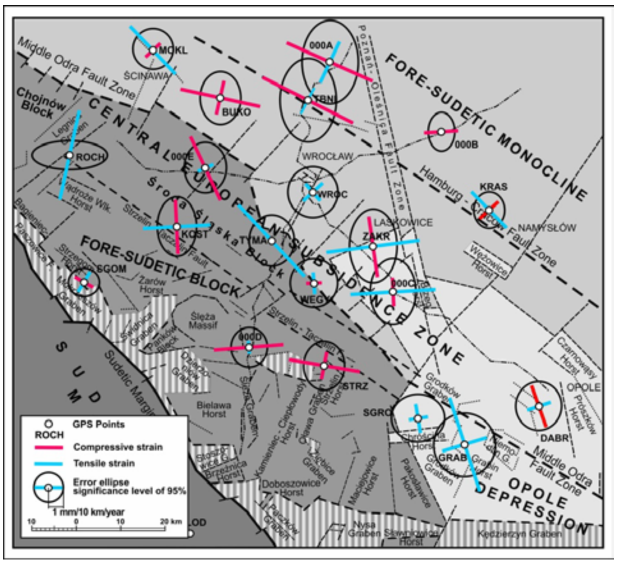

Fig. 15. Horizontal strain in the study area calculated on the basis of velocities of GPS points obtained from measurements in 2008-2010 (Grzempowski et al., 2012)

Cacon et al. (2012) presented the results of repeatable precise levelling in three geodetic micro-networks from Szczeliniec Wielki in the Bohemian Massif. The authors confronted the results of levelling and displacements from 3D monthly records with recent investigations of tectonic micro-deformations. Analysis of precise levelling data and data acquired with a total station showed changes in heights of selected network points, what confirmed the gravitational deformations in that area. The recent geodynamic effects were recognized as ones of an aseismic origin.

Bogusz et al. (2012a) determined the horizontal velocity field derived from 3-years' time series of topocentric components of the EPN and ASG-EUPOS stations. The determination of the velocity field was performed using robust estimation (*M*-estimators). The presented effects, which could decrease the velocity estimation reliability, have been grouped into four categories. Finally the regional absolute and intraplate velocity fields were presented (Fig. 16).

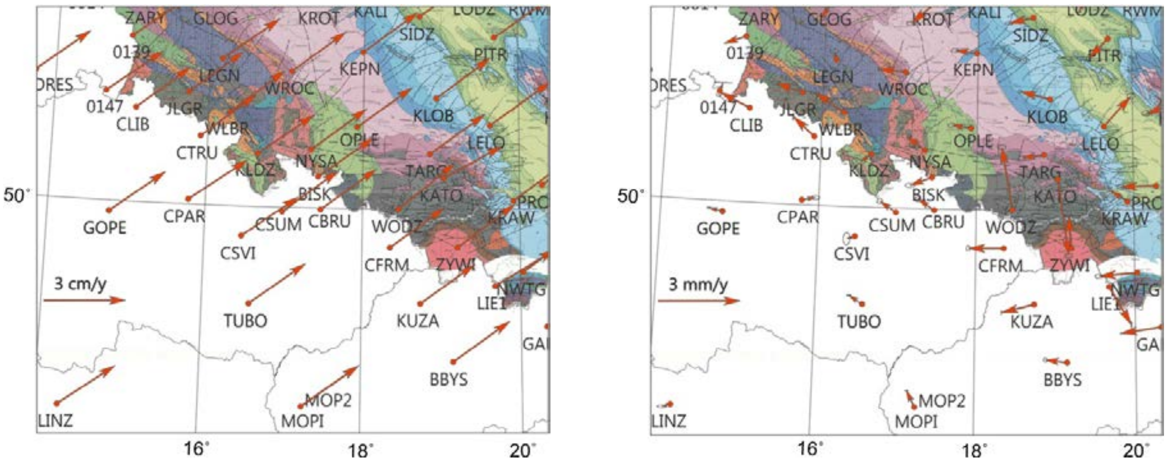

Fig. 16. Absolute (in ITRF2005, left) and intraplate (in ETRF2000(R05), right) velocities with error ellipses (Bogusz et al., 2012a)

Rajner et al. (2012) have studied the effect of gravity variations associated with the changes of soil water on global scale in Lower Silesia (SW Poland). They used data acquired with the FG5-230 gravimeter of 2 μGal peak to peak amplitude and showed that neglecting the changes of soil may result in detecting secular gravity changes which is an artefact.

Ksiaz Observatory. The Ksiaz Massif is located in the central part of a structural geological unit known as the Swiebodzice Depression/Basin, which belongs to the regional mosaic of evolving Sudetic Palaeozoic sedimentary basins. A water-tube tiltmeter (WT) system consisting of two perpendicular tubes was installed in the underground galleries of the Geodynamic Laboratory of the SRC in the Ksiaz Castle, Central Sudetes, in 2003. The partially filled water tubes of several tens of metres long are equipped with high-precision interferometric recording gauges at their ends. The recording gauges continuously measure water level changes in the tubes with single-nanometre accuracy which corresponds to 0.005 mas of plumb line variations. Kaczorowski and Wojewoda (2011) discussed the phenomenon of great non-tidal signals recorded by the two water-tube tiltmeters of the Geodynamic Laboratory in Ksiaz. They found strong symmetrical and asymmetrical signals in water level variation, which may origin from active bedrock deformation due to contemporary tectonic movements of the Ksiaz Massif. The authors concluded that if the fault blocks are a subject of 3D rotations, the WT tiltmeter would detect only the vertical component of block movement. Kaczorowski (2013) found the harmonic oscillations of water level changes in two water-tube tiltmeters in Geodynamic Laboratory in Ksiaz that were unrecognized before. Their amplitudes are of several hundred nanometres and frequencies of a dozen or so harmonic modes from 10 to 100 minute periods (10^{-3} Hz). The author concluded, that the signals are propagated in the atmosphere and tried to find out the origin of these infrasounds. He excluded a range of phenomena from the nearest surrounding of laboratory and stated that the observed micro-vibrations of air pressure can be generated thousand kilometres away. Kasza et al. (2014) described tectonic activity in the Ksiaz area derived from water-tube tiltmetres data and surveying data from the network in underground corridors of Geodynamic Laboratory. The presence of several zones of tectonic faults of rock mass was shown. The results confirmed the geodynamic nature of signals recorded by WT caused by vertical movements and the slopes of rock blocks during tectonic events. Numerous comparisons confirmed that the damages observed in the structure of Ksiaz castle can be caused by recent tectonic activity. In 2010 became operational a GPS station KSIA devoted to investigate the episodic displacements of rocks in the Ksiaz Massif to support the interpretations made with water-tubes in the Geodynamic Laboratory, in particular to reduce the disturbance effects of geophysical origin from water-tubes analysis (Zdunek, 2012). The 3-years long time series from GPS KSIA and KSI1 stations (Fig. 17) was analysed (Zdunek et al., 2014). The velocity vector determined for that station was compared with velocity vectors of others selected reference stations located in different azimuths, tectonic units and distances from KSIA. Different displacements of the Swiebodzice Depression and Ksiaz unit in relation to selected GPS stations were observed. Significant deformation of the Pelcznica river meander, geological indicators such as trends and dips of faults as well as kinematic models of deformations of Ksiaz massif indicate possible interpretation of the reasons of differences between KSIA GPS station displacements determined.

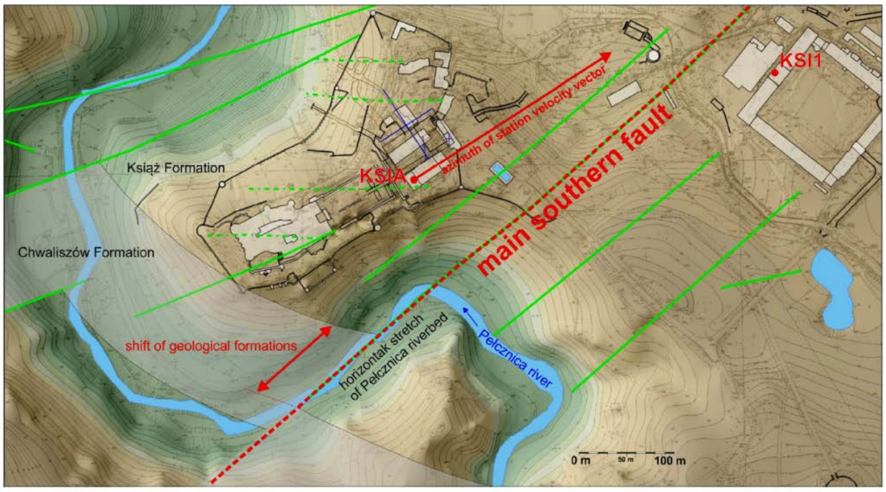

Fig. 17. Location of the new established GPS station KSI1 in relations to the existing station KSIA. Red dotted line represents the 'main southern fault', green dotted lines – indirect faults class 2 (Zdunek et al., 2014)

A methodology of the ‚determination of surface elevation changes with cartographic modelling in geographic information system (GIS) was described (Blachowski and Milczarek, 2014). The authors focused on two areas of Walbrzych Coal Basin around the city of Walbrzych in SW Poland and calculated mining terrain subsidence in the time span of 123 years (1886-2009). The elevation changes determined using interpolation methods and map algebra operations were compared with subsidence predicted by other authors, present-day orthophotomap of the area of Walbrzych and predictions made with Knothe method. The calculated subsidence reached 24 m and 36 m depending on the area analysed which corresponds to 0.2 and 0.3 m/year. The obtained results exhibit high correlation level with predictions from Knothe method – up to 0.9. A new deformation information system (DIS) that uses the modular structure concept to facilitate studies of mining-induced ground deformations was proposed (Blachowski et al., 2014). The system is to calculate various parameters that characterize the ground deformations in space and time. It integrates spatial and attributive data as well as interactive 3D geological and mine models. The system was verified for underground mines in Walbrzych in SW Poland. The results of 5 annual GPS observing campaigns carried out at the open pit mine Kozmin between 2008 and 2012 were presented and their usefulness for monitoring ground deformation were underlined (Baryla et al., 2014). The horizontal displacements not exceeding ±8 mm with downward trend dominating were obtained. The authors concluded that the accuracy of displacements measured with GPS at the level of a few millimetres for each topocentric component and the accuracy of ±3 mm of 3D position are possible to achieve.

Szczerbowski et al. (2011) analysed local changes of plumb line direction in Inowroclaw in central Poland on the basis of GPS, levelling and gravimetric surveys. The authors showed that the vertical deflection in a small flat area may change as a result of a local disturbance in mass distribution represented by the salt deposit. The total changes were found to be at the level of 1.7" at the distance of 4 km. It has been stated that the mismodelled local quasigeoid can cause a maximum error of up to 11 mm in normal heights determined by GPS technique and therefore the increase of its resolution is necessary. A concept of a complete system of monitoring the magnitude and rate of rock mass surface deformations in planned sub-level caving mining operation in Kvannevann mine in Northern Norway (Fig. 18) was proposed (Blachowski et al., 2011). Specific conditions (e.g. location and climate) and expected deformations from numerical modelling made by the SINTEF Rock Engineering with Finite Element Method (FEM) were taken into account in the system. The authors proposed the accuracy of ±2 cm, the measurements taken at least twice a year, and locations of control points what would provide the sufficient set of data for further analyses.

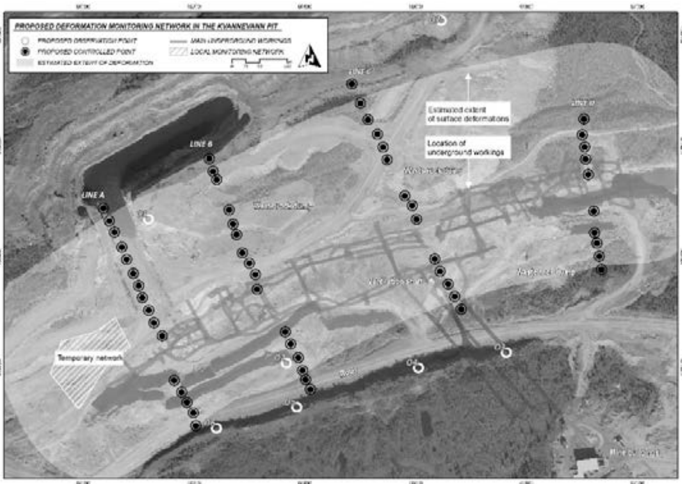

Fig. 18. Locations of controlled and observation points against the background of the production levels, estimated zone of deformation and surface features (Blachowski et al., 2011)

The effects of monitoring of underground mining with sub-level caving system on the surrounding rock mass in a Kvannevann mine was described (Blachowski and Ellefmo, 2012). The authors implemented the surveying network for monitoring the displacements of control points and then numerically modelled the rock mass deformations with Finite Element Method. The network points were stabilised with 3 m long metal pipes to a depth and 2.5 m below the surface. The measurement campaigns were conducted in October and November

2011 at a 3 week interval. The analyses performed with FEM provided the information on general state of the rock mass in stages of large horizontal stresses undergoing mining.

Two new methods for transferring the heights from benchmarks, for which the levelling cannot be done, were proposed (Kuchmister et al., 2014). First one is based on the mono-photogrammetry with Direct Linear Transformation, and the second one – on the levelled laser beam that is emitted from the benchmark towards the levelling staff. The picture of staff graduation with the laser light spot taken with a digital camera is then processed to obtain the value of the reference. The first results show that the height can be determined with sub-millimetre accuracy.

Perski and Mroz (2012) showed the analysis of Persistent Scatterers Interferometry (PSI) for Sambia peninsula (Kaliningrad district of Russia) to give an answer whether the surface deformations result from tectonic processes related to the earthquake from 21 September 2004 or not. They processed the Synthetic Aperture Radar (SAR) data from ERS-1 and ERS-2 satellites from 1992-2001 for that region and obtained velocities of a few points with strictly linear trend. The analysis of 4 sets of PSI confirmed the tectonic origin of deformations with a few mm/year. Szostak-Chrzanowski and Chrzanowski (2014) used the GPS and satellite Interferometric Synthetic Aperture Radar (InSAR) data to monitor the separate ground subsidence due to gas withdrawal in the area of lower Mackenzie River Delta in Northern Canada from the total surface deformation resulting from natural causes such as permafrost degradation and post-glacial isostatic or tectonic uplift/subsidence of the area. They recommended the GPS technique to be a core of the monitoring scheme with a minimum of 25 monitoring points. The InSAR technique on the other hand will provide the information on the total accumulated surface subsidence. Cmielewski et al. (2012) described the instrument built by the Institute of Geodesy and Geoinformatics with the use of optoelectronic techniques. They showed that this instrument can measure the relative inclinations of engineering objects and inanimative nature phenomena with sub-millimetre accuracy. The authors showed, that the proposed device can be used for the determination of surface deformations caused by mining exploitation or hydrogeologic, geotechnical or constructional influences.

