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Contents

1. REFERENCE FRAMES AND REFERENCE NETWORKS[1]

1.1. INTRODUCTION

This part of the Polish National Report on Geodesy is the quadrennial report on research activity concerning reference frames and reference networks performed in Poland in a period of 2007–2010. It contains a summary of the works on implementation of IAU2006, IUGG2007 and IAU2009 resolutions on reference frames, implementation of the ETRS in Poland, present status of permanent GNSS IGS/EPN stations operating in Poland, operation of active GNSS station networks in Poland, maintenance of vertical network, Polish national gravity control network, Polish national magnetic control as well as theoretical works on network solutions. The activities concerning reference networks were conducted mainly in the following research centres, listed in an alphabetic order:

- Department of Applied Geomatics, Military University of Warsaw;
- Department of Engineering Surveying, Warsaw University of Technology;
- Department of Geodesy and Geodetic Astronomy, Warsaw University of Technology;
- Department of Geodesy and Geodynamics, Institute of Geodesy and Cartography in Warsaw;
- Department of Planetary Geodesy, Space Research Centre, Polish Academy of Sciences in Warsaw;
- Department of Surveying Engineering, University of Warmia and Mazury in Olsztyn;
- Institute of Geodesy, University of Warmia and Mazury in Olsztyn;
- Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences;
- Institute of Structural Engineering, University of Zielona Gora.

The extensive information on the activities concerning reference networks in Poland within the reported period are contained in the annual national reports to the IAG Sub-commission for EUREF (Krynski and Rogowski, 2007, 2008, 2009, 2010).

The bibliography of the related works is given in references.

1.2. IMPLEMENTATION OF IAU2006, IUGG2007 AND IAU2009 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, 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. 1.2.1) starting form 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-

[1] The content of the chapter was compiled by **Jan Krynski** with the use of the material provided by Andrzej Araszkiewicz, Jarosław Bosy, Slawomir Cellmer, Robert Duchnowski, Jozef Gil, Leszek Jaworski, Waldemar Kaminski, Jan Krynski, Witold Proszynski, Elzbieta Welker, Zbigniew Wisniewski, and Lukasz Zak.

definition of the Barycentric Celestial Reference System (BCRS) and Geocentric Celestial Reference System (GCRS) as well as re-definition of the Barycentric Dynamic Time. It should be noted that the distinction between the Celestial Intermediate Reference System and the Terrestrial Intermediate Reference System as well as more precise description of the orientation of BCRS and GCRS given in the IAU2006 resolutions were independently found out by the team of the Astronomical Almanac of the Institute of Geodesy and Cartography, Warsaw, and implemented already in its 2004 edition.

Fig. 1.2.1. The Astronomical Almanac of the Institute of Geodesy and Cartography: 2007–2010 editions

The 2008 edition of the Astronomical Almanac (Krynski and Sekowski, 2007) additionally implemented the resolution adopted by the IUGG XXIV General Assembly (Perugia, 2007) concerning the re-definition of the International Terrestrial Reference System as a specific case of the Geocentric Terrestrial Reference System (GTRS).

The resolution of the IAU XXVI General Assembly (Prague, 2006) on the replacement of the precessional part of the IAU2000A precession-nutation model with the P03 model was recommended for implementation starting from 1 January 2009. Numerous computing programs were respectively modified to implement the P03 model for the 2009 edition of the Astronomical Almanac (Krynski and Sekowski, 2008). 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, 2009, 2010a).

The 2010 edition of the Astronomical Almanac (Krynski and Sekowski, 2009), following resolutions of the IAU XXVII General Assembly in Rio de Janeiro in 2009, implemented a new set of astronomical constants named IAU2009.

1.3. IMPLEMENTATION OF THE ETRS IN POLAND

For the purpose of geodesy and geodynamics the ETRS89 was realized in Poland through positioning with GPS measurements of a campaign or permanent stations: using recent ITRF$_{yy}$ station coordinates and IGS precise ephemeredes.

The first implementation of the ETRS89 in Poland was **EUREF89** which corresponds to the extension of **ETRF89 at epoch 1989.0** on the territory of Poland by means of the network of 11 EUREF-POL stations positioned in a campaign in 1992 together with a number of European stations of known ETRS89 coordinates. The EUREF89 was then densified on the territory of Poland by means of 348 stations positioned in a POLREF campaign in 1994/1995.

Independent implementation of the ETRS89 in Poland is done by means of Polish EPN GNSS stations. The network of the EPN GNSS stations in Poland originated in 1993 with the first permanent station, and grew up in 2010 to 18 stations which are quite homogeneously distributed. The EPN stations in Poland provided thus all consecutive ETRF realizations of the ETRS89: **ETRF89**, **ETRF90**, …, **ETRF2005**.

Recent implementation of the ETRS89 in Poland, supported by the Head Office of Geodesy and Cartography is **ETRF2000 at epoch 2005.0** which is realized by means of permanent GNSS measurements at 18 EPN stations and the ASG-EUPOS system of 98 stations (Krynski and Rogowski, 2010).

1.4. OPERATIONAL WORK OF PERMANENT IGS/EUREF STATIONS IN POLAND

Permanent GNSS stations of IGS and EUREF networks operate in Poland since 1993. The number of permanent GNSS stations in Poland was growing within last years. Recently 18 permanent GNSS stations operate in Poland within the EUREF program. They are Biala Podlaska (BPDL), Borowa Gora (BOGO, BOGI), Borowiec (BOR1), Bydgoszcz (BYDG), Cracow (KRAW, KRA1), Gorzow Wielkopolski (GWWL), Jozefoslaw (JOZE, JOZ2), Lamkowko (LAMA), Lodz (LODZ), Katowice (KATO), Redzikowo (REDZ), Suwalki (SWKI), Ustrzyki Dolne (USDL), Wroclaw (WROC) and Zywiec (ZYWI) (Fig. 1.4.1, Table 1.4.1).

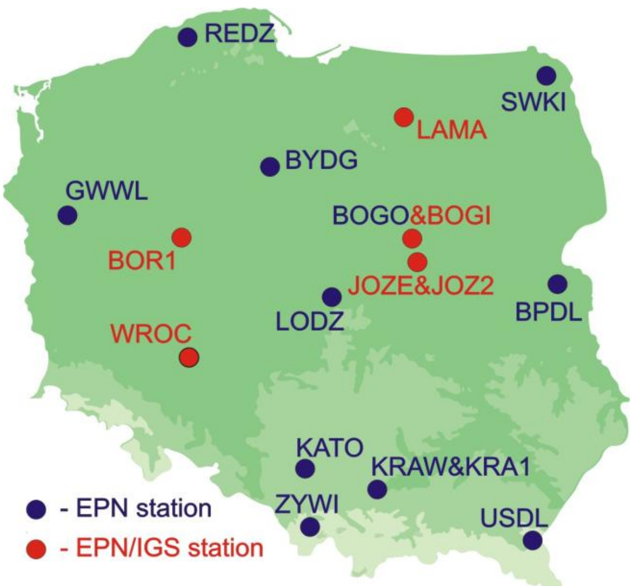

Fig. 1.4.1. EPN/IGS permanent GNSS stations in Poland (2010)

The stations BOGI, BOR1, JOZE, JOZ2, LAMA and WROC operate also within the IGS network (http://www.epncb.oma.be/_trackingnetwork/stations.php).

Table 1.4.1. 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 NetR5
Cracow (KRAW)	50º03'58"	19º55'14"	EUREF	Ashtech μZ-12
Cracow (KRA1)	50º03'58"	19º55'14"	EUREF	TRIMBLE NetR5
Gorzow Wielkopolski (GWWL)	52º44'17"	15º12'19"	EUREF	TRIMBLE NetR5
Jozefoslaw (JOZE)	52º05'50"	21º01'54"	IGS, EUREF	Trimble 4000 SSI
Jozefoslaw (JOZ2)	52º05'52"	21º01'56"	IGS, EUREF	LEICA GRX1200GGPRO
Katowice (KATO)	50º15'11"	19º02'08"	EUREF	TRIMBLE NetR5
Lamkowko (LAMA)	53º53'33"	20º40'12"	IGS, EUREF	LEICA GRX1200GGPRO
Lodz (LODZ)	51º46'43"	19º27'34"	EUREF	TRIMBLE NetR5
Redzikowo (REDZ)	54º28'21"	17º07'03"	EUREF	TRIMBLE NetR5
Suwalki (SWKI)	54º05'55"	22º55'42"	EUREF	TRIMBLE NetR5
Ustrzyki Dolne (USDL)	49º25'58"	22º35'09"	EUREF	TRIMBLE NetR5
Wroclaw (WROC)	51º06'47"	17º03'43"	IGS, EUREF	LEICA GRX1200GGPRO
Zywiec (ZYWI)	49º41'12"	19º12'21"	EUREF	TRIMBLE NetR5

A brief characteristics of those stations is given in Table 1.4.2 (http://www.epncb.oma.be/_trackingnetwork/stations.php). 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.

Table 1.4.2. 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	**3JAN2001/** since 265/2002 (GPS week No 1185)	**LB-710HB** LAB-EL Poland **MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS Astrometry Gravity Geomagnetic field Ground water level
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	GPS/GLONASS Astrometry Gravity Geomagnetic field Ground water level

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	**4DEC2007/** 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 NetR5** TRM55971.00 TZGD	**4DEC2007/** since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS
GWWL	12225M001	**Gorzow Wielkopolski** Head Office of Geodesy and Cartography	**Trimble NetR5** TRM55971.00 TZGD	**10DEC2007/** since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS
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	GPS Astrometry Gravity tidal Ground water level
JOZ2	12204M002	**Jozefoslaw** Inst. of Geodesy and Geod. Astr., WUT	**Leica GRX1200GGPRO** LEIAT504GG NONE	**3JAN2002/** since 257/2003 (GPS week No 1236)	**LB-710RHMS** LAB-EL Poland **MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS Gravity absolute Gravity tidal Ground water level
KATO	12219S001	**Katowice** Marsh. Off. of the Siles. Prov.	**Trimble NetR5** TRM57971.00 TZGD	**30JAN2003/** since 222/2003 (GPS week No 1231)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS
KRAW	12218M001	**Cracow** 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	**Cracow** 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** Inst. of Geodesy, UWM	**Leica GRX1200GGPRO** LEIAT504GG LEIS	**01DEC1994/** since 365/1995 (GPS week No 0834)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS Gravity Ground water level
LODZ	12226M001	**Lodz** Head Office of Geodesy and Cartography	**Trimble NetR5** TRM55971.00 TZGD	**3DEC2007/** since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS
REDZ	12227M001	**Redzikowo** Head Office of Geodesy and Cartography	**Trimble NetR5** TRM55971.00 TZGD	**7DEC2007/** since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS
SWKI	12228M001	**Suwalki** Head Office of Geodesy and Cartography	**Trimble NetR5** TRM55971.00 TZGD	**5DEC2007/** since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS
USDL	12229M001	**Ustrzyki Dolne** Head Office of Geodesy and Cartography	**Trimble NetR5** TRM55971.00 TZGD	**3DEC2007/** since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS
WROC	12217M001	**Wroclaw** Univ. of Env. & Life Sciences	**Leica GRX1200GGPRO** LEIAT504GG LEIS	**28NOV1996/** since 329/1996 (GPS week No 0881)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS Ground water level
ZYWI	12220S001	**Zywiec** Marsh. Off. of the Siles. Prov.	**Trimble NetR5** TRM55971.00 TZGD	**30JAN2003/** since 222/2003 (GPS week No 1231)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/GLONASS

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://www.epncb.oma.be/_organisation/projects/euref_IP/index.php) (Fig. 1.4.2, Table 1.4.3). Three of them, i.e. BOGI, BOR1 and JOZ2 participated also in IGS-IP project. A number of other Polish GNSS stations participate in the EUREF-IP project (Table 1.4.4).

Table 1.4.3. Characteristics of Polish EPN stations participating in the EUREF-IP project

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)
Cracow	KRAW	GPS	50.01	19.92	Ashtech μZ-12	RTCM 2.2 - 1(1),3(60),16(60),18(1), 19(1),22(60)
Cracow	KRA1	GPS+GLO	50.01	19.92	TRIMBLE NetR5	RTCM 3.0 - 1004(1),1006(10),1008(10), 1012(1),1013(10),1033(10)
Jozefoslaw	JOZ2	GPS+GLO	52.02	21.03	Leica GRX1200GGPro	RTCM 3.0 - 1004(1),1006(60),1008(60), 1012(1)
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)
Wrocław	WROC	GPS+GLO	51.11	17.06	Leica GRX1200GGPro	RTCM 3.0 - 1004(1),1006(15),1008(15), 1012(1)

Table 1.4.4. Characteristics of other Polish GNSS stations participating in the EUREF-IP project

Location	St. ID	Observations	Latitude [deg]	Longitude [deg]	Receiver	RTCM type - message types (update rate [s])
Cracow	AGH0	GPS	50.01	19.92	Ashtech μZ-12	RTCM 2.2 - 1(1),3(60),16(60),18(1), 19(1),22(60)
Elblag	ELBL	GPS	54.16	19.40	Ashtech μZ-12	RTCM 2.0 - 3(60),18(1),19(1)
Gdansk	GDAN	GPS	54.33	18,66	Ashtech μZ-12	RTCM 2.2 - 3(60),18(1),19(1),22(60)
Jozefoslaw	JOZ3	GPS+GLO	52.02	21.03	Leica GRX1200GGPro	RTCM 3.0 - 1004(1),1006(15), 1008(15),1012(1),1033(15)
Olsztyn	KROL	GPS	53.75	20.46	Javad Alpha	RTCM 2.0 - 3(10),18(1),19(1),22(10)
Olsztyn	OLSZ	GPS	53.75	20.45	Ashtech Z-XII	RTCM 2.3 - 1(1),3(60),18(3),19(3)
Poznan	POZN	GPS	52.43	16.93	Ashtech μZ-12	RTCM 2.3 - 3(5),18(5),19(5),22(5)
Szczecin	SZCZ	GPS+GLO	53.43	14.55	Leica GX1230GG	Leica - Leica(1)
Tychy	TYCH	GPS	50.19	19.01	Leica GRX1200GGPro	RTCM 2.3 - 18(1),19(1)
Udorpie	UDOR	GPS	54.15	17.49	Ashtech μZ-12	RTCM 2.1 - 1(1),3(60),18(1),19(1)
Warsaw	WARS	GPS+GLO	52.00	21.00	Leica GRX1200GGPro	RTCM 3.0 - 1004(1),1006(15), 1008(15),1012(1)
Warsaw	LGPL	GPS	52.24	21.09	Leica GRX1200GGPro	RTCM 2.3 - 3(60),18(1),19(1) / Leica - Leica(1)

Since March 2005 Ntrip Broadcaster is installed at the AGH University of Science and Technology (gps1.geod.agh.edu.pl). The Ntrip Caster broadcasts RTCM and raw GNSS data from 17 sources, mainly from KRAW EPN permanent station in the framework of EUREF-IP project.

Fig. 1.4.2. Polish EPN stations participating in the EUREF-IP project (2010)

1.5. ACTIVE GNSS STATION NETWORKS IN POLAND

The ASG-EUPOS network of about 100 active GNSS stations – designed for surveying practice – covers homogeneously the whole territory of Poland. There are also some other GNSS networks of local use in Poland, e.g. for geodynamic research.

1.5.1. ASG-EUPOS - a Multifunctional Precise Satellite Positioning System in Poland

The agreement between the Head Office of Geodesy and Cartography (GUGiK) in Poland and the Polish Ministry of Economy on financial support for the establishment of a network of EUPOS reference stations in Poland (Krynski, 2007) has been signed in August 2005. The respective fund for the realization of the Project EUPOS was accepted and support was given from the structural ERDF EU (European Regional Development Fund) programme.

A sub-network of the ASG-PL with data processing centre operating in Upper Silesia from the end of 2002, as a pilot project of governmental and regional Silesian authorities, extended in 2006 by new 4 stations in Malopolska region preceded the establishment of the ASG-EUPOS (Krynski, 2007).

The Head Office of Geodesy and Cartography, the consortium: WASKO S.A., Geotronics Poland S.A., and Trimble Europe BV have signed in 2 January 2007 a contract for building the ASG-EUPOS multifunctional precise satellite positioning system in Poland. The consortium completed setting up the system in April 2008. After conducting successfully a number of tests the Head Office of Geodesy and Cartography opened in 2 June 2008 the ASG-EUPOS for all users. The ASG-EUPOS multifunctional system for precise satellite positioning is a part of the EUPOS project involving countries of Central and Eastern Europe (Bosy et al., 2007, 2008).

The receiving segment (ground control segment) consists of a network of GNSS reference stations located evenly on the whole territory of Poland. Comply with EUPOS and project of the ASG-EUPOS system standards distances between neighbouring reference stations should be of 70 km what results in a total number of 98 stations (Fig. 1.5.1). According to rules of the EUPOS organization 22 foreign stations were added to the system (in the frame of cross-border data exchange): 3 reference stations from Lithuania (LITPOS), 6 stations from Germany (SAPOS), 7 stations from Czech Republic (CZEPOS) and 6 stations from Slovakia (SKPOS) (Fig. 1.5.1) (Bosy et al., 2008, 2009a).

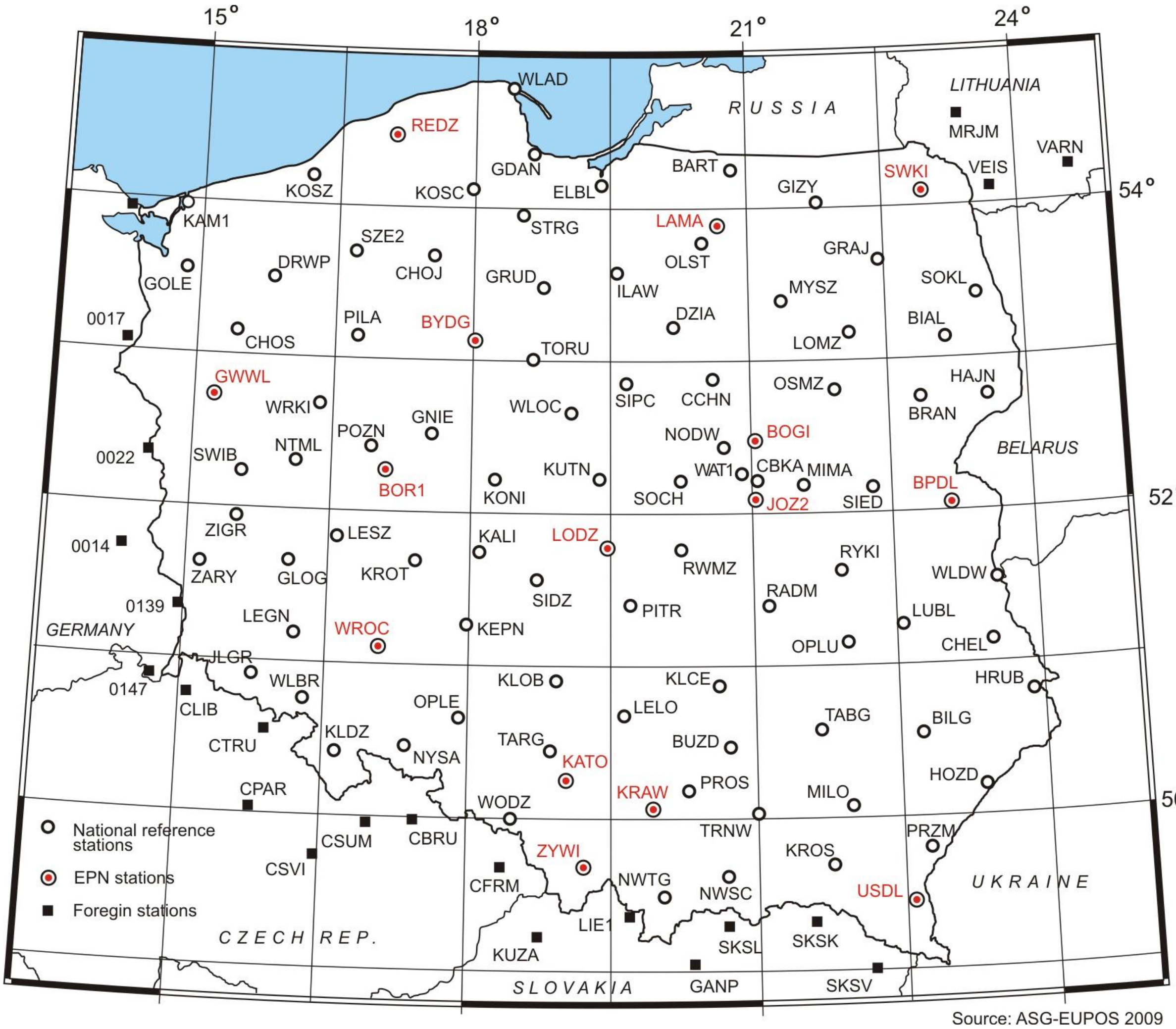

Fig. 1.5.1. Reference stations included in ASG-EUPOS (www.asgeupos.pl)

The ASG-EUPOS network provides a signal for both positioning of geodetic control points as well as for land, air and marine navigation. Several levels of positioning accuracy are offered. Standard services, as required by the general EUPOS assumptions including the following sub-services: NAVGIS (network RTK for real time kinematic DGNSS applications), NAV-GEO (network RTK for precise real time kinematic DGNSS applications), POSGEO DGNSS for precise DGNSS post processing applications are offered (Krynski, 2007).

The ASG-EUPOS network will define the European Terrestrial Reference System ETRS89 in Poland. A close connection of the ASG-EUPOS stations and 15 out of 18 Polish EPN stations will control the realization of the ETRS89 on the Polish territory.

All reference stations of the ASG-EUPOS system are equipped with the modern GNSS receivers (Table 1.5.1). Their antennae were calibrated using the absolute calibration procedure (ftp://igscb.jpl.nasa.gov/igscb/station/general/igs05.atx).

Table 1.5.1. GNSS equipment on the ASG-EUPOS reference stations

Number of stations	Receiver	Antenna
72	Trimble NetR5	Trimble Zephyr Geodetic w/Radome (*TRM41249.00 TZGD*)
12	Ashtech μZ-12	Ashtech L1/L2 Choke Ring SNOW (*ASH701945C M SNOW* - D/M element, REV.C, chokering with radome NGS)
8	Trimble NetR5	Trimble Zephyr GNSS Geodetic II w/Radome (*TRM55971.00 TZGD*)
4	Leica GRX1200GGPro	Leica L1/L2 Choke Ring, using DM-T style (*LEIAT504GG LEIS*)
1	Javad TRE_G3T DELTA	Ashtech L1/L2 Choke Ring SNOW (*ASH701945C M SNOW* - D/M element, REV.C, chokering with radome NGS)
1	Trimble NetRS	Dorne Margolin T Choke Ring (*AOAD/M T NONE*)

At 14 Polish EPN stations the new uniform meteorological infrastructure Paroscientic, Inc. MET4A sensors were installed (Table 1.4.2). The EPN station Borowiec (BOR1) is equipped with the equivalent meteorological infrastructure: NAVI Ltd. HPTL.3A and Skye Instruments Ltd. sensors. At all those stations the basic meteorological parameters:

- atmospheric pressure with accuracy of ±0.08 hPa from 500 to 1100 hPa,
- temperature with accuracy of ±0.2ºC from –50 to +60ºC,
- relative humidity with accuracy of ±2% from 0 to 100%,

are measured close to the GNSS antenna.

The ASG-EUPOS system will ensure a stable and uniform ETRS89 reference system realization in Poland. The ASG-EUPOS system includes three independent levels for the control of the stability of the ETRS89 realization. The system accessibility and the realization of precise positioning service will be carried out in real time and homogeneous reference frame in the territory of Poland (Bosy et al., 2008, 2009a).

The calibration campaign of the ASG-EUPOS network was conducted in the period 23 April – 11 May 2008 as a joined effort of a few institutions under the leadership of the University of Warmia and Mazury in Olsztyn. Besides the ASG-EUPOS stations the GPS test campaign covered most of the stations of the EUREF-POL and EUVN network as well as over 100 stations of the POLREF network. Acquired data together with data from the EPN/IGS sites in the region were processed in the Department of Planetary Geodesy of the Space Research Centre of the Polish Academy of Sciences (Jaworski et al., 2008). The calibration campaign integrated the existing classical and modern (satellite) networks with new-established network of permanent stations of ASG-EUPOS in a common, precise reference system in Poland. The method of measurements and implemented solution of the GPS observations is compliant with EPN standards of computation and ensure the high precision of determined coordinates. The results obtained indicate high stability of the network investigated (Jaworski et al., 2008).

The experience gained in the Space Research Centre PAS with GNSS techniques such as GPS, EGNOS and Galileo as well as with modelling environmental effects on GNSS data resulted in establishing the new project named EGNOS-EUPOS Integration (EEI) (Jaworski and Swiatek, 2009). The previous analyses showed that accuracy and availability of corrections determined in the eastern part of Europe are degraded because no EGNOS corrections are considered. The main purpose of EEI project is to improve the effectiveness and range of applications of the EGNOS system, by achieving the full compatibility and integration with the EUPOS system.Since April 2009 the Centre of Applied Geomatics of the Military University of Technology, Warsaw processes for the Head Office of Geodesy and Cartography the archive data from the ASG-EUPOS stations in order to evaluate the most reliable coordinates on those stations and to estimate sites' activity (Figurski et al., 2009, 2010a). In particular, the stability of the ASG-EUPOS stations was investigated (Figurski et al., 2010b). Concentrating on the ASG-EUPOS stations with the most reliable solutions the geodynamic research is conducted using time and time-frequency analyses (Figurski et al., 2010c).

1.5.2. IGS/EPN Reference Frame Realization in Local GNSS Networks

Permanent EPN/IGS stations are reference stations for local GNSS networks. The reference is made to the closest stations and the existence of the relevant number of such stations in the area surrounding the local network is important. One of the local GPS networks is the GEOSUD network operated by the Institute of Geodesy and Geoinformatics of the Wroclaw University of Environmental and Life Sciences (Fig. 1.5.2a).

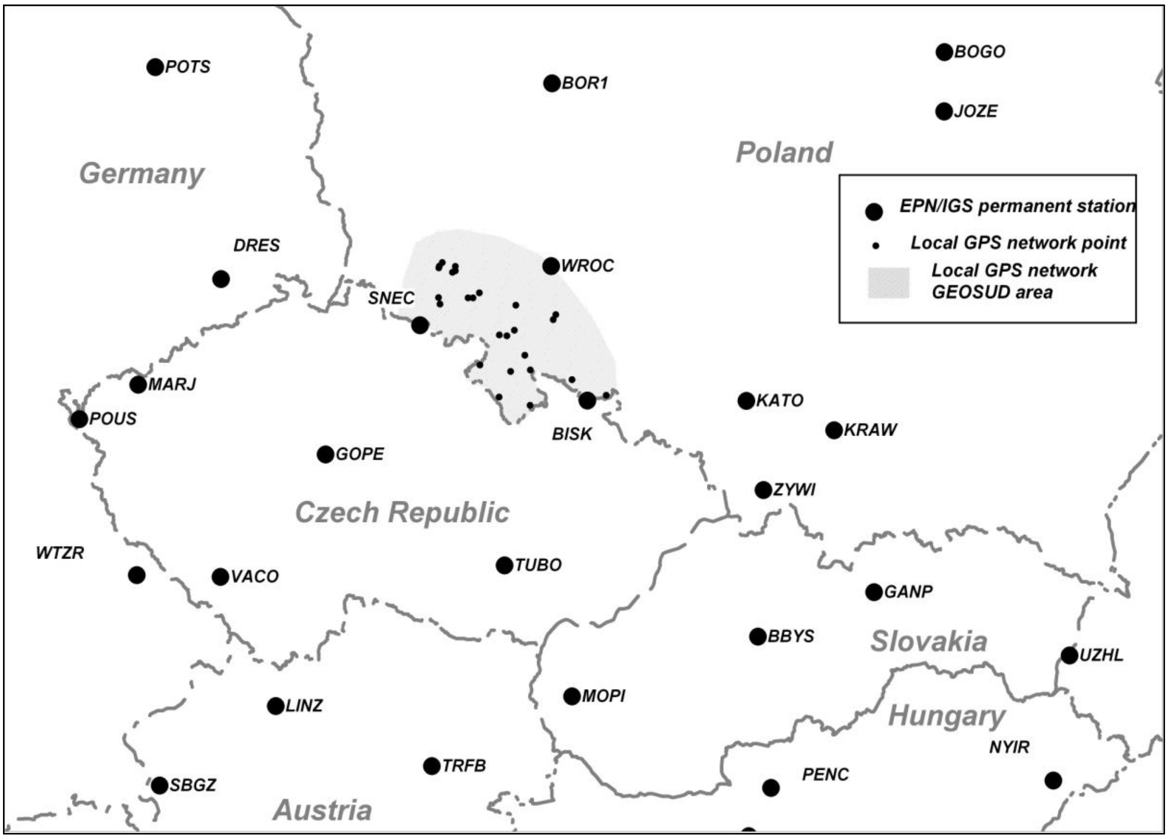

Fig. 1.5.2a. Local GPS network GEOSUD and nearest EPN/IGS permanent stations

Connecting local GPS networks to permanent EPN/IGS stations is necessary to align the local network to ITRF. The EPN/IGS products may be applied for local network processing.

The concept of combined solution of permanent and epoch GPS observations to process local network as the whole in order to estimate velocities concerns simultaneous processing of heterogeneous observations from permanent EPN/IGS stations, semi-permanent stations and epoch stations. Processing procedure benefits from the EPN/IGS products such as: station coordinates and velocities, ionosphere model and Tropospheric Zenith Delay (TZD). Figure 1.5.2b presents the diagram for combined processing of permanent and epoch observations.

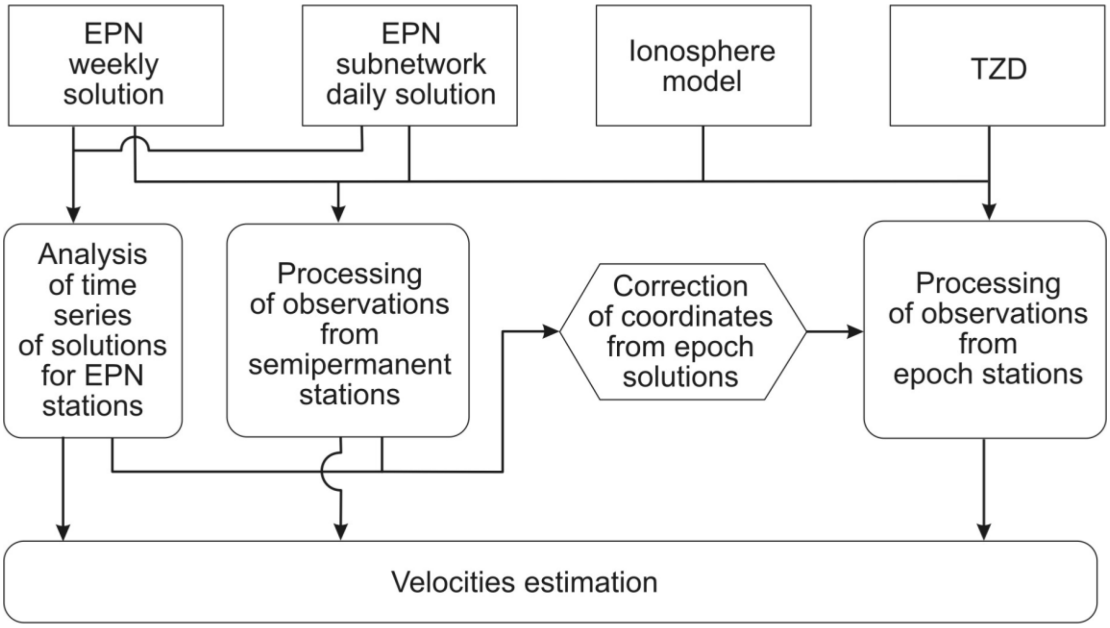

Fig. 1.5.2b. Diagram of GPS data processing strategy for combined processing of permanent and epoch observations

The coordinate time series of the local networks stations include additional effects, e.g. seasonal variations. To remove those effects from the time series a method was developed which is based on the interpolation of the residuals of permanent and semi-permanent stations. The method of mean trend congruency analysis for EPN/IGS stations coordinates time series is one of the criteria for the selection of reference stations for local GPS networks (Fig. 3.2.2 in Chapter 3) (Bosy et al., 2009b).