3.4. Tidal investigations

The Borowa Gora Geodetic-Geophysical Observatory of IGiK is located 35 km north of Warsaw. In 2009 three LaCoste&Romberg (LCR) gravimeters owned by the Institute of Geodesy and Cartography were upgraded with the LRFB-300 feedback system. The upgrade made it possible to record gravity data with 10 nm/s^2 readout resolution and near 2 Hz temporal resolution. The gravimetric tides are collected since the beginning of 2011 but unfortunately the first year of recording is complete only in 73%. At the beginning of 2012 a set of Linux shell scripts has been developed to provide reliable and fully automatic tidal recordings (via Bluetooth) as well as automatic handling of any exceptional situations. The system runs with the LCR G1036 from the beginning of February 2012, and since then the completeness of the recording was improved to nearly 98-99%. The first complete tidal analysis of 745 days of gravimetric recordings from 2012, 2013 and the beginning of 2014 was performed in early 2014 (Dykowski and Sekowski, 2014). Last classic calibration of the LCR G1036 on the gravimetric calibration baseline was performed in June 2011. During the period of consistent tidal recordings, calibration of the tidal gravimeter was performed 4 times with absolute gravimeters: 3 times with the A10-020 gravimeter of IGiK (Dykowski, 2012) and once with the FG5-230 gravimeter of WUT. Each time at least 1.5 days of simultaneous recordings of the LCR G1036 with an absolute gravimeter were performed. The estimated accuracy of the scale factor is close to 1%. Last calibration of the LCR G1036 was performed at the end of 2013 (Dykowski and Sekowski, 2014). Tidal records from 745 days were used for the tidal adjustment. Due to the 8 day gap in December 2012 the data set was divided into two blocks. For the tidal analysis HW95 tidal catalogue was used as well as Wahr-Dehant inelastic Earth model. Results for the determined tidal components are presented for 5 minute (blue) and 1 hour data (dark blue) in Figure 19. The calculated standard deviations reach 2.9 nm/s^2 and 5.0 nm/s^2 for 1 hour and 5 minute solution, respectively as shown in Figure 19. The linear barometric coefficient calculated during the tidal adjustment is –3.098 nm/s^2/hPa which is only slightly larger than the standard value of –3.0 nm/s^2/hPa. Nevertheless, it will cause a visible barometric correction difference only at significant local pressure changes.

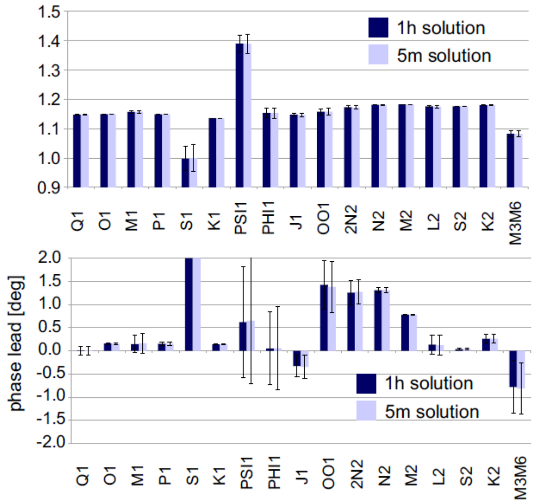

Fig. 19. Tidal factors (top) and phase leads (bottom) for the local model (Dykowski and Sekowski, 2014).

3.5. Astrometric observations

Krynski and Zanimonskiy (2012) analysed the long-standing rotational time data series from 1986-2010 based on astrometric observations with the transit instrument at Borowa Gora Geodetic-Geophysical Observatory of IGiK. Spectral analysis performed showed a number of periodic signals (including a weekly term) in the time series investigated. The authors attempted to find a reliable interpretation of those signals. The numerical model of (UT1 – UTC)^{BG} – (UT1 – UTC)^{BIH} at Borowa Gora was developed. The results were compared with the spectra taken from IERS data (Fig. 20).

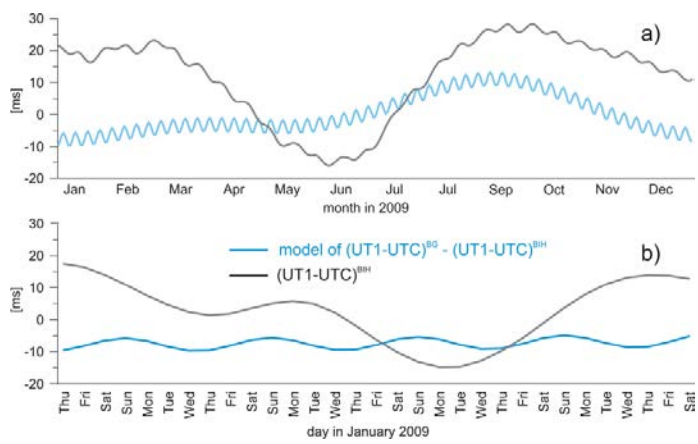

Fig. 20. Annual (a) and monthly (b) fragments of the time series of the model of (UT1 – UTC)^{BG} – (UT1 – UTC)^{BIH} at Borowa Gora and (UT1 – UTC)^{BIH} from EOP internet site (Krynski and Zanimonskiy, 2012)

3.6. Precise levelling

The first model of recent vertical movements in the area of Poland was developed by Wyrzykowski i in. 1987 using precise spirit (optical) levelling data from 1871–1882, 1926-1937, 1952–1956 and 1975–1977 campaigns of measuring the national vertical control. The newest model of recent vertical movements in the territory of Poland was developed by Kowalczyk in 2006 based on state precise spirit levelling data from 1974–1982 and 1997–2003 campaigns. After several years of GPS observations at about one hundred of permanent stations of the ASG-EUPOS network, a verification of those models became possible on the basis of independent (satellite) measurements. The model determined with the use of satellite data was compared with the models based on spirit levelling (Kontny and Bogusz, 2012) (Fig. 21).

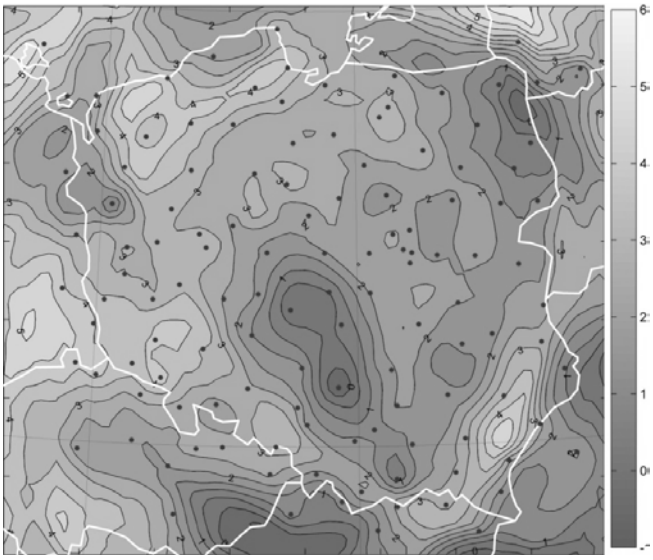

Fig. 21. Contour lines of the difference between the velocity model from the ASG-EUPOS and the model developed by Kowalczyk in 2006 [mm/yr] (Kontny and Bogusz, 2012)

Kowalczyk et al. (2011) collected data from four precise levelling campaigns conducted in Poland in 1926–1937, 1953–1955, 1974–1982 and 1997–2003 to standardize the levelling database structure, and presented the database schemes, relationships between different entities and examples of retrieving information with SQL queries. Kowalczyk and Rapinski (2012) described the methodology of common adjustment of the relative vertical crustal movements in Poland basing on three first order levelling campaigns. They unified the data from four campaigns, identified the common benchmarks and adjusted them in various scenarios. The authors further evaluated the usefulness of last three campaigns of precise levelling in Poland in terms of the development of vertical movement model concluding that the data from 1953–1955 and 1974–1982 campaigns should be of limited-trust (Kowalczyk and Rapinski, 2013). The adjusted data from three campaigns did not show much convergence of vertical movements for the nodes of double and triple levelling. The proposed hypothesis on mutual independence of residuals of triple levelling data turned out, however, to be correct.

4. Earth magnetic field

Long-term research on secular variations of the geomagnetic field in Europe was continued at the Institute of Geodesy and Cartography, Warsaw. On the basis of the geomagnetic data obtained from the European observatories (INTERMAGNET) and from magnetic field stations, the chart of amplitudes changes of *Y* magnetic field component (magnetic declination too) in Poland and the chart of time shift between Belsk Observatory – the Central Geophysical Observatory of the Institute of Geophysics of the Polish Academy of Sciences – and other measurement points records were processed. The results should show whether or not a special reduction procedure is needed to be applied. In 2010 and 2011, the new 17 field stations were operating in Poland (Fig. 22) and the records containing variations of *D* (magnetic declination), *H* (horizontal component of magnetic intensity vector) and *Z* (vertical component of magnetic intensity vector) components provide a new material for analysis of the regional and local geomagnetic field changes.

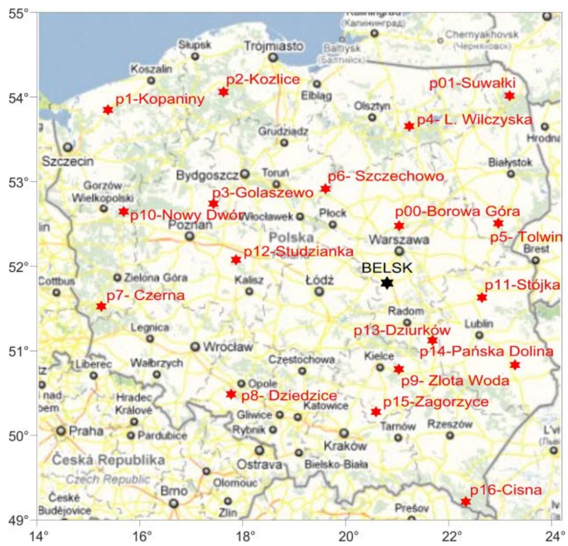

Fig. 22. The new variograph stations 2010-2011 in Poland (Welker, 2011)

The Fourier transformation was applied for the elaboration of the data from magnetic field stations in the same way as it has been done for magnetic observatory data. Figure 23 shows variations of declination recorded on all stations and in Belsk Observatory in a chosen period of 2011.

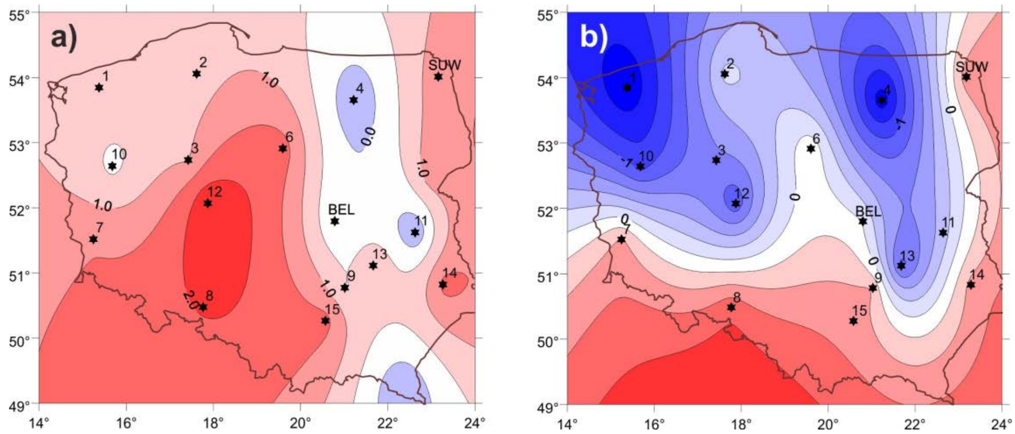

Fig. 23. Amplitude changes of declination reduced to Belsk Observatory from data of 2010 and 2011 – daily means a), and results of Fourier transformation b) (Welker, 2011)

Cross correlation obtained for observatories and stations data allows to show the chart of time shift between the records of *Y* component at the investigated magnetic points and Belsk Observatory records (Fig. 24).

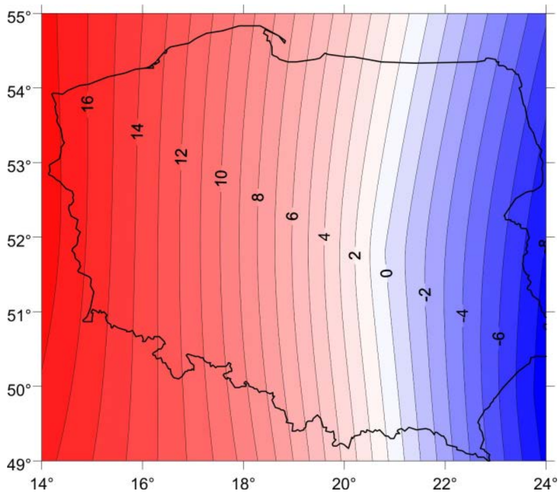

Fig. 24. Time shift between the records of the stations and others European observatories and Belsk Observatory records (*Y* component) (Welker, 2011)

Only declinations variations (*Y* variations) have a linear trend; the trend grows from East to West of Poland; the declination (*Y* component) can be predicted but only up to 3–5 years ahead. The changes of amplitudes of *D* and *Y* components in Poland are so small that they do not affect the reduction of magnetic measurements. Time corrections (from +6 to –15 minutes) should be applied when elaborating magnetic measurements data on continental scale in Europe. When processing magnetic data in Poland, those corrections can be neglected since they generate error smaller than measurement error (result of verification). It has been shown that the reduction of magnetic measurements from the points around central observatory (100–200 km) does not generate any error influencing declination accuracy. The magnetic measurements near Polish borders should be reduced to one of the closest observatories: Belsk, Hel, Hurbanovo, Niemegk or Lviv.

5. Summary

In this review an outline of researches concerning Earth rotation and geodynamics carried out by Polish scientific institutions from 2011 to 2014 is presented.