1.6. MAINTENANCE OF VERTICAL CONTROL IN POLAND

Reliability of the two-stage adjustment of the Polish 1st order vertical control with the use of data acquired during the 4th levelling campaign in Poland in 1999–2002 (Krynski, 2007) was investigated at the University of Warmia and Mazury for the Head Office of Geodesy and Cartography. It was shown that the two-stage adjustment of a levelling network, consisting of rigorous least squares adjustment of pseudo-observations, and with calculation of heights of intermediate points, based on proper condition equation for each levelling line yields practically the same results which would have been obtained in the process of rigorous least squares adjustment of observations. The two-stage adjustment of a levelling network is thus a rigorous adjustment of all the observations which make up a network (Gajderowicz, 2007a). The new vertical reference system for Poland was proposed (Gajderowicz, 2007b).

1.7. MAINTENANCE OF GRAVITY CONTROL

Activities concerning the maintenance and modernization of national gravity control were performed not only in Poland, as it has traditionally been done, but also in Finland where the absolute gravity was measured with the use of the Polish A10-020 free-fall gravimeter at the points of the Finnish First Order Gravity Network.

1.7.1. Maintenance of Gravity Control in Poland

The Polish Gravity Control Network POGK97, established in 1993–1998, consisted of 351 field gravity stations surveyed with spring 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 and extended by the Institute of Geodesy and Cartography, Warsaw. By 2006 it included 2 new absolute gravity stations and 8 new field gravity stations that all were tied to the existing gravity control with relative gravity measurements (Krynski, 2007).

The joint team of the Institute of Geodesy and Cartography, Warsaw, and the Warsaw University of Technology conducted an extensive research on the modernization of the Polish national gravity control (Krynski and Rogowski, 2007). First three stages of the modernization procedure have been specified as follows: 1st – densification of the absolute gravity network, 2nd – modernization of two gravimetric calibration baselines for relative measurements, 3rd – re-measurement of gravity at the remaining absolute gravity stations in Poland (Barlik and Krynski, 2007).

Fig. 1.7.1. The Polish national gravity control (2010)

In 2007–2008 five new absolute gravity stations of the Polish gravity control network as well as 11 new absolute gravity stations along the Central and Western Gravimetric Calibration Baselines (Fig. 1.7.1) were established and surveyed (Barlik et al., 2009; Krynski and Rogowski, 2009).

From 2006 to 2009 the unified gravimetric reference system for the Polish GNSS stations and geodynamic test field was established by the team of the Warsaw University of Technology (see in detail Chapter 2) using the FG5-230 free-fall gravimeter. In Southern Poland, in the mountainous areas, the differences between gravity values determined with the FG5-230 and values obtained from the adjustment of the POGK97 exceed 5÷6 μGal (Walo, 2010).

Substantial modernization of the Polish gravity control network is in progress. The excentric sites of the ASG-EPOS network stations are considered to be included into the gravity control network. Also the densification of the absolute gravity points surveyed using the laboratory-type ballistic gravimeters with the absolute gravity points surveyed using the portable A10 free-fall gravimeter are taken into consideration (Sekowski and Krynski, 2010).

1.7.2. Maintenance of Gravity Control in Finland

The Finnish gravity network (FOGN) is recently being modernized. In the framework of scientific cooperation between the Finnish Geodetic Institute and the Institute of Geodesy and Cartography, Warsaw, 51 sites of the FOGN were surveyed with the A10-020 free-fall gravimeter of the IGiK with a repeatability better than 4 μGal in four campaigns: one in 2009 and three in 2010 (Kryński and Sękowski, 2010b; Sękowski and Krynski, 2010; Kryński and Rogowski, 2010; Mäkinen et al., 2010a, 2010b, 2010c, 2010d). For control, 9 Finnish absolute gravity stations were occupied with the A10-020 altogether 25 times. From preliminary computations, the offset of the A10-020 to the FG5-221 of the Finnish Geodetic Institute was negligible and the RMS difference was 3 μGal. More detail information is given in Chapter 2.

1.8. MAINTENANCE OF MAGNETIC CONTROL IN POLAND

The magnetic repeat station network in Poland, established in 1955, consists of 19 field stations 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. Beginning from 1970, the survey is performed every 2 years. Data from two Polish magnetic observatories – Belsk and Hel are also used for the determination of secular variations of the Earth magnetic field in Poland.

The magnetic repeat station networks were also established in Belarus in the framework of the Polish-Belarusian cooperation and in Lithuania in the framework of the Polish-Lithuanian cooperation in 1997 and 1999, respectively. In both countries the magnetic surveys have been performed with participation of specialists from the Institute of Geodesy and Cartography, Warsaw, using magnetometers of that Institute. The survey campaigns have been repeated every 2÷3 years and the data acquired is analysed in cooperation of the teams involved. The integrated magnetic repeat station network is shown in Figure 1.8.1.

Polish magnetic repeat station network is getting improved continuously (Sas-Uhrynowski and Welker, 2007) according to the European standards defined by MagNetE of IAGA. 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 not longer fulfilled, it is displaced to the other site; at the new location a special procedure is applied to secure the continuity of observations. In 2007 the 4 repeat stations (Cisna, Naleczow, Kruszwica and Domaszkow) were moved to the new location. The list of the Polish and Lithuanian repeat stations measured in the period 2007–2010 is given in Table 1.8.1.

Table 1.8.1. Polish and Lithuanian magnetic repeat stations measured in the period 2007–2010

POLAND						
Station name	Latitude [º ' "]	Longitude [º ' "]	2007	2008	2009	2010
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	×			
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	×			
Bialowieza II	52 42 32	23 51 04	×			×
Peckowo II	52 35 40	16 19 20	×			×
Rzepin II	52 15 35	14 44 31	×			×
Komorowo III	52 50 16	21 46 18	×			×
Naleczow II	51 14 15	22 11 12	×		×	
Podzamcze	51 24 16	18 09 05		×		
Kruszwica	52 40 25	18 18 30	×			×
LITUANIA						
Station name	Latitude [º ' "]	Longitude [º ' "]	2007	2008	2009	2010
Ziezmariai	54 47 31	24 22 30	×			
Dusetos	55 43 17	25 50 47	×			
Paroveia	56 14 26	24 54 59	×			
Tryskiai	56 06 27	22 35 10	×			
Syliai	55 24 00	21 45 00	×			
Saukotas	55 35 47	23 26 03	×			

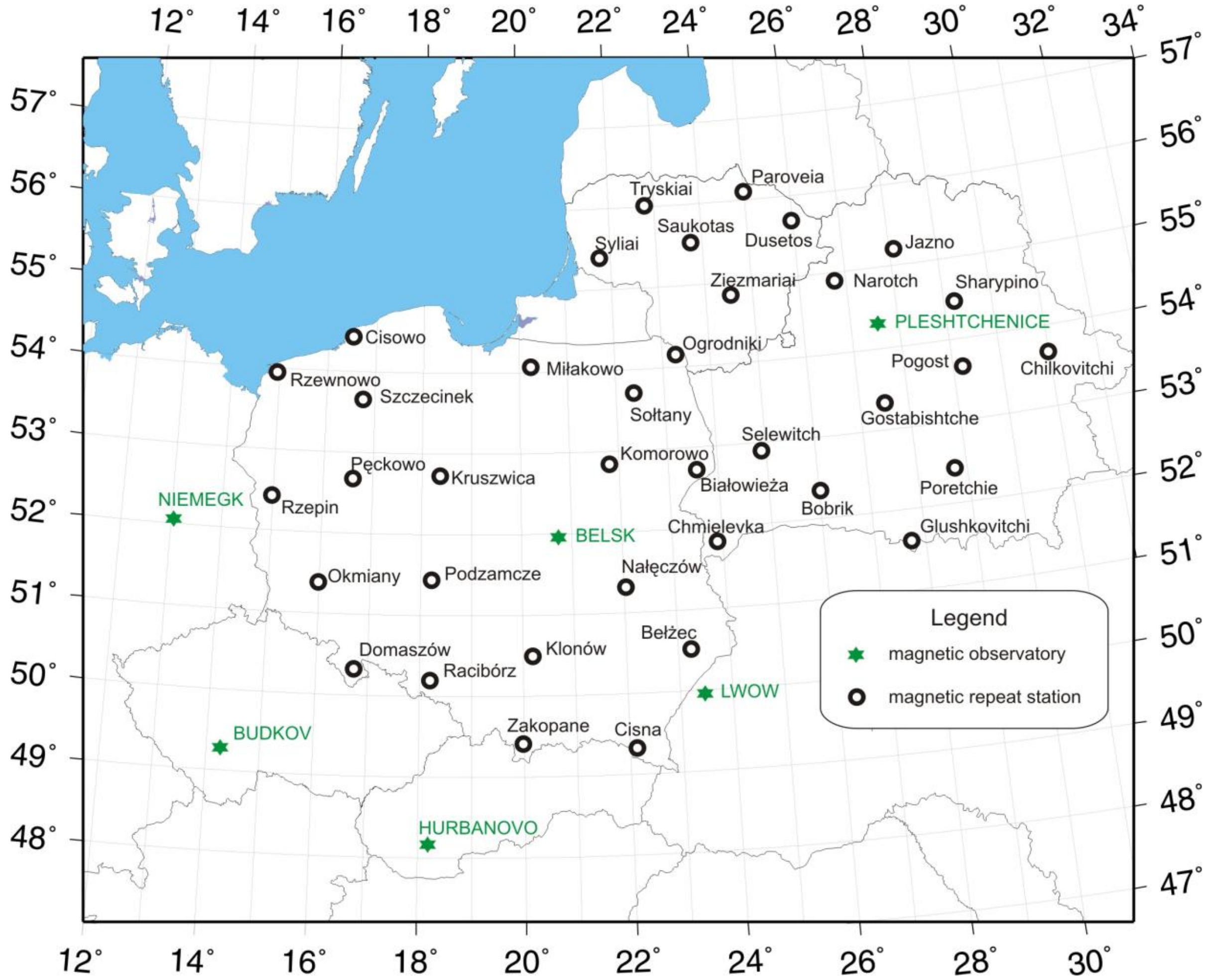

Fig. 1.8.1. Integrated Polish, Belarussian and Lithuanian magnetic repeat station network

1.9. ADVANCED THEORY ON NETWORK SOLUTIONS

Theoretical investigations on new methods concerned analysis or adjustment of geodetic observations, theory of GNSS data processing, reliability analysis and detection of outliers, theory and use of neural network.

1.9.1. Theory of Estimation

Research on the theory of estimation was conducted at the Institute of Geodesy of the University of Warmia and Mazury in Olsztyn. The basic R-estimates were adapted for geodetic purposes and some of their applications were proposed. The R-estimation can be applied to detect and eliminate non-random errors from observation data sets. Such application, namely the elimination of the effects of gross errors, was implemented to the traditional least squares method that resulted in R-LS adjustment (Duchnowski, 2008).

Referring to the theory of R-estimation, it was also proposed to estimate a shift between parameters of two different functional models. In this context, R-estimates were applied to assess vertical displacements of levelling network points (Duchnowski, 2009). Such application was the basis for the new strategy for testing the stability of the possible reference marks. The role of R-estimation is to assess vertical displacements of the network points, thus to identify unstable reference marks. However, it should often be supported by some robust estimates of the standard deviation. In more complex cases, such estimates are necessary to verify if the so estimated displacements are true ones or if they are a consequence of the displacements of the other points (Duchnowski, 2010).

Another filed of interest was the theory of M-estimation. The further properties of the method were analysed considering the theory of equivalent matrices. The method was applied to free geodetic networks (Duchnowski and Wiśniewski, 2007) and free geometric navigation structures (Czaplewski and Wiśniewski, 2007). The M-estimation that accepts asymmetric distributions was developed (Dumalski and Wiśniewski, 2007).

New applications of M-estimation in precise navigation were proposed in cooperation with Polish Naval Academy in Gdynia. The proposed method, namely the Hybrid M-estimation, accepts free geometric navigation structures (Czaplewski and Wiśniewski, 2008). The theory of adjustment of navigation observations with application of deterministic models of measurement errors was also developed.

The other research that was conducted at the Institute of Geodesy of the University of Warmia and Mazury in Olsztyn resulted in the theory of M_{split} estimation. The basics of the method were presented (Wiśniewski, 2008a, 2008b). The main assumption is that an observation may result from a realization of either of two different random variables, different from one another at least in the main characteristics. A quantity that describes the opportunity of identifying a single observation with one random variable is assumed to be known. That quantity, called the elementary split potential, is strictly referred to the amount of information that an observation can provide about two competitive assumptions concerning the observation distribution. Parameter assessments that maximize the global elementary split potential (concerning all observations), are called M_{split} estimators. A generalization of M_{split} estimation (Wiśniewski, 2008b) refers to the theoretical foundation of M-estimation. The reference between M_{split} estimation and the theory of information and further analyses of theoretical as well as practical properties of the method were presented (Wiśniewski, 2009a, 2009b). Recently, a generalization of M_{split} estimation, namely $M_{split(q)}$ estimation, was also proposed. The new method (Wiśniewski, 2010) assumes that a single observation can be identified with one of q functional models that compete with one another. Parameters of the competitive functional models are estimated by maximizing the split potential globally over for the whole observation data set. Additionally, such $M_{split(q)}$ estimates minimize the amount of information that could be provided by other estimates computed for the same observation data set. The method is a certain kind of extension of the maximum likelihood method, and if one considers the generalizations presented in the paper it can also be regarded as the development of M-estimation. The special attention is paid to the squared $M_{split(q)}$ estimation where the objective function is a squared one. If $q = 1$ then the squared $M_{split(q)}$ estimation is equivalent to the least squares method.

The accuracy of estimation results obtained by the method of Least Absolute Deviations (LAD) was analysed at the Institute of Geodesy of the University of Warmia and Mazury in Olsztyn. The LAD method is an alternative adjustment to the Least Squares Method, especially when observation results contain gross errors. One of the factors discouraging the application of the LAD method is its complicated algorithm, which employs the principles of linear programming. It seems that taking into the consideration its interesting properties, mainly the identification of observations suspected of containing gross errors, the method should gain more popularity. The covariance matrices of the vector of parameters and the vector of residuals were derived. Theoretical considerations were verified using an example of a simulated levelling network (Kamiński, 2009a).

The Displacements and Strains using Transformation and Free Adjustment (DiSTFA) method was developed. It enables the determination of displacements and strains of the engineering objects in a situation when there is unstable reference system. The results of the empirical tests indicated that the analysis of the residuals does not clearly show whether the object was displaced or not. In case the interpretation of the estimation results is facilitated by the calculations made with thw use of DiSTFA method. It was shown that the object displacements (horizontal and vertical) can be determined through the determination of the angles differences. The important advantage of the DiSTFA method is the possibility of the detection only the object settlement (Kaminski 2008).

Properties of the accuracy of estimation results obtained by the DiSTFA method in monitoring displacements and strains were investigated. The analysis of the results obtained in the numerical experiments on simulated observations indicates that the parameters of displacements represented by rotation angels determined in different measurement epochs as well as their differences provide information about the stability of the reference system used. It further shows that with the additional parameters the DiSTFA method can also be applied for the determination of the objects' deformation. The DiSTFA method allows the use of the results of the measurements with a single technique for the determination of displacements and deformations in unstable reference systems (Kamiński, 2009b).

1.9.2. Theory of GNSS Data Processing

At the Institute of Geodesy of the University of Warmia and Mazury in Olsztyn there was also conducted an advanced research on the theory of GNSS data processing.

Two new methods of Integer Least Squares Adjustment (ILSA) were developed. First one is based on well known search approach. In this method a new formula of objective function with condition equations (integer constraints) was derived and computational efficiency was improved by optimising a search region (Cellmer, 2008). The second method of ILSA is a Modified Ambiguity Function Approach (MAFA) (Cellmer et al., 2010). The MAFA algorithm ensures the condition of parameter "integerness" without the necessity for the additional stage of the integer search. It is based on the least squares adjustment algorithm with condition equations in the functional model. In order to derive such functional model an appropriate formula for the function of the condition equation was derived. This method was implemented in GPS data processing. Because of relatively weak model of carrier phase data, different linear combinations of L1 and L2 GPS carrier phase observables were applied in the cascade adjustment in order to assure the appropriate convergence of the computational process.

The research on the use of the pseudolites to augment GPS positioning was continued. Differences in functional models of GPS and pseudolite observation equations were considered (Rzepecka et al., 2007). An impact of linearisation process on the results of positioning on the basis of pseudolite's signals was estimated (Cellmer and Rapinski, 2010).

1.9.3. Reliability Analysis and Detection of Outliers

Research on reliability analysis and detection of outliers as well as testing quality analysis for quantifying reliability properties was performed at the Department of Engineering Surveying of the Warsaw University of Technology.

A preliminary attempt was made to formulate some general principles regarding the integration of multi-source data (Prószyński, 2007).

Some improvements and findings were presented, as regards the concept of the vector space of imperceptible observation errors in linear Gauss-Markov models with uncorrelated observations, initially proposed in the earlier work of the author. The gross errors falling into this space pass absolutely undetected through all the possible statistical tests set in the least squares estimation and unnoticeably distort the resulting values of one or more of the model parameters. The relationship was established between the concept of imperceptible gross errors and the concept, proposed by other authors, of the gross errors which can be detected but not identified due to specific properties of a network's structure. Both the concepts are useful in the design of geodetic networks with respect to reliability (Prószyński, 2008).

The Vaniček concept of network robustness to observation gross errors, being a merger of the reliability and strain analysis, has been investigated with respect to basic assumptions and requirements of continuum mechanics. The investigations showed that the main problem in applying the strain analogy to robustness analysis of geodetic networks is their discrete nature (Gambin et al., 2008).

In a proposal of non-tensor replacement for network robustness measures based on strain analogy, the traditional concepts of internal and external reliability are used. The new measures, being node displacements and element deformations as responses to MDB in an individual observation, are applicable to all types of geodetic networks with uncorrelated observations. The proposal provides a direct link between the robustness and the accuracy analysis of a network, and has a clear interpretation in terms of mechanical strength analogy (Prószyński and Parzynski, 2009).

An approach to internal reliability analysis was presented which, compared to existing approaches, offers further insight into the system responses to observation gross errors. The proposed reliability measures are defined on the diagonal and non-diagonal elements of the modified reliability matrix being an oblique projector. The system responses to a single gross error, such as the local, the quasi-global or the global response, are discussed and their consistency with non-correlation case is proved. Also the reliability criteria interpretable in terms of those responses are proposed. An attempt was also made to relate the global responses to reliability numbers that are the basis for determining the magnitude of the minimal detectable bias (MDB). Some differences of the new reliability measures in relation to existing measures were indicated (Prószyński, 2010).

The results of quality analysis testing for quantifying reliability properties show that the Prószyński Reliability Criterion (PRC) is fulfilled if the measurement variance is greater than its prediction function based on the remaining observations (Nowak, 2007). Such prediction function can be interpreted as an observational norm. It has been proven that if the prediction function is within certain limits then a reliable observational system (i.e. each observation fulfils the PRC) can be achieved. These analytical findings have some significant practical consequences, e.g. they can provide not only robust and reliable but also efficient and economically wise engineering observational system.

1.9.4. Theory and Use of Neural Network

Research on approximation abilities of neuro-fuzzy systems and the use of neural network in surveying was performed at the Institute of Structural Engineering of the University of Zielona Gora.

It was indicated that fuzzy logic systems have a particular ability to approximate non-linear multivariable functions because of the possibility of using them in practice. It was also shown that the structure of a fuzzy logic system formed by a set of fuzzy rules, data describing the membership function and the mechanisms of inference and aggregation, and as a result implication, make it possible to deduce the cause and effect connection between the input and output of fuzzy logic systems, which could not be obtained by means of neural networks (Mrówczyńska and Gil, 2009).

The approximation abilities of neural networks and the Wang-Mendel fuzzy logic system were evaluated. The numerical results indicate that the Wang-Mendel fuzzy logic system makes it possible to obtain the smallest generalisation error. It was shown that the minimisation of the energy function, defined as the sum of squares of the differences between the values of the output signals and the values assigned is the optimum criterion in terms of the norm l_2, when the errors of the results of the experiment are in normal distribution. For errors being in Cauchy distribution, the optimum minimisation criterion is the norm l_1, and errors in regular distribution require the norm l_∞ (the Chebyshev norm) (Mrówczyńska, 2009).

The Hopfield neural network was investigated in the aspect of the stabilization of the displacement phenomenon. A dynamic memory with the structure of a Hopfield network, which reproduces remembered associations close to the standards, was used to assess stable points. The state of the Hopfield association memory is characterised by its energy function, which reaches a local minimum in the process of updating the network in the vicinity of the real attractor. Attractors make it possible to analyse the motion of the system, which can by regular or chaotic. However, the minimum number of evolutions while reaching the attractor of change in the difference of height are not enough to determine whether two points maintain stability, because they can be moved parallel to one another. In order to determine the stability of points it is necessary to determine the Lapunov exponents of two neighbouring trajectories of changes in the difference of height. It was shown that the stability of points in a measurement-control geodetic network or the parallel displacement of points can be assessed on the basis of the number of time evolutions while changes in height reach the attractors with a predetermined accuracy, Lapunov exponents or the analysis of the value changes in height (Gil and Mrówczyńska, 2007).

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2. GRAVITY FIELD MODELLING AND GRAVIMETRY2[2]

2.1. INTRODUCTION

This part of the Polish National Report on Geodesy is the quadrennial report on research activity concerning gravity field modelling and gravimetric works performed in Poland in a period of 2007–2010. It contains a summary of the results of activities concerning theoretical research on gravity field modelling, geoid modelling in Poland, evaluation of geopotential models, absolute gravity surveys in Poland and overseas, maintenance of gravimetric calibration baselines, investigations of the non-tidal gravity changes, and the use of satellite gravity space missions. Those activities were conducted mainly at the following research centres listed in an alphabetic order:

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

The extensive information on the activities concerning gravity field modelling and gravimetric works performed in Poland within the reported period are contained in the annual national reports to the IAG Sub-commission for EUREF (Krynski and Rogowski, 2007, 2008, 2009, 2010).

The bibliography of the related works is given in references.

2.2. GEOID MODELLING AND STUDY ON THE GRAVITY FIELD IN POLAND

An extensive activity in the field of modelling precise geoid in Poland and quality assessment of geoid models developed was continued at the Institute of Geodesy and Cartography, Warsaw, and the University of Warmia and Mazury, Olsztyn. It concerned, in particular the assessment of the quality the existing data that might be used to geoid modelling, the determination of terrain corrections, evaluation of the EGM2008 with the use of GPS/levelling and gravity data as well as existing geoid models, and developing new geoid models with the use of deflections of the vertical. Also the implementation of long, medium and short wave components of the signals of functionals of the disturbing potential in the process of modelling geoid was investigated (Kloch and Krynski, 2008d).

2.2.1. Data Quality Investigations

Quality of both gravity and height data, besides of data resolution is one of major components of determining the quality of geoid model developed at the Institute of Geodesy and Cartography, Warsaw.

The methodology of quality assessment of height data used for precise geoid modelling was developed to make use of all kinds of relevant available data. It was verified with the use

[2] The content of the chapter was compiled by **Marcin Barlik** with the use of the material provided by Marcin Barlik, Janusz Bogusz, Jan Krynski, Marek Kaczorowski, Adam Lyszkowicz, Marcin Rajner. Marek Trojanowicz, Janusz Walo, and Janusz Zielinski.

of data from Poland consisting of heights, positions, gravity and point Bouguer anomalies at the gravity points from the gravity database, DTED2 and SRTM3 DTMs as well as a number of topographic maps. The results obtained indicate not only the importance but also the necessity of quality assessment of height data used for precise geoid modelling. Although it directly concerns heights but indirectly it also concerns positions of gravity points from the gravity database as well as gravity that might have been acquired by a few generations of surveyors over a few decades. DTMs and in some cases topographic maps are as well important components of such quality assessment. The results of numerical tests performed indicate the efficiency of complex analysis based on the methodology developed and its usefulness. The developed procedures of repairing both heights and coordinates of gravity points due to gross errors seem quite reliable. Classification of gravity points in terms of their height accuracy treated as the integrated representative of quality of height, position and gravity, resulting from the complex analysis performed is highly reliable. The analysis based on the methodology developed results in particular in efficient and reliable detection of outliers (Kloch and Krynski, 2008a).

2.2.2. Determination of Terrain Corrections

Modelling geoid at centimetre level of accuracy requires high precision in terrain corrections determination. To model a precise geoid terrain corrections should be applied to surveyed gravity not only at gravity stations located in rough topography regions but also in almost flat areas.

Quality of terrain corrections „1992" (Krynski, 2007b) calculated for 27% of gravity stations in Poland using terrain slopes data surveyed in the vicinity of each gravity point (inner zone) and data from topographic maps (middle and outer zone) within the radius of 22.5 km was investigated at the Institute of Geodesy and Cartography, Warsaw. With few exceptions, only the final values of terrain corrections „1992", i.e. the total contributions of all three zones are available. Low resolution of height data used, limitation of the maximum radius of terrain correction computation to 22.5 km around gravity station, the use of different algorithms and probably different standards substantially affect the quality of terrain corrections „1992". Quality estimate of „1992" terrain corrections and the analysis of their use for the computation of terrain corrections in Poland that fulfil the requirements of centimetre geoid was performed with the use of the survived data records. The records contain the contributions of the inner, middle and outer zone to terrain corrections for 3327 gravity stations in Babia Gora area (gravity survey in Western Carpathians 1975) (Kloch and Krynski, 2007b).

Research on the optimisation of the strategy of the determination of terrain corrections in Poland with the use of prism method was conducted. It concerned the choice of heights of gravity stations (surveyed ones or obtained from DTM), the determination of the optimum radius of the integration cap when using both planar and spherical approaches, the issues of negative terrain corrections and convergence of terrain corrections with growing distance from the gravity station (Kloch and Krynski, 2007a). The strategy developed has been verified in 5 representative test areas in Poland using heights of gravity stations from the gravity database for Poland and from digital terrain models (DTMs) DTED2 as well as SRTM3 (Kloch and Krynski, 2008b, 2008c).

The effect of uncertainty in height and position of gravity points as well as uncertainty of DTM on the accuracy of computed terrain corrections was extensively investigated at the Institute of Geodesy and Cartography, Warsaw (Szelachowska and Krynski, 2009a). Analytical formulae for the respective error propagation were developed and they were supported, when needed, by numerical evaluations. Propagation of height data errors on calculated terrain corrections was independently conducted purely numerically. Numerical calculations were performed with the use of data from gravity database for Poland and digital terrain models DTED2 and SRTM3. The results obtained using analytical estimation are compatible with the respective ones obtained using pure numerical estimation. The results of numerical tests supported by analytical estimations enable to conduct the estimation of error propagation of input data on terrain corrections for Poland. The results of the investigations are presented in Table 2.2.2 (Szelachowska and Krynski, 2009b).

Table 2.2.2. The effect of the input data errors on terrain correction errors for Poland

Data error	Terrain correction error [mGal]
Error of the height of a gravity station (2÷7 m)	0.2÷0.9
Error of the height of a DTM (50 m)	0.3÷0.8
Error of the horizontal position of a gravity station (2÷7 m)	0.0÷0.3
Error of the horizontal position of a DTM (15 m)	0.0÷0.2

It has been shown that the estimated accuracy of terrain corrections computed using height data available for Poland is sufficient to model gravimetric geoid with a centimetre accuracy (Szelachowska and Krynski, 2009b).

2.2.3. Evaluation of the EGM2008

The development of the Earth Gravitational Model EGM2008 of unprecedented resolution and accuracy, provides powerful and more reliable tools for evaluating regional geoid models as well as vertical components of GPS/levelling sites. Almost immediately after being publicly released, the EGM2008 model became a subject of extensive investigations by numerous research groups, starting with its evaluation.

The performance of the new global geopotential model (GGM) EGM2008, over Poland, has been evaluated at the Institute of Geodesy and Cartography, Warsaw, and at the University of Warmia and Mazury, Olsztyn. The tide-free release of the EGM2008 model was also used for the assessment of quality of three precise quasigeoid models developed in the last decade in Poland. The EGM2008 model was compared with precise GPS/levelling (Krynski and Kloch, 2009; Lyszkowicz, 2009) as well as regional gravimetric quasigeoid models (Krynski and Kloch, 2009).

The investigation of the performance of the EGM2008 indicates remarkably good fit of EGM2008 to the gravity field over Poland. It should be noted, however, that the model was developed with the use of recently determined 5' × 5' free-air gravity anomalies from Poland. Two independent studies were simultaneously performed. First evaluation (Krynski and Kloch, 2009) was based on the heights of more than 1000 GPS/levelling sites (342 POLREF, 58 EUVN, 524 WSSG, and 184 GPS/levelling control traverse established in 2003-2004 by the Institute of Geodesy and Cartography, Warsaw, for evaluating geoid models) as well as regional quasigeoid models. In the second one (Lyszkowicz, 2009) more than 400 GPS/levelling sites (360 POLREF, and 43 GPS/levelling control traverse) as well as regional quasigeoid models were applied.

The fit of height anomalies calculated from EGM2008 to GPS/levelling heights in Poland is almost as good as the height anomalies from best regional quasigeoid models available. The example of the fit of EGM2008 to two local quasigeoid models: GDQ08 (quasigeoid model, developed for Poland using remove-compute-restore method with EGM2008 on the basis of the uniform gravity data including the existing deflections of the vertical), and GUGiK 2001 (the official quasigeoid model in Poland recommended by the Head Office of Geodesy and Cartography for surveying with the use of GNSS techniques) is shown in Table 2.2.3 and Figure 2.2.3 (Krynski and Kloch, 2009).

Table 2.2.3. Statistics of differences of height anomalies obtained for investigated grids [m]

Number of grid points	Statistics	$\zeta_{EGM2008} - \zeta_{GDQ08}$	$\zeta_{EGM2008} - \zeta_{GUGiK\ 2001}$
32 781	Min	–0.008	–0.164
	Max	0.130	0.275
	Mean	0.057	–0.039
	Std dev.	0.017	0.028
	Dispersion	0.138	0.438

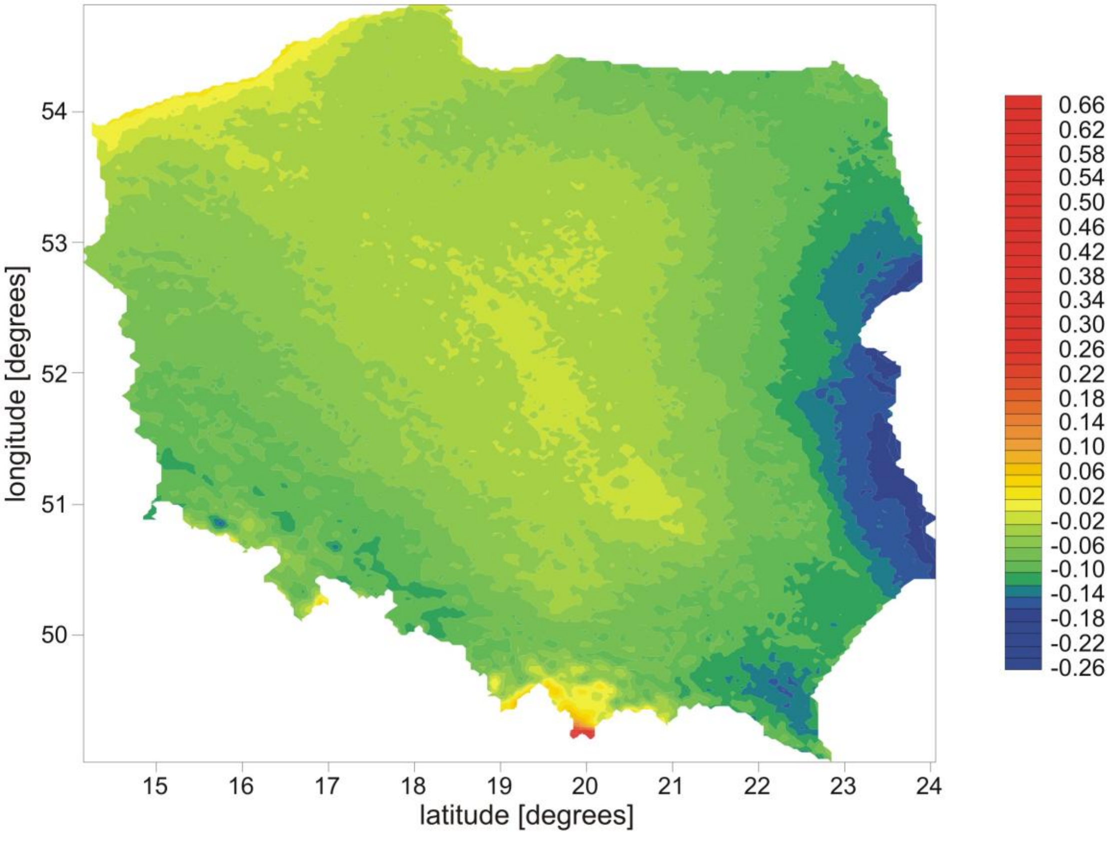

Fig. 2.2.3. Map of differences of height anomalies $\zeta_{EGM2008} - \zeta_{GUGiK2001}$

The results obtained confirm high quality of quasigeoid models in Poland. They are in agreement with the previous estimate of their accuracy. EGM2008-based quasigeoid model was also used to detect outlying GPS/levelling heights in the data set used for the assessment of quality of gravimetric quasigeoid models in Poland (Krynski and Kloch, 2009). The results reveal that EGM2008 offers a major improvement (more than 80%) in the agreement level among height anomalies, ellipsoidal and normal heights over the area of Poland, compared to the performance of previous combined geopotential models, e.g. EGM96 for the same area.

The performance of the global geopotential models EGM96 as well as EGM2008 has been evaluated over Lower Silesia, at the Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences, with the use of gravity disturbances at 92 546 gravity points, and height anomalies at 29 sites of the POLREF network (Trojanowicz, 2009). The results obtained confirmed superior accuracy of the EGM2008; standard deviation of residual height anomalies equals to 16 cm for EGM96 and 2.8 cm for EGM2008, while standard deviation of gravity disturbances equals to 14.3 mGal for EGM96 and 6.6 mGal for EGM2008.

2.2.4. Geoid Modelling

Research initiated in the framework of the project on the determination of geoid model in Poland at centimetre level of accuracy (Krynski et al., 2007; Krynski and Rogowski, 2007) conducted in 2002–2005 has been continued at the Institute of Geodesy and Cartography, Warsaw, the University of Warmia and Mazury, Olsztyn (Krynski, 2007a, 2007b, 2007c) as well as at the Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences.

An extensive study was conducted to improve the astro-gravimetric geoid model in Poland by improving the procedure of astro-gravimetric geoid modelling and by using improved data (Lyszkowicz and Krynski, 2008). Accuracy of the components of the deflections of the vertical was estimated and the weights of astro-geodetic and astro-gravimetric deflections of the vertical were determined. Astro-geodetic and astro-gravimetric geoid models were determined from archival deflections of the vertical with the use of astronomical levelling. Other astro-geodetic and astro-gravimetric geoid models were calculated by least squares collocation with the use of gravity anomalies instead of archival astro-gravimetric deflections of the vertical. Computed geoid models were mutually compared. They were also compared with the GPS/levelling geoid spanned on the sites of the POLREF network as well as with 2005 astro-gravimetric geoid model. The results obtained (Fig. 2.2.4) indicate that both astro-geodetic geoid and astro-gravimetric geoid determined from the same input data using least squares collocation approach are by factor 5 to 7 more accurate than the respective ones obtained using classical astronomical levelling. Both astro-geodetic and astro-gravimetric geoid models developed with the use of least squares collocation approach are thus substantially improved as compared with the existing models developed on the basis of astronomical levelling algorithm (Lyszkowicz and Krynski, 2008). The improvement of pure gravimetric quasigeoid model by simultaneous use of deflections of the vertical with gravity data for modelling quasigeoid was shown when using least squares collocation (Lyszkowicz et al., 2009).

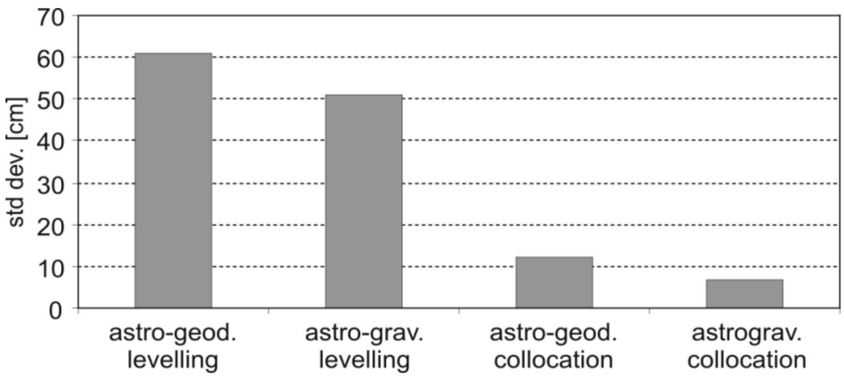

Fig. 2.2.4. External accuracy of astro-geodetic and astro-gravimetric geoid models developed, represented by the standard deviation of their fit to the GPS/levelling geoid at the sites of the POLREF network

A method of modelling quasigeoid on local scale, that uses the gravity inverse approach, was developed (Trojanowicz, 2007). In the method, the disturbing potential modelled consist of three components: the potential T_{Ω} generated by topographic masses Ω laying above the geoid, with density distribution function ρ, the potential T_{κ} generated by disturbing masses κ occurring under the geoid surface, with density distribution function δ, and the potential T_{γ} which represents the remaining effects and is approximated by harmonic polynomials of low degree. The parameters of the model are functions of density distribution ρ and δ inside the defined regions Ω and κ, and polynomial coefficients of T_{γ}. The method applied to different test areas (Trojanowicz, 2007, 2008b) demonstrates high accuracy of local quasigeoid models determined with the use of local data; it was at the level of 1.5÷2.0 cm, i.e. within the range of accuracy of the used GNSS/levelling test data. Due to a small edge effect the method can be applied to small areas only, using gravity data only from a region, for which quasigeoid model is to be determined, as well as from its closest surrounding. As compared to classical integral methods, the approach requires less gravity data and a lower resolution DTM (Trojanowicz, 2007, 2008b). The shortcoming of the method is the need of using GNSS/levelling height anomalies.

The importance of gravity data, DTM and global geopotential model EGM96 in quasigeoid height interpolation was examined. The effects of the omission of DTM, gravity data and GGM in the interpolation procedure were estimated (Trojanowicz, 2008a). Test calculations were performed in mountainous, mountains foreland and low-land areas of Lower Silesia. The results obtained indicate that the omission of each of those data sets affects significantly the accuracy of the interpolation of height anomaly, even in low-land area.

2.3. ABSOLUTE GRAVITY SURVEYS

2.3.1. Absolute Gravity Surveys for the Maintenance of National Gravity Control in Poland

The joint team of the Institute of Geodesy and Cartography, Warsaw, and the Warsaw University of Technology conducted an extensive research on the modernization of the Polish national gravity control (Krynski and Rogowski, 2007). The project concerning the densification of the absolute gravity network and the modernization of two meridional gravimetric calibration baselines for relative measurements was conducted in 2006–2008. 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 difference between the stations will range from 40 to 120 mGal (Fig. 2.3.1). Five new absolute gravity stations were established; they make the distribution of zero-order points of national gravity control network much more homogeneous. Along the Central and Western Gravimetric Calibration Baselines 11 new absolute gravity stations were established (Fig. 2.3.1). The Western Gravimetric Calibration Baseline, besides a longitudinal part contains a newly established Vertical Gravimetric Calibration Baseline in Sudeten Mountains (Krynski and Rogowski, 2009).

The team of the Department of Geodesy and Geodetic Astronomy of the Warsaw University of Technology surveyed absolute gravity with the use of FG5-230 gravimeter with an error not exceeding 3 μGal (Krynski and Rogowski, 2008).

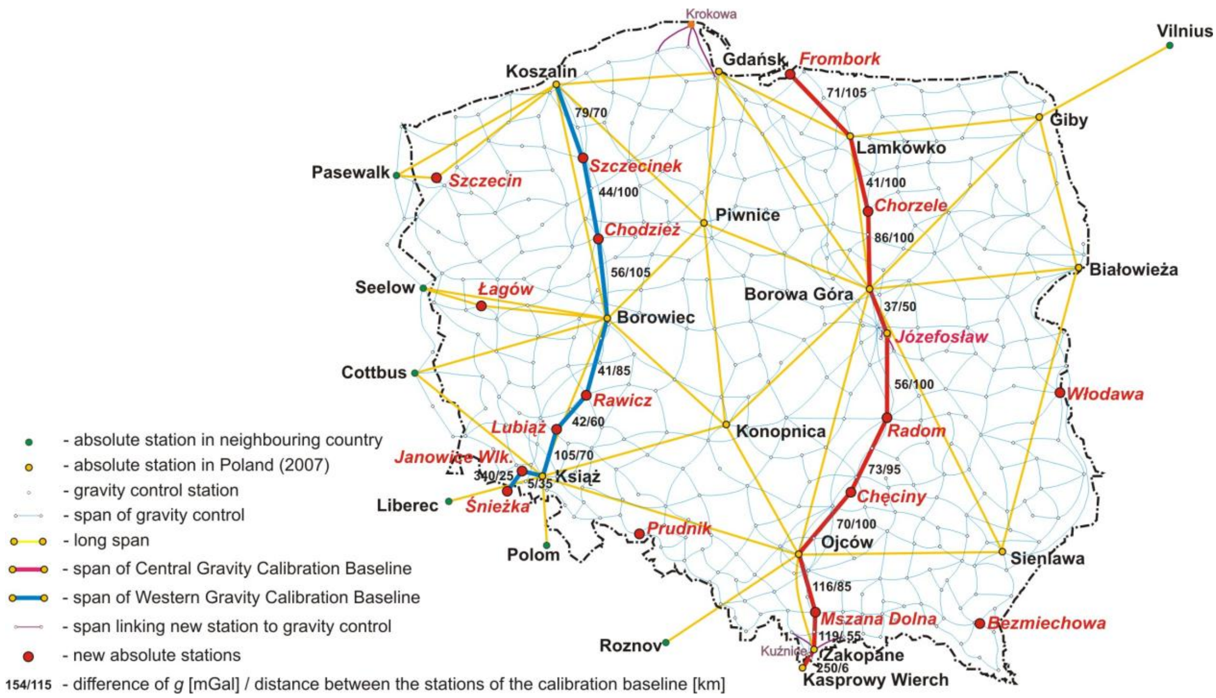

Fig. 2.3.1. Polish Gravimetric Control Network in 2009

2.3.2. Absolute Gravity Surveys for the Maintenance of National Gravity Control in Finland

In 2008 the Institute of Geodesy and Cartography, Warsaw, received the outdoor free-fall gravimeter A10 No 020. Time series of gravity taken with it since September 2008 at the Borowa Gora Geodetic-Geophysical Observatory in Poland show that the A10-020 provides high quality measurements in laboratory as well as in field conditions.

In the framework of scientific cooperation between the Finnish Geodetic Institute and the Institute of Geodesy and Cartography, Warsaw, 51 field sites of the Finnish gravity network (FOGN) (Fig. 2.3.2) were surveyed with the A10-020 gravimeter of the IGiK in four campaigns: one in 2009, and three in 2010 (Kryński and Sękowski, 2010; Sękowski and Krynski, 2010; Kryński and Rogowski, 2010; Mäkinen et al., 2010a, 2010e).

The strategy of the field survey with the A10, developed for absolute gravity survey in the field in Poland, was adopted for surveying the FOGN sites. Two independent setups, rotating the gravimeter by 180° in between, were performed. The single setup is followed by 8 sets with 120 drops each, with 1 second drop interval; it takes only 24 minutes (Mäkinen et al., 2010b). There is practically no time when the gravimeter runs and the team is free to do supporting measurements, e.g. levelling, vertical gradient, a relative tie from an eccentric site, documentation (photos, sketches), GNSS positioning, etc. Practically, with 150 km between stations, only 2 stations per day could be surveyed.

For control, 9 Finnish absolute gravity stations were occupied with the A10-020 altogether 25 times, with a repeatability better than 4 μGal. The results obtained with the A10-020 were compared with the respective ones obtained with the FG5-221 of the FGI. From preliminary computations, the offset of the A10-020 to the FG5-221 of the Finnish Geodetic Institute was negligible and the RMS difference was 3 μGal (Mäkinen et al., 2010c, 2010d, 2010e).

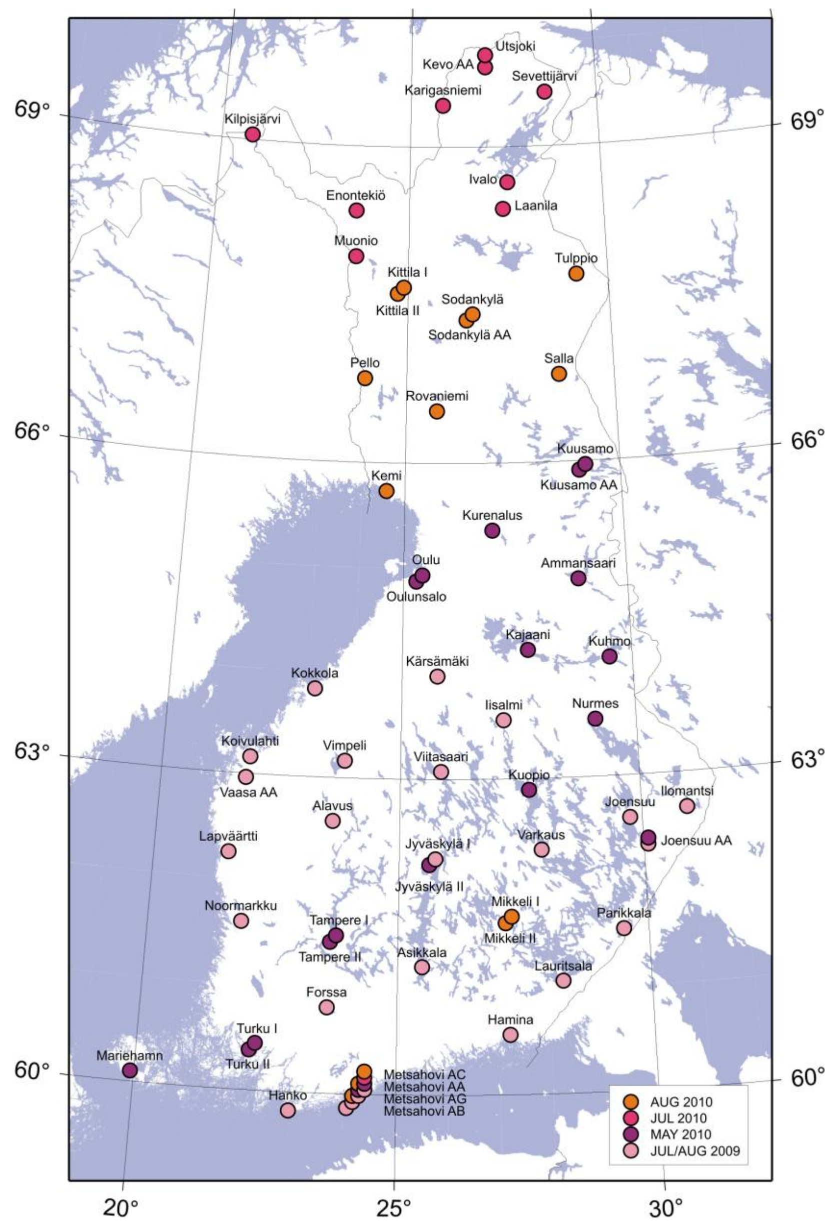

Fig. 2.3.2. Stations of the Finnish Gravity Control Network re-surveyed with the A10-020 in 2009 and 2010; the laboratory-type absolute-gravity sites where comparisons with measurements with the FG5-221 were made have two letters after the name

2.3.3. Absolute Gravity Surveys for Geodynamic Research

Precise absolute gravity measurements have been carried out for geodynamics research since 1990. at five stations in Poland: Borowiec, Giby, Jozefoslaw, Lamkowko, and Ojcow (Barlik et al., 2007, 2009; Krynski and Rogowski, 2008) (Fig. 3.6.2a in Chapter 3).

From 2006 to 2009 the unified gravimetric reference system for the Polish GNSS stations and geodynamic test field was established by the team of the Warsaw University of Technology in the framework of the research project (Olszak et al., 2008; Walo, 2010) with the use of the FG5-230 free-fall gravimeter. It was done with the highest currently available accuracy. All Polish IGS permanent GNSS stations (Borowa Gora, Borowiec, Jozefoslaw, Lamkowko, Wroclaw) as well as one EPN station (Cracow) were included into the project. In addition, seven absolute gravity stations were established in the area of two geodynamic test fields: Pieniny – Tatra Mountains and Sudety Mountains (Fig. 2.3.3a).

Fig. 2.3.3a. Distribution of absolute gravity stations surveyed in the framework of the project

Those stations were located in the buildings close to the GNSS sites so that they are subject to the same tectonic and environmental effects. All stations have a permanent monumentation (concrete pillar) which ensures stability required for absolute gravity measurements. Two eccentric gravity points were selected for each of those stations outside the building. The position and height of the sites were determined in current geodetic datum (position accuracy of 0.5 m) and vertical datum (normal height accuracy of 2÷5 cm) using GPS and total station as well as precise levelling, respectively.

The LCR-G gravimeter was used to determine vertical gravity gradients at the stations of absolute gravity measurements as well as gravity at eccentric points by linking them to the sites of national gravity control. The gradient was calculated from the measurements conducted at two altitudes: one corresponding to the location of the meter directly on the monumented site and the other at height of about 1.30 m above the monument (close to the altitude of measured gravity with the FG5).

Absolute gravity was measured using the FG5-230 in 24h observation sessions. The observations were performed in 1h intervals, 100 drops in each series, totally about 2400 drops. The final gravity value was calculated taking into account the following corrections: effect of Earth's and oceans tides (ET GTAB procedure), atmospheric air pressure effects, polar motion influence, decrease of gravitational acceleration due to the actual vertical gravity gradient. RMS at the level of 2÷3 μGal represents the accuracy of gravity value determined.

In 2007, frequency of gravimeter's rubidium clock was calibrated by Central Office of Measures in Warsaw. To assure the reliable standard of gravity measurements the FG5-230 participated in the campaign of the European Comparison of Absolute Gravimeters (ECAG) at Walferdange, Luxembourg, in 2007 (Francis et al., 2008). The reference level for FG5-230 system comparing to ECAG 2007 level differs by +0.1 μGal only (Fig. 2.3.3b). This correction was thus not applied to the surveyed gravity value.

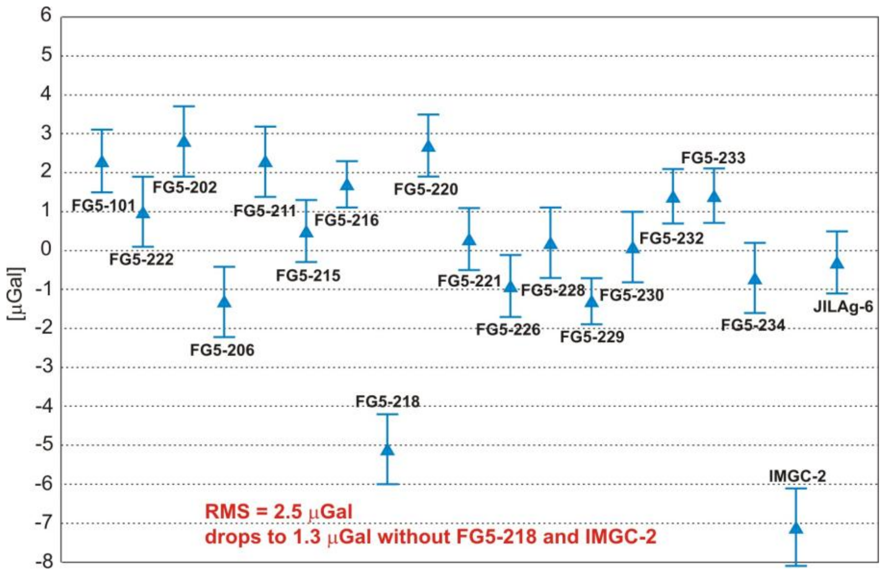

Fig. 2.3.3b. Results of the European Comparison of Absolute Gravimeters (ECAG) at Walferdange, Luxembourg, in 2007

In the period of 2006–2009 gravity slightly decreased at two sites: from 2 µGal in Jozefoslaw to 2÷3 µGal in Borowiec, and increased at two other sites: from 1.2 µGal in Lamkowko to 4.5 µGal in Cracow. Taking into consideration the mean error of ±2 µGal in gravity determination with the FG5, the gravity changes observed do not exceed the limit errors. The gravity values, obtained from two measuring epochs, should thus be treated as initial values for further studies.

2.4. MAINTENANCE OF GRAVIMETRIC CALIBRATION BASELINES IN POLAND

A gravimetric calibration baseline is a crucial element of the gravimetric control network, which currently consists mainly of points where gravity has been determined using absolute measurements. It enables the gravimetric unit to be transferred to the entire control network, and thus to all the gravimetric points tied to that network. This means that such a calibration baseline should cover the gravity range of the whole territory of the country in which it is used.

For each newly established absolute gravity station of gravity network and of gravimetric calibration baseline within the project of modernisation of national gravity control network in 2006–2008, two eccentric gravity points were established; they were interconnected by relative gravity measurements with the precision not worse than 15 µGal. New absolute gravity points together with their eccentric points have also been linked with precise relative gravity survey to the stations of the fundamental gravity control network by the specialists of the Institute of Geodesy and Cartography, Warsaw, with the use of a set of LCR-G gravimeters (Krynski and Rogowski, 2008).

The idea of an alpine baseline in Poland's Tatra Mountains originated in 1950. The first stage of the project on the establishing such gravimetric calibration baseline Zakopane – Kasprowy Wierch was carried on by the team of the Institute of Geodesy and Cartography, Warsaw, in 1999–2004, with the full acceptance and support of Poland's Head Office for Geodesy and Cartography (Sas and Cisak, 2007) (Fig. 2.4.1). On both ends of the baseline (Zakopane and Kasprowy Wierch) the absolute gravity measurements with a very high accuracy (±3 μGal) have been performed. Between them three intermediate points have also been established and surveyed using spring gravimeters.

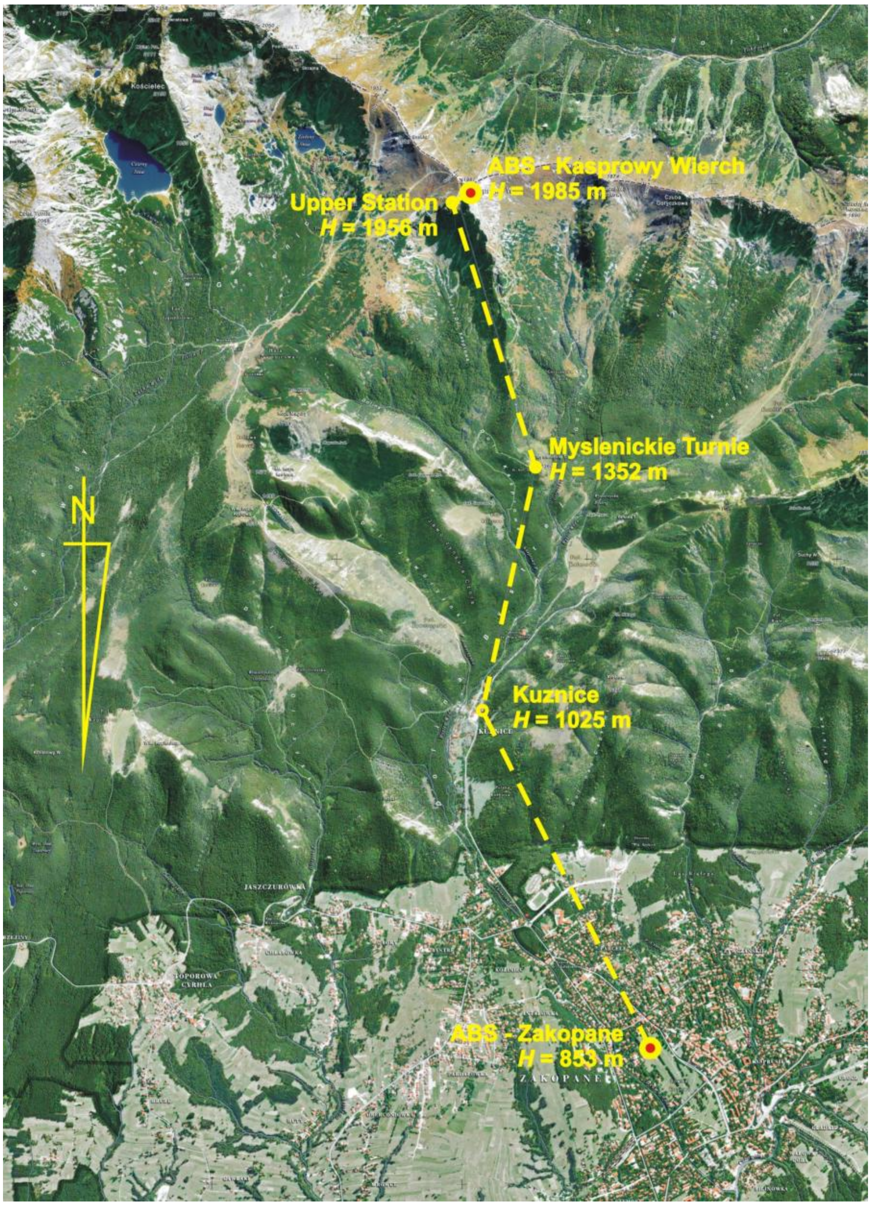

Fig. 2.4.1. Alpine calibration baseline marked on a tourist photomap of the Polish Tatra Mountains in scale 1:20 000, developed at the Institute of Geodesy and Cartography, Warsaw, 2002 (Drachal)

The baseline was established in response to the recent rise in geodynamic research in mountainous areas and the related need to calibrate the gravimetric scale used in gravimetric works requiring a high degree of accuracy. A methodology for performing static gravimeter calibration on that baseline has been developed. The impact which rapid changes in atmospheric pressure and environmental temperature may exert on the performance of gravimeters used in such survey was investigated. It was also important to study how the method by which the instruments were transported (by automobile, cable car, or on foot) affected their performance. Works on the Vertical Gravimetric Calibration Baseline in Tatra Mountains, which is an extension of the Central Gravimetric Calibration Baseline in Poland, were completed with formulating recommendations describing how to proceed with scaling the gravimeters on such a baseline (Sas et al., 2009).

2.5. INVESTIGATIONS OF NON-TIDAL GRAVITY CHANGES

Gravity field variations by the use of terrestrial geodetic methods were extensively investigated. Combination of the AG with the SG data as well as the results of repeated gravity survey were analysed (Barlik and Krynski, 2008).

2.5.1. Absolute Gravity Surveys in Gravimetric Laboratories

The joint laboratory for the regional absolute gravimeters comparison campaigns in Poland: Borowa Gora Geodetic-Geophysical Observatory (Institute of Geodesy and Cartography, Warsaw) and Jozefoslaw Astro-Geodetic Observatory (Warsaw University of Technology) was set up (Krynski and Barlik, 2007). Four ballistic gravimeters can simultaneously be compared at each of those observatories.

2.5.1.1. Absolute Gravity Surveys in Borowa Gora

Since September 2008 the Institute of Geodesy and Cartography, Warsaw uses its absolute ballistic A10-020 portable gravimeter (Krynski and Rogowski, 2009). A series of absolute gravity measurements at the gravimetric laboratory of the Borowa Gora Geodetic-Geophysical Observatory (Fig. 2.5.1a, Table 2.5.1a) as compared with those obtained with the JILAg-5 and four different FG5 gravimeters within last 15 years shows high quality of A10-020 data (Kryński and Sękowski, 2010; Sękowski and Krynski, 2010; Mäkinen et al., 2010e). Red line in Figure 2.5.1a corresponds to average of all *g* determinations using the A10-020.

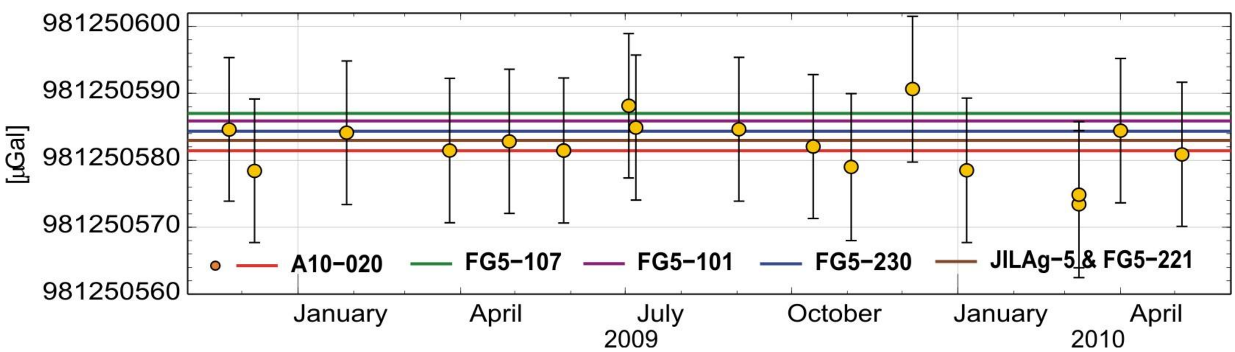

Fig. 2.5.1a. Results of absolute gravity measurements with the A10-020 at Borowa Gora laboratory station

Table 2.5.1a. Statistics of measurements with the A10-020 at Borowa Gora laboratory station [μGal]

No of observations	Max – Min	Std Dev.	RMS	Offset
27	20.6	4.5	5.6	–3.4

High quality of the results obtained with the A10 indicates its potentiality for monitoring non-tidal gravity variations (Krynski, 2009; Krynski and Roguski, 2009).