Research on Earth rotation in Poland focused on modelling the observed time variation of EOP as well as on the excitation studies based on available geophysical excitation data and models. An important part of modelling efforts concerned an application of the complex demodulation technique for analysis of diurnal and subdiurnal variations in Earth rotation. Such high frequency signal could be extracted from both the routine VLBI observations of EOP and the geophysical excitation series (AAM, OAM) with subdaily resolution. The earlier studies on the observed free oscillations in Earth rotation, the Chandler wobble and the free core nutation, have been continued in the reported period. The research on Earth rotation included also further improvements of the prediction techniques applied for the EOP data. Several publications have been devoted to the polar motion excitation studies. Particular attention was paid to the contribution of land hydrosphere to the excitation balance, which can be estimated either from the hydrology models or from the time variations of Earth gravity field detected by the satellite mission GRACE. Also the research on regional contributions to the excitation of polar motion has been continued, including the seasonal variations as well as the 14-month free Chandler wobble. The section on Earth rotation contains also a summary of the studies on the associated geodynamic phenomena like the geocenter motion which has not been investigated so far in Poland. Another subject, which is a continuation of earlier research, concerns the sea level change with particular attention paid to the role of ENSO phenomenon. The output of the sea level research consists of several publications including an extensive review of ENSO and selected environmental consequences (Niedzielski, 2014), as well as implementation at the University of Wroclaw of the near-real time system and service "Prognocean" for sea level prediction.

Due to serious failures of the laser module the Polish SLR station Borowiec did not operate in the considered time period, but the analyses on changes of other stations' positions were carried out as well as some attempts towards homogeneous reprocessing of GPS and SLR observations in the frame of GGOS. Several measurements and analyses concerning local geodynamics in the Southern Poland were done, especially on the geodynamic network of the Sudety Mts, established in 1996 and investigated until now. Separate research carried out in Ksiaz Observatory equipped with water-tube tiltmeter and with two GPS receivers was pointed out. The tidal investigation is currently performed in three observatories: the Borowa Gora Geodetic-Geophysical Observatory of IGiK, Jozefoslaw Astrogeodetic Observatory of WUT and Ksiaz Observatory of SRC. All of them observed tidal changes of gravity with spring gravimeters; additionally clinometric tides are observed in Ksiaz with hydrostatic clinometer. The results support the knowledge on elastic response of the Earth on the tidal forces. Astrometric observations made at Borowa Gora Observatory were re-processed to find and interpret periodic signals in time series and numerical model of $(UT1 - UTC)^{BG} - (UT1 - UTC)^{BIH}$ at Borowa Gora was developed. The model of recent vertical movements in the area of Poland, based on the precise levelling was developed and compared with the vertical velocities derived from the GPS observations at the ASG-EUPOS stations. Finally, the long-term research on secular variations of geomagnetic field in Europe was performed.

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Positioning and applications

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Abstract: The paper presents national report of Poland for IAG on positioning and applications. The selected research presented was carried out at leading Polish research institutions and concern precise multi-GNSS satellite positioning – relative and absolute – and also GNSS-based ionosphere and troposphere modelling and studies. The research resulted in noticeable advancements in these subjects confirmed by the development of new algorithms and methods. New and improved methods of precise GNSS positioning were developed, and also GNSS metrology was studied. New advanced troposphere models were presented and tested. In particular, these models allowed testing IPW variability on regional and global scales. Also, new regional ionosphere monitoring web-based services were developed and launched.

Keywords: precise positioning, troposphere, ionosphere, GPS, Galileo, GNSS

1. Introduction

The subject of positioning and applications covers important IAG activities. Therefore the IAG Commission 4 "Positioning and Applications" was established to promote research into the development of a number of geodetic tools that have practical applications to engineering and mapping (IAG C4 TOR). Recognizing the central role that Global Navigation Satellite Systems (GNSS) plays in many of these applications, the Commission's work focuses on GNSS-based research in precise positioning, remote atmosphere sounding including InSAR and other space-geodetic techniques. This report presents summary of the selected research carried out at leading Polish research institutions, focusing on broad range of multi-GNSS systems applications, that is only a part of the broad research carried out in Poland on the subject. It starts from different aspects of positioning and continues into remote GNSS atmosphere sounding (in particular ionosphere and troposphere).

2. Positioning

2.1. Studies on Inter System Bias in multi-GNSS precise positioning

In 2011–2015 extensive studies on relative precise positioning algorithms were carried out at the University of Warmia and Mazury in Olsztyn (UWM). A new methodology allowing for instantaneous (single epoch) precise positioning using medium to long baselines was developed. The most recent precise positioning model is developed to be applied in multi-GNSS relative positioning (Paziewski and Wielgosz, 2014). On the other hand this approach forces additional modelling of hardware biases which are introduced in tightly combined multi-GNSS model (Paziewski and Wielgosz, 2015).

Nowadays, combining observations from different GNSS systems often relies on the mathematical model requiring different reference satellites for each system. This approach can be referred to as loose combining and it is used when GNSS systems with different frequencies are applied. On the other hand, overlapping (i.e., the same) frequencies, like L1/E1 and L5/E5a in GPS and Galileo, support creating double-differences (DD) between satellites of different GNSS systems. This approach is known as tight combining, and the observational model assumes a single reference satellite for all the observations. However, when this approach is introduced, one must take into account not only time and coordinate system differences, but also the difference between the receiver hardware delays affecting the signals from different systems. This bias is termed as inter system bias (ISB). The ISB is caused by the correlation process within the GNSS receiver, thus it is present in both carrier phase and code data.

Figure 1 presents example estimates of the code and carrier phase ISBs obtained from single epoch solutions during the experiment conducted at UWM in 2014. In addition, the right hand plots in Figure 1 present Galileo satellite elevations during the experiment. The plots show that the estimated values of the ISB were stable. Higher noise of the code ISB at the beginning and at the end of the experiment coincides with the low elevations of the observed Galileo-IOV satellites.

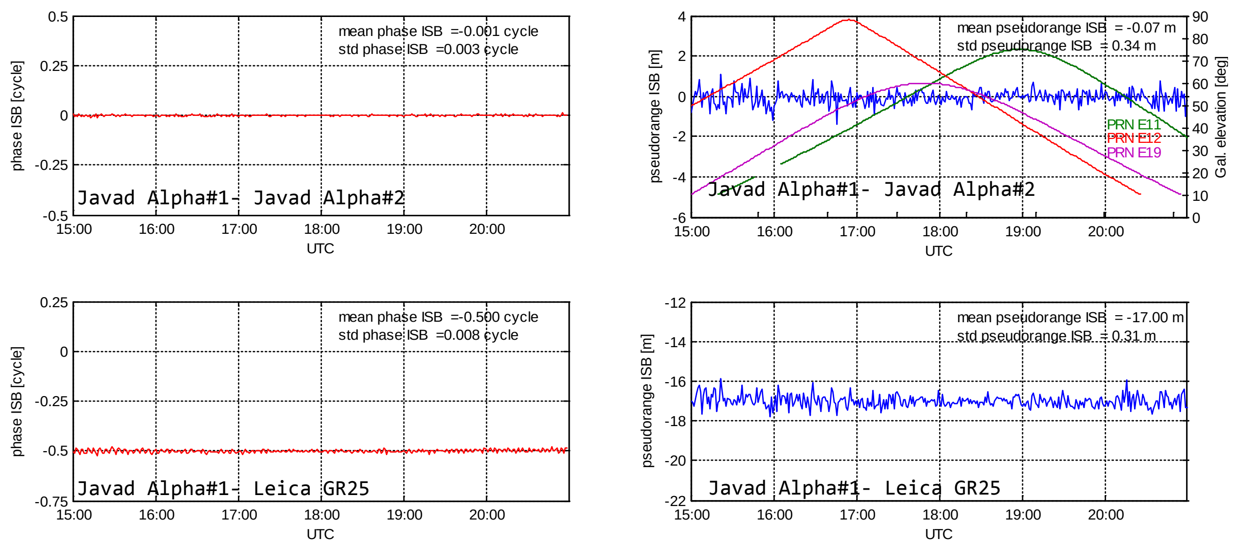

Fig. 1. Estimated carrier phase (left) and code (right) L1/E1 ISBs in the single-epoch solution for different receiver pairs (UWM experiment in 2014)

The presented results show that in the tightly combined GPS+Galileo processing the receiver inter system bias is absent when a baseline is formed with receivers of the same type (including the same OEM boards and firmware versions, Javad Alpha#1- Javad Alpha#2 in this example). For a baseline formed with receivers of different types (e.g. , Javad Alpha#1- Leica GR25), the ISB shows significant values that cannot be neglected. This indicates that the ISB is receiver-type dependent.

The phase and code ISBs also show high epoch-by-epoch repeatability during several hours of the experiment. The mean ISB estimated in the single-epoch solution is very close to values estimated in the 10-minute sessions. It was shown that the phase ISB can be estimated in the single epoch solution with 1–2 mm of noise. At the same time, the accuracy of the instantaneous code ISB is at a decimetre level. The ISB values estimated as a single (constant) parameter in longer sessions show better repeatability than epoch-varying parameter in single-epoch solutions. These facts indicate that ISB parameters are rather stable in time and may be estimated as one parameter per session. The sum of the phase and code ISB in the triangle built of three receiver pairs equals zero. This means that one can directly compute ISB for, e.g. B–C receiver pair if ISBs for A–B and A–C pairs are known. It was also shown that the code and phase ISBs depend on signal frequency and differ for L1/E1 and L5/E5a signals. Also, the carrier phase and code ISBs for a particular receiver pair can be estimated once and introduced as a known correction in GPS+Galileo tightly combined processing. The positioning experiment showed that the introduction of the known ISB parameter had an advantage over the estimation of the ISB. The positive impact was also observed in the performance of the carrier phase ambiguity resolution. From more details see a paper by Paziewski and Wielgosz (2015).

2.2. Development of ambiguity function methods

The MAFA method (Modified Ambiguity Function Approach) is the new strategy of carrier phase data processing developed at UWM in 2010. In this strategy the arrangement of computational process is different from the classical three-stage (float solution, integer ambiguity resolution, fixed solution) approach. The basic idea of this strategy relies on adding condition equations to a functional model of the adjustment. The ambiguities are not explicitly solved in this approach. However, due to condition equations, their integer nature is preserved in the final solutions. The functional model for the carrier phase adjustment is relatively weak. Therefore, different techniques of improving the efficiency of the MAFA method have been proposed. Three of them are the most important: cascade adjustment, integer de-correlation and search procedure (Cellmer, 2012, 2013) These procedures allow obtaining the correct solution, even if the a priori position is several meters away from the actual one. The tests performed show that the strategy is highly efficient and allows to obtain a precise position from a single epoch. An important advantage of the new strategy is its robustness to the "cycle slip" effect in subsequent observation epochs.
The general formula of the residual equations in the MAFA method is

$$\mathbf{v} = \frac{1}{\lambda}\,\mathbf{A}\mathbf{x} + \boldsymbol{\delta} \tag{1}$$

with

$$\boldsymbol{\delta} = \mathrm{round}\left(\boldsymbol{\Phi} - \frac{1}{\lambda}\boldsymbol{\rho}_0\right) - \left(\boldsymbol{\Phi} - \frac{1}{\lambda}\boldsymbol{\rho}_0\right) \tag{2}$$

where
v – vector of residuals (n×1),
x –vector of parameters (increments to a priori coordinates vector x0),
A – design matrix (n×3),
δ –vector of misclosures (n ×1),
Φ – double differenced (DD) carrier phase observation,
$\boldsymbol{\rho}_0$ – DD geometric distance vector computed using a priori position and satellite coordinates,
round(.) – function rounding to the nearest integer.

Recently, the foundations for some validation techniques in the MAFA method have been elaborated. Each of them is based on forming the confidence region and then testing whether the final solution is inside it or not.

2.3. Studies on an advanced stochastic model

The studies on an advanced stochastic model for precise positioning were carried out at the Warsaw University of Technology (WUT). The main goal was to improve the reliability of the position in carrier phase-based relative GNSS real-time kinematic technique that utilizes reference stations network, known as Network-based RTK method. The reliability of the rover positioning was defined as the resultant of two parameters: solution availability and accuracy. Solution availability describes the possibility of achieving the correct carrier-phase ambiguity fix, i.e. integer estimation of ambiguity as well as their acceptance in the validation test. It may be defined as a quantitative parameter on the basis of solution results as the ratio of the number of solutions for which correct ambiguities were obtained to the total number of solutions for a given period or as a parameter describing the potential probability of correct fixing of ambiguities for a given solution (epoch), i.e., Ambiguity Resolution Success Rate or Probability of Correct Fix. The solution accuracy describes the accuracy of the rover position estimated for fixed baseline solution and its value can by determined using position variance estimations or the standard deviation for the given set of solutions.

In the reported studies a solution availability and accuracy were analysed using a new approach to account for the residual errors within the stochastic model of GNSS observations, called Network-Based Stochastic Model (NBSM) (Prochniewicz, 2014). This approach is based on the assumption that residual errors of observations remaining after applying network corrections can be described using the variances of those corrections. It is possible to utilize correction terms' variances in the stochastic modelling of the observations. The determination of the correction variances directly in the network solution together with the corrections allows to capture the current residual error values based on observations from a single epoch. This predisposes that new approach for application in instantaneous Network RTK positioning.

The schematic description of the Network-Based Stochastic Model is presented by the following equation

$$\mathbf{D}\{l\} = \mathbf{C}_l = \mathbf{C}_\varepsilon + \mathbf{C}_\delta \tag{3}$$

where $\mathbf{C}_l$ is the variance-covariance matrix of observations (observed-minus-computed values), the variance-covariance matrix $\mathbf{C}_\varepsilon$ describes the observations noise characteristic, and the variance-covariance matrix $\mathbf{C}_\delta$ the stochastic properties of correction terms; $\mathbf{D}\{l\}$ denotes the dispersion operator. Detailed mathematical formula and application algorithm of NBSM is presented in (Prochniewicz, 2014).

Determination of the correction variance based on the network solution results in the variance estimation being performed independently for ionospheric and geometric corrections for each observation (for each satellite or for each double-difference). From the point of view of GNSS models' classification, the NBSM is the Ionosphere-Weighted Troposphere-Weighted Model. On the other hand, neglecting the correction errors ($\mathbf{C}_\delta$) in Eq. (3) is referred as the Ionosphere-Fixed Troposphere-Fixed Model. The comparison of the non-zero elements of the variance-covariance matrix for the Ionosphere-Fixed Troposphere-Fixed Model with the NBSM is shown in Figure 2. The presented examples correspond to dual-frequency phase and code observations for six satellites for which the cross-correlation between observations of the given type for two frequencies are taken into account. Gray and black colours mark the non-zero elements of the relevant matrices $\mathbf{C}_\delta$ and $\mathbf{C}_\delta$. Based on this comparison it can be noted that the NBSM takes into account additional correlations of the observation that were not included in the Fixed Model.