Absolute gravity has also been systematically measured with the A10-020 at the field station 156 Borowa Gora of the Polish Gravity Control Network (POGK97). The results obtained were compared with gravity value (LCR) – blue line – obtained from the adjustment of the POGK97 (Fig. 2.5.1b, Table 2.5.1b) (Mäkinen et al., 2010e). Red line in Figure 2.5.1b corresponds to average of all *g* determinations using the A10-020.

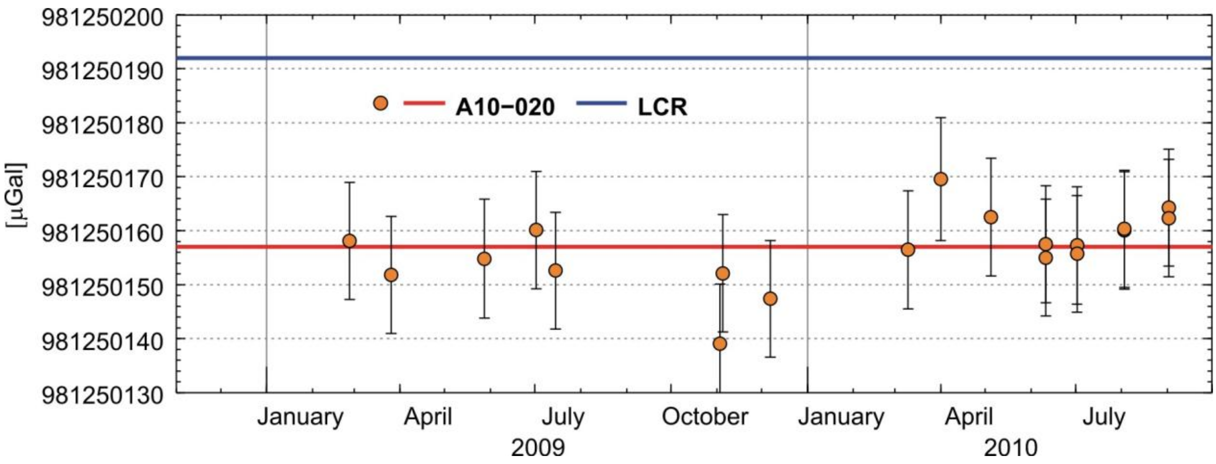

Fig. 2.5.1b. Results of absolute gravity measurements with the A10-020 at Borowa Gora field station

Table 2.5.1b. Statistics of measurements with the A10-020 at Borowa Gora field station [µGal]

No of observations	Max – Min	Std Dev.	RMS	Offset
20	30.5	6.7	6.6	–35.6

The dispersion of gravity surveyed with the A10 at the field station (Table 2.5.1b) is substantially larger than the one obtained for gravity surveyed in the laboratory (Table 2.5.1a). The offset of gravity determined at the field station 156 Borowa Gora with respect to the gravity value obtained from the adjustment of the POGK97 seems large when considering the accuracy of adjusted gravity of the POGK97 station estimated equals 10 µGal. It indicates the need for further modernisation of the existing gravity control in Poland (Kryński and Sękowski, 2010; Sękowski and Krynski, 2010).

Mobile gravimetric laboratory has been set up at the Institute of Geodesy and Cartography, Warsaw, for field measurements with the A10-020 gravimeter (Fig. 2.5.1c). The VW Transporter has been adapted for such laboratory. The A10 gravimeter is transported in two special boxes, together with the complete infrastructure of the measuring system. An additional equipment, such as a tent for protecting the A10 against external weather conditions during field measurements has been developed.

Fig. 2.5.1c. Field survey with the A10-020 using mobile gravimetric laboratory

The absolute gravimeter A10-020 took part in the in the Pilot Study of the International Comparison of Absolute Gravimeters ICAG2009 at BIPM in Paris (Kryński and Sękowski, 2010; Sękowski and Krynski, 2010). The results show that both precision and repeatability of the A10-020 data are almost as good as the ones of the FG5 data.

2.5.1.2. Absolute Gravity Surveys in Jozefoslaw

Since June 2005 the Department of Geodesy and Geodetic Astronomy of the Warsaw University of Technology uses its absolute ballistic (non-symmetrical, Micro-g Solutions) FG5-230 free-fall gravimeter (Krynski and Rogowski, 2007). At the Jozefoslaw Astro-Geodetic Observatory the special stand was built in gravimetric laboratory, in the Observatory basement, at 6 m depth, mostly to avoid microseismses, for permanent gravity observations and also for comparison absolute gravimeters. The results of absolute measurements of gravity with the FG5-230 gravimeter in the Jozefoslaw Observatory obtained since 2005 are presented in Figure 2.5.1d.

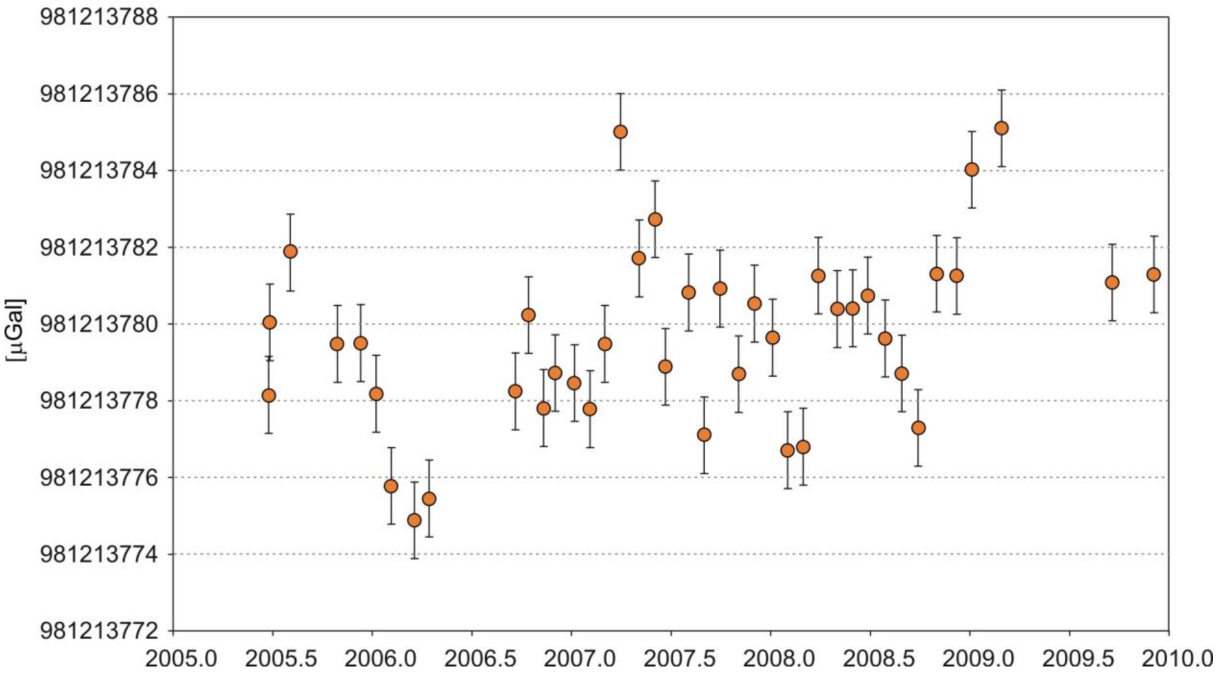

Fig. 2.5.1d. Results of absolute gravity determinations at Jozefoslaw

Time series of monthly absolute gravity survey at Jozefoslaw station, over five years, indicates quasi-periodic non-tidal variations. Obtained values show linear trend of +0.43 µGal/year and long wave (ca. 750 days) with 1.43 µGal amplitude for sine curve fitting. Once the environmental effects of local water table level and soil moisture changes are removed the linear trend reduces to 0.38 µGal/year and shorter harmonic wave to a period of ca. 270÷300 days and 1.06 µGal amplitude (Barlik et al., 2010). A substantial component of those changes can be interpreted in terms of gravitational effect of global hydrology changes as well as an influence of the ground water level changes in a vicinity of Observatory building (Rogowski et al., 2010). As compared with the absolute gravity determinations from 1990. using Polish ZZG ballistic gravimeter as well as IMGC, JILAg-5, JILAg-6, FG5-101, FG5-206, the decrease of the average value of the absolute gravity at Jozefoslaw over the period 2006–2009 by 9 µGal has been noted (Barlik et al. 2009).

The FG5-230 gravimeter took part in the European Comparison of Absolute Gravimeters campaign in November 2007 in Luxembourg as well as in the Pilot Study of the International Comparison of Absolute Gravimeters ICAG2009 at BIPM in Paris. In both cases the analysis of the results shows that the data obtained with the FG5-230 are of high quality. The gravimeter offset did not exceed 1.5 μGal in comparison with average value of gravity computed for all absolute gravimeters taking a part in those campaigns.

Since 2002 gravity data were also recorded at the Jozefoslaw Observatory with LCR ET-26 tidal gravimeter. Both gravimeters, the absolute and the relative one, in connection with JOZE permanent GNSS station provide a unique data for the investigation of geodynamic and geophysical phenomena on a regional scale of Poland (Bogusz and Klek, 2008a, 2008b; Barlik et al., 2009).

Continuous gravity measurements with LCR ET-26 gravimeter in Jozefoslaw Observatory from last three years were analysed (Rajner, 2010). Tidal gravity parameters in diurnal and semi-diurnal bands were computed using international standard data processing techniques. Accuracy as well as variation in time of tidal gravity parameters were evaluated. Long series of consistent data allowed to investigate ocean loading effects in relatively weak signals of gravity changes. Good agreement was found between measurements and ocean loading computed using most recent ocean models.

Gravity values obtained in Jozefoslaw Observatory using the FG5-230 were used for calibration the LCR ET-26 spring gravimeter (Bogusz and Klek, 2008a, 2008b; Rajner and Olszak, 2010). Different computational approaches were analysed using almost 30 parallel measurements of spring and FG5 gravimeters (Rajner and Olszak, 2010).

2.5.2. Investigations of Irregular Effects of Tilting of Foundation on the Basis of Measurements of Long Water-Tubes and Horizontal Pendulums in the Geodynamic Laboratory in Ksiaz

Since 2003, in the Geodynamic Laboratory of the Space Research Centre of the Polish Academy of Sciences in Ksiaz, the plumb line variations are monitored with a system of long water-tubes (WT). The WT tilt-meters allow to determine plumb line variations with internal resolution better than 10^{-2} mas for several dozen meters long tubes. Such high resolution, lack of instrumental drift in case of application of differential method for data reduction as well as other advantages, make possible to investigate non-tidal gravity signals.

The measurements carried out in 2004–2007 with the long water-tube tilt-meter contained five epochs of strong (>100 mas) non-tidal signals (Kaczorowski, 2007, 2008) (Table 2.5.2). Such strong signals occurred in the autumn-winter and winter-spring transition periods as well as in the middle of summer in July 2006. Large non-tidal signals recorded with WT and pendulums tilt-meters cannot be simply explained by local effects such as pressure or temperature variations in the underground laboratory. It is very difficult, maybe impossible, to show any mechanism of generation of several weeks lasting air pressure gradient in laboratory, as well as to explain a mechanism of simultaneous decreasing and increasing pressure at opposite ends of the gallery. In addition, observations of water-tube and observations carried out with horizontal pendulums also contain strong non-tidal signals (Kaczorowski, 2009b). Small size of pendulums, their construction and location in underground, exclude the temperature and pressure effects as reason of strong non-tidal signals. On the basis of previous experiences one can conclude that large non-tidal signals exceeding 100 mas are neither of instrumental nor of atmospheric origin.

First suggestion of the existence of non-tidal effect comes from measurements carried on earlier with quartz horizontal pendulums. From 1973 to 2002 almost every year one or two epochs of unstable work of pendulums associated with rapid (several days) variations of azimuths of equilibrium were observed. Substantial differences between pendulums and WT tilt-meters as well as detected correlation of signals re-iterated by both instruments confirmed the thesis that large signals observed are of geodynamic, not of instrumental origin.

Table 2.5.2. The strongest non-tidal signals determined with differential method from channels 1-2 and 3-4 (1,2,3,4 – numbers of channels) in 2004–2007; since September 2007 strong signals have not been recorded

Periods of strong signals and days of duration			Azimuths and amplitudes of phenomena in [mas]		Mean velocity of plumb line variations [mas/day]		Resultant azimuth of plumb line variations
From	To	Number of days	Tube 1-2 –121.4 (58°.6)	Tube 3-4 –31.4 (148°.6)	Tube 1-2	Tube 3-4	
17 Nov 2004	13 Dec 2004	26	60	No data	2.31	No data	No data
11 Mar 2005	28 Mar 2005	17	45	–140	2.64	–8.24	–13°
16 Dec 2005	09 Jan 2006	23	56	–131	2.43	–5.70	–8°
24 Mar 2006	14 Apr 2006	20	–156	–290	–7.80	–14.50	–3°
28 Jul 2006	18 Aug 2006	20	–109	–350	–5.45	–17.50	–13°

Plot of strong non-tidal signals shown in Figure 2.5.2 is very similar to other plots of strong events given in Table 2.5.2.

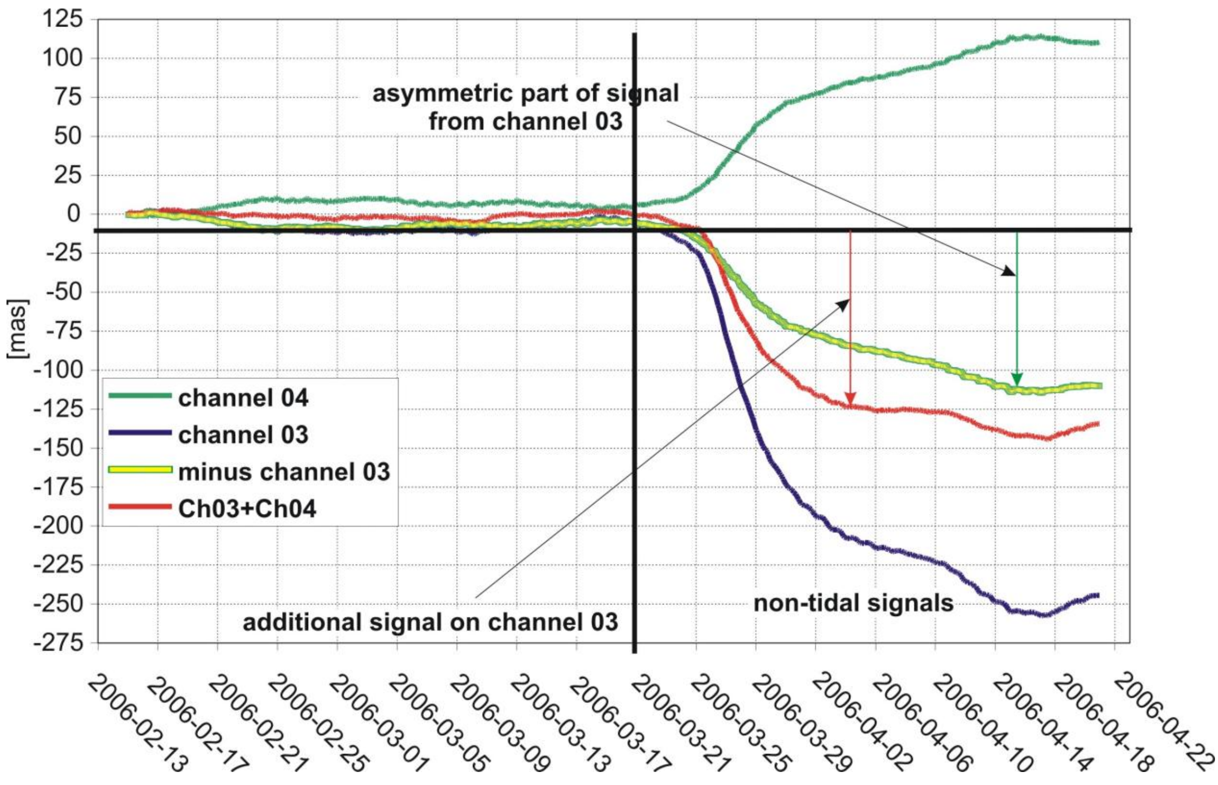

Fig. 2.5.2. Non-tidal signals observed by tube 03-04 in March 2006 in azimuth 148.6 (event 4th)
after the elimination of tidal and evaporation signals

It should be noted that after reducing the tidal and evaporation signals initial parts of plots become almost exactly horizontal while their following parts are partially mirror-symmetric.

The signal from channel 03 consists of mirror-symmetric signal to channel 04 and residual signal. It means that the observed decrease of water level on measuring platform 03 is larger than the increase of water level on platform 04. Mirror – symmetric part of water level variations describes the effect of tilting of whole orogen (whole foundation of the instrument) while the residual part of signals is associated with the effect of additional lowering of platform 03 in relation to platform 04 of about 0.03 mm. Residual signals take place only when strong tilting signals occur. During tidal or Earth's free oscillations no asymmetry between registration from 03 and 04 gauges was observed. The orogen in which Ksiaz Laboratory is situated is divided by about 20 cm wide layer of discontinuity built with not glued sand. That layer crosses both tubes 01-02 and 03-04 of WT instrument. It is quite probable (Kaczorowski, 2009a) that additional displacements of gauges 01 and 03 in relation to gauges 02 and 04 take place on this layer. Resultant azimuths of tilts effects, presented in Tab. 2.5.2, are close to N-S direction; obtained residual signals indicate tectonic reason of clinometric effects observed in Ksiaz Laboratory. It is a subject of the actual investigations

2.6. SATELLITE GRAVITY SPACE MISSIONS

Data from the GRACE mission provide information on time variations of the gravity field, that can be interpreted in terms of time variations of geoid heights, sea level, ice cap thickness and inland water distribution with unprecedented temporal resolution. To achieve, however, accurate and reliable results (variations of geoid heights, hydrology, etc.) it requires the use of a method that suits to the goal and scale of investigations (global, regional, local). Geopotential models developed from GRACE data at different computation centres, i.e. CSR, GFZ, JPL, GRGS were analysed at the Institute of Geodesy and Cartography, Warsaw, in terms of their best suitability for the determination of time variations of the gravity field. The effect of filtering method on the calculated results was investigated. Also the usefulness of the available hydrological models was analysed. The most suitable time series of geopotential models, filtering method for the determination of time variations of geoid heights over Europe as well as the hydrological data appropriate for comparing with GRACE models were indicated (Szelachowska et al., 2010).

The GRACE observations over the territory of Poland were analysed at the Wroclaw University of Environmental and Life Sciences and a regionally improved GRACE geoid model was derived from this data. That improved regional geoid model was compared with the Polish quasigeoid models and differences between the global and regionally improved GRACE GGM02s solutions were discussed. The study shows that the error of the official GRACE GGM02s solution was reduced by 50% due to regional refinement (Antoni et al., 2009).

Study on possible determination of the speed of the gravity signal in space with help of gradiometry was conducted in the Space Research Centre, PAS, Warsaw, in cooperation with the Institute of Physics, PAS, Warsaw and the Institute of Physics of Interplanetary Space, Italy. The velocity of the gravitational signal can be determined using the rotating Earth as the signal generator, and GNSS together with gradiometry as a detector. It seems that such concept is realistic, but of course not easy. The required accuracy of gravity vertical gradient measurements, positions of satellites and time tagging for the determination of the propagation velocity of the gravity signal was estimated. The motivation for the development of the gradiometry technology and the extension of the spectrum of scientific applications of GNSS was indicated (Zielinski et al., 2007, 2008).

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3. GEODYNAMICS AND EARTH ROTATION[3]

3.1. INTRODUCTION

This part of the Polish National Report on Geodesy is the quadrennial report on research activity concerning geodynamics and Earth rotation performed in Poland in a period of 2007–2010. It contains a summary of works on establishment, maintenance and analysis of geodynamic networks of local, and regional scale, theoretical research on Earth rotation, evaluation and prediction of its parameters and analysis of the respective data, Earth tides monitoring, monitoring of geodynamic phenomena on both local and global scales, and the determination of secular variation of the Earth magnetic field. The activities concerning geodynamics and Earth rotation were conducted mainly in the following research centres, listed in an alphabetic order:

- Department of Applied Geomatics, Military University of Warsaw;
- Department of Geodesy and Geodetic Astronomy, Warsaw University of Technology;
- Department of Geodesy and Geodynamics, Institute of Geodesy and Cartography in Warsaw;
- Department of Planetary Geodesy, Space Research Centre, Polish Academy of Sciences in Warsaw;
- Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences.

Annual national reports to the IAG Sub-commission for EUREF (Krynski and Rogowski, 2007, 2008, 2009, 2010) contain the extensive information on the activities concerning reference networks in Poland within the reported period.

The bibliography of the related works is given in references.

3.2. MAINTENANCE OF LOCAL GEODYNAMIC NETWORKS

3.2.1. Polish Geodynamic Network and Related Investigations

The concept of a new geodynamics research project concerning the study of the relationship between the tectonic stress and the deformation of the lithosphere in the territory of Poland was presented (Jarosinski et al., 2007). The main goal of the project designed in the framework of cooperation of the Institute of Geodesy and Cartography and the Warsaw University of Technology with the Polish Geological Institute, is the complex analysis of recent geokinematics and geomechanics of the Earth crust in the territory of Poland with the use of the archive data as well as the new data acquired during the realisation of the project.

3.2.2. Geodynamics with the Use of Local GNSS Networks

The method of combined solution of permanent and epoch GPS observations to process local network as the whole in order to estimate velocities based on simultaneous processing of heterogeneous observations from permanent EPN/IGS stations, semi-permanent stations and epoch stations was developed at the Wroclaw University of Environmental and Life Sciences (Fig. 1.5.2a in Chapter 1) (Bosy et al., 2009). It has been shown that the mean trend

[3] The content of the chapter was compiled by **Aleksander Brzeziński** with the use of the material provided by Andrzej Araszkiewicz, Marcin Barlik, Janusz Bogusz, Aleksander Brzezinski, Stefan Cacon, Marek Kaczorowski, Bernard Kontny, Wieslaw Kosek, Jan Krynski, Jolanta Nastula, Tomasz Niedzielski, Jerzy B. Rogowski, Miloslawa Rutkowska, and Janusz Sledzinski.

congruency analysis for EPN/IGS stations coordinates time series is the efficient criterion for the selection of reference stations for local GPS networks (Fig. 3.2.2).

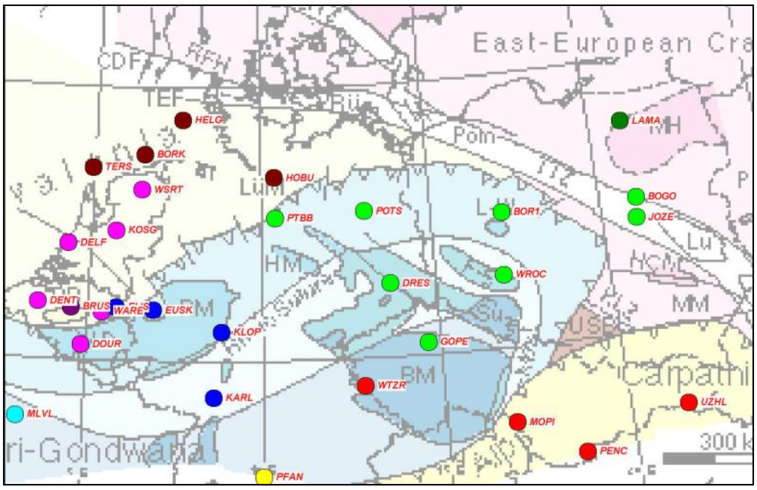

Fig. 3.2.2. The results of cluster analysis of Central Europe EPN stations velocities – 12 clusters

The outcome of this analysis is the group of Mid-European stations situated in Variscan and Caledonia Units isolated from other stations. Grouping of EPN/IGS stations based on the cluster analysis verifies mean trend congruency analysis methods that were used for the selection of appropriate reference stations. Figure 3.2.2 presents the results of cluster analysis for EPN stations and shows that the set of stations was divided into 12 groups. The most numerous group – marked with green colour – includes stations in the eastern part of Variscides (BOR1, DRES, GOPE, POTS, PTBB, WROC). BOGO and JOZE stations also belong to that group although they are situated in Teisseyre-Tornquist Zone. Stations in western part of Mid-European Zone – marked with brown and pink colour – are divided into two groups: DELF, DENT, DOUR, KOSG, WARE and WSRT in the western part of Variscan Unit and BORK, HELG, HOBU and TERS in the Caledonia Unit. Two further groups are constituted by stations (blue, and red colour) in the Aphides area (BZRG, GENO, GRAS, SJDV, TORI, ZIMM in the Central Alps and GRAZ, MOPI, PENC and UZHL in the Eastern Alps and the Carpathians). WZTR station is claimed to belong to the latter group despite the fact that it is placed in Bohemian Massive. Generally, classification of the stations made by means of cluster analysis method correlates to their location within particular main European tectonic units. The results of the above analysis enabled reference stations selection for GPS GEOSUD local network (BOR1, GOPE, WROC – were chosen from the group of stations in Variscides, PENC from Alps and WTZR from Bohemian Massive). This information is essential for the geodynamical interpretation of geodetic monitoring results from local GPS networks.

3.2.3. Geodynamic Research in the Sudeten Mountains and Fore-Sudetic Block (SW Poland)

Monitoring of active tectonic structures of Sudeten Mountains and Fore-Sudetic Block (SW Poland) were continued in 2007–2010 by the team of the Institute of Geodesy and Geoinformatics of Wroclaw University of Environmental and Life Sciences with partners (Fig. 3.2.3a).

A nearly 133 km long portion of the Sudetic Marginal Fault (SMF) (99.7 km in Poland and 33.8 km in the Czech Republic), comprised between Zlotoryja in the NW and Jesenik in the SE was analysed (Badura et al., 2007).

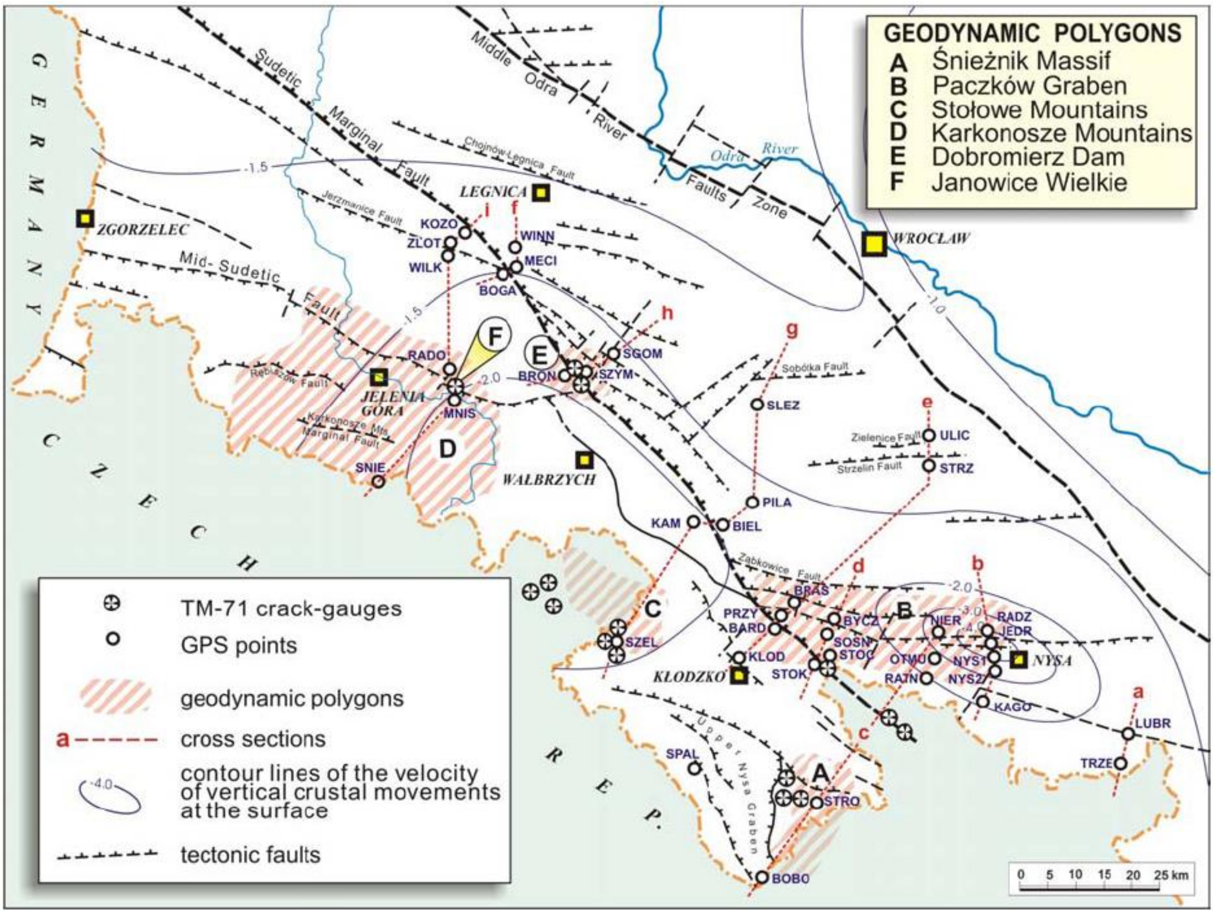

Fig. 3.2.3a. Sudeten Mountains and Fore Sudetic Block geodynamic areas. GEOSUD network and geodynamic polygons

The study in the Walbrzych Coal Basin concentrated on analysis of heterogeneous rock mass deformations in the final years of underground coal extraction and during the revitalisation period after the end of mining (Blachowski et al., 2009).

The final results of geodynamic research in Poland, Italy and Greece realized during COST Action 625 “3D Monitoring of Active Tectonic Structures” were presented by Cacon et al. (2007).

Metamorphic phenomena formed geological and tectonic structure of the Snieznik Klodzki Massif, Klodzko Valley, SW Poland. Snieznik Massif is crossed by the section of tectonic faults zone in direction NW-SE. Several transverse faults are located near the major tectonic zone. In 1992 twenty seven points of local geodynamic network in Czech and Polish sides of the Massif were established for the determination of the Snieznik Massif crust activity. Repeated periodic GPS, total station, gravimetric, clinometric and crack gauges as well as precise levelling measurements were conducted. Long term data acquisition allows to interpret and evaluate the object surface deformation (Jamroz, 2008).

Geological structure, including main faults and faults zones, of the Gory Stolowe National Park originated in Neogene. Displacements on faults in the Porici-Hronov and the Czerwona Woda fault zones have been revealed at present times. A network of 11 stations (Fig. 3.2.3a) was established to register this process and phenomena associated with it. The first campaign of GPS and gravimetric measurements, was performed in 2008. It has been complemented with relative measurements of the faults in selected places where crack-gauges have been installed (Cacon et al., 2009).

A collaborative group between Greek, Polish, and Slovak researchers installed a dense network of non-permanent GPS stations and extensometers to monitor active faults in the eastern part of the Gulf of Corinth, Greece. The network includes eleven GPS stations across the Kapareli fault and the Asopos rift valley to the east and two TM-71 extensometers that were installed on the Kapareli fault plane (Ganas et al., 2007). So far the GPS network has been measured in three campaigns within the last three years with very good accuracy (1-4 mm in the horizontal plane).

Benchmark height changes along national 1st order precise levelling lines crossing the Middle Odra Fault Zone in the Wroclaw area were analysed. The analysis was extended to benchmarks elevations changes in the 3rd order levelling network (Grzempowski and Mąkolski, 2007). The zone separates Fore-Sudetic Block from the Fore-Sudetic Monocline and is one of the main geological structures in Lower Silesia. Five national precise levelling lines surveyed in 1956–1958, 1975–1980 and 1999, cross the investigated area. Changes of benchmark heights have been presented in comparison with geological cross-sections along the levelling lines. In the result, areas of the greatest relative vertical displacements correlated with geology and tectonics have been found. Figure 3.2.3b (Grzempowski et al., 2009) shows the example of geological cross-section Zabkowice–Wroclaw–Sycow.

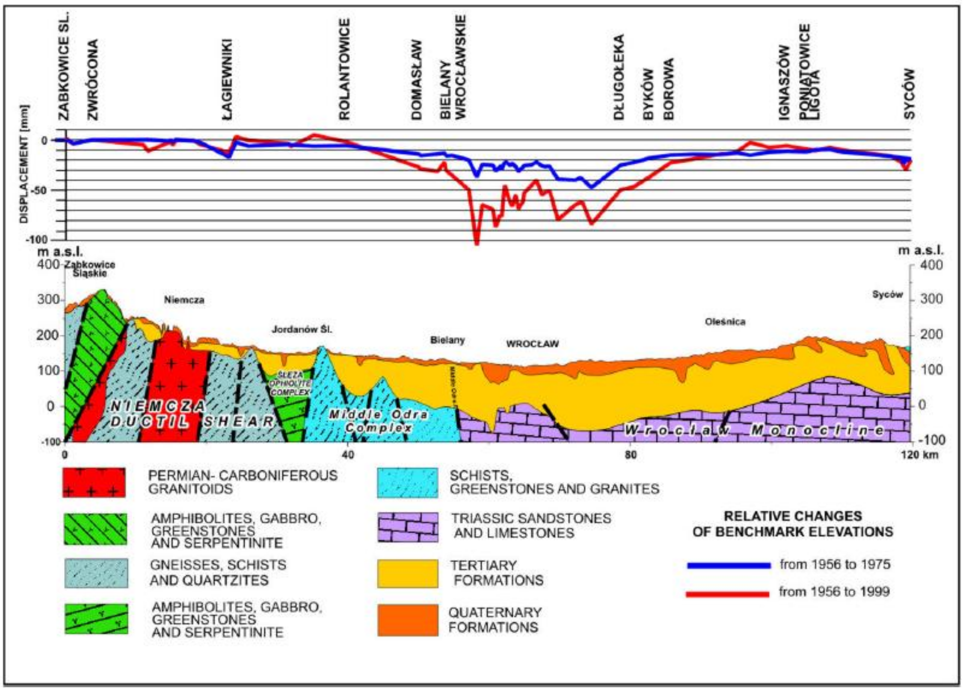

Fig. 3.2.3b. Simplified geological profile along the Zabkowice Sl. – Wroclaw – Sycow levelling line

Tectonic activity of the Marginal Sudetic Fault (MSF) was investigated (Kaplon and Cacon, 2009). Velocities of points obtained from processing GPS measurements in the GEOSUD network and results of national precise levelling networks have been analysed. Results of 1996–2005 GPS measurements and results of measurements of selected points from the 2006–2007 period were taken into consideration. The velocities calculated by means of the Bernese GPS Software v5.0 were used to test the hypothesis on present-day strike-slip movement activity of the Marginal Sudetic Fault (Fig. 3.2.3c). The relationship between the calculated velocities and the length of projection onto the fault's line was studied. Relative vertical velocities of benchmarks, making up the 1st and the 2nd order national precise levelling lines crossing the fault line, were also analysed to study its vertical activity.

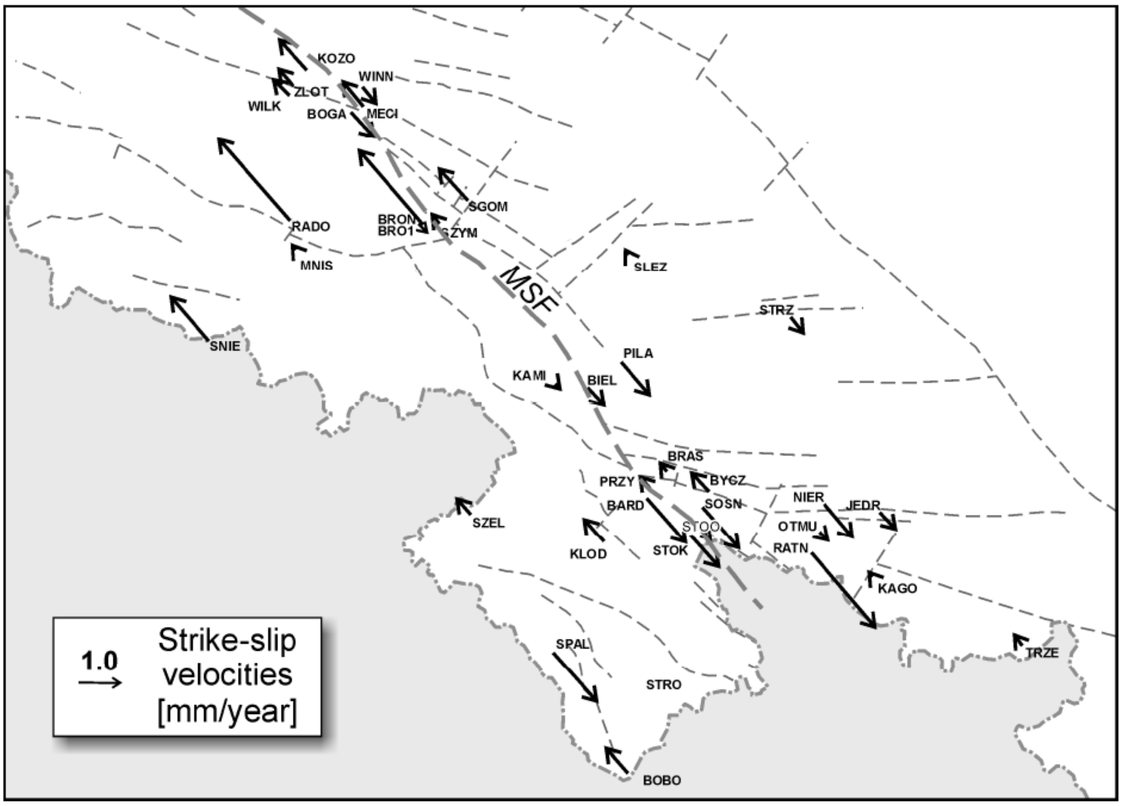

Fig. 3.2.3c. Strike - slip velocities of the GEOSUD network points

Bear Cave under Mt. Snieznik is located near the Lower Silesian Village of Kletno in a wider tectonic fault zone of Sudeten, Klodzko Valley, Southern Poland. Precise levelling network was established about 20 years ago for detecting vertical movements in the cave and its vicinity (Makolski et al., 2008). In the cave two fault zones of major risk have been checked also with TM-71 crack gauges and records have been taken with a month frequency.

Recently, gradual subsidence of some levelling benchmarks was observed; also some periods of increased micro-displacements on the tectonic crack zones were determined (Kostiak et al., 2007).

The results of a long-term monitoring study undertaken during the period 2002–2007 presented by Stemberk et al. (2010). The study recorded the displacement of various widely-distributed tectonic structures along the generally aseismic Bohemian Massif (Czech Republic) and specifically along the Sudeten Marginal Fault Zone. The dominant displacements were vertical. It is clear that this period is associated with collision along the Sudeten Marginal Fault Zone (Fig. 3.2.3d).

The southern flank was repeatedly downthrust beneath the northern flank, which caused the latter to continually uplift and subside. The period of increased geodynamic activity is terminated by earthquake activity.

A reliability of site movement assessments determined from GPS data monitored during eight two-day epoch measurements on the regional geodynamic EAST SUDETEN network (the Bohemian Massif, Central Europe) is discussed in details (Schenk et al., 2010). Statistical tests of site positions processed by the Bernese GPS software, their linear approximations for site movement velocity assessments and an establishment of probabilistic thresholds for the reliability of the GPS data for regional geodynamic studies are provided. The thresholds define necessary observation periods for annual epoch measurements performed on the networks with aim to obtain reliable movement estimates for geodynamic studies.

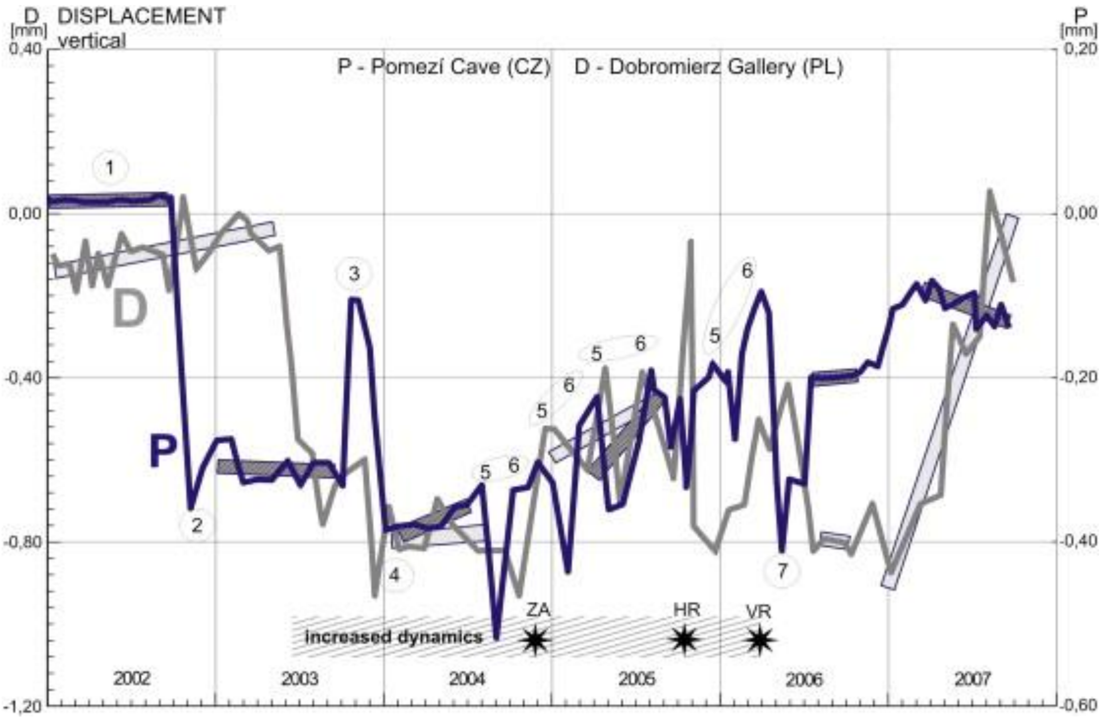

Fig. 3.2.3d. Data demonstrating variations in vertical displacement recorded at Na Pomezí Cave (Site P) and Dobromierz Dam Gallery (Site D) on the Sudetic Marginal Fault. A rising line represents relative uplift of the southern flank of the fault at the respective sites. Numbers 1÷7 indicate the stages of kinematic development with specific reference to Na Pomezí Cave: 1 stability (calm or minor scatter); 2 relaxation (dramatic drop with no reversal); 3 pressure pulse (uplift in the south with corresponding reversal in the north); 4 compaction (neutral and gradually positive); 5 downthrust (sudden negative peak - pressure submersion reaction in the south which is then compensated by depression in the north); 6 compaction (neutral and gradually positive); 7 relaxation (dramatic drop with no reversal)

Statistical analyses of site velocity movements allowed three probability thresholds for site movements to be defined: (a) probable, (b) possible, and (c) credible movements. To reach similar reliable levels of GPS data, it is recommended to follow the way of epoch measurements and data processing described. It was found that the probable / credible site horizontal movements can be obtained for the north component in 4 or 5 annual epochs and for the east component in 3 or 4 annual epochs, respectively. When more than 4 annual epoch solutions are available, then mean values of velocity components can already reach the category of the credible velocity. As to the site vertical movements their values need more annual epoch solutions, probably close to 10 epochs, to reach the category of probable / credible site movements.

The probabilistic thresholds defining reliable site movements brought further important recommendation for the GPS practice. It is evident, if any GPS measurements are planned on regional networks aimed to geodynamic studies then the fact that whole period of these planned measurements would not be less than six years should be taken into account. This conclusion is imperative for many recent project proposals planned for geodynamic and any geodetic interpretations (Schenk et val., 2010).

Results of epoch satellite GPS and gravimetric measurements performed on the geodynamic network in central part of the Stolowe Mts. between 1993 and 2009 were presented (Cacon et al., 2010). They show significant changes of gravity on most of the points and significant horizontal movement of one point in the central part of the area. The results confirm present day activity of the zone where faults Policky, Belsky and Czerwona Woda Fault Zone exist (Fig. 3.2.3e and Fig. 3.2.3f). In addition, they correspond with the studies of seismic activity in this part of the Sudeten Mts.

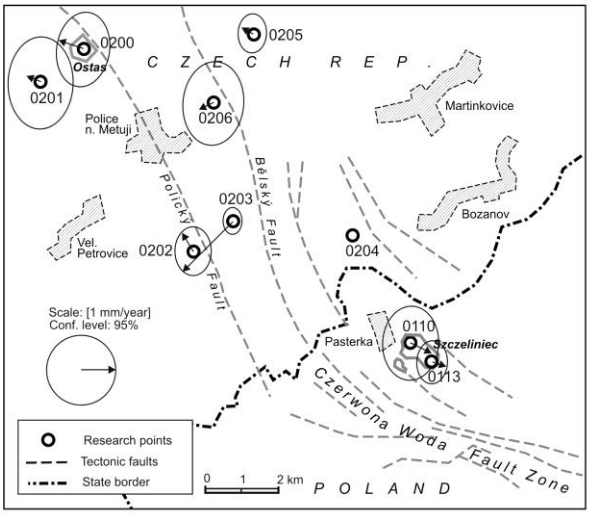

Fig. 3.2.3e. Horizontal velocity vectors and their confidence ellipses at the 95% level

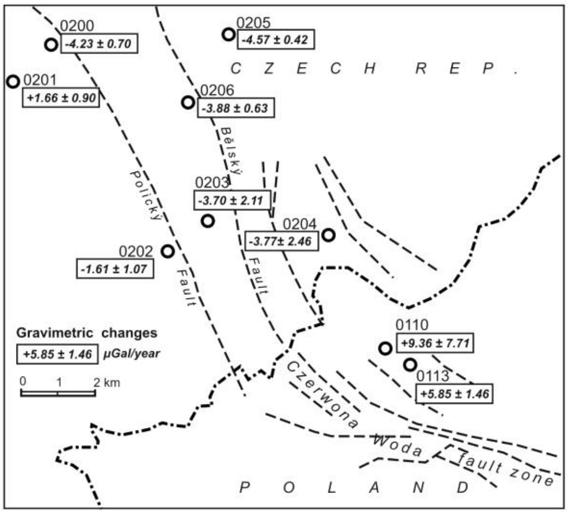

Fig. 3.2.3f. Velocities of gravity changes and their mean errors on network points in 1993–2009

3.2.4. Geodynamic Network in Pieniny Klippen Belt

Geodynamic investigations were continued in the Pieniny Klippen Belt by the Department of Geodesy and Geodetic Astronomy of the Warsaw University of Technology using geodetic methods. The geological structure of that area is rather complicated, as a result of tectonic processes during the Alpine orogeny,. In 1969 the Faculty of Geodesy and Cartography Warsaw University of Technology, Institute of Geodesy and Geodetic Astronomy has established the geodynamic network around the Pieniny Klippen Belt. Since 1969, at the sites of the geodynamic network levelling, gravimetric and distance measurements were carried out. Later, in 1990. GPS measurements and absolute gravity measurements there were additionally conducted.

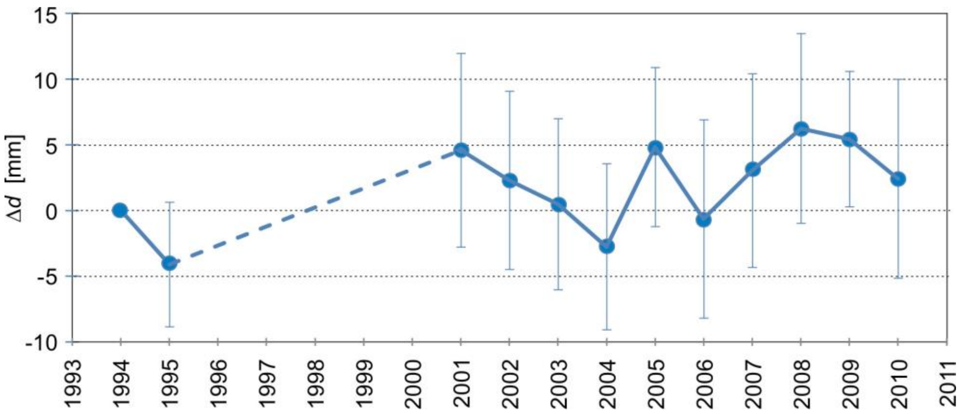

Fig. 3.2.4a. Distance changes between Podhale Flysh and Magura Nappe

The results revealed vertical and horizontal movements of the crust and periodic changes in gravity. Periodic vertical movements of 0.5÷1.5 mm/year are correlated with the interaction between the geological structures of the Magura Nappe and the Podhale Flysh. The direction (Fig. 3.2.4b) and velocity (Fig. 3.2.4c) of the horizontal movements have changed in irregular manner, reaching maximum of 10 mm over 17 years (Pachuta, at al., 2010).

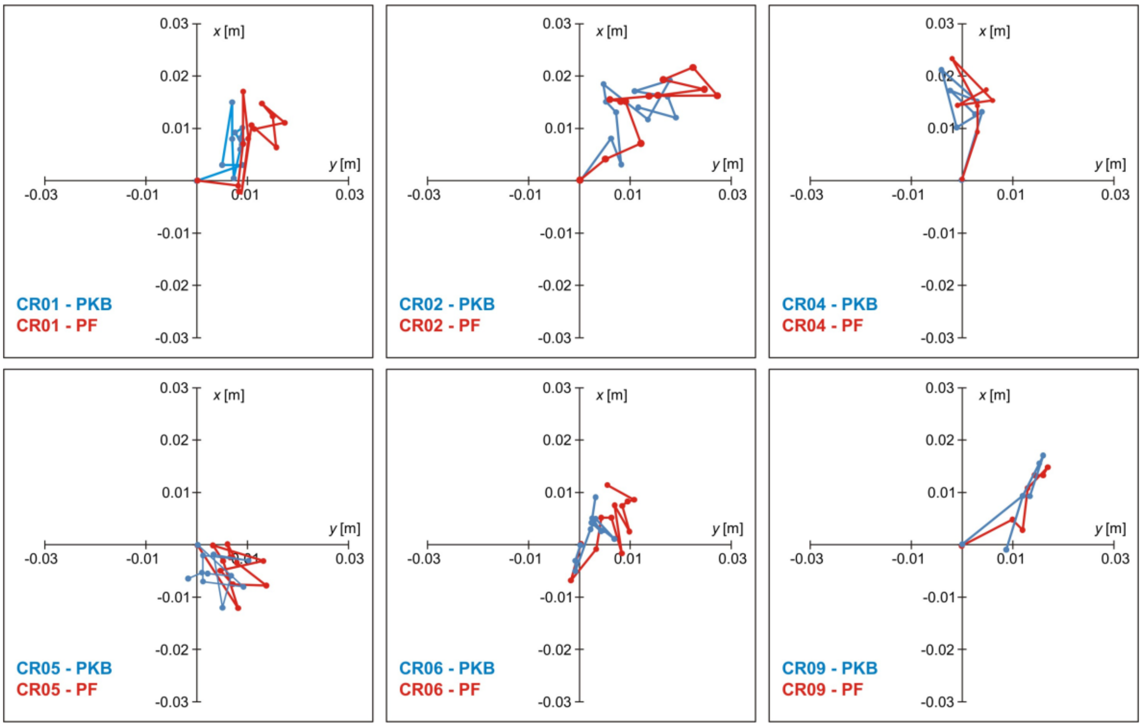

Fig. 3.2.4b. Points movements within the Pieniny Klippen Belt PKB
(relative the Magura Nappe – blue, and Podhale Flysh PF – red)

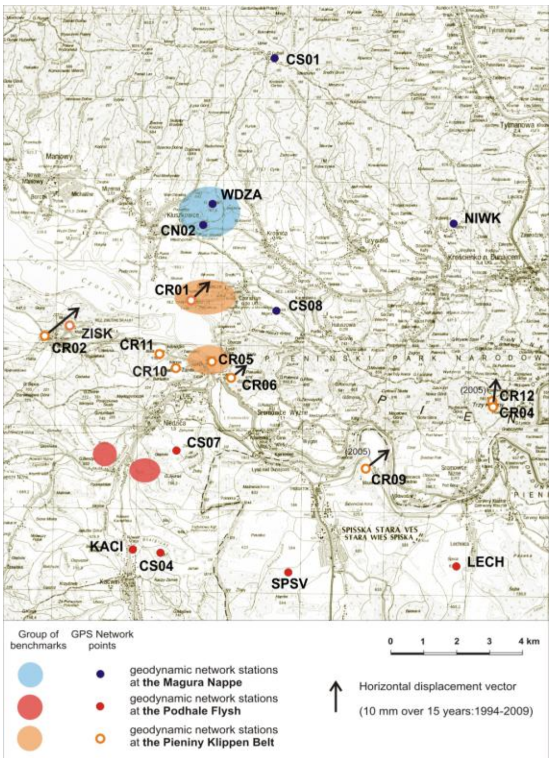

Fig. 3.2.4c. Velocity vectors at selected points at the Pieniny Klippen Belt

In 1990s, the Dunajec river dam and the water reservoirs in Czorsztyn and Sromowce Wyżne have been built. This has created a new aspect in the investigations related to the effect of tectonic movements on the dam. Taking that into account, the study was revived in 2001. After six year break, the investigations were revived and extended to aspect related to the erected water reservoirs.

Gravimetric measurements were carried out using LaCoste&Romberg G and D models, and Scintrex Autograv CG-3M gravimeters. Since 2007, absolute measurements have been performed at three points with the FG5-230 absolute gravimeter (Szpunar at al., 2010). Changes in gravity at the polygon points reach 120 μGal over 30 years. However, it primarily is the result of interaction of water mass. Quasi-periodic changes in gravity with amplitude of 20 μGal were determined in the area around Czorsztyn and Niedzica station.

Fig. 3.2.4d. FG5-230 at the Niedzica station

The precise levelling was performed six times in a period from 2001–2009 along the Wdżar–Czorsztyn line and the Kacwin–Niedzica line with the Trimble DiNi12 instrument. After filling the Czorsztyn reservoir vertical displacement of 7 mm was determined.

Since 2001, distance measurements between points of the geodynamical network have been carried out using GNSS technology. Difference between distances performed before and after 2001 has been reported less than 1 cm, which can be explained by the influence of the Czorsztyn reservoir. There is no movement of the geological structures of the Magura Nappe and the Podhale Flysh against each other; differences in distance do not present any linear trend. In turn, there can be reported north-east linear displacement of 15÷20 mm over 15 years at almost all points.

Slight changes observed in position, height and gravity of the test points were caused by presence of water mass. It has been found that the establishment of the water reservoir in Czorsztyn does not affect the position of the geological structures of the Magura Nappe and the Podhale Flysh. It also does not have any negative impact on the hydrological structure of the dam.

3.2.5. Geodynamic Research in Test Areas in Greece and Italy

International cooperation of the team of the Institute of Geodesy and Geoinformatics of the Wroclaw University of Environmental and Life Sciences with the research groups from Italy and Greece in monitoring active tectonic structures in the test areas: Sudeten Mts. (southern Poland), Gargano GPS Network in the Mattinata Fault (Gargano Peninsula, Italy), Norcia Network in Norcia Tectonic Basin (Central Apennines, Italy) and Kaparelli Network in the Kaparelli Fault Zone (Gulf of Corinth, Greece) using GPS surveying campaigns were continued within the EU project – COST Action 625.

Research was conducted using a self-developed control and measurement system (Cacon et al., 2007). The results of measurement performed in 2000–2006 indicate slight movements of observation points in the Sudeten Mts. reaching several millimetres. They confirm recent mobility of tectonic structures of this area. The results obtained in the Mediterranean Region – in Gargano, Norcia (Italy) and Kaparelli (Greece) – indicate movements of stations reaching over a dozen of millimetres, particularly in the Gargano area. Continuation of cyclic control measurements on these objects was fully justified.

Independent analysis of data from the period of 2000–2006 from the Kaparelli test area (Fig. 3.2.5) was analysed, where since November 2003 a collaborative Greek, Polish and Slovak group installed a dense network of non-permanent GPS stations and extensometers to monitor active faults in the eastern end of the Gulf of Corinth. The network includes eleven GPS stations across the Kaparelli fault and the Asopos rift valley to the east as well as two TM-71 extensometers installed on the Kaparelli fault plane (Ganas et al., 2007a, 2007b).

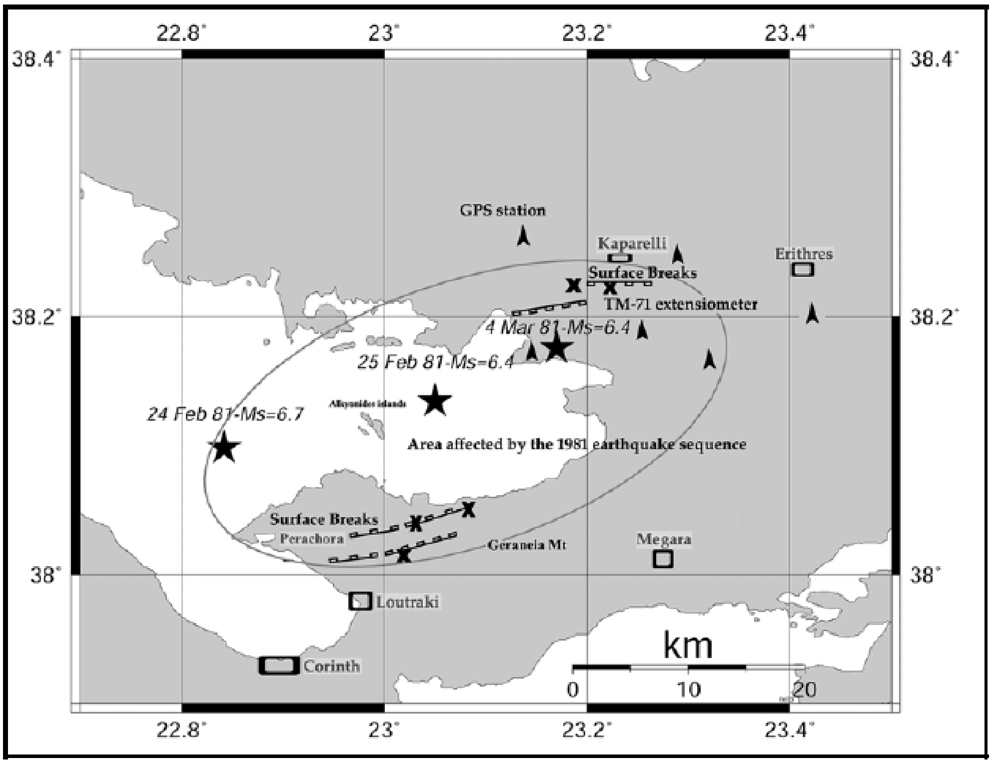

Fig. 3.2.5. Map of Kaparelli test area with epicentres of the 1981 earthquake sequence (stars). X marks show the locations of the TM-71 instrument and black arrows indicate the locations of non-permanent GPS stations installed during 2003. Lines with barbs indicate normal faults that ruptured during the 1981 earthquake sequence

The motions recorded by the TM-71 instruments show agreement with long-term fault kinematics and comparable rates. The GPS network has been measured in three campaigns (2004, 2005 & 2006) with very good accuracies (1÷4 mm in the horizontal plane). Given that the total offset on the Kaparelli fault is small, and the geological data suggesting a segmented character of this fault, we expect in the near future to differentiate fault slip and strain accumulation among segments.

3.3. REGIONAL GEODYNAMIC NETWORKS

3.3.1. CERGOP Project

The project CERGOP-2 started on 1 April 2003 as a continuation of Central European Regional Geodynamic Project (CERGOP) of the Central European Initiative (CEI) initiated in 1992. It mainly uses GPS for a steady monitoring of the Earth surface within the Central European Regional GPS Geodynamic Reference Network (CEGRN) with use of additional terrestrial measurements, e.g. absolute gravity. CEGRN delivers the main data-input for long term determination of station coordinates. Time series developed are used to investigate long term secular influences, i.e. geokinematics (crust movements, velocity fields, strain fields) as well as short term effects (local earthquakes, landslides, space weather, troposphere and other environmental impacts like sea-level rise and sea surface topography). They are the bases for geodynamic investigations like force models for the physics of dynamic processes and energy transfer (earthquake prediction). The project was officially terminated on October 31, 2006 and financially closed at the end of 2007. The results of investigations were published mainly in the “Reports on geodesy” of the Warsaw University of Technology. The last report of the series was (Sledzinski, 2007). The basic final output is presented in (Caporalli et al., 2008).

3.3.2. International Carpathian Geodynamic Network

Geodetic, geological and geophysical data form Central Europe indicate the need for the establishment of the International Carpathian Geodynamic Network ICGN (Krynski et al., 2008). The main framework of the project on the establishment of the ICGN was designed by the team of the Institute of Geodesy and Cartography, Warsaw University of Technology, Institute of Geophysics of the Polish Academy of Sciences, and its multiple aspects concerning reference systems, structure of the network, localization of stations and their monumentation, observation techniques, data processing were discussed.

3.4. EARTH ROTATION

In the recently established Global Geodetic Observing System (GGOS) Earth rotation has been 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, 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 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 rotation parameters are also essential for the realization of global reference systems, the International Terrestrial Reference System ITRS and the International Celestial Reference System ICRS.

In the last few years quick developments of investigations of geophysical excitation functions of Earth rotation have been observed. The new models of Atmospheric Angular

Momentum (AAM), Oceanic Angular Momentum (OAM) and Hydrological Angular Momentum (HAM) have been developed. Important progress has also been achieved in the observation of Earth rotation. An overview of the recent advances in observation and modelling of Earth rotation can be found in the reports (Brzezinski et al., 2009b, 2010b; Brzezinski, 2008b).

In Poland, investigations concerning Earth rotation has been done mostly by the researchers of the Space Research Centre of the Polish Academy of Sciences in Warsaw. They participated in the activity of the international scientific organizations (IAG, IAU, IERS, etc.) and of their commissions and working groups. They were also active in organization of the national and international meetings devoted to the subject of Earth rotation. 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 publications are presented below.

3.4.1. Analysis of Earth Rotation Observations and the Related Excitation Data

3.4.1.1. Geophysical Excitation of Earth Rotation, Long Periods

Main part of the observed variation of Earth rotation is caused by the influence of the dynamically coupled system atmosphere-oceans. This problem has been investigated by the researches from the Space Research Centre PAS (Aleksander Brzezinski, Barbara Kolaczek, Anna Korbacz, Jolanta Nastula). Their works concern both the theoretical problems – parameterisation of Earth rotation, equations of motion, methods of data analysis, and the analysis of the available Earth rotation and related geophysical excitation data. The last mentioned part of research benefited from close cooperation with the scientists from the GeoForschungsZentrum (GFZ) Potsdam, Germany (Maik Thomas, Henryk Dobslaw, Robert Dill). This subsection review results concerning the long periodic components of excitation, i.e. with periods of several days and longer. The diurnal and subdiurnal effects will be considered in the next subsection.