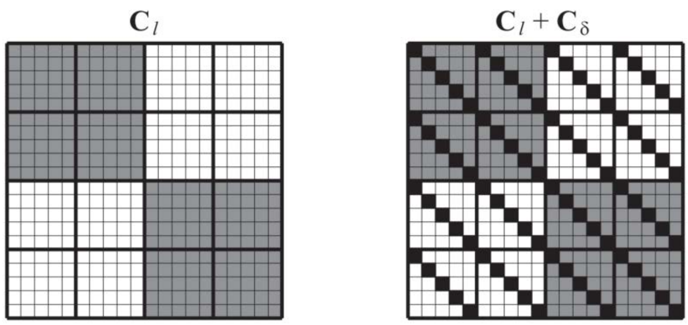

Fig. 2. Comparison of the non-zero elements of the variance-covariance matrix for the Ionosphere-Fixed Troposphere-Fixed Model with the NBSM

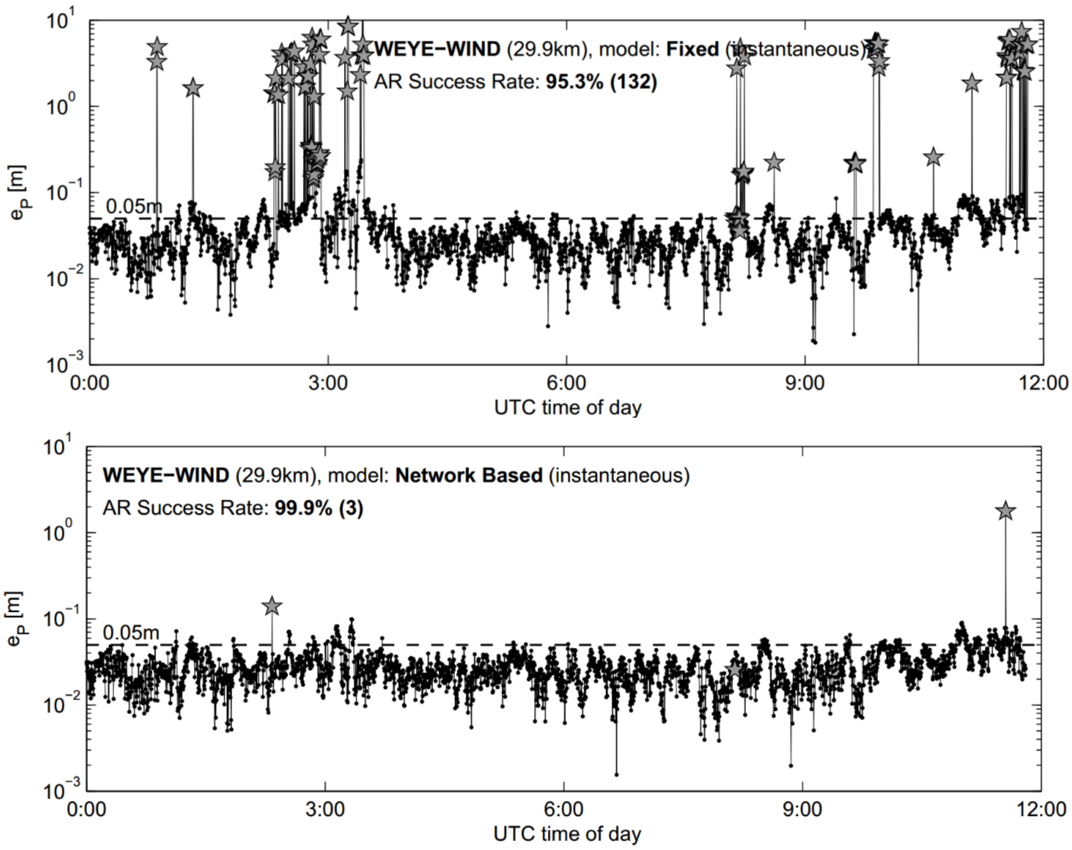

Fig. 3. Resulting position comparison for the ionosphere/troposphere fixed model (upper plot) and NBSM (bottom)

In order to analyse the influence of the correction accuracy characteristic on the reliability of instantaneous Network RTK solution results, the Fixed Model and proposed NBSM approach were compared. The network used in the test was a fragment of Austrian regional network EPOSA characterized by significant differences in station elevation. Also, the test GPS data were collected during a severe ionospheric disturbances. Two reference stations (WIND and LIEZ, baselines length of 30 km and 46 km) located within the area covered by the reference station network were excluded from the network solution and used as test stations (user stations). The tests performed include ambiguity estimation, ambiguity validation and position estimation for compared models. The resultant errors of the user position calculated on the basis of the comparison of the estimated position and known (reference) positions are shown in Figures 3 and 4. Star symbol marks solutions for which ambiguity was estimated incorrectly. It can be observed that utilizing the estimated correction accuracy in the NBSM model increases the number of correct ambiguity estimation solutions by approximately 5–8% to a level of 98.9–99.9%. In addition, the results of validation of the ambiguity estimation for the test data for three discrimination tests (R-ratio, F-ratio and D-test) show that using NBSM allows to increase the Ambiguity Resolution Success Rate by 3–15%. It was shown that use of the NBSM model makes possible a significant improvement in the precision of the estimated positions by approximately 30% for horizontal components, and approximately 20% for vertical component. The test results support the conclusion that including the real correction accuracy in the stochastic model for instantaneous positioning, as proposed in the NBSM approach, is an effective method that increases the reliability of Network RTK positioning.

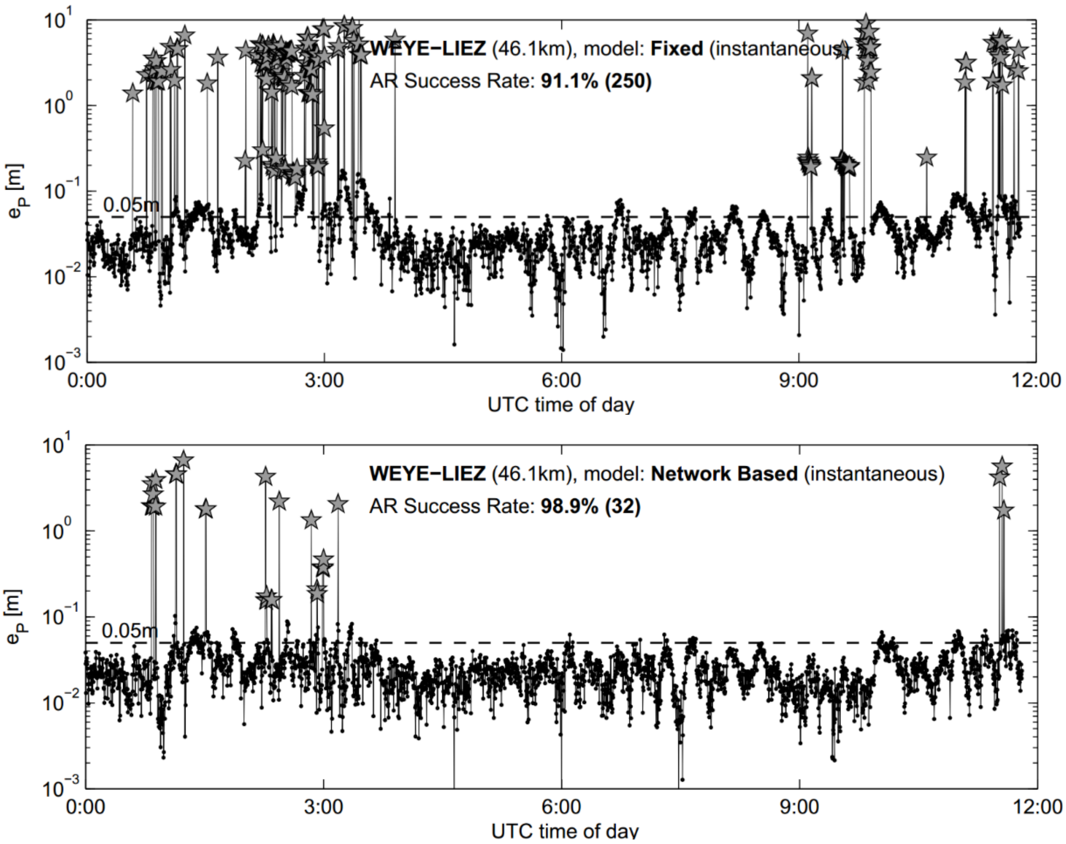

Fig. 4. Resulting position comparison for the ionosphere/troposphere fixed model (upper plot) and NBSM (bottom)

2.4. Studies on calculation of the satellite positions

In the years 2011–2014, some practical aspects of implementing the generalized problem of two fixed centres, for computing positions and velocities of GNSS satellites were studied at AGH University of Science and Technology (AGH). The problem of two fixed centres is a special case of the restricted three – body problem. The equations of motion of the satellites in the generalized problem of two fixed centres are integrable in quadratures. The intermediate orbit of the satellite, based on solving the generalized problem of two fixed centres, fully takes into account the influence of the second J2 and third J3, as well as a major part of the fourth zonal harmonic of the expansion of the Earth's gravity potential. The analytical algorithms of computation of orbital elements and positions of GLONASS satellites, based on the asymmetric variant of the generalized problem of two fixed centres, have been described (Goral and Skorupa, 2012). Other main disturbing accelerations, i.e. due to the Moon and the

Sun attraction, were also computed analytically. Proposed analytical method of computation position and velocity of GLONASS satellites is an interesting alternative for presently used numerical methods. The obtained results open up new prospects for practical applications of the generalized problem of two fixed centres (Goral and Skorupa, 2012). They can be used for analytical studies of the motion of not only GLONASS satellite but also GPS and Galileo satellites.

2.5. Studies on calculation of the satellite positions

The Polish Head Office for Geodesy and Cartography supports and maintenances an active GNSS reference network – ASG-EUPOS (Bosy et al., 2007). ASG-EUPOS provides a variety of positioning services, including on-line automatic post-processing service – POZGEO. In order to improve ASG-EUPOS services, POZGEO in particular, ASG+ project was carried out (Figurski et al., 2011). A new automatic GNSS data post-processing module POZGEO-2 was developed as one of the tasks within the project (Paziewski et al., 2014). The module internal methodology is based on the approach used in the scientific GNSS post-processing software – GINPOS, which was developed at UWM (Paziewski, 2012). POZGEO-2 requires minimum of 5 minutes of dual-frequency carrier phase and pseudorange GNSS data (with interval of 10 seconds). RINEX data files are sent by the users through a dedicated web page. The data processing is performed using relative geometry-based model. A position is obtained in a network (multi-station) solution using GNSS data from three surrounding ASG-EUPOS permanent stations. The model parameter estimation is based on sequential LSA (Least Squares Adjustment) with constraint equations. In the adjustment, all mathematical correlations between the observations are taken into account. The LAMBDA method is applied for the ambiguity resolution. POZGEO-2 uses information about atmospheric delays from other modules, dedicated for atmosphere modelling, which were also developed within the ASG+ project. The new module is capable of processing GPS and Galileo data (L1/E1, L2 and L5/E5a frequencies). It is expected that POZGEO-2 will offer horizontal position with accuracy of 2 cm.

2.6. Investigation of uncertainty of GNSS-based distance metrology

Nowadays surveyors and researchers in geosciences are facing the challenge of measuring distances over several hundreds of metres up to 1 kilometre with uncertainties at a single millimetre level and below. Electronic distance meters and GNSS are available for this task and long length metrology complies with GNSS-based short distance measurements. Both approaches, however, are currently not capable of achieving traceability to the SI definition of the metre with one or even sub-millimetre uncertainty over the respective distances.

Therefore, researchers from the Institute of Geodesy and Cartography (IGiK, Warsaw) in cooperation with scientists from UWM, and also from the NSC Institute of Metrology (Kharkiv, Ukraine) and Institute of Radio Astronomy of NAS (Kharkiv, Ukraine) have carried out research aimed at better understanding of the uncertainty of GNSS-based distance metrology. Long time series of vector components, derived from processing GNSS data from double EPN stations, were analysed. The time series provided extremely rich information on variability of GNSS solutions that together with the external data enabled qualitative and quantitative analysis of those variations as well as their reliable statistical estimate. The experiments performed concerned the investigation of the response of the measuring system to tropospheric perturbations as well as to site specific effects vs. measured distance. Numerical experiments conducted indicate that the potentiality of GNSS positioning is not fully exploited in high-end applications. Also, analysis of time series of GNSS solutions may result in improvement of modelling of GNSS observations and GNSS-based distance metrology (Zanimonskiy et al., 2014).

3. Atmosphere remote sensing and modelling

3.1. Troposphere

One of main objectives of WUT LAC is a routine ZTD estimation, monitoring of the results and research on Integrated Precipitable Water (IPW) time series derived both from GNSS and NWP (Numerical Weather Prediction) models. Two operational numerical prediction models: COSMO-LM (maintained by Polish Institute of Meteorology and Water Management) with two different resolutions of 14 km and 2.8 km, and a global model GFS (operated by NCEP) were used as input data to generate IPW and ZTD required for GNSS tropospheric products quality assessment. Various factors affect the final results of the determination of IPW and ZTD from the model grid, i.e. interpolation of data in space, numerical integration in zenith direction, correction for topography, physical equations applied for humidity parameters conversions, etc. Different models with different GNSS products exhibit systematic differences. For individual stations the observed bias might substantially vary (Kruczyk and Liwosz, 2012). Annual model for multi-year series of ZTD from IGS was applied to detect climate change signal in residuals. Also more complicated model consisting of annual and semiannual terms as well as linear trend was fitted using the least squares approach. The authors showed that the application of the more advanced model reduced RMS of the residuals. They provide several examples confirming that findings, but also show that no climate changes were detected.

The ZTD is a valuable input for weather forecasting and nowcasting, however full exploitation of results requires validation in challenging weather conditions. The joint team of Wroclaw University of Environmental and Life Sciences (WUELS) – Royal Melbourne Institute of Technology University, Australia (RMIT University) discussed this problem (Rohm et al., 2014a). The baseline, network or Precise Point Positioning approach using post-processed and predicted orbits and clocks were used. The results are quite optimistic: GNSS proves to be an optimal integrated water vapour data source in all weather conditions, e.g. IWV standard deviation with respect the radiosonde data below 3 mm. In the presence of severe weather the variability of troposphere estimates is observed doubled and it should be reflected in the applied constraints. Otherwise the formal errors increase also by a factor of two.