A broad band excitation study of polar motion and UT1/LOD, including the intraseasonal, seasonal, interannual and decadal signals was performed (Korbacz et al., 2007, 2008). The authors used the AAM series calculated from the output fields of the atmospheric general circulation model ERA-40 reanalysis, and the OAM series which was an outcome of global ocean model OMCT simulation driven by global fields of the atmospheric parameters from the ERA-40 reanalysis. The excitation data covered the period between 1963 and 2001. Results were compared to those derived from the alternative AAM/OAM data sets. A summary of this research including diurnal/subdiurnal variations and nutation was given in the review work of Korbacz (2009).

Seasonal excitation balance of polar motion using recent geophysical data sets and models were investigated (Brzezinski et al., 2009). Attention was focused on the contribution of the land hydrology which was expressed either by models, such as CPC, GLDAS, LaD, or by the observations provided by the experiment GRACE (Gravity Recovery and Climate Experiment). Geophysical excitation series were compared to each other and to the excitation inferred from the space geodetic observations of polar motion. Comparison showed that three models of land hydrology considered in the paper differ considerably; adding the corresponding excitation series to the combination of atmospheric and oceanic excitation data did not clearly improve agreement with observations. Combination of the GRACE-derived mass term of excitation with the motion terms of atmospheric and oceanic excitations brought, however, the excitation balance considerably closer in case of the retrograde/prograde annual and retrograde semiannual components of polar motion. For other seasonal components as well as for the nonharmonic residuals, the estimated contributions of hydrology did not improve the excitation balance of polar motion.

The excitation of seasonal polar motion based on the AAM, OAM and HAM functions obtained from European Centre for Medium Range Weather Forecasts atmospheric data and corresponding simulations with the Ocean Model for Circulation and Tides (OMCT) and the Land Surface and Discharge Model (LSDM) was also considered (Dobslaw et al., 2010). Mass exchanges among the subsystems were realized by means of freshwater fluxes. Since differences to geodetic excitations were not substantially reduced and regional decompositions demonstrated the large spatial variability of contributions to seasonal polar motion excitation that compensate each other when integrated globally, it was concluded that the closure of the seasonal excitation budget is still inhibited by remaining model errors in all subsystems.

The 14-month 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 Chandler wobble excitation problem was investigated using the analysis scheme developed by Brzezinski and Nastula in but more recent determinations of the AAM and OAM functions (Brzezinski et al., 2010a). The authors also tried to assess the role of land hydrology in the excitation balance by taking into account the HAM estimates. The results of analysis generally confirmed earlier conclusions concerning the atmospheric and oceanic excitation. Adding the hydrological excitation was found to increase slightly the Chandler wobble excitation power, while the improvement of coherence depended on the geophysical models under consideration (Fig. 3.4.1a).

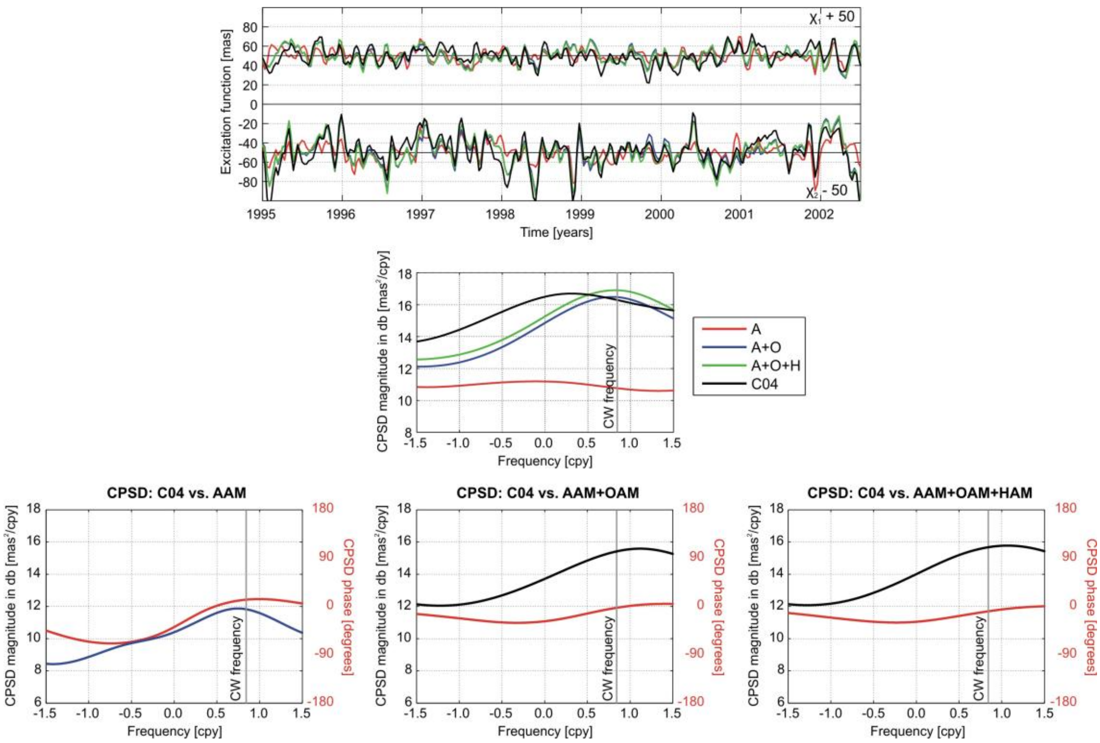

Fig. 3.4.1a. Comparison of the observed (C04) and modelled (AAM – NCEP-NCAR reanalysis, OAM – data assimilating model ECCO, HAM – NCEP water) excitations of polar motion. Power spectrum and cross-power spectrum estimates were calculated using the maximum entropy method algorithm.
Period of analysis: 1993.0–2009.0

3.4.1.2. Subdiurnal Perturbations of Earth Rotation

Polar motion and UT1 contain physical signals within the diurnal and subdiurnal frequency bands. A common feature, besides the high frequency, is their small size: the total peak-to-peak size is only up to about 1 mas corresponding to 3 cm at the Earth surface. Such variations could not be observed by using the methods of optical astrometry and early space geodetic measurements, because the observations were not sufficiently accurate and their sampling interval was significantly longer than 1 day. Hence all earlier predictions were purely theoretical based on the knowledge about the shape and internal constitution of the Earth. All observational evidence of diurnal and subdiurnal variations in Earth rotation has been gathered during the last two decades. The high resolution observations of Earth orientation are still under development. An important and independent method of modelling diurnal/subdiurnal variations in Earth orientation is by the high resolution estimation of the total angular momentum of geophysical fluids, primarily the atmosphere (AAM) and the oceans (OAM).

Despite the small size, the diurnal and subdiurnal signals in Earth rotation are important for understanding the high frequency global dynamics of the solid Earth and the overlying fluid layers. The research concerning such signals is also important for validation of the high resolution determinations of Earth rotation parameters and of the procedures applied for data reduction. A possible benefit from such research could be empirical verification of the equations of Earth rotation at high frequencies. Recent advances in theoretical modelling and observation of Earth rotation at daily and subdaily periods were reviewed by Brzezinski (2009).

Geodetic observation. Monitoring changes in Earth rotation with subdiurnal resolution became recently an important task of modern geodesy. For instance, one purpose of the VLBI 2010 system is continuous measurement of the Earth Orientation Parameters (EOP). Brzezinski and Bolotin (2007) discussed how the diurnal and semi-diurnal signals in polar motion and UT1 can be estimated from the routine VLBI observations with one session in 3 to 5 days. The method relies upon the so-called complex demodulation technique. The authors demonstrated the application of the algorithm to real data by using the VLBI analysis software Steel-Breeze. Spectral analysis of the demodulated time series revealed significant corrections to the conventional model of the ocean tide variations as well as the broad band variability with excess of power near the frequencies of the tidal lines S1 and S2. The demodulated series are suitable for the time domain comparisons with the available sub-diurnal estimates of the atmospheric and oceanic excitation.

The ring laser gyroscope is a promising emerging technology for directly and continuously measuring changes 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). However, due to the instrumental drift the measurements are not stable over periods longer than a few days therefore only the diurnal and subdiurnal variations in polar motion can be estimated. Among several instruments which have been developed so far, the most accurate for monitoring high frequency polar motion is the G ring laser in Wettzell, Germany. Considerable progress has been attained recently in the analysis and interpretation of the ring laser measurements, as discussed by Cerveira et al. (2009). Brzezinski (2009) addressed the question about the possible benefits from the use of the ring laser data for monitoring variations of Earth rotation. He demonstrated that the observations of ring laser are much less accurate than VLBI in determining those components of rotation which are currently expressed as precession-nutation of the CIP, but are potentially useful for continuous monitoring of the prograde diurnal and retrograde/prograde semidiurnal signals in polar motion. However, for significant results the uncertainty of the estimated position of the IRP should be better than 0.1 mas. The observations of ring laser can be combined with space geodetic polar motion data using the first-order kinematical relationships between the motions of the CIP and IRP.

Geophysical excitation. The diurnal cycle in solar heating give rise to variations in AAM and OAM with main components S1, S2 of periods 24 and 12 hours, respectively, and their side lobes due to seasonal modulations. These variations of AAM and OAM excite small perturbations in all three components of Earth rotation, including precession-nutation, polar motion and UT1. So far, only the S1 contributions to Earth rotation could be detected in both geophysical models and space-geodetic observations. However, comparison done in the works (Brzezinski, 2007b, 2008a) revealed significant differences between estimates from different models and different observation techniques, as well as between the models and observation. Investigations should be continued using improved geophysical models and space-geodetic data derived by improved reduction procedures.

The nearly diurnal retrograde variations of the AAM and OAM contribute to the precession-nutation residuals which are expressed by time series of the so-called celestial pole offsets. A simple digital filter for application to studies concerning geophysical excitation of nutation was derived (Brzezinski, 2007a). Attention was focused on the inverse solution, i.e. inferring the excitation function from the celestial pole offsets observed by VLBI. Filter properties were discussed by comparing its transfer function to that of the original differential equation of nutation. An excellent agreement in both the amplitude and phase response was shown at frequencies between -5 and +5 cycles per year, which is the frequency band with expected geophysical signals.

Libration in polar motion and UT1. The Earth orientation parameters contain small subdiurnal components (amplitudes up to 0.03 mas) designated as “libration”, due to direct influence of the tidal gravitation on those features of the Earth's density distribution which are expressed by the non-zonal terms of the geopotential. Brzezinski and Capitaine (2010) considered in detail the subdiurnal libration in UT1. They derived an analytical solution for the structural model of the Earth consisting of an elastic mantle and a liquid core which are not coupled to each other. The reference solution for the rigid Earth was computed by using the satellite-determined coefficients of the geopotential and the recent developments of the tide generating potential (TGP). The draw the conclusion that the set of terms with amplitudes exceeding the truncation level of 0.005 mas consists of 11 semidiurnal harmonics due to the influence of the TGP term u_{22} on the equatorial flattening of the Earth expressed by the Stokes coefficients C_{22}, S_{22}. The proposed model of the UT1 libration has been included in the new version of the IERS Conventions (2010; www.iers.org).

3.4.1.3. Comparison of Polar Motion Excitation Series Derived from GRACE and from Analyses of Geophysical Fluids

A method for deriving the excitation functions of polar motion χ_1, χ_2 due to variations of geophysical mass distribution using the GRACE gravity solutions, as a substitute for deriving such excitations from direct observations and modelling of geophysical fluids have been explored. Three different sets of degree 2, order 1 harmonics of the gravity field, derived from the GRACE data at the GFZ, JPL and CSR were used to compute the gravimetric polar motion excitation functions. Comparison of these functions with the mass terms derivable from independent geodetic observations, series IERS CO4 and from the geophysical excitation functions of polar motion (mass terms of atmospheric, oceanic and continental hydrology excitations) in seasonal time scales shows differences up to 20 mas in the years 2004–2005. There are the distinct annual oscillations in χ_2 of all considered series (Nastula et al., 2007, 2008).

3.4.1.4. The Use of Gravimetric Data from GRACE Mission in the Understanding of Polar Motion Variations

Tesseral coefficients C_{21} and S_{21} derived from GRACE observations allow to compute the mass term of the polar-motion excitation function. This independent estimation can improve the geophysical models and, in addition, determine the unmodelled phenomena. The polar motion excitation derived from GRACE's last release (GRACE Release 4) computed by different institutes: GFZ, CSR, JPL and GRGS were studied. These excitations functions were compared first to the mass term obtained from observed Earth's rotation variations, free of the motion term, and then to the mass term estimated from geophysical fluids models. There is the large improvement of the CSR solution. It was shown that the GRGS estimate is also well correlated with the geodetic observations. Significant discrepancies (about 20 mas), exist between the solutions of each computing centre (Fig. 3.4.1b). The source of these differences is probably related to the data processing strategy. The residuals computed after removing the geophysical models or the gravimetric solutions from the geodetic mass term were also analysed. It was shown that the residual excitation based on models is smoother than the gravimetric data, which are still noisy. They are, however, still comparable for the χ_2 component. Finally, for assessing the impact of the geophysical fluids models choice on the results obtained, two different oceanic excitation series were checked. Significant differences in the residuals correlations, especially for the χ_1 that is more sensitive to the oceanic signals were shown. Amplitudes and phases of the annual harmonic found in the gravity signal and in geodetic excitation as well as geophysical fluid models are consistent except for the GRGS solution, which has discordant phase value in the annual retrograde band. The semi-annual variations are three times smaller and not well determined by the least-square analysis. Future release of GRACE solution will probably lead to a better understanding of polar motion excitation and help to improve the geophysical model (Seoane et al., 2009).

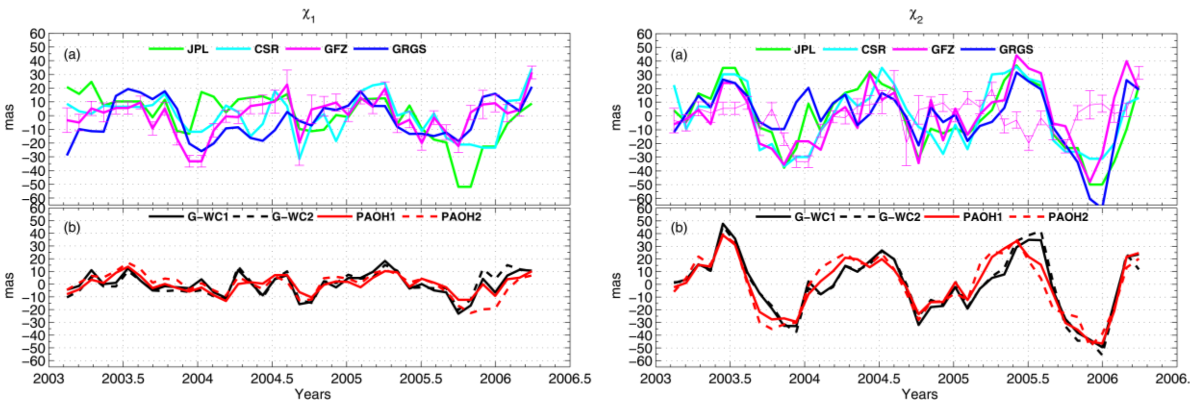

Fig. 3.4.1b. Mass part of excitation functions χ_1 (top left panel) and χ_2 (top right panel) obtained from gravity field variations by CSR, GFZ, GRGS, JPL. Mass part of excitation functions χ_1 (bottom left panel) and χ_2 (bottom right panel) obtained from geodetic observations and from geophysical fluids models.
G-WC1 – geodetic mass term estimated using the wind term from NCEP/NCAR reanalysis and the current term from SBO series; G-WC2 – geodetic mass term estimated using the wind term from NCEP/NCAR reanalysis and the current term from ECCO-GODAE series; PAOH1 – atmospheric (NCEP/NCAR) + oceanic (SBO) + hydrological (CPC) pressure term; PAOH2, atmospheric(NCEP/NCAR) + oceanic (ECCO-GODAE) + hydrological (CPC) pressure term

3.4.1.5. Hydrological Effects on Polar Motion Compared to GRACE Observations

The influence of the continental hydrologic signals on polar motion is not well known. Different models have been developed to evaluate and compare these effects to geodetic observations. Previous studies have shown large disagreements mainly due to the lack of global measurements of related hydrological parameters. The recent GRACE mission allows to compute excitation functions ($\chi_1 + i\chi_2$) of polar motion due to unmodelled variations like hydrological processes. This gravimetric-based excitation was compared to the excitation estimated from a hydrological model and from geodetic observations for the period February 2003 to December 2006. The residuals of the geodetic excitation are not fully explained, neither by the hydrological model nor by the gravimetric data. However, considering annual variations, there is a good agreement between geodetic and gravimetric excitations especially in amplitude. The hydrological model-based excitation has significant discrepancies for the real component of the excitation χ_1. It has been found that all series show common interannual oscillations of nearly 1.3 year period coinciding with Amazon's water storage variations (Seoane et al., 2008).

3.4.1.6. Patterns of Atmospheric Excitation Functions of Polar Motion from High-Resolution Regional Sectors

Regional values of equatorial components of the atmospheric excitation function of polar motion, which are proportional to the equatorial components of angular momentum (AAM), were computed at high spatial resolution in 3312 equal-area sectors from the surface pressure fields of the NCEP-NCAR reanalyses. The inverted barometer (IB) model of oceanic isostatic adjustment is applied to readjust the effective atmospheric pressure fields. The analyses determine regional sources of polar motion excitation by surface pressure variations in the atmosphere in different spectral bands, from subseasonal to interannual period ones (Fig. 3.4.1c). The large regions over Eurasia and North America were identified as principal atmospheric excitation sources for polar motion. The results revealed that atmospheric excitation over land regions in the northern middle latitudes, especially over Asia, is exceptionally strong, generally noted in previous studies, though without identifying detailed features. With the exception of the interannual period band the regional variations of atmospheric polar motion excitation are mostly significantly correlated with the global atmospheric and geodetic variations in many regions. In the case of the series data in the interannual period band, the correlation coefficients obtained are significant only over some region in Africa. The cross variability of regional and global signals, as measured by correlation, can be exceptionally strong, even close to one for the annual oscillation over land regions in the northern middle latitudes, especially over Asia. The structure of this variability relates largely to the high-altitude topography of Asia and North America. The Himalayan Mountains, for example, form a small minimum surrounded by larger values of covariance in a ring-like formation. For the other spectral scales, the excitations are important in the region over central Eurasia, as well as over the western part of North America. Correlation coefficients of semiannual oscillations reach 0.7 over Eurasia, and those of the other timescales are somewhat smaller. The pressure term of the atmospheric excitation of polar motion over the ocean, including the IB correction, although containing a clear annual signal, has weak amplitude on the considered spectral scales (Nastula et al., 2009).

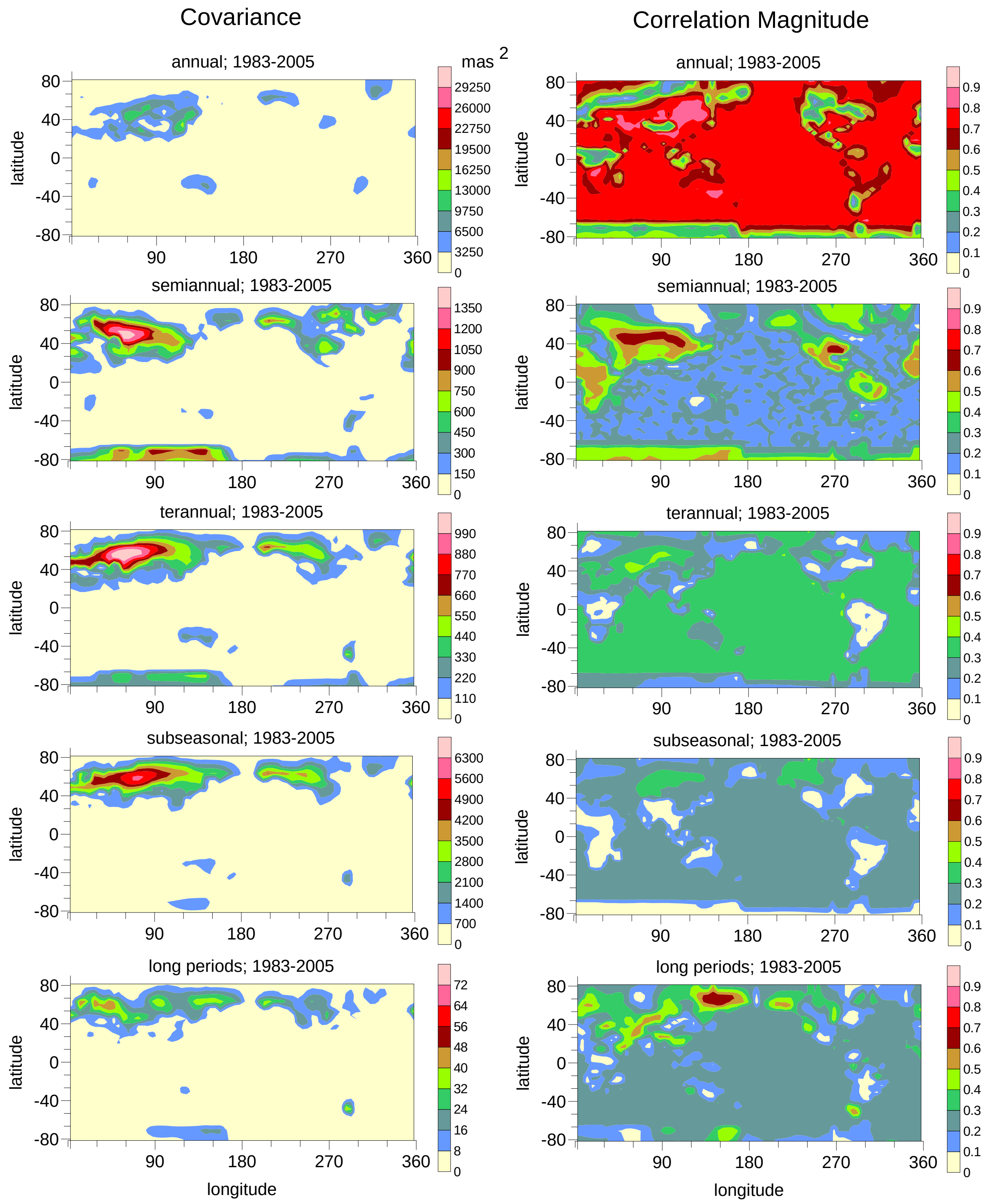

Fig. 3.4.1c. Maps of covariances and correlation coefficients magnitude between complex components ($\chi_1 + i\chi_2$) of regional atmospheric (pressure with the IB correction) and global geodetic excitation functions of polar motion, computed for different spectral bands

3.4.1.7. Spectral Characteristics of Polar Motion in the 2005–2006 and 1999–2000 Winters Seasons

Comparison of the polhody IERS C04 before and after removing oscillation shorter than 30 days shows that the loops in the winter seasons of 2005–2006 and 1999–2000 are caused by the oscillations of polar motion with periods shorter than 30 days (Fig. 3.4.1d). These short periodical oscillations of geodetic excitation function of polar motion were correlated with those of the atmospheric and oceanic excitation functions. There are high correlations with coefficients equal to 0.8÷0.9 during epochs when loops occur (Nastula and Kolaczek, 2007).

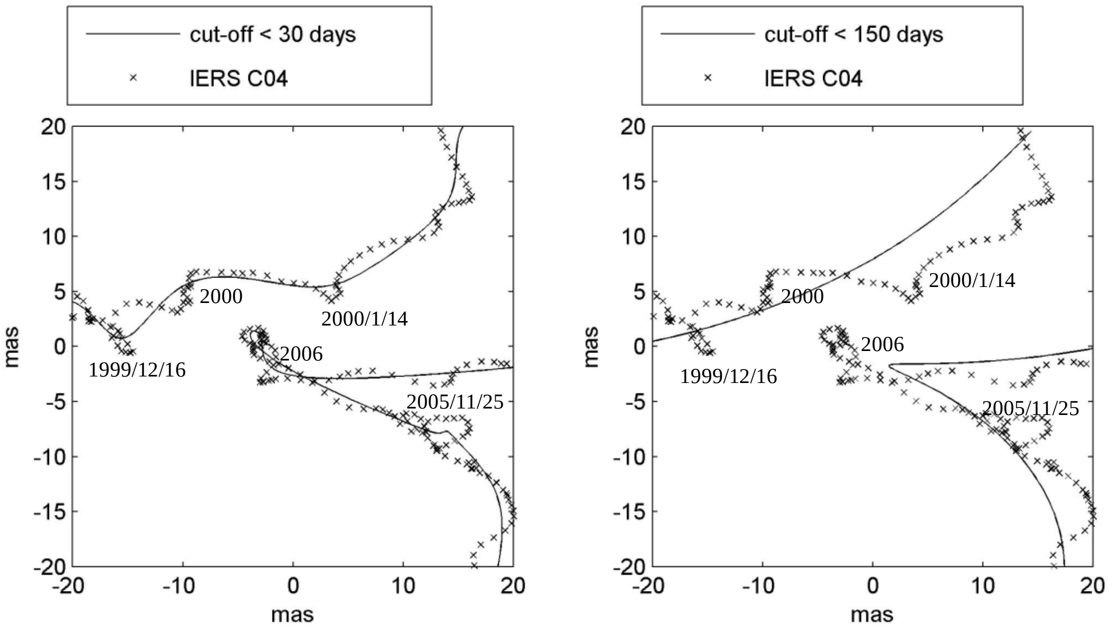

Fig. 3.4.1d. Comparison of polhody - IERS C04, (crosses) with polhody computed from the IERS C04 pole coordinates (solid line) after removing oscillations shorter than 30 days (left panel), and shorter than 150 days (right panel)

3.4.1.8. Time Variations of the Gravity Field of the Earth from Terrestrial and GRACE Data

The determination of time variations of gravity field with the use of both terrestrial geodetic methods (Barlik and Krynski, 2008) as well as satellite gravity missions was investigated. Data from the GRACE mission provide information on time variations of the gravity field, that can be interpreted in terms of time variations of geoid heights, sea level, ice cap thickness and inland water distribution with unprecedented temporal resolution. To achieve, however, accurate and reliable results (variations of geoid heights, hydrology, etc.) it requires the use of a method that suits to the goal and scale of investigations (global, regional, local). Geopotential models developed from GRACE data at different computation centres, i.e. CSR, GFZ, JPL, GRGS were analysed at the Institute of Geodesy and Cartography, Warsaw, in terms of their best suitability for the determination of time variations of the gravity field (Szelachowska et al., 2010). The effect of filtering method on the calculated results was investigated. Also the usefulness of the available hydrological models was analysed. The most suitable time series of geopotential models, filtering method for the determination of time variations of geoid heights over Europe as well as the hydrological data appropriate for comparing with GRACE models were indicated.

3.4.2. Prediction of Earth Rotation Parameters and Related Geophysical Parameters

3.4.2.1. Sea Level Change and its Prediction

The investigation carried out by at the Space Research Centre aims at estimating the minimum time span of data required to detect statistically meaningful trend in the global mean sea level change (Niedzielski and Kosek, 2007). It has been found that such estimates are vulnerable to the selection of altimetric data sets and to filtering approaches. Considering the global mean sea level change time series obtained from TOPEX/Poseidon and Jason-1 observations it has been found that after 4.3 years the trend in this data set is detectable with high probability close to 1 (Niedzielski and Kosek, 2007). This finding has been obtained for altimetric time series without annual and semiannual terms, but with high frequency signals shorter than 120 days.

Two specific techniques, i.e. extrapolation of the polynomial-harmonic deterministic model and extrapolation of the same model combined with the autoregressive forecast, have been applied in order to determine the medium-term predictions of sea level variability in the eastern tropical Pacific (Niedzielski and Kosek, 2009a, 2009b, 2009c). It has been found that applying stochastic autoregressive approaches allows to reduce the prediction errors. However, such a reduction is different for various episodes of the El Niño/Southern Oscillation (ENSO). It has been shown that for El Niño and La Niña events one cannot yield the accuracy typical for normal conditions. The possible interpretations can be sought amongst uneven amplitudes of harmonic oscillations and nonlinearities present in the stochastic residuals around the deterministic signal. First, the polynomial-harmonic model cannot adapt to the ENSO-driven amplitude alteration (Niedzielski and Kosek, 2009a, 2009c). Second, the linear autoregressive model is not able to capture the non-Gaussian stochastic dynamics controlled by the nonlinear heating of sea surface (Niedzielski, 2010a; Niedzielski and Kosek, 2010a). As a consequence, it has been recommended that nonlinear time series techniques should be applied in the process of forecasting stochastic residuals of sea level change in the ENSO-vulnerable regions. Furthermore, the spatial patterns of such nonlinearities in the entire equatorial Pacific have been investigated and interpreted (Niedzielski and Kosek, 2010a, 2010b).

3.4.2.2. Earth's Orientation Parameters, their Excitation and Prediction

The wavelet transform coherence and new time series analysis techniques, e.g. coherence amplitude, phase synchronisation, semblance and polarisation functions, have been used to compare the geodetic excitation of polar motion and the corresponding fluid excitation functions in the frequency domain as well as in the time-frequency domain. The fluid excitation functions consist of the equatorial components of atmospheric, ocean and land hydrology excitation functions or the sum of those functions. The greatest coherence and phase synchronisation occur between geodetic and atmospheric as well as between geodetic and ocean excitation functions, for the annual and semiannual oscillations. Phase synchronisation between the geodetic and atmospheric or ocean excitation functions are smaller than the corresponding coherence between them which means that decrease of the coherence cannot be explained by the variable phases of oscillations, but also variable amplitudes. Coherence and phase synchronisation between the geodetic and the sum of atmospheric and ocean excitation functions are greater than the coherence between the geodetic and atmospheric or ocean excitation functions and addition of land hydrology excitation function does not change the coherence or phase synchronization values significantly (Rzeszotko et al., 2009). The time-frequency polarisation functions of pole coordinates data and pole coordinates model data computed from fluid excitation functions showed that oscillations with periods greater than 230 days are prograde and almost circular; for shorter period oscillations they are still prograde but become more elliptic, and for oscillations with periods less than 25 days they become more retrograde than prograde (Fig. 3.4.2) (Kosek, 2010a).

The atmospheric, ocean and hydrologic excitation functions as well as their sums have been used to compute the *x*, *y* pole coordinates model data using numerical integration of differential equation for polar motion. It has been shown that the prediction errors of the IERS pole coordinates data from 1 to 100 days in the future are not caused by variable amplitudes and phases of the most energetic oscillations in these data but they are caused by wideband short period oscillations in joint atmospheric-ocean excitation functions (Kosek, 2010a, 2010b). The prediction errors of *x*, *y* pole coordinates and UT1 – UTC data cannot be explained by the most energetic monochromatic oscillations in these data with variable amplitudes and phases (Rzeszotko et al., 2008). The contribution of atmospheric and ocean excitation function to the mean prediction errors of the IERS pole coordinates data for prediction lengths less than 100 days are of the same order and explain about 60% of the total prediction error of the IERS pole coordinates data. The contribution of ocean excitation functions to the mean prediction errors of pole coordinates data for prediction lengths greater than 100 days becomes greater than the contribution of the atmospheric excitation function.