The high standard ZTD to IPW conversion procedures and quality monitoring of integrated ASG-EUPOS – meteorological ground sensors network for water vapour retrieval was studied (Hordyniec, 2014). The author utilized alternative data sources in case direct measurements at the GNSS stations were unavailable. He has proved that the pressure from standard empirical models (GPT, GPT2, UNB3m) would induce a noise in IWV at the level of 2.5 mm. In contrary, hourly data of Numerical Weather Prediction model reduce this discrepancy roughly by 0.6 mm. Still, the numerical forecast needs to be treated with care when applied for high altitude stations as additional bias can occur. A priori wet delay modelling using Saastamoinen model provides rather crude IWV estimate as 3 mm and higher uncertainties were achieved.

In order to satisfy real-time users with more precise products, IGS launched a real-time service (IGS-RTS) on 1 April 2013. Although RTS products are under daily monitoring, an additional, detailed analysis were performed at WUELS, in order to assess the quality of RTS products (Hadas and Bosy, 2015). It was shown, that the general availability of GPS correction was over 95%, and for GLONASS over 90%. From the comparison of RTS products with ESA/ESOC final products (Fig. 5), it was confirmed that the RTS orbits are of high accuracy—in general at the level of 48 mm for GPS and 132 mm for GLONASS. Real-time clocks accuracy was 84 mm (0.28 ns) and 245 mm (0.82 ns) for GPS and GLONASS, respectively, so estimation of real-time GLONASS clocks require further development to reach the target level of 0.3 ns. Further studies were related to RTS corrections quality degradation over time and to attempts short-time prediction of correction on the basis of prior data. The relation between the product latency and accuracy, with respect to GPS block and type of onboard clock or GLONASS year of launch, was determined. On average, 5 cm of additional error is expected when using orbit corrections with 3 minutes of latency and clock correction with 1 minute latency. Using polynomial fitting, it is possible to reliably forecast the orbit corrections up to 8 minutes for GPS and 4 minutes for GLONASS. The proposed short-term prediction methodology can be used, e.g. for the outliers detection in RTS corrections.

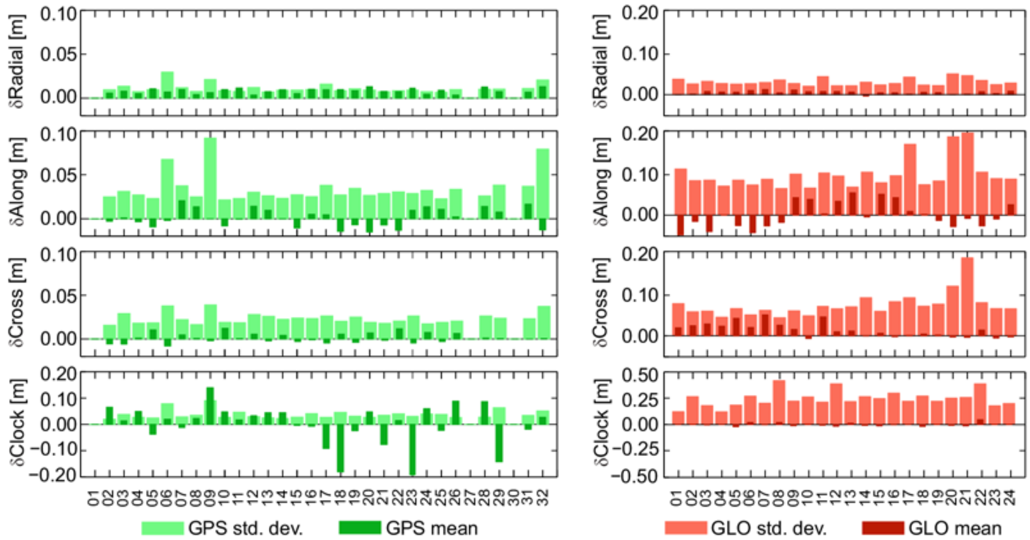

Fig. 5. RTS orbits and clocks quality with respect to ESOC final products during DOYs 208–214, 2013

These products, i.e. real-time orbits and clocks, were used to resolve one of the current challenge of GNSS meteorology that is a real-time (zero latency) ZTD/IWV retrievals. Joint WUELS – RMIT research teams developed and globally tested (Yuan et al., 2014) methodology that address this issue. The solution was based on the BNC PPP solution, however a number of modifications were implemented, i.e. antenna phase centre variation models, ocean and earth tides, advanced mapping functions and a priori information (GPT2), Kalman filter stochastic and functional model modification. These advancements tested against globally distributed IGS stations and radiosonde profiles show that the real-time retrieval of integrated water vapour is feasible with an accuracy of 3 mm.

Another research direction at WUELS was related with real-time kinematic Precise Point Positioning (PPP) and its support with regional tropospheric delay model obtained from near real-time (NRT) GBAS network analysis and/or meteorological data. A common procedure in PPP is to have the adjustment model accounting for the correction to an a priori value of the troposphere delay given at the first epoch of data processing, and the delay filter is updated epoch by epoch. This approach requires some time so that a change in constellation geometry allows to efficiently de-correlate among tropospheric delay, receiver clock error and user height.

At first, it was investigated how the regional troposphere models may support kinematic PPP in post-processing and real-time modes, by providing a priori information on zenith total delay (ZTD) (Hadas et al., 2013). It was demonstrated, that a reliable a priori troposphere information allows to reduce PPP convergence time and improves the precision and accuracy, especially for vertical component, when compared to a standard PPP procedure that uses Saastamoinen formula. In the same way, the PPP was used as a method to validate the developed troposphere models. It was noted, that the ZTD model based on meteorological data only (IGGHZ-M) requires further improvement in aspects of the interpolation in time/space procedures. The ZTD model performance was much better, however a reduction of its latency (currently over 1 hour) should provide improvements in real-time positioning.

Finally, it was demonstrated how regional, near-real time ZTD model may improve real-time kinematic PPP by constraining the ZTD estimates (Fig. 6). The difference between unconstrained solution and the constrained one is significant for the vertical component, while the horizontal coordinates remain similarly accurate. In standard approach, the height residuals may reach tens of centimetres and the error may reach up to 20 cm; at the same time the ZTD estimates were poor (large residuals with respect to reference, near-real time solution). In case the troposphere delay was constrained, the standard deviation for the vertical component was reduced by 40%, from 14 cm to 8 cm. From the very beginning of the data processing, the residuals for all three coordinates were much smaller, even though the estimated error was relatively large. The results confirmed the usefulness of near-real time troposphere delay models in real-time PPP kinematic processing and a significant improvement should be observed in unusual or severe weather conditions.

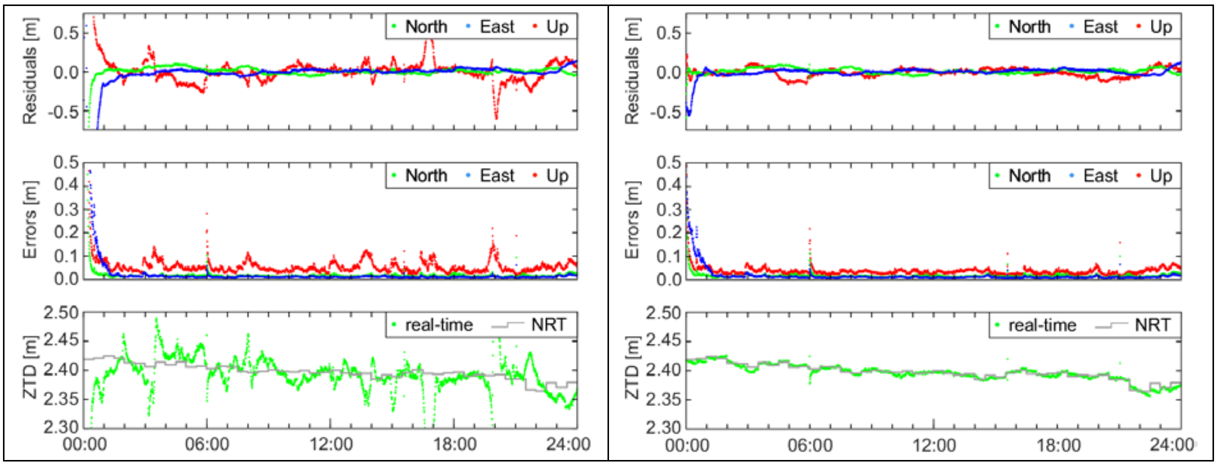

Fig. 6. Results of unconstrained (left) and NRT-ZTD constrained (right) kinematic PPP solution for station WROC, DOY 116, 2014

Continuing development of GNSS tomography methodology, GNSSandMeteo Working Group team from WUELS removed constraints and apply robust Kalman filtering to retrieve wet refractivities (Rohm et al., 2014b). The authors identify that the major problem for further advance in tomography models and their applications in atmosphere sciences are linked with the constraint equations that limit variability of the troposphere. Therefore the implicit constraints were removed from the tomography equation system and Kalman filter was applied to tie the troposphere conditions between observations epochs and to resolve the equation system iteratively with procedure removing outliers in place.

Applying tomography models to resolve vertical and horizontal structure of Mesoscale Convection System was one of the first attempts world-wide to observe internal processes of severe weather using GNSS signal (Manning et al., 2014), collaboration between RMIT University and WUELS resulted in resolving one storm event (6 March, Victoria, Australia) using tomography approach (Fig. 7). The solution was validated against the weather radar data, showing strong correlation of intensive rain with rapid drop of wet refractivity and increase of the wet flux at the front of the storm. These results were found to be in agreement with the conceptual model of Mesoscale Convection System.

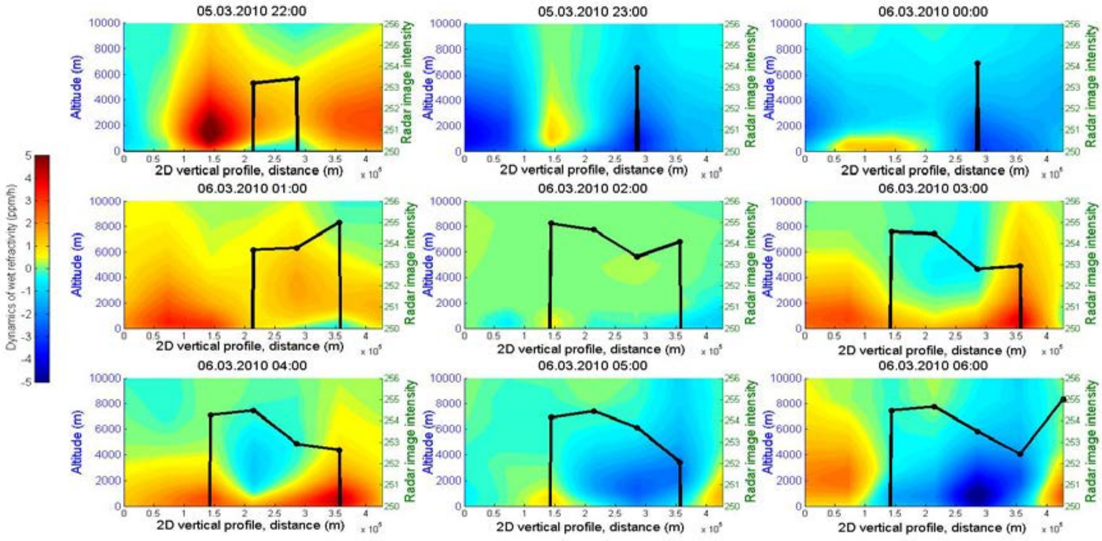

Fig. 7. Cross section of tomography model along the storm propagation line (from 0 to 10 000 m), colour-coded are wet refractivities variations in time, whereas the black line shows the radar rain intensity and location of storm

The same team together with the experts in Radio Occultation from RMIT University and Australian Bureau of Meteorology have investigated the quality of RO profiles in Australia region comparing it with the gold-standard for atmosphere profiling – radiosonde measurements (Norman et al., 2014). The mid and top troposphere retrievals were resolved exceptionally well in the RO profiles, but unexpected bias in temperature near the stratosphere was detected.

Another field of study included the application of the new troposphere models for supporting of precise GNSS positioning. Researchers from WUELS and UWM collaborate on this topic. They carried out analyses of two near real-time tropospheric delay estimation models, IGGHZG (Institute of Geodesy and Geoinformatics one Hour ZTD GNSS) and IGGHZM (Institute of Geodesy and Geoinformatics one Hour ZTD Meteo), in fast-static precise positioning (Wielgosz et al., 2013). The former model is based on the processing of GPS data collected from ground-based reference stations, the latter one uses metrological data fed into the Saastamoinen model. The applicability of these models to precise positioning was studied by their application to ultra-fast static positioning. Baselines from 65 km to 72 km, with height differences from 39 m to 379 m were processed. The authors concluded that ZTDs derived in near real-time based on GPS data from the reference network gave much better results. This was confirmed by the ultra-fast static positioning tests. In addition, the IGGHZM model based on meteo data gave significantly worse results regarding both coordinate repeatability of the height component and the ambiguity resolution, and could not be recommended for precise positioning. However, the WUELS research group is currently conducting extensive work on the development of both IGGHZG and IGGHZM models (Hadas et al 2013), and it may be expected that these models will bring improved results in the future.

3.2. Ionosphere studies

The reporting period covered the last phase of the solar minimum. Researchers at UWM analysed the ionosphere behaviour during moderate geomagnetic storm which occurred on 11 October 2008. The electron density profiles retrieved from the COSMIC radio occultation measurements were examined in order to estimate the possibility of its use as additional data source to study changes in electron density distribution occurred during ionospheric storms. The short-term positive effect was clearly revealed in GPS TEC and ionosonde measurements that was also confirmed by RO profiles (Zakharenkova et al., 2012).

A new regional ionosphere monitoring service over the ASG-EUPOS network was launched at UWM (http://ginpos.uwm.edu.pl/iono/index_en.php). For the ionospheric modelling, dual-frequency GPS data from the Polish national ground based augmentation system ASG-EUPOS are used. This permanent GNSS network operating since 2008, opened new possibilities for accurate regional modelling of Earth's upper atmosphere. The network consisting of ~110 stations with mean distance between stations of 70 km is a part of the European Position Determination System (EUPOS) project involving 18 countries of Central and Eastern Europe. At the beginning of its operation, the service used carrier phase-smoothed pseudoranges as its input observables (Krypiak-Gregorczyk et al., 2013). Since 2014, however, the regional ionospheric model is computed using only precise, absolute (undifferenced) carrier phase GNSS measurements, a few orders of magnitude more precise comparing to pseudorange measurements. Also, new total electron content (TEC) parameterization algorithms based on geometry-free linear combination of the carrier phase data and two-dimensional functions (local polynomials), was implemented. The main product of the service is precise local ionospheric model over ASG-EUPOS network. The model has spatial resolution of 0.25° × 0.25° and temporal resolution of 5 minutes. In addition, the new ionosphere monitoring service provides mean hourly TEC values over Poland. Another important products of the service are the differential code biases (DCBs). The service provides daily and monthly DCB calibrations for every GNSS receiver of the ASG-EUPOS system (Krypiak-Gregorczyk et al., 2014).