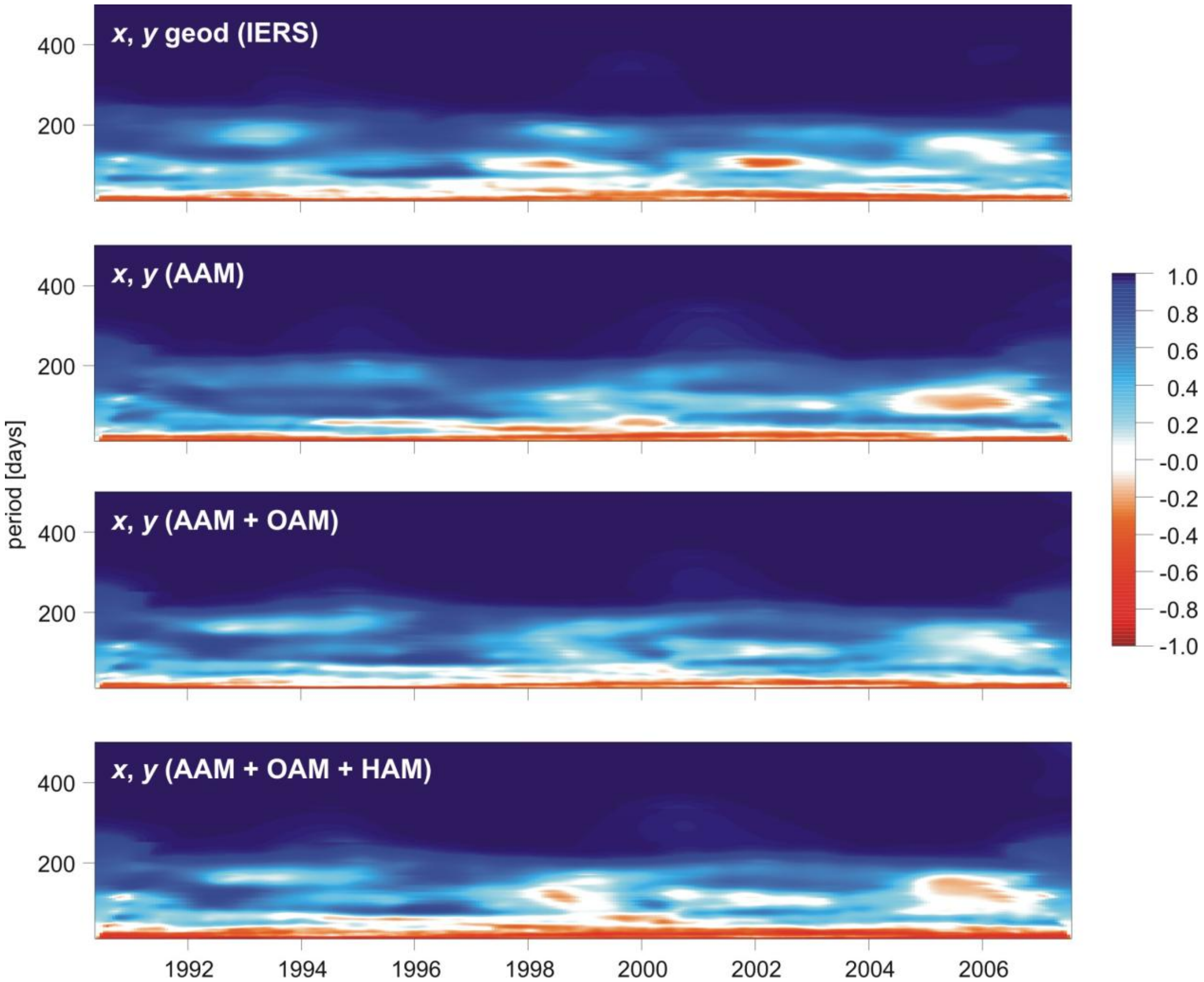

Fig. 3.4.2. The Morlet Wavelet Transform spectro-temporal polarization functions of *x*, *y* IERS pole coordinates data and the model pole coordinates data computed from fluid AAM, AAM+OAM and AAM+OAM+HAM excitation functions (blue colour denotes prograde and red colour retrograde oscillations and when colour fades to white oscillations become more elliptic)

The contribution of joint atmospheric-ocean excitation function to the mean prediction errors of the IERS pole coordinates data is at the level of 80÷90% (Kosek, 2010a; Kosek et al., 2009). Some considerable prediction errors of pole coordinates data in 1981–1982 are caused by wideband oscillations in ocean excitation functions and in 2006–2007 are caused by wideband oscillations in joint atmospheric-ocean excitation functions (Kosek, 2010b).

The land hydrology angular momentum excitation function has very small influence on polar motion prediction errors (Kosek et al., 2008b, 2009).

Short term EOP prediction errors of the EOP data can be much smaller when these data are smoothed by removing the high frequency components computed by the discrete wavelet transform band pass filter (DWTBPF). It means that these data should not be smoothed before predicting them (Kosek, 2010a, 2010b). The joint atmosphere and ocean angular momentum excitation of the pole coordinates data cause an increase of their prediction errors up to 100 days in the future, similarly as in the case of prediction errors of the pole coordinates model data created as the sum of Chandler, annual and shorter period frequency components computed by the DWTBPF (Kosek et al., 2008a). The reconstruction model of pole coordinates data with variable amplitudes and phases detected by the wavelet method was proposed also by Rzeszotko (2007).

Combining the length-of-day (LOD) and the axial component of atmospheric angular momentum (AAM χ_3) time series allows to forecast the Earth's rotation rate (Niedzielski and Kosek, 2008a). Such combination has been attained by using the bivariate autoregressive model for stochastic residuals. The resulting predictions of LOD or Universal Time (UT1 – UTC) time series are obtained as a combination of the polynomial-harmonic least squares model for deterministic components and the bivariate autoregressive model for stochastic residuals. This approach works particularly well in the case of UT1 – UTC predictions calculated during warm and cold ENSO episodes (Niedzielski and Kosek, 2008a, 2008b) and is said to be efficient amongst other forecasting tools (Kosek et al., 2008a). It is possible to address the issue of how fundamental statistical properties of LOD time series influence the prediction accuracy of the Earth's rotation rate (Sen et al., 2009; Niedzielski et al., 2009). It has been inferred that the underlying probability distributions of LOD data do not significantly depart from the normal distribution. Thus, the linear modelling and prediction have been confirmed to be appropriate for statistical processing of LOD or UT1 – UTC time series. The prediction accuracy has later been shown to be controlled by the intrinsic features of individual geodetic solutions EOPC04 and EOPC0405 (Niedzielski and Kosek, 2010c).

The EOP prediction results from the Earth Orientation Parameters Prediction Comparison Campaign (EOP PCC), which started in October 2005 and finished in March 2005, were calculated in Space Research Centre of the Polish Academy of Sciences using the same statistical methods. The respective comparison results were presented at different international conferences. It was shown that combined predictions are better than most individual predictions, predictions of UT1 – UTC must be based on the atmospheric angular momentum forecast data and the best techniques to predict polar motion variations are combinations of the least squares extrapolation and the autoregressive prediction (Kalarus et al., 2008, 2010). The main problem of any prediction technique is to predict simultaneously long and short period oscillations in EOP data and this problem has been solved using the combination of the wavelet transform decomposition with the autoregressive prediction. This prediction method was included in the EOP PCC for prediction of x, y pole coordinates data.

3.4.2.3. El Niño/Southern Oscillation (ENSO)

There are several global-scale processes in geodesy and geophysics for which ENSO is said to be one of a few key driving forces. Among others, they include sea level change, variable Earth's rotation rate and remote climatic or hydrologic teleconnections. In most cases, ENSO impact on these processes amends their regular variability.

Indeed, water redistribution in the equatorial Pacific due to Kelvin and Rossby waves and local thermosteric effects, both driven by ENSO, irregularly alter local sea level and hence make its predictions tough. The impact of ENSO on sea level change forecasting has been investigated (Niedzielski and Kosek, 2009a, 2009b, 2009c). The detailed explanation on how specific ENSO-related processes influence sea level change time series and its prediction has been proposed (Niedzielski, 2010a; Niedzielski and Kosek, 2010a, 2010b, 2010c) (for details see section on Sea level change and its prediction).

Moreover, the oscillation in question is correlated with the Earth's rotation rate variability. This is due to ENSO-driven decrease in the equatorial easterly trade winds during El Niño, consequent weakening of the Walker Circulation and strengthening of the Hadley Circulation. This results in strengthening of the west-east jet streams leading to the increase in AAM χ_3. The momentum of the atmosphere-solid Earth system is conserved and thus the Earth slows down resulting in the increase in LOD. Hence, ENSO may have a significant impact on the prediction accuracy of LOD and UT1 – UTC time series. This has been confirmed and thoroughly discussed (Niedzielski and Kosek, 2008a, 2008b) in the light of the bivariate prediction approach proposed by these authors. In addition, the detailed investigation on how ENSO is responsible for irregular variations in LOD/UT1 – UTC has been provided (Sen et al., 2009; Niedzielski et al., 2009) (for details see section on Earth's rotation rate and its prediction).

Another intriguing feature of ENSO is its ability to drive remote hydrometeorological teleconnections which transfer ENSO signal to regions located very far from the tropical Pacific. The ENSO-climate associations for Europe are said to be present only in winter and reveal rather weak strengths. However, there are only a few regional-scale investigations on ENSO-hydrology teleconnections for specific European countries. Various ENSO indices were examined along with hydrologic time series from SW Poland (Niedzielski, 2010b). It has been shown that there is a weak but significant link between ENSO signal and Polish surface hydrology. In addition, a detailed geophysical interpretation of such teleconnections was given (Niedzielski, 2010b). They have been said to control winter river discharges and negative lag-correlations have been found to be associated with snow cover variation. As a consequence, ENSO has been assumed to affect the generation of snow-melt peak flows in winter or early spring in Poland.

Niedzielski (2010c) has reviewed a recent book by Allan J. Clarke on ENSO dynamics.

3.5. EARTH TIDE INVESTIGATIONS IN POLAND IN 2007–2010

3.5.1. Monitoring of Vertical Component of Tidal Signals

Earth tides are monitored in the Astro-Geodetic Observatory of the Warsaw University of Technology in Jozefoslaw using LaCoste&Romberg (LCR) ET-26 gravimeter since January 2002 (Krynski and Rogowski, 2009). Continuous gravity measurements with LCR ET-26 gravimeter in Jozefoslaw Observatory from 2006-2009 were analysed (Rajner, 2010). Tidal record was used to create new model of the gravimetric Earth tides for Jozefoslaw Observatory with accuracy of 3.2 nm/s^2 (Fig 3.5.1) (Bogusz, 2008, 2009; Barlik et al., 2009a). The data acquired is analysed with one year spacing and the results are sent to the International Centre for Earth Tides. To obtain more reliable Earth tides model many environmental effects like tidal variations in the ocean, atmosphere and ground water level, influence of soil moisture changes, rainfalls and snowfalls should be taken into consideration. Monitoring of those effects started in 2004 (Bogusz, 2007a, 2007b) and were continued in 2008 (Bogusz, 2008). In 2008 the calibration factor of LCR ET-26 was determined using absolute gravity measurements with FG5-230 (Bogusz and Klek, 2008b, 2008c). The theoretical studies on the modulation of the tidal waves confirmed the annual periodicity changes of the amplitude and phase of particular tidal waves (Bogusz and Klek, 2008a). Research on the application of wavelet transform for the analysis tidal record was conducted. Analysis of the 3-year data record indicated the usefulness of the method for investigating frequencies and calculating the amplitude, but the determination of the phase shift is impossible which is its serious limitation (Araszkiewicz and Bogusz, 2008, 2010).

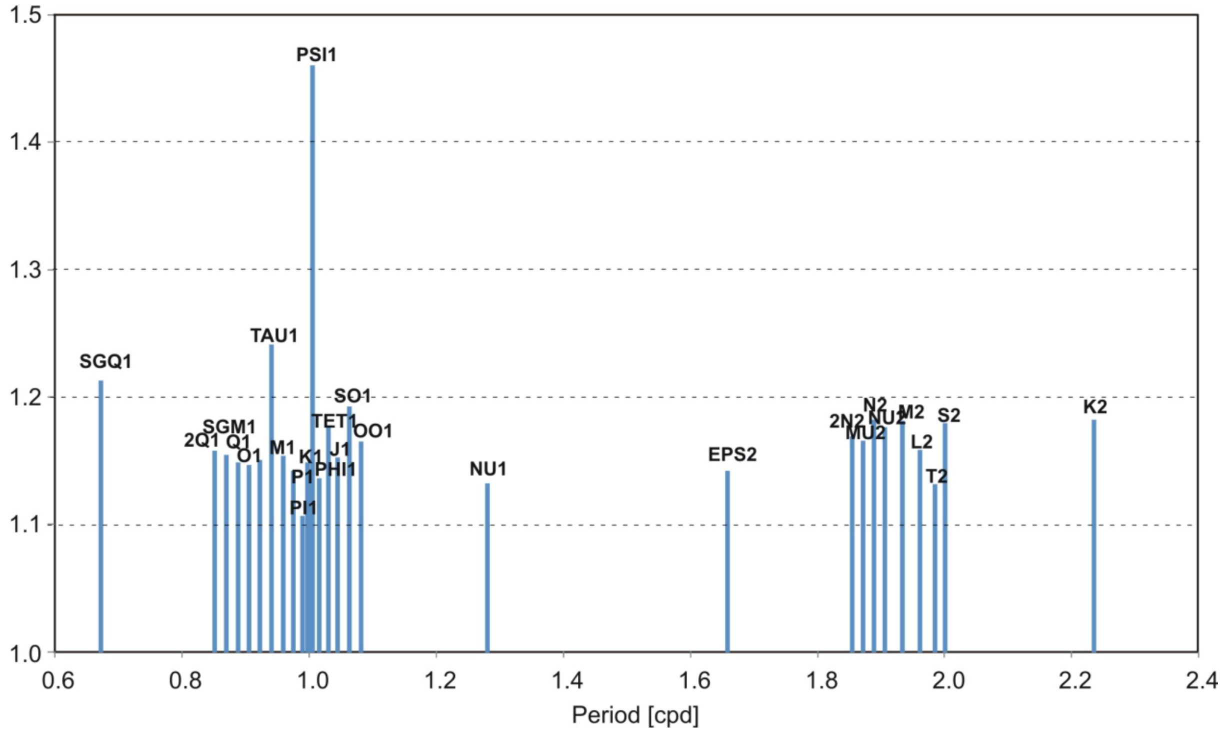

Fig. 3.5.1. Amplitude factors of the empirical tidal model based on observations of the Jozefoslaw Observatory

3.5.2. Monitoring of Horizontal Component of Tidal Signals

The Geodynamic Laboratory of Space Research Centre PAS in Ksiaz in Sudeten Mountains operates since 1974. Primarily there were installed quartz horizontal pendulums equipped with photographic system of registration that was later replaced with electronic registration. In 2002 in the Laboratory there were installed two long water-tube tiltmeters consisting of perpendicular tubes 65 and 83 m long, partially filled with water (Krynski and Rogowski, 2009). In 2007 the laboratory equipment was extended by the LCR G-648 gravimeter of tidal resolution for future investigation of Love’s numbers *h* and *k* for Sudeten Mountain area. The LCR G-648 gravimeter operates in the underground chamber equipped with the pillar for absolute gravimetry measurements. It allowed to carry on three sessions of absolute gravity measurements with help of the FG5 gravimeters. The measurements with LCR gravimeter were used for reduction of absolute gravity measurements (Kaczorowski and Olszak, 2010).

Investigations of systematic and long periodic plumb line variations were conducted (Fig. 3.5.2) (Kaczorowski, 2007, 2008, 2009). Results of previous investigations, including short period (non-tidal) plumb line variations associated with phenomenon of the Earth free oscillations were briefly presented in the Polish National Report on Geodesy 2003–2006 to the IUGG (Krynski, 2007).

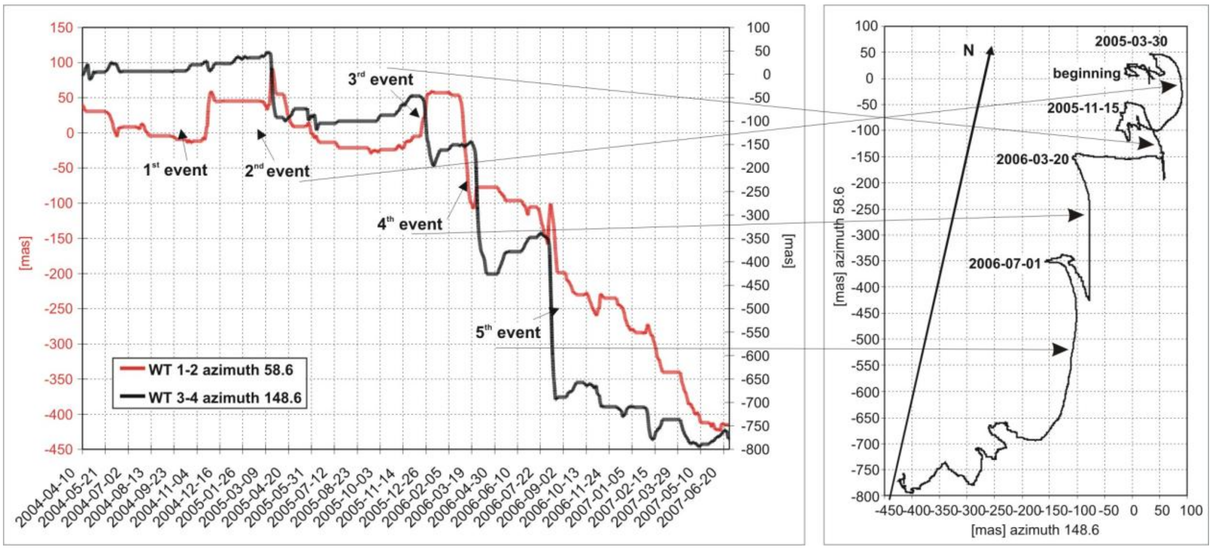

Fig. 3.5.2. Non-tidal signal observed by long water-tube tiltmeter in period 2004–2007

3.5.3. Tidal Signals in GNSS Data

Time series of station coordinates obtained using the precise network solution of GNSS data was analysed by the team of the Military University of Technology. Frequency analysis applied showed the existence of tidal components in GNSS-derived coordinates (Figurski et al., 2009). In particular, diurnal and sub-diurnal oscillations were found in the time series of those coordinates (Figurski et al., 2010a).

3.6. MONITORING OF GEODYNAMIC PHENOMENA

3.6.1. Monitoring of the Earth's Crust Deformations

Data from third (1974–1982) and fourth (1999–2002) levelling campaigns were analysed at the University of Warmia and Mazury in terms of the vertical crustal movement. The relative land uplift and the land uplift referred to the mean sea level were computed and modelled by the least square collocation method. The results obtained were compared with those published in 1986 by the Institute of Geodesy and Cartography (Krynski and Rogowski, 2007).

Analysis of existing geodetic networks had been carried out within the project of the determination of deformation of the Earth's crust in Poland (Bogusz et al., 2008). The aim was to determine the potential for their usage within the project.

In a frame of agreement between the Military University of Technology (MUT) and the Polish Head Office of Geodesy and Cartography, the Centre of Applied Geomatics (CAG) of MUT processes the data and analyses solutions to ensure additional control and monitoring of the ASG-EUPOS system (Figurski et al., 2010c) (for details concerning the ASG-EUPOS system see Chapter 1). The research on the application of GNSS solutions within short observational periods to geodynamic investigations have been performed in the CAG (Araszkiewicz et al., 2010). The data collected at the ASG-EUPOS system's sites may also contain information about the local dynamics. The research on the Earth's crust response to the tidal forces was carried out (Araszkiewicz et al., 2009). That gave the opportunity of validation of the solid Earth tides model used in the Bernese GPS software.

Basing on GPS data, the CAG conducts geodynamical research using the time and time-frequency analyses (Figurski et al., 2010b).

To separate absolute changes in sea level from vertical land movements tide gauges are often co-located with Continuous GPS (CGPS) network. Data from the CGPS network of the European Sea Level Service from the period of 2000–2003 were analysed (Kierulf et al., 2008). Independent results from six different analysis centres obtained using three different GPS processing softwares and a number of different analysis strategies were compared. The comparison reveals large differences in the day-to-day variations of the coordinate time series and also in the seasonal cycle contained in these. The trends show systematic differences, depending on software and strategy used. To a large extent, the latter deviations can be explained by differences in the realisation of the reference frame, while some parts may be due to other, as yet, unidentified contributions. The results obtained suggest that the reference frame and its relation to the centre of mass of the Earth system may be the main limitation in achieving the accuracy goal for the secular velocity of vertical land motion.

The variation of coordinates of the WROC EPN/IGS Station was modelled at the Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences, using time series of the EPN weekly solutions from the period of 10 years. Three models of the point's movement were assumed: a linear model with invariable velocity monotonous movement (using robust estimation for linear model coefficients determination); model in which point location periodically changes and a model with episodic displacement, or with coordinate jump. It has been shown that a linear model parameters consist of mainly Euro-Asiatic continental plate velocity. Residual (intraplate) velocity remains up to 1.5 mm/y NW after removing plate movement. Periodic changes of WROC station location were confirmed by results of spectral analysis. Periodical components for all coordinates have a character of long period oscillations with amplitude 1.2 mm/y and 2.2 mm/y for horizontal coordinates, N and E respectively, and 3.8 mm/y for vertical one. Coordinate jumps (episodic displacements) were not detected. The usefulness of this stations for geodynamic studies was confirmed (Kontny et al., 2007).

Study of land deformations in urban area was also conducted at the University of Warmia and Mazury. The concept of using static GPS measurements for the determination of vertical and horizontal land deformations in urban area was discussed (Baryła et al., 2007a). The results of the first GPS measurement campaign in the Main and Old City of Gdańsk were presented (Baryła et al., 2007b).

3.6.2. Absolute Gravity Measurements for Geodynamics Research

Precise absolute gravity measurements with the FG5-230 of the Warsaw University of Technology have been carried out for geodynamics research since 1990. at five stations in Poland: Borowiec (Borowiec Astrogeodynamic Observatory of the Space Research Centre, Polish Academy of Sciences), Giby (fundamental station of national gravity control), Jozefoslaw (Astrogeodetic Observatory of the Warsaw University of Technology), Lamkowko (Satellite Observatory of the University of Warmia and Mazury), Ojcow (Seismic Observatory of the Polish Academy of Sciences) (Fig. 3.6.2a) (Krynski and Rogowski, 2008).

Information connected with soil moistures have been included into the analysis. The results obtained indicate the decrease of gravity at each station. A rate of gravity change can be interpreted in terms of hydrological effects and probably, up to certain extent, in terms of vertical displacements of gravity stations. Obtained results in comparison with previous determinations indicate the decrease of gravity for about 15 μGal during 10÷12 years (Barlik et al., 2009b; Krynski and Rogowski, 2009; Walo, 2010).

Fig. 3.6.2a. Location of gravity stations in Poland included in the geodynamics research

In the framework of scientific cooperation between the Finnish Geodetic Institute and the Institute of Geodesy and Cartography (IGiK), Warsaw, about 60 stations of the Finnish gravity network (Fig. 2.3.2 in Chapter 2) were surveyed with the A10-020 gravimeter of the IGiK in four campaigns in 2009 and 2010 (Krynski and Sekowski, 2010; Krynski and Rogowski, 2010; Mäkinen et al., 2010a). The gravity changes were determined, and their comparison with estimates from other sources and from PGR models was made. First results obtained with the data from 10 points of the Finnish gravity network (Fig. 3.6.2b) have already been presented (Mäkinen et al., 2010b).

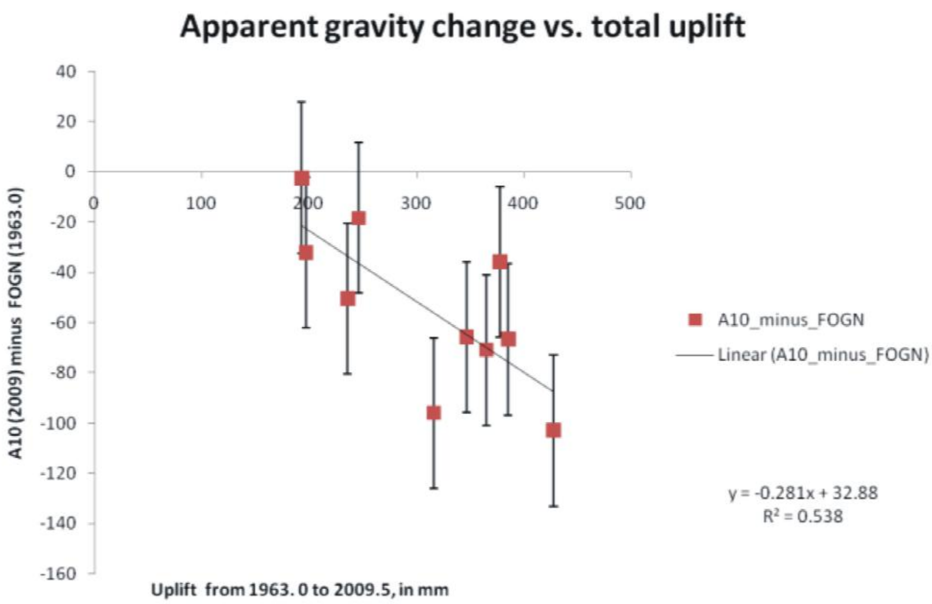

Fig. 3.6.2b. Apparent gravity change at 10 stations of the Finnish Gravity Control Network re-surveyed with the A10-020 in 2009 and 2010 vs. total uplift

3.6.3. Plumb Line Variations From the Long Time Series of Astronomic Observations

The investigations on the use of long time series of astronomic observations from the Borowa Gora Geodetic-Geophysical Observatory of the Institute of Geodesy and Cartography, Warsaw, for modelling time variations of the direction of the plumb line were continued. A new method of modelling time variations of astronomical longitude in terms of the sum components modulated in the amplitude as well as in phase was developed and verified with the use of data from time span of 1986.0–2009.0 (Zanimonskiy et al., 2009).

3.6.4. Tectonic Plate Motion Estimated from the SLR Data

The influence of the number and localization of station on accuracy of the estimated tectonic plate motion parameters was investigated (Kraszewska and Rutkowska, 2007). The study was based on the shifts of station positions published in ITRF2000 for SLR (ITRF2000_SLR.SSC) and for GPS (ITRF2000_GPS.SSC) techniques, separately. The Eurasian, North-American, Australian and Pacific plates were analysed with the use of a sequential method. For the Eurasian plate, ten SLR stations and thirty GPS stations were investigated. The GPS stations were split up into three groups, each containing ten stations with the random distribution. The estimated parameters of the plate rotation vector (latitude Φ, longitude Λ) and their errors (m_{Φ}, m_{Λ}) are shown in Figure 3.6.4. There is quite good agreement of the adjusted parameters for three GPS groups of stations. The difference between results from SLR and GPS is smaller than 2º for Φ, and 3º for Λ. The stability of the estimated parameters was reached for eight stations. Similar results were obtained for other plates leading to the conclusion that the eight randomly distributed stations are sufficient for representing the plate motion.

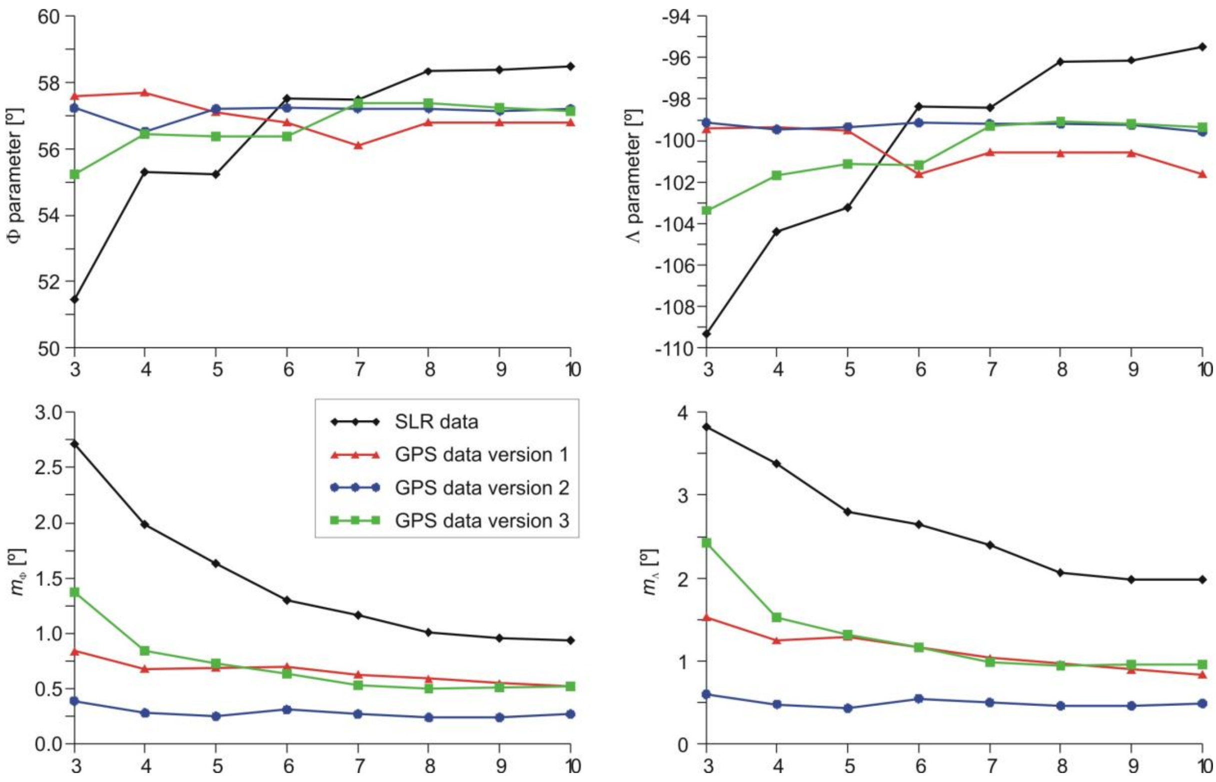

Fig. 3.6.4. Parameters Φ (upper left) and Λ (upper right) of the tectonic plate motion and their errors m_{Φ} (lower left) and m_{Λ} (lower right) estimated from the SLR and GPS techniques (Eurasian plate)

3.6.5. Estimation of the Love and Shida Numbers from the SLR Data

The second degree Love and Shida numbers h_2 and l_2 can be estimated using SLR data. The study was based on SLR data from the LAGEOS 1, LAGEOS 2 and STELLA satellites observed during 2 years from 3 January 2005 until 1 January 2007 by 17 globally distributed ground stations (Rutkowska and Jagoda, 2009, 2010a, 2010b). Raw SLR data for satellite passes above stations were compressed to normal points which further were processed in 30-day arcs for LAGEOS 1 and LAGEOS 2, and 7-day arcs for STELLA. Computations were performed using the GEODYN II software provided by NASA/GSFC.

The adjustment of the global elastic parameters h_2 and l_2 was done by applying the sequential method (Rutkowska and Jagoda, 2009) (Fig. 3.6.5).