Another ionosphere monitoring system developed at UWM is also based on processing GPS observations and concerns the ionospheric irregularities at the Northern high latitudes (Cherniak et al., 2014). Monitoring of these irregularities is important for both scientific point of view and GNSS applications, as the occurrence of the ionospheric irregularities can impact a variety of communication and navigation systems. Cherniak et al. (2014) described the methodology and the service for continuous generation of high-resolution maps of the ionospheric irregularities at high latitudes. They use data collected from three ground-based GPS networks of the Northern Hemisphere. The service is based on ROT (rate of TEC change) and ROTI (index of ROT) parameters employed to study the occurrence of TEC fluctuations. ROTI maps are provided as a horizontal grid with 2° × 2° resolution in the magnetic local time and corrected magnetic latitude frame. The ROTI maps allow estimation of the overall fluctuation activity and auroral oval evolutions. In general, the ROTI values are correlated with the probability of GPS signals phase fluctuations. It was demonstrated that the occurrence and magnitude of TEC fluctuations increased dramatically during space weather events.

4. Summary

This report provides selected examples of research activities on GNSS data processing applications carried out at Polish research institutions during years 2011–2015. The research concerns multi-GNSS relative and absolute positioning. In particular, improvements in the stochastic models and carrier phase ambiguity resolution were demonstrated. The application of new real-time IGS products, ionosphere and troposphere modelling and orbit estimation also brought new advances in precise GNSS applications. The obtained results were published in high-quality scientific journals, and the studied problems are currently further investigated as they concern still open research issues in the field of geodesy.

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Theoretical geodesy

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ABSTRACT: The paper presents a summary of research activities concerning theoretical geodesy performed in Poland in the period of 2011–2014. It contains the results of research on new methods of the parameter estimation, a study on robustness properties of the *M*-estimation, control network and deformation analysis, and geodetic time series analysis. The main achievements in the geodetic parameter estimation involve a new model of the *M*-estimation with probabilistic models of geodetic observations, a new Shift-M_{split} estimation, which allows to estimate a vector of parameter differences and the Shift-$M_{split}^{(+)}$ that is a generalisation of Shift-M_{split} estimation if the design matrix **A** of a functional model has not a full column rank. The new algorithms of the coordinates conversion between the Cartesian and geodetic coordinates, both on the rotational and triaxial ellipsoid can be mentioned as a highlights of the research of the last four years. New parameter estimation models developed have been adopted and successfully applied to the control network and deformation analysis.

New algorithms based on the wavelet, Fourier and Hilbert transforms were applied to find time-frequency characteristics of geodetic and geophysical time series as well as time-frequency relations between them. Statistical properties of these time series are also presented using different statistical tests as well as 2nd, 3rd and 4th moments about the mean. The new forecasts methods are presented which enable prediction of the considered time series in different frequency bands.

Keywords: *M*-estimation, robust estimation, reliability, time series, polar motion

1. Introduction

In the last decades some new measurement technologies have been developed, e.g. laser scanning technology and several variants of its technical realization. Properties and a structure of data collected by these new sensors have triggered the evolution of the existing data modelling methods and the development of new ones, especially for parameter estimation, in order to exploit all information contained in the data. A good example to illustrate this process is M_{split} estimation introduced by Wiśniewski in his previous research. This method allows an estimation of parameters in a split functional model of observations. In the period from 2011 to 2014 which is a subject of this review paper some new variants of *M*-estimation have been proposed. In the section 2 the *M*-estimation with probabilistic model of geodetic observation and the Shift-M_{split} estimation are featured. The last mentioned parameter estimation model was a subject of modification and adoption for geodetic control network analysis. All these aspects are discussed in detail in this paper. The robustness of the parameter estimation methods have been studied by the Polish researcher for many years. This issue have been also considered in the last four years. Another issue reported in the section 2 is a reliability analysis of observation systems, which is deeply studied in case of Errors-in-Variables models.

Development during last decades of the time-frequency analysis methods based on the wavelet and Fourier as well as Hilbert transforms enable computation of variable amplitudes and phases of oscillations with different frequencies in geophysical time series, e.g. the Earth orientation parameters and their fluid excitation functions, sea level anomalies data, Earth centre of mass coordinates, the coordinates of sites of permanent networks, zenith tropospheric delay and gravimetric measurements at permanent GGP stations. The semblance function introduced in the beginning of this century, as a modification of the coherence function, enable estimation of time-frequency correlation coefficients between two time series. It has also been very useful to compute a common signal in two time series. One of the problems of forecast algorithms which is simultaneous prediction of time series in different frequency bands can be solved using the combination of polynomial harmonic extrapolation and the autoregressive based methods which enable predictions of extrapolation residuals. This problem can be also solved using combination of the discrete wavelet transform band pass filter with a prediction method, e.g. autocovariance or autoregressive predictions.

In the last part of this review paper some original algorithms of the computational geodesy, especially related to the rotational and triaxial ellipsoid are briefly presented.

2. Geodetic parameter estimation

2.1. M-estimation and its variants

M-estimation is a well-studied standard method for parameter estimation in the presence of outlying observations. In order to reduce the impact of outlying observations a proper weighting function is applied and the estimation is performed iteratively. In addition to multiple weighting functions in use Banaś and Ligas (2014) introduced six new weighting functions, which have been derived using the following base functions: Wigner semicircle distribution, Epanechnikov kernel, Tricube kernel and Jacobi orthogonal polynomials (1^{st}, 2^{nd} and 3^{rd} degree). For these functions the authors computed also tuning constants assuring 95% efficiency with respect to the standard normal distribution. The performance of the introduced weighting functions was tested empirically together with the *M*-estimators of Huber, Tukey and Hampel. As the numerical example, a simple levelling network was used, wherein the original observations were sequentially contaminated with blunders. The overall number of performed tests was 432 and the tests showed that the performance of *M*-estimators depends highly on the dataset considered. The presented research showed the imperfection of *M*-estimation due to its dependence on model residuals only.

Wiśniewski (2014) developed a new variant of *M*-estimation with probabilistic models of geodetic observations that is called M_P estimation. This new model depends on the variance but also on the kurtosis, excess and asymmetry of the observation error distribution. To consider these characteristics of observation in the adjustment procedure, a proper probabilistic model of observation errors has to be assumed. In the paper (Wiśniewski, 2014) the Pearson distributions of type IV or VII are assumed to describe leptokurtic distributions with asymmetry. As an alternative approach the approximation of the Pearson distributions by Gram-Charlier series ($M_{G\text{-}C}$ method) is also considered.

Since the influence function of M_P estimation is based on the differential equations of Pearson distribution, the central moments μ_k, $k = 2, 3, 4$, are the parameters of this function. According to the assumed models of influence functions, the weight functions were derived for different cases of M_P estimation. It was shown that the M_P estimation belongs to the class of robust estimation. The performance and properties of the new estimation method were tested numerically on simulated levelling network in comparison to the least squares and M-estimation of Huber. Both the theoretical analysis and the numerical tests showed that the $M_{G\text{-}C}$ estimation method loses their robustness when large gross errors occur. The M_P estimation that includes Pearson distribution is especially effective as a robust estimator. The robustness of the method increases with the growing values of kurtosis, if the asymmetry coefficient is constant.

Let the observation set be a mixture of realizations of two random vectors $\mathbf{Y}_\alpha$ and $\mathbf{Y}_\beta$ with the respective expected values $\mathrm{E}\{\mathbf{Y}_\alpha\}$ and $\mathrm{E}\{\mathbf{Y}_\beta\}$. The observation vector $\mathbf{y}$, which contains disordered elements of the considered vectors may be assigned either to the two competitive vectors of expected values $\mathrm{E}_\alpha\{\mathbf{y}_i\} = \mathbf{AX}_\alpha$ or $\mathrm{E}_\beta\{\mathbf{y}_i\} = \mathbf{AX}_\beta$, with the design matrix $\mathbf{A}$. The simultaneous estimation of different parameter vectors $\mathbf{X}_\alpha$ and $\mathbf{X}_\beta$ was proposed by Wiśniewski in his previous works and is called as M_{split} estimation. For some practical applications (e.g. deformation analysis of control networks) it is interesting to know the difference $\mathbf{\Delta_X} = \mathbf{X}_\beta - \mathbf{X}_\alpha$ between the parameter vectors. $\mathbf{\Delta_X}$ can be estimated directly from $\mathbf{\Delta} = \mathbf{AX}_\alpha - \mathbf{AX}_\beta = -\mathbf{A\Delta_X}$ by applying M_{split} estimation. For this reason Duchnowski and Wiśniewski (2011) developed so called Shift-M_{split} estimation method, which allows to estimate a vector of parameter differences without estimating the particular parameter vectors. The optimization problem of M_{split} estimation in relation to the shift of parameters was solved by the use of two equivalent systems of normal equations. Possible application of Shift-M_{split} estimates in deformation analyses was presented on exemplary illustration. The robustness property was also discussed in the paper and it was shown that Shift-M_{split} estimates are usually affected by gross errors and the method is robust in special cases only.

A generalization of the above mentioned method is given by Duchnowski and Wiśniewski (2012). In this case it was assumed that the design matrices $\mathbf{A}$ of functional models may not have a full column rank. The proposed new estimation procedure is called Shift-$M_{split}^{(+)}$ and the optimization problem is solved iteratively using Moore-Penrose inverses. The iterative process ends usually after six or seven iterations.

2.2 Control networks and deformation analysis

The Shift-$M_{split}^{(+)}$ (Duchnowski and Wiśniewski, 2012) has been developed primary for a deformation analysis of free networks or for testing the stability of network points. In this case the shift vector $\mathbf{\Delta_X}$ to be estimated is related to the changes in the coordinates of the network points at two different measurement epochs. The authors tested the $M_{split}^{(+)}$ method on a levelling control network and showed that the new method is not only an alternative to the conventional determination of point displacements but in some cases it is better than the traditional approaches.

Classical robust methods used in the deformation analysis are based on the results of separate adjustments by the least squares method of two measurement epochs, i.e. on the adjusted coordinates, wherein the term "robust" does not refer to outliers but to single-point movements. The main step of these methods is the S-transformation (Helmert similarity transformation) of the coordinate differences with the optimization conditions of a robust estimation, which leads to iterative weighted similarity transformation method.

Deformation measurements are carried out as repeated campaigns with the same instruments, methods, geometrical conditions and in similar environmental conditions.

Therefore it is well-founded to assume that the results of deformation measurements can be distorted by both random and some no-random errors, which are constant in both measurement epochs. Such errors are not completely eliminated, when the displacement vector is determined by means of robust S-transformation of adjusted coordinate differences. The existence of constant errors reduces the quality of deformations analysis. To eliminate effects of those errors in deformation analysis Nowel and Kamiński (2014) proposed a new robust alternative method called robust estimation of deformation from observation differences (REDOD). This method is based on the assumption, that the vector **d** is a function of differences between independent observations, $\mathbf{d} = f(\mathbf{l}_{(2)}^{obs} - \mathbf{l}_{(1)}^{obs})$, and

$$\left(\mathbf{l}_{(2)}^{obs} - \mathbf{l}_{(1)}^{obs}\right) \xrightarrow{\text{robustestimation}} \hat{\mathbf{d}}^{R}$$

where $\hat{\mathbf{d}}^{R}$ is the robust estimator of **d**. The proposed estimation procedure was tested on both levelling and horizontal control networks. The conducted numerical test showed that:

- the REDOD method completely eliminates effects of additional constant errors from deformation analysis results,
- results of deformation analysis using the REDOD method estimates are very similar to those obtained with classical iterative weighted similarity transformation method if the results of deformation measurements are distorted only by random errors.

The REDOD method is highly recommended in case of automated, continuous control measurements, where there is a high risk that the errors of measurement of the same geometric elements in both epochs may contain a constant factor in both epochs.

One of the basic approaches to the robust estimation is *R*-estimation (also known as Hodges-Lehmann estimates) distinguished by its high robustness against outliers. Application of this method to the deformation analysis was successful, but there are some disadvantages. One of them is a limitation of its application to the cases when all observations are of the same accuracy. Another disadvantage of the method is a need for using initial residuals.

Let us consider two independent samples x_i, $i = 1, 2, ..., m$ and y_j, $j = 1, 2, \ldots, n$, which are realizations of random variables X_i and Y_j, respectively. Furthermore let the distributions of these variables differ from each other in a shift Δ only. When applying Wicoxon test in order to estimate the shift one can get the well-known form of *R*-estimates of the shift between two samples

$$\hat{\Delta}^{R} = \mathrm{med}(y_j - x_i)$$

To overcome the above mentioned limitation of *R*-estimates Duchnowski (2013) proposed to use weighted median $\hat{\Delta}^{W} = \mathrm{medw}(y_j - x_i)$ instead of median (med), wherein weights are determined using proper statistic. This allows taking into account the differences in measurement accuracy of the observations. It has been shown how to apply the new approach in surveying problems. The coordinates of objective points are to be computed by using all possible independent ways and such created set to Hodges-Lehmann weighted estimates is to be applied instead of initial residuals, which are used in the typical *R*-estimates. The proposed method holds the property of high robustness against outliers, which was confirmed by numerical tests performed on horizontal control network.

An important task in the deformation analyses is to find a stable reference frame and therefore the stability of the possible reference points has to be controlled. To test such stability Duchnowski (2011a) used the *R*-estimation investigating several strategies and several empirical influence functions. The tests showed that the robustness of the method depends on the number of unstable network points and it increases if their number decreases.

The similar problem was studied by Duchnowski (2011b) on a levelling control network. The *R*-estimate and two other robust estimates of the standard deviation were used for the examination of a strategy of monitoring the stability of levelling reference marks. It has been shown that a robustness of the estimates does not result in a robustness of the strategy itself. This is due to the fact that beside gross errors also unstable points cause outliers. The research indicated that the robustness of the strategy depends strongly on the number of unstable points.

The classical deformation analysis based on Gauss-Markov adjustment model provides correct results if gross and systematic errors are previously eliminated. In this case the quality of deformation analysis is determined by the precision of measurements only. In case of non-homogenous monitoring network, i.e. networks in which measurements were carried out with different equipment, in different atmospheric conditions, there is an additional risk of erroneous a priori estimation of weights. This can lower quality of deformation analysis. For deformation analysis of non-homogenous monitoring networks Kamiński and Nowel (2013) proposed a modification of classical algorithm and analysis procedure by introducing local variance factor estimators assigned to distinguished homogenous groups of observations. The numerical experiment performed leads to the following recommendations:

- in case of non-homogenous monitoring networks, deformation analysis should be carried out using local variance factor estimators,
- the global variance factor estimator can be applied for deformation analysis in case of homogenous monitoring networks only.

The consequences of erroneous weighting and their impact on displacement analysis in non-homogenous monitoring network have also been studied by Nowel and Kamiński (2103). The conclusions of the study were the same as the above mentioned (Kamiński and Nowel, 2013).

One of the most important tasks of engineering surveying is measurements of displacements and strains of engineering objects and their environment. Due to the technological process of the construction, it may happen that the measurements are performed from temporary sites and it will be not possible to continue the observations measurement on those sites in future. This leads to the problem of determination of displacements and strains, when measurements were carried out in an unstable reference system. In addition, observations can be distorted by gross errors. Kamiński (2011) introduced the displacement and strain using transformation method robust to gross errors (DiSTFAG), which allows to determine the displacement and strain parameters in above indicated situations. The method based on an estimation of two vectors, where one of them corresponds to the distance between the random surface and optimal plane and the other consists of rotation angles. These vectors estimated using robust approach are later used to calculate displacements and strains. The method proposed consists of two stages:

- stage 1 is the initial adjustment, that allows to point out the observations affected by gross errors and to correct of measurement results,
- stage 2 is the use of the method in question to determine displacements and strains.

The issue of determination of an optimal structure of horizontal control network consisting of directional measurements was studied by Mrówczyńska (2013) using entropy concept. According to this study an optimal number of observation results from the entropy difference of parameters vector corresponding to one additional observation.

2.3. Reliability analysis of observation systems

The problem of an internal reliability of observation systems was studied by Prószyński (2013a, 2013b, 2014) in different aspects and for several parameter estimation models. Prószyński, (2013a) presents an approach to internal reliability analysis of observation systems known as Errors-in-Variables (EIV) models with the parameters estimated by least squares method. The total least squares adjustment or orthogonal regression are typically used for parameter estimation in case of EIV. Starting from a functional model of the total least squares adjustment (also known as the Gauss-Helmert model) and using standardized observations the author derived a formula for a matrix **H**. The rank of **H** is crucial for the internal reliability analysis. Since the matrix **H** is an oblique projector, for EIV models with correlated observations, a two-parameter measure for *i*th observation is proposed,

$$h_{(i)} = (h_{ii} - w_{ii})$$

where h_{ii} is the *i*th diagonal element of **H** and w_{ii} is the asymmetry index for *i*th row and *i*th column of **H**. The index h_{ii} is called a "local response of the model", what means the response in the *i*th residual to a possible gross error in that observation. In the mentioned paper, formulae for reliability analysis of specific cases of quasi-linear EIV models, i.e. multiple linear regression, 2D similarity transformation and 3D affine transformation are given in comparison to the ordinary Gauss-Markov (GM) model. Theoretical consideration and numerical experiments concluded that in terms of average reliability indices EIV models are at least twice weaker then GM models. The reliability criteria for EIV models should thus be set at a lower level than for GM models. Moreover it should be noticed that the relatively low response–based reliability of EIV models may indicate lower effectiveness of outlier detection in comparison to GM model.

In Prószyński (2014) the problem of determination of realistic upper-bounds for internal reliability of systems with uncorrelated observation was studied. Based on an experimental material, i.e. post-adjustment documentation of 63 networks of different size Adamczewski has developed in his previous work so called "law of gross errors". This law was a subject of further investigation with help of probabilistic theory and Prószyński (2014) formulated the probability-derived formula for occurrence of Gaussian-type gross errors:

$$P(Y = k) = \binom{n}{k} p^k (1-p)^{n-k}, \quad k = 1, 2, ..., n$$

where $P(Y = k)$ is the probability that k gross errors occur in n observations and p is determined from the normal distribution $N(0, \sigma)$ for a specific interval $r\sigma$, e.g. $p = 0.0027$ if $r = 3$. According to the discussed research:

- increasing the number of observations raises the network internal reliability without increasing number of potential gross errors providing that, the network consists of up to 50 parameters and no more than 100 observations,
- a proper level of internal reliability cannot be practically secure if the number of observations increases and networks consist of more than 100 parameters.

The links of internal and external reliability with system conditionality in Gauss-Markov models with uncorrelated observations were investigated by Prószyński (2013b). The external reliability was expressed both as a vector of parameter distortions (according to Baarda) and in the form of L_2 norm of this vector. All considered values, condition numbers of the design matrix, internal and external reliability were decomposed using the Singular Value Decomposition (SVD) and compared. Following this research the internal reliability and the conditionality are defined on different components of the SVD of a design matrix in GM models, so these characteristics are not interrelated. Meanwhile the external reliability depends on both, the conditionality and the internal reliability of a model.

The effectiveness of some chosen robust estimation methods was investigated by Kwaśniak (2011) in comparison to a level of network reliability. The study was performed on a levelling network using computer-simulated observation systems and it has showed that the effectiveness of gross error detection by means of robust estimation methods depends on the level of internal reliability of a network. Furthermore for effective detection of a single gross error, the surveying network should be designed in such way that for each observation the standard deviation of a residuum should fulfil $\sigma_v \geq 0.71$.

3. Geodetic time series analysis

Pole coordinates data were predicted using the combination of least squares (LS) extrapolation and autoregressive (AR) prediction. In this LS+AR prediction algorithm first the LS model which consists of the Chandler circle, annual and semi-annual ellipses and linear trend is fit to the complex-valued pole coordinates data. The difference between pole coordinates data and its LS model is equal to the LS residuals. Prediction of pole coordinates data is the sum of the LS extrapolation model and the AR prediction of the LS residuals. The smallest mean prediction errors of such combination are obtained when the length of pole coordinates data to fit the LS model is equal to 10 years and the length of the AR model to fit the LS residuals is equal to 850 days. The problem of any prediction algorithm is to predict time series in all its frequency bands. To compute the prediction of UT1 – UTC data the combination of discrete wavelet transform (DWT) and autocovariance (AC) prediction was applied to the length of day (LOD) designed as Δ – δΔ data which is the first derivative of the UT1 – UTC data from which the leap seconds and tidal model were removed. In this prediction algorithm the Δ – δΔ data are decomposed into frequency components using the discrete wavelet transform band pass filter (DWT BPF) with the Meyer wavelet functions and each frequency component is predicted by the AC prediction. The DWT BPF enables decomposition of any time series into frequency components in such a way that their sum is exactly equal to these series. It was also found that the mean LS+AR prediction errors for a few days in the future of the pole coordinates model data obtained after removal two highest frequency components computed by the DWT BPF with Shannon wavelet functions are several times smaller than the mean prediction errors of the pole coordinates data. The short term mean prediction errors of the UT1 – UTC model data obtained after removal two highest frequency components computed by the DWT BPF with Meyer wavelet functions are also several times smaller than the mean prediction errors of the UT1 – UTC data (Kosek, 2012).

The pole coordinate data predictions from different prediction contributors of the Earth Orientation Parameters Combination of Prediction Pilot Project (EOPCPPP), initiated by the IERS in 2010 were studied to determine the statistical properties of polar motion forecasts by looking at third and fourth moments about the mean. The differences between the future pole coordinates data and their predictions are the prediction residuals which can be checked whether they satisfy normal distribution. The skewness values of these prediction residuals for different participants of EOPCPPP show that their probability distribution becomes more nonsymmetrical when the prediction length increases. The kurtosis values usually decrease with the prediction length, which means that the probability distribution becomes more flat and has larger tails than a normal distribution. Both statistics show that the prediction residuals are not of normal distribution and their distribution becomes more uniform than normal when the prediction length increases (Kosek et al., 2011b).

The wavelet technique enables comparison of the complex-valued geodetic and fluid excitation functions of polar motion in different frequency bands, e.g. by looking at the semblance function of the order of r between them. The semblance function is the product of the coherence function and the cosine of the phase synchronization function $\Delta\hat{\phi}_{xy}(t,a)$ to the even power of r

$$\hat{\vartheta}^{r}_{xy}(t,a)=\frac{\left|\hat{S}_{xy}(t,a)\right|}{\sqrt{\hat{S}_{xx}(t,a)\hat{S}_{yy}(t,a)}}\cdot\cos^{r}[\Delta\hat{\phi}_{xy}(t,a)],\quad t=m_0+m/2,\quad m_0=0,1,\ldots,n-1-m,\quad r=1,3,5\ldots$$

Such function is interpreted as the frequency- and time-dependent correlation coefficient between two complex-valued time series. It varies within the interval <−1, 1> which shows oscillations with different frequencies in two time series, which are out of phase (−1) and in phase (1). The coherence and phase synchronization functions are computed from the wavelet spectra $\hat{S}_{xx}(t,a)$ and $\hat{S}_{yy}(t,a)$ of two time series and the cross-spectrum $\hat{S}_{xy}(t,a)$ between them, which are estimated from the wavelet transform coefficients obtained by computation of the convolution of time series and modified Morlet wavelet function. To speed up computations such convolution was performed in the frequency domain using the inverse Singleton fast Fourier transform (FFT) of the product of the FFT of time series and frequency domain modified Morlet wavelet function. The considered fluid excitation functions χ consist of the atmospheric angular momentum (AAM) or the sums of atmospheric and ocean angular momentum (AAM+OAM), and atmospheric, ocean and land hydrology angular momentum (AAM+OAM+HAM) excitations. The geodetic excitation functions ψ were computed from the IERS pole coordinates data. The semblance functions between these fluid and geodetic excitation functions increase when OAM excitation is added to the AAM one, and become still greater when the HAM excitation function is taken into account. Moreover, adding hydrology excitation function to the sum of atmospheric and ocean terms improves the phase agreement between the geodetic and fluid excitation in the annual frequency band which can be seen better when the order r of semblance function increases. Figure 1 shows the mean (averaged in time) semblance functions between the geodetic and fluid excitation functions for the semblance orders equal to zero (which gives the mean coherence) and equal to 3.

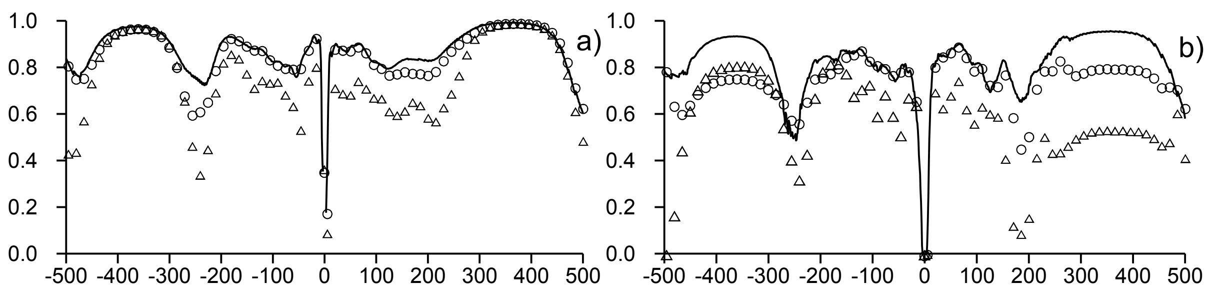

Fig. 1. The semblance functions of the orders 0 a) and 3 b) between the polar motion geodetic and fluid excitation functions AAM (triangles), AAM+OAM (circles) and AAM+OAM+HAM (solid line) (Kosek et al., 2011a)

The wavelet based semblance filtering enables the determination of the common signals in both geodetic and fluid excitation functions of polar motion (Fig. 2). In the semblance filtering first the wavelet transform coefficients are computed of both time series using Shannon wavelet functions. Using these wavelet transform coefficients both time series can be reconstructed using the inverse wavelet transform. Semblance filtering is performed by keeping in the reconstruction formulae of both time series only the wavelet transform coefficients for which the semblance exceeds a given threshold value, e.g. equal to 0.9. Other wavelet transform coefficients of both time series, for which the semblance is below the adopted threshold, are set to zero. It was found that increase of this threshold value makes filtered oscillations in two time series more similar, however at the same time the amplitudes of them decrease (Kosek et al., 2011a).

Similar algorithm of wavelet based semblance filtering was applied to the 3D centre of mass time series determined by the space geodetic techniques such as SLR, GNSS and DORIS, which were projected into the planes of the International Terrestrial Reference Frame (ITRF) to get three complex-valued time series in each plane. This algorithm enables computation of common oscillations in these series and it was found that there exists a common retrograde annual oscillation in the equatorial plane between the GNSS and SLR geocenter time series. Such result was confirmed using the spectro-temporal semblance function between these centre of mass time series projections as well as spectro-temporal polarization functions computed for each space geodetic technique. The spectro-temporal polarization function detects turning directions of ellipses in complex-valued time series for different oscillation periods (Kosek et al., 2014).

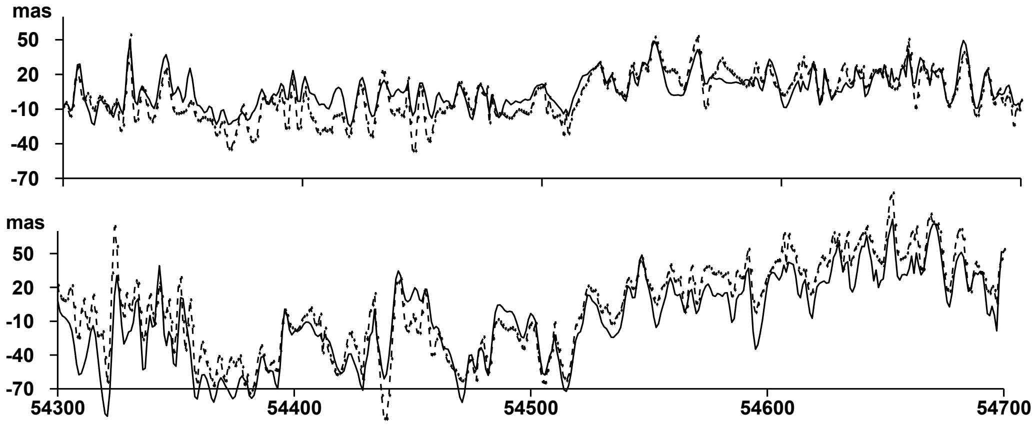

Fig. 2. An example of common oscillations in the equatorial components ($\psi 1/\chi 1$ - upper graph, $\psi 2/\chi 2$ - lower graph) of geodetic (solid line) and fluid AAM+OAM+HAM (dashed line) excitation functions, computed using wavelet based semblance filtering with threshold value equal to 0.90 (Kosek et al., 2011a)

The combination of the Fourier Transform Band Pass Filter (FTBPF) with the Hilbert transform (HT) was applied to compute variable amplitudes and phases of seasonal and subseasonal oscillations in real-valued time series, e.g. altimetric sea level anomaly (SLA) data as a function of geographic location. In this algorithm the complex-valued time series is created from real-valued oscillation filtered by the FTBPF and the HT of this oscillation put into the imaginary part. It was found that this algorithm is slightly modified FTBPF method in which the parabolic transmittance function is multiplied by [1+ sign(ω)] where ω is the central frequency of the filtered oscillation. To speed up computation the Singleton FFT and its inversion were applied to perform the FTBPF algorithm. Such seasonal and subseasonal variations are mostly irregular and cause the increase of prediction errors of the SLA data for a few weeks in the future. In order to detect the impact of these irregular variations on the SLA prediction errors, standard deviations maps of both amplitude time differences of the products of phase time differences and amplitudes were examined. The SLA data prediction errors in certain geographic regions of the ocean seem to be caused mainly by nonlinear behaviour of the broadband annual oscillation. The broadband character of the annual oscillation is manifested by the peaks in the SLA spectra which correspond to the integer multiplicities of the annual frequency, e.g. the semi-annual, 120-day and quarter-annual oscillations. The amplitude maxima of the semi-annual oscillation and other shorter period oscillations are located in geographic regions where the amplitude maxima of the annual oscillation occur. The mean prediction errors of the SLA data for two weeks in the future are usually considerable in geographic regions where amplitude maxima of the annual oscillation are the largest (Kosek et al., 2013).

Bogusz et al. (2013) applied wavelet decomposition with symmetric Meyer mother-wavelet to process data from two GGP sites (The Global Geodynamics Project). The time series that reflected Earth's gravity field changes with 5-second sampling rate were recorded at the time of earthquake and at the time when the gravimeters worked without any disturbances. The authors found that the wavelet decomposition may be considered as a good method of data interpolation and noise reduction for earthquake periods. The signal approximation at the highest level of the decomposition after removing tidal effects may be a good representation of the SG drift.

Klos et al. (2014a) showed how the unmodeled effects influence the estimated character of probability density function. They simulated daily time series with white plus flicker noise which is widely recognized to characterize the GPS time series to compare the Gaussian and non-Gaussian data. They added then different values of trend as well as seasonal terms and described how the skewness and kurtosis values change with each of them. The analyses were then performed for real data in the ETRF2000 reference frame. The authors found the lower bound for relationship between skewness and kurtosis to be equal to quadratic function. They concluded, that the uncertainties of velocities determined from ETRF2000 time series are underestimated by up to 5 mm/year when comparing the power-law noise model with white noise only.

Klos et al. (2014b) showed that a median absolute deviation is an optimum criterion for outliers removal in the GNSS time series. They used 12 most noisy EPN time series and compared different criteria commonly used for outliers detection. The results show that the removal of outliers is necessary before any further analysis, otherwise one may obtain quite odd and unrealistic values.

Klos et al. (2014c) used daily time series from the EPN stations in Poland to investigate the effect of the type of GPS antenna monument on the type and amplitude of noise. They analyzed the 5-years time series with Maximum Likelihood Estimation (MLE). The noise caused by the monument is thought to follow the random-walk character, therefore the authors analyzed noises twofold. Firstly as the combination of white, flicker and random-walk models what resulted in no conclusions on the monuments' stability level due to the domination of flicker noise in the time series and then as the sum of white plus random-walk noise characters, what showed that concrete pillars are better than buildings as GPS monuments.

Klos et al. (2014d) analyzed the daily GPS time series from the area of Sudeten with three different assumptions of noise models: a white noise – to show how the omitting of correlations in the stochastic part of the GPS time series results in underestimation of the velocity uncertainties, a white plus flicker plus random-walk noise – to estimate which of the power-law noise with the known spectral index prevails in the GPS time series, and white plus power-law noise – to estimate which coloured noise fits best the stochastic part. On the basis of MLE's values they showed that the combination of white plus power-law noise fits best the data. The spectral indices of power-law range from -1.6 to -0.4 for the horizontal components and from -1.0 to -0.4 for the vertical component, which confirms the prevalence of fractional white and Brownian motion quite close to flicker noise with amplitudes of power-law noise of 2-5 $mm*yr^{\kappa/4}$ and 4-12 $mm*yr^{\kappa/4}$, respectively. For this combination, the uncertainties of the estimated velocities reach in the most extreme case even 0.8 mm/year for the Up component.

Bogusz et al. (2014b) used a locally weighted scatterplot smoothing (LOESS) method which parameters are smoothing parameter and polynomial degree to analyze the autocorrelations in the daily changes of topocentric components of EPN stations in Poland. The authors showed that the trend-related behaviour due to plate motion is modelled best by both smoothing parameter and polynomial of degree 1. The polynomial of degree 2 with smoothing parameter close to 0.1 fits seasonal components quite well. Larger values of smoothing parameter flatten time series too much, while smaller ones detect higher frequency variations. The LOESS function has also shown to be a good approximation of time series residua and helpful in long-range dependencies analyses.

Bogusz et al. (2014c) showed how the improper data pre-analysis may affect the quality of fit of trend line interpreted as velocity into GPS time series. The unremoved outliers and offsets, although giving quite satisfying fit, change the velocity values up to 1.3 mm/year. The velocities suffer not only from improperly removed factors at the pre-processing stage, but also from seasonal components not sufficiently modelled.

Bogusz et al. (2014a) analyzed how the different systematic errors due to mis-modelling of satellite orbits or satellite antenna phase centre corrections affect the regionally correlated errors, called common mode errors (CME). They implemented the stacking method for ASG-EUPOS permanent stations with daily time series and showed that the time series residua (data with no trend and seasonal terms) are correlated for stations located even 200 km apart. After removal of CME values from time series, the correlations were estimated again. Their values did not exceed 0.01 what stands for the decrease of correlation value of 300% in comparison to correlation coefficients before spatial filtering and practically irrelevant spatial correlation of analysed ASG-EUPOS network. The obtained improvement (decrease) of the correlation coefficient between the ASG-EUPOS permanent stations testifies that the CME can be treated as the homogeneous for the area of Poland.

The problem of the impact of environmental effects on observed gravity is crucial. Satellite systems are not as susceptible to changes in local hydrology or atmospheric effects, although significant influences are clearly visible in the change of coordinates. Bogusz et al. (2011) showed potential environmental influences to GNNS coordinates on the example of the ASG-EUPOS network. Two solutions: daily and sub-daily were considered in order to identify the factors that may cause degradation of precision of coordinates and velocity determined. Separate analyses were performed for GPS and GPS+GLONASS solutions. GPS time series (by means of North, East and Up components) are the sum of the deterministic and stochastic part. The first one is the sum of the initial value, linear velocity and seasonal components. The annual curves determined by least squares estimation with assumption of stationarity of amplitude and phase, and uncertainties calculated with the coloured noise assumption using the First Order Gauss Markov model were shown (Bogusz and Figurski, 2014). The velocity bias due to annual oscillation could range from –0.6 to +0.5 mm/y. Some part of periodic changes in the deterministic part of GPS-derived time series could be of artificial reasons (numerical and observational). In the papers by Bogusz and Hefty (2011) and Bogusz and Figurski (2012) the unmodelled or mismodelled short-period (e.g. tidal) oscillations in Up components at more than 100 ASG-EUPOS stations were analysed. The analysis of the residua from IERS2003 tidal model was performed using least squares method with the ETERNA software upon the idea of Chojnicki. It confirmed the existence of significant energy in the frequencies corresponding to S1 (thermal influences), K1 and K2 (dynamic changes of satellites' constellation and network geometry or multipath). Bogusz and Kontny (2011) analysed the stochastic part of the 3-hour sampled time series with the use of the autoregressive integrated moving average (ARIMA) model providing Box-Pearce and Ljung-Box tests for rejecting null hypothesis about "whiteness" of the residua. As the processed network contained 130 sites the spatial distribution of the noise parameters was also investigated. Szafranek et al. (2014) analysed Zenith Tropospheric Delay (ZTD) time series resulted from the EUREF Permanent Network reprocessing performed by the Military University of Technology. Time series were analyzed in order to find short- and long-term trends which could be associated with the meteorological conditions and climate change. In particular linear trend and seasonal components (annual and semi-annual) were estimated on the basis of IWV (Integrated Water Vapour) time series for Matera (Italy) permanent station using least squares estimation.

A few time series analysis techniques have been used for analyzing and predicting geodetic time series, namely length of day (LOD) data, axial component of atmospheric angular momentum (AAM X_3), global mean sea level (MSL) as well as local and regional sea level anomalies (SLA). These techniques can be divided into interpretation-oriented approaches, the aim of which is to understand governing processes, and prediction-oriented ones that lead to the anticipation of future values of geodetic time series. Amongst the first group of methods, the cross-correlation analysis interpreted along with the wavelet coherence has been used to show El Niño/Southern Oscillation (ENSO) teleconnections, and LOD and AAM X_3 have been used as ENSO indices (Niedzielski, 2011, 2014). Wavelets are widely used not only in LOD/AAM X_3 data analysis (Kosek et al., 2011a), but also in the process of understanding deterministic harmonic oscillations in SLA time series (Świerczyńska et al., 2012, 2014). In order to analyze SLA residuals, in the form of time series free of deterministic signals, moment-based statistics have been found as efficient tools for evaluating SLA data nonlinearity (Niedzielski and Kosek, 2012a). Another method utilized for the purpose of inference about data variability and its characteristics was a sea level trend analysis, performed using the Cox-Stuart test on altimetric MSL time series (Niedzielski and Kosek, 2011).

The prediction-oriented time series techniques are closely associated with autoregression, in its numerous versions. In general, the deterministic signal is predicted with extrapolating the polynomial-harmonic model, and the residuals are satisfactorily predicted when autoregression is applied for residuals. Indeed, multivariate (vector) autoregressive model (MAR) have been shown to perform better than the autoregressive model (AR) in the process of forecasting LOD time series (Niedzielski and Kosek, 2012b). The same methods, together with the threshold autoregressive model (TAR) and generalized space-time autoregressive (GSTAR) model, are used to forecast sea level dynamics. In the first version of the Prognocean system implemented at the University of Wroclaw (Niedzielski and Miziński, 2013), these methods are used to predict SLA data in real time.

4. Diverse algorithms

The conversion between Cartesian and geodetic coordinates $(x, y, z) \leftrightarrow (\varphi, \lambda, h)$ on the rotational ellipsoid is a basic, well investigated issue in geometrical geodesy. There are few algorithms that can be used for this purpose. Ligas and Banasik (2011) proposed a new approach based on the solution of the system of nonlinear equations. The proposed algorithm consists of two steps. The first step is a projection of a point onto the ellipsoid and computation of the coordinates of the projected point by solving nonlinear equations with the use of the generalized Newton method. The second step is a straightforward computation of latitude and height. The performance of the proposed algorithm was compared in numerical tests with six existing algorithms of the coordinate conversion.

The same concept underlies a new method of coordinates conversion on a triaxial ellipsoid proposed by Ligas (2012). The method is based on solving a nonlinear system of equations for coordinates of the point being the projection of a point located outside or inside a triaxial ellipsoid along the normal to the ellipsoid. The nonlinear system of equations is solved by means of generalized Newton method. The numerical tests were performed for several celestial bodies and compared with the only existing Feltens's method. These tests showed that, the new approach is more universal and applicable to broad class of objects

Determination of the covariance function and its parameters is a crucial step in least squares collocation. Jarmołowski and Bakuła (2014) have studied the issue of precise covariance parameter estimation in least squares collocation using restricted maximum likelihood (LEML) method. The authors have implemented REML method for estimation of the variance, correlation length and a noise of the Gauss-Markov second order function, which is frequently used as a correlation function when interpolating gravity anomalies. The method proposed was tested on two data sets. The first set includes terrain elevations measured with GNSS and the second includes terrestrial free-air gravity anomalies. A hold-out method was used for cross validation of the parameters estimated by REML.

Keller and Borkowski (2011) proposed a new algorithm for building identification and segmentation in laser scanning data. The algorithm bases on multi-resolution analysis in wavelet domain and works on gridded data. The wavelet-based segmentation proceeds in the following main steps: wavelet decomposition up to appropriately chosen level, thresholding on the chosen and adjacent levels, removal of all coefficients in the so-called influence pyramid and wavelet reconstruction. If buildings on several scaling spaces have to be segmented, the procedure has to be applied iteratively.

5. Summary and conclusions

In this review paper an outline of research activities concerning theoretical geodesy performed in Poland in the period from 2011 to 2014 is presented. The studies reported in this review are partially continuation of studies started in previous years. Several fundamental achievements have been gained in the last four years. The new models of parameter estimation, new results related to the robustness of *M*-estimation and related to reliability of observations systems can be mentioned as the main achievements of the Polish researchers. Especially, it can be emphasize as the highlights:

- The new model of *M*-estimation with probabilistic models of geodetic observations, which depends on the variance, kurtosis, excess and asymmetry of the observation errors distribution.
- The new Shift-M_{split} estimation, which enables to estimate a vector of parameter differences without estimating the particular parameters vectors.
- The Shift-$M_{split}^{(+)}$ as a generalisation of Shift-M_{split} estimation if the design matrix **A** of a functional model has not a full column rank.
- The new algorithms of the coordinates conversion between the Cartesian and geodetic coordinates, both on the rotational and triaxial ellipsoid.
- The algorithm of computation of common oscillations in two complex-valued time series using wavelet semblance filtering with discrete Shannon wavelet functions.
- The algorithm of computation of spectro-temporal semblance function between two complex-valued time series with application of the modified Morlet wavelet function.
- The algorithm to compute variable amplitudes and phases in real-valued time series based on the combination of the Fourier Transform Band Pass Filter (FTBPF) with the Hilbert transform (HT). This algorithm utilizes the Singleton Fast Fourier Transform to speed up computations.
- The algorithms for prediction by combination of extrapolating the polynomial-harmonic model with the multivariate (vector) autoregressive model (MAR) and threshold autoregressive model (TAR) as well as the generalized space-time autoregressive model (GSTAR).
- The algorithm for forecasting by combination of the discrete wavelet transform band pass filter with discrete Shannon wavelet functions and the autocovariance prediction.

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