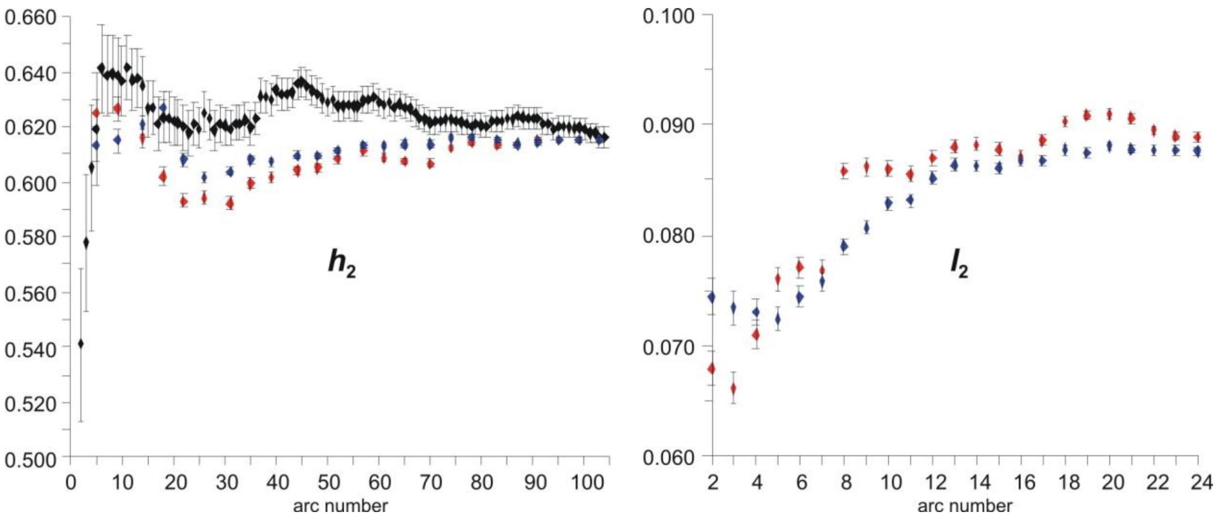

Fig. 3.6.5. The sequential solution for the Love numbers h_2 and l_2 based on LAGEOS 1 (red), LAGEOS 2 (blue) and STELLA (black) data

Adjustment of the elastic parameters achieved stability at about 2 years time interval. Three independent analyses for LAGEOS 1, LAGEOS 2 and STELLA converge to the values shown in Table 3.6.5.

Table. 3.6.5. Love number h_2 and Shida number l_2 estimated from the SLR data

Satellite	Number of normal points	h_2		l_2	
		estimate	std dev.	estimate	std dev.
LAGEOS 1	73692	0.6151	0.0008	0.0886	0.0003
LAGEOS 2	71266	0.6152	0.0008	0.0881	0.0003
STELLA	48509	0.6151	0.0037	Not estimated	

3.6.6. Monitoring Glacier Surface with GPS Technique

During the XXVIII Polar Expedition of the Institute of Geophysics of the Polish Academy of Science to Spitsbergen the quasi-continuous GPS monitoring of the Hans Glacier surface was conducted to determine the glacier velocity and its height changes (Walo et al., 2007). Static survey in 30 minute observing sessions repeated every 3h was applied to minimize power consumption. The experiment lasted 9 months (15 September 2005 – 30 June 2006) what ensures a representative data for analysis of the glacier behaviour in different seasons.

The results obtained indicate the glacier height decrease of 1÷2 cm/day in average. It has been shown that the surveying technology applied provides valuable information on the glacier behaviour for glaciologists to better understand the phenomena occurring on the glacier in different seasons.

3.7. SECULAR VARIATIONS OF THE 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. Changes of the magnetic field of the Earth in the period 1985–2005 on the basis of changes of declination and the length of the total intensity vector **F** were investigated (Welker, 2007a, 2007b). The results obtained confirm the necessity of continuous examination of the geomagnetic field and of conducting systematic measurements within networks of secular magnetic stations in Europe.

The common research on the geomagnetic field space and time distribution in Europe as well as collecting data and its analysis were undertaken in the framework of the international project MagNetE (Magnetic Net For Europe). The project constitutes the grounds for theoretical works on geomagnetic field models and their parameters. It is also the basis for studying the genesis of the geomagnetic field secular variations and their mechanism. The maps of isopors developed present secular variations of the magnetic declination *D*, horizontal intensity vector **H** and the total intensity vector **F** of the geomagnetic field, in the intervals 1995–2000 and 2000–2005. In several regions of Europe it has been found the unexpectedly large secular variation anomalies. Anomalies of so high frequency and large amplitude cannot exist. They are probably caused by data errors, which may have different sources (Sas-Uhrynowski and Welker, 2008, 2009).

Variations of Earth's magnetic field were investigated in collaboration of the Institute of Geodesy and Cartography, Warsaw, with the Vilnius Gedyminas Technical University, with the use of data from two magnetic observatories: Belsk and Hel. Correlation of the components of geomagnetic field were analysed (Skeivalas et al., 2008).

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4. POSITIONING AND APPLICATIONS – ADVANCED SPACE TECHNIQUES[4]

4.1. INTRODUCTION

This part of the Polish National Report on Geodesy is the quadrennial report of works on advanced space techniques performed in Poland in a period from 2007 to 2010. It contains a summary of investigations such as operational activity of SLR and GNSS EPN/IGS permanent stations, time transfer and time comparison, data analysis and orbit determination including the activity of Local Analysis Centres, modelling of ionosphere and troposphere, GNSS applications including positioning of moving objects, and activities within Galileo Program. The activities concerning advanced space techniques were conducted mainly in the following research centres, listed in an alphabetic order:

- Department of Applied Geomatics, Military University of Warsaw;
- Department of Engineering Surveying and Civil Engineering, AGH University of Science and Technology in Cracow;
- Department of Geodesy and Geodetic Astronomy, Warsaw University of Technology;
- Department of Geodesy and Geodynamics, Institute of Geodesy and Cartography in Warsaw;
- Department of Planetary Geodesy, Space Research Centre, Polish Academy of Sciences in Warsaw;
- Department of Satellite Geodesy and Navigation, University of Warmia and Mazury in Olsztyn;
- Institute of Geodesy, University of Warmia and Mazury in Olsztyn;
- Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences;

Annual national reports to the IAG Sub-commission for EUREF (Krynski and Rogowski, 2007, 2008, 2009, 2010) contain the extensive information on the activities concerning positioning and applications – advanced space techniques in Poland within the reported period.

The bibliography of the related works is given in references.

4.2. SATELLITE LASER RANGING

The Satellite Laser Ranging station in Astrogeodynamic Observatory of the Space Research Centre of the Polish Academy of Sciences at Borowiec (ILRS 7811) (Fig. 4.2.1) acquired, produced and delivered during 2007–2010 almost 600 000 observed raw points to the scientific user community, tracking 1476 successful passes of 27 satellites in the framework of the International Laser Ranging Service (ILRS) and EUROLAS Consortium. Average single shot RMS, normal points RMS and orbital analysis provided by Analysis Centres that reflect the quality of SLR data provided by Borowiec SLR station, equal to 25 mm, 3 mm and 15 mm, respectively. The results of observations are available at Crustal Dynamics Data Information System NASA (http://cddis.nasa.gov/slr_datasum.html) and EUROLAS Data Center (www.dgfi.badw-muenchen.de/edc/). The data of the Borowiec SLR station supported

[4] The content of the chapter was compiled by **Jerzy B. Rogowski** with the use of the material provided by Jaroslaw Bosy, Stanislaw Cellmer, Mariusz Figurski, Leszek Jaworski, Andrzej Krankowski, Michal Kruczyk, Jan Krynski, Leszek Kujawa, Tomasz Liwosz, Jerzy Nawrocki, Jerzy B. Rogowski, Stanislaw Schillak, and Pawel Wielgosz.

research programs and was used for orbit calculations and the determination of geodynamic parameters by many institutions and international organizations (Krynski and Rogowski, 2007, 2008, 2009, 2010).

Fig. 4.2.1. Telescope of the satellite laser ranging system at Borowiec

The activity of the Borowiec SLR station was limited in 2007–2009 by significant modernization of both hardware and software of the SLR system. First, from November 2006 through March 2007 the laser pavilion was renovated and an air-conditioning system was installed to ensure better operating conditions. Than, in 2007 the telescope’s transmission and receiving optical systems were modernized (Schillak, 2008). In 2008 a new Hamamatsu MCP-PMT detector was installed, system software was upgraded, and new control computers and a new gating system were introduced (Schillak et al., 2009). Finally, in 2009 the Event Timer A032-ET, parallel to Stanford Time Interval Counter, with a new operating software was installed. The new data format – Consolidated Laser Ranging Data Format (CRD) was introduced. The last two changes enabled the participation of the Borowiec SLR station in the time scales comparison using laser technique (Time Transfer by Laser Link-T2L2). The modernization of the Borowiec SLR system significantly restricted, or at times, prevented, regular laser ranging observations.

The Borowiec SLR staff organized and hosted the 16th International Workshop on Laser Ranging, held on 13 –17 October 2008 in Poznan. Over 140 delegates attended the workshop, giving 125 oral and poster presentations (Schillak, 2009). The Workshop Proceedings and presentations are also available on the websites: http://cddis.gsfc.nasa.gov/lw16/ or http://www.astro.amu.edu.pl/ILRS_Workshop_2008/index.php.

4.3. GNSS PERMANENT STATIONS

The number of GNSS permanent EPN stations operating in Poland has been increased since 2007 from 10 to 18 in 2010 (Krynski and Rogowski, 2007, 2008, 2009, 2010) (Fig. 4.3.0).

Fig. 4.3.0. EPN/IGS permanent GNSS stations in Poland (2010)

4.3.1. Biała Podlaska (BPDL) Permanent GPS/GLONASS Station

The permanent GPS/GLONASS station BPDL (IERS domes number 12223M001) operates since December 2007 in the City Office in Biala Podlaska. The responsible agency is the Head Office of Geodesy and Cartography, Warsaw. The station is equipped with the Trimble NETR5 receiver and TRM55971.00 antenna installed on the roof of the building (Fig. 4.3.1). The station started operating as a permanent station in the EPN network in June 2008.

Data from BPDL station in 30 s rate in 24h and 1h blocks are available at BKG, and OLG GNSS Data Centres. Data in 5 s and 1 s rates are transferred to the Polish ASG-EUPOS Network Managing Centre in Warsaw**.**

Meteorological data collected in 10 min sampling interval using MET4A meteorological sensors are transferred in RINEX METEO format with GNSS data.

Fig. 4.3.1. BPDL Antenna monumentation

4.3.2. Borowa Gora (BOGI) Permanent GPS/GLONASS Station

BOGI permanent GPS/GLONASS station (IERS domes number 12207M003) operates since January 2001 at the Geodetic-Geophysical Observatory Borowa Gora of the Institute of Geodesy and Cartography (IGiK), Warsaw, and since September 2002 is a permanent station of both EPN and IGS networks. The Observatory is located 35 km north of Warsaw. The antenna ASH701945C_M SNOW of the station is installed at the concrete pillar of the EUREF 0217 site, about 100 m from the main building of the Observatory (Fig. 4.3.2). The Javad Eurocard receiver originally installed at BOGI station has later been replaced by Javad JPS Legacy and then by Javad JPS E_GGD. Since January 2010 a new GPS/GLONASS receiver Javad TRE_G3T DELTA is operating at the station.

The external rubidium frequency standard FTS-74 is a source of input frequency of 5 MHz for the receiver.

Data from BOGI in 30 s rate in 24h and 1h blocks are available at BKG, OLG GNSS as well as IGiK servers. Independently, GNSS data from BOGI station in 5 s and 1 s rate are provided since September 2008 to the Polish ASG-EUPOS Network Managing Centre in Warsaw. The real time data stream from BOGI is also available as Ntrip within the EUREF IP project.

Meteorological data collected in 10 min interval using LB-710HB meteorological sensor and transformed to the RINEX METEO format are transferred with GNSS data. The second meteorological sensor MET4A installed in 2008 the Observatory provides meteorological data in 10 min interval to the ASG-EUPOS system. The ARP point has directly been levelled to the first order levelling benchmark.

Fig. 4.3.2. BOGI antenna location and monumentation

4.3.3. Borowa Gora (BOGO) Permanent GPS/GLONASS Station

BOGO permanent GPS/GLONASS station (IERS domes number 12207M002) operates at the Geodetic-Geophysical Observatory Borowa Gora of the Institute of Geodesy and Cartography (IGiK), Warsaw since June 1996. In 2010 the Observatory celebrated its 85 anniversary. The station BOGO tracks GPS satellites since July 1996 in the framework of the EPN network. The Observatory is located 35 km north of Warsaw. The antenna ASH700936C_M SNOW of the station is installed on the unused chimney above the roof of the Observatory main building, directly connected to the ground (Fig. 4.3.3). In 11 January 2007 the GPS/GLONASS receiver TPS EUROCARD S/N MT312310851 replaced the original Ashtech Z-12 receiver. Since September 2010 a new GPS/GLONASS receiver TPS Eurocard is operating at the station. No antenna has been changed.

The external rubidium frequency standard FTS-74 is a source of input frequency of 5 MHz for the receiver.

Data from BOGO in 30 s rate in 24h and 1h blocks are available at BKG, OLG GNSS as well as IGiK servers. Until September 2008 data in 5 s rate in 1h blocks were provided to the ASG-PL Pilot Project Managing Centre in Katowice.

Meteorological data collected in 10 min interval using LB-710HB meteorological sensor and transformed to the RINEX METEO format are transferred with GNSS data. The ARP point has directly been levelled to the first order levelling benchmark. Tidal and absolute gravity observations are periodically made in the Observatory. The ground water is also measured in the Observatory. The magnetic field components are permanently registered and elaborated in the Observatory. The Station is a part of the ECGN network.

Fig. 4.3.3. BOGO antenna location and monumentation

4.3.4. Borowiec (BOR1) Permanent GPS/GLONASS Station

The permanent GPS/GLONASS station BOR1 (IERS domes number 12205M002) operates since January 1994 at the Borowiec Astrogeodynamical Observatory of the Space Research Centre of the Polish Academy of Sciences, 20 km south-east of Poznan. It became a permanent station of the IGS network since January 1994, and of the EPN network – in December 1995. Initially the TurboRogue SNR 8000 receiver with AOAD/M_T antenna was installed at BOR1station (Fig. 4.3.4). The original antenna was replaced with identical one in May 1999. Since July 2007 a new TRIMBLE NetRS receiver operates at BOR1 station.

The external caesium frequency standard is a source of input frequency of 5 MHz for the receiver.

Data from BOR1 in 30 s rate in 24h and 1h blocks is available at BKG, OLG GNSS GOPE Data Centres. Until September 2008 data in 5 s rate in 1h blocks were provided to the ASG-PL Pilot Project Managing Centre in Katowice. Since September 2008 GNSS data from BOR1 station in 5 s and 1 s rate are provided to the Polish ASG-EUPOS Network Managing Centre in Warsaw.

Meteorological data are collected using HPTL.3A and ARG 10/STD meteorological sensors with data sampling interval 30 min and in the RINEX METEO format are transferred with GNSS data.

SLR observations are permanently performed in the Observatory within the ILRS. As the active SLR station BOR1 has been included in the network of the IGS Reference Frame realization IGS2000 and retained in IGS2005. Absolute gravity observations are periodically made in the Observatory.

Fig. 4.3.4. BOR1 antenna location and monumentation

4.3.5. Bydgoszcz (BYDG) Permanent GPS/GLONASS Station

The permanent GPS/GLONASS station BYDG (IERS domes number 12224M001) operates since December 2007 in the City Office in Bydgoszcz. The responsible agency is the Head Office of Geodesy and Cartography, Warsaw. The station is equipped with the Trimble NETR5 receiver and TRM55971.00 antenna installed on the roof of the building (Fig. 4.3.5). The station started operating as a permanent station in the EPN network in June 2008.

Data from BYDG station in 30 s rate in 24h and 1h blocks are available at BKG, and OLG GNSS Data Centres. Data in 5 s and 1 s rates are transferred to the Polish ASG-EUPOS Network Managing Centre in Warsaw**.**

Meteorological data collected in 10 min sampling interval using MET4A meteorological sensors are transferred in RINEX METEO format with GNSS data.

Fig. 4.3.5. BYDG Antenna monumentation

4.3.6. Cracow (KRAW) Permanent GPS Station

The permanent GPS station KRAW (IERS domes number 12218M001) equipped with the Astech μZ-12 CGRS receiver operates since June 2000. It is a permanent GPS station of the EPN network since January 2003. Its Ashtech choke ring ASH701945C_M SNOW antenna is located on the roof of the building of the Faculty of Mining Surveying and Environmental Engineering of the AGH University of Science and Technology(AGH-UST) (Fig. 4.3.6).

Data from KRAW in 30 s rate in 24h and 1h blocks is available at BKG, OLG GNSS GOPE Data Centres. Until September 2008 data in 5 s rate in 1h blocks were provided to the ASG-PL Pilot Project Managing Centre in Katowice. Since September 2008 GNSS data from KRAW station in 5 s and 1 s rate are provided to the Polish ASG-EUPOS Network Managing Centre in Warsaw.

Meteorological data collected in 15 min interval using LB-710 meteorological sensor and transformed to the RINEX METEO format are transferred with GNSS data.

KRAW station also participates in the EUREF-IP Project. Since May 2003 GPS data stream from station KRAW are broadcasted via BKG's Ntrip Caster. In early 2005 the Ntrip Caster software was installed at the Faculty of Mining Surveying and Environmental Engineering, and since February 2005 data stream from KRAW is also broadcasted via AGH's NtripCaster (http://gps1.geod.agh.edu.pl:2101).

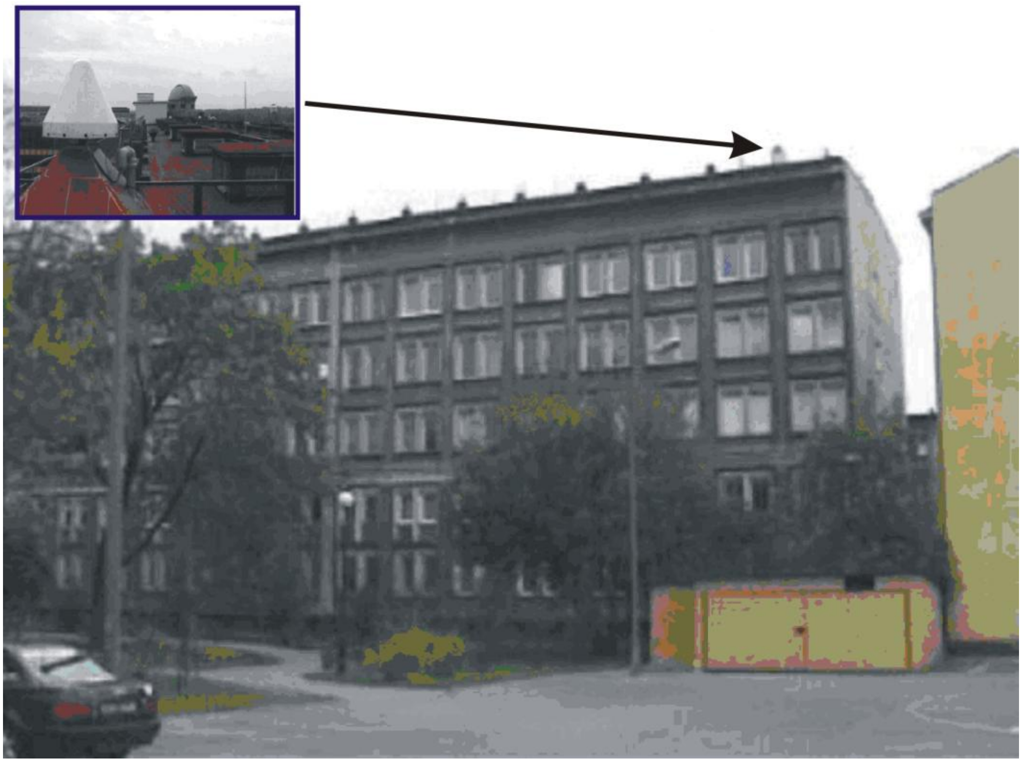


Fig. 4.3.6. KRAW antenna location and monumentation

4.3.7. Cracow (KRA1) Permanent GPS/GLONASS Station

The permanent GPS/GLONASS station KRA1 (IERS domes number 12218M002) equipped with the Trimble NetR5 receiver operates since January 2010. It is a permanent GPS station of the EPN network since March 2010. Its TRM57971.00 antenna with no radome is located on the roof of the building of the Faculty of Mining Surveying and Environmental Engineering of the AGH University of Science and Technology (Fig. 4.3.7).

Data from KRA1 in 30 s rate in 24h and 1h blocks is available at BKG, OLG GNSS GOPE Data Centres. Data from KRA1 station in 5 s and 1 s rate are provided to the Polish ASG-EUPOS Network Managing Centre in Warsaw.

Meteorological data collected in 10 min sampling interval using MET4A meteorological sensors are transferred in RINEX METEO format with GNSS data.

Fig. 4.3.7. KRA1 antenna monumentation

4.3.8. Gorzow Wielkopolski (GWWL) Permanent GPS/GLONASS Station

The permanent GPS/GLONASS station GWWL (IERS domes number 12225M001) operates since December 2007 in the City Office in Gorzow Wielkopolski. The responsible agency is the Head Office of Geodesy and Cartography, Warsaw. The station is equipped with the Trimble NETR5 receiver and TRM55971.00 antenna installed on the roof of the building (Fig. 4.3.8). The station started operating as a permanent station in the EPN network in June 2008.

Data from GWWL station in 30 s rate in 24h and 1h blocks are available at BKG, and OLG GNSS Data Centres. Data in 5 s and 1 s rates are transferred to the Polish ASG-EUPOS Network Managing Centre in Warsaw.

Meteorological data collected in 10 min sampling interval using MET4A meteorological sensors are transferred in RINEX METEO format with GNSS data.

Fig. 4.3.8. GWWL antenna monumentation

4.3.9. Jozefoslaw (JOZE) Permanent GPS Station

The permanent GPS station JOZE (IERS domes number 12204M001) is operates since August 1993 at the Jozefoslaw Astrogeodetic Observatory 15 km south of Warsaw and belongs to the Department of Geodesy and Geodetic Astronomy of the Warsaw University of Technology (WUT). In 2008 the Observatory celebrated 50 anniversary of observation activity (Rogowski and Kolaczek, 2008). In December 1995 JOZE started operating as a permanent GPS station of the EPN network. It operates also as a permanent station of the IGS network. The Trimble 4000SSE receiver originally installed at JOZE station has been replaced in May 2009 by Trimble 4000SSI receiver. The TRM14532.00 antenna (Fig. 4.3.9) remains the same from the beginning of operation of JOZE station.

The external rubidium frequency standard TEMEX NEUCHATEL TIME SA is a source of input frequency of 10 MHz for the receiver.

Data from JOZE in 30 s rate in 24h and 1h blocks are available at BKG, OLG GNSS, GOP, CDDIS, and IGNI Data Centres as well as at WUT server.

Meteorological data collected in 30 min interval using LB-710RHMS meteorological sensor and transformed to the RINEX METEO format are transferred with GNSS data. The ARP point has directly been levelled to the first order levelling benchmark. Both tidal and absolute gravity observations are conducted in the Observatory. The magnetic field components are permanently registered and elaborated in the Observatory. The ground water and soil humidity are also measured in the Observatory.

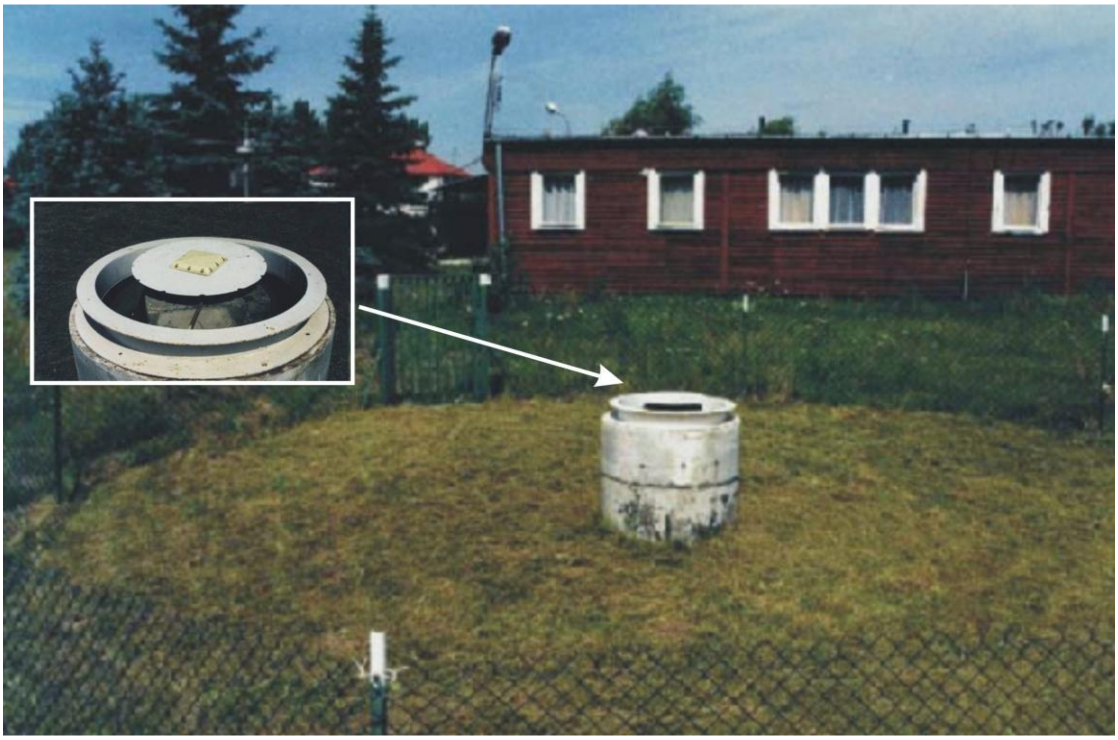


Fig. 4.3.9. JOZE antenna location and monumentation

4.3.10. Jozefoslaw (JOZ2) Permanent GPS/GLONASS Station

The permanent GPS/GLONASS station JOZ2 (IERS domes number 12204M002) operates since January 2002 at the Jozefoslaw Astrogeodetic Observatory 15 km south of Warsaw and belongs to the Department of Geodesy and Geodetic Astronomy of the Warsaw University of Technology. It operates as a permanent GPS/GLONASS station since September 2003 of the EPN network. It operates also as a permanent station of the IGS network. The Ashtech Z18 GPS+GLONASS receiver with ASH701941.B SNOW antenna originally installed at JOZ2 station has been replaced in March 2008 by Leica GRX1200GGPRO with LEIAT504GG choke ring antenna whiteout dome (Fig. 4.3.10).

The external rubidium frequency standard TEMEX NEUCHATEL TIME SA is an external source of input frequency of 10 MHz for the receiver.

Data from JOZ2 in 30 s rate in 24h and 1h blocks are available at BKG, OLG GNSS and WUT servers. Until September 2008 data in 5 s rate in 1h blocks were provided to the ASG-PL Pilot Project Managing Centre in Katowice. Since September 2008 that data are provided to the Polish ASG-EUPOS Network Managing Centre in Warsaw. The real time data stream from JOZ2 is also available as Ntrip within the EUREF IP project by the NtripCaster address: www.euref-ip.net:2101 – mountpoint (JOZ20).

Meteorological data collected in 15 min interval using LB-710RHMS meteorological sensor and transformed to the RINEX METEO format are transferred with GNSS data. The second meteorological sensor MET4A installed in 2008 in the Observatory provides meteorological data in 10 min interval to the ASG-EUPOS system. The ARP point has directly been levelled to the first order levelling benchmark.

Fig. 4.3.10. JOZ2 antenna location and monumentation

4.3.11. Katowice (KATO) Permanent GPS/GLONASS Station

The permanent GPS/GLONASS station KATO (IERS domes number 12219M001) operates since January 2003 in the Regional Centre of Documentation of Geodesy and Cartography in Katowice. It became the permanent station of EPN network in August 2003. The responsible agency is the Head Office of Geodesy and Cartography, Warsaw. The original Ashtech μZ-12 receiver with ASH701945C_M SNOW antenna placed on the roof of the building was replaced in April 2008 with the new TRIMBLE NetR5 receiver with TRM41249.00 TZG antenna (Fig. 4.3.11). The antenna was replaced by TRM55971.00 TZG antenna in December 2010.

Data from KATO station in 30 s rate in 24h and 1h blocks are available at BKG, and OLG GNSS Data Centres. Data in 5 s and 1 s rates are transferred to the Polish ASG-EUPOS Network Managing Centre in Warsaw**.**

Meteorological data collected in 10 min sampling interval using MET4A meteorological sensors are transferred in RINEX METEO format with GNSS data.

Fig. 4.3.11. KATO antenna location and monumentation

4.3.12. Lamkowko (LAMA) Permanent GPS/GLONASS Station

The permanent GPS/GLONASS station LAMA (IERS domes number 12209M001) operates since December 1994 at the Lamkowko Satellite Observatory (Fig. 4.3.12), 30 km north-east of Olsztyn, of the University of Warmia and Mazury in Olsztyn. It operates since December 1995 as a permanent station of the IGS network, using originally the TurboRogue SNR 8000 receiver with AOAD/M_T antenna installed at EUREF 0302 site, replaced by the Ashtech Z-12-3 receiver with ASH700936F_C SNOW choke ring antenna. Since November 2007 a new Leica GRX 1200 GGPRO receiver with LEIAT504GG antenna operates at the LAMA station. In December 1995 LAMA station was also included to EPN network.

Data from LAMA in 30 s rate in 24h and 1h blocks are available at BKG, and OLG GNSS, Data Centres. Independently, GNSS data from LAMA station in 5 s and 1 s rate are provided since September 2008 to the Polish ASG-EUPOS Network Managing Centre in Warsaw.

Meteorological data collected in 10 min sampling interval using MET4A meteorological sensor and transformed to the RINEX METEO format are transferred with GNSS data. The ground water and soil humidity are measured in the Observatory since 2005.

Fig. 4.3.12. Lamkowko Satellite Observatory building and LAMA antenna monumentation

4.3.13. Lodz (LODZ) Permanent GPS/GLONASS Station

The permanent GPS/GLONASS station LODZ (IERS domes number 12226M001) operates since December 2007 in the City Office in Lodz. The responsible agency is the Head Office of Geodesy and Cartography, Warsaw. The station is equipped with the Trimble NETR5 receiver and TRM55971.00 antenna installed on the roof of the building (Fig. 4.3.13). The station started operating as a permanent station in the EPN network in June 2008.

Data from LODZ station in 30 s rate in 24h and 1h blocks are available at BKG, and OLG GNSS Data Centres. Data in 5 s and 1 s rates are transferred to the Polish ASG-EUPOS Network Managing Centre in Warsaw**.**

Meteorological data collected in 10 min sampling interval using MET4A meteorological sensors are transferred in RINEX METEO format with GNSS data.

Fig. 4.3.13. LODZ antenna monumentation

4.3.14. Redzikowo (REDZ) Permanent GPS/GLONASS Station

The permanent GPS/GLONASS station REDZ (IERS domes number 12227M001) operates since December 2007 in the City Office in Redzikowo. The responsible agency is the Head Office of Geodesy and Cartography, Warsaw. The station is equipped with the Trimble NETR5 receiver and TRM55971.00 antenna installed on the roof of the building (Fig. 4.3.14). The station started operating as a permanent station in the EPN network in June 2008.

Data from REDZ station in 30 s rate in 24h and 1h blocks are available at BKG, and OLG GNSS Data Centres. Data in 5 s and 1 s rates are transferred to the Polish ASG-EUPOS Network Managing Centre in Warsaw**.**

Meteorological data collected in 10 min sampling interval using MET4A meteorological sensors are transferred in RINEX METEO format with GNSS data.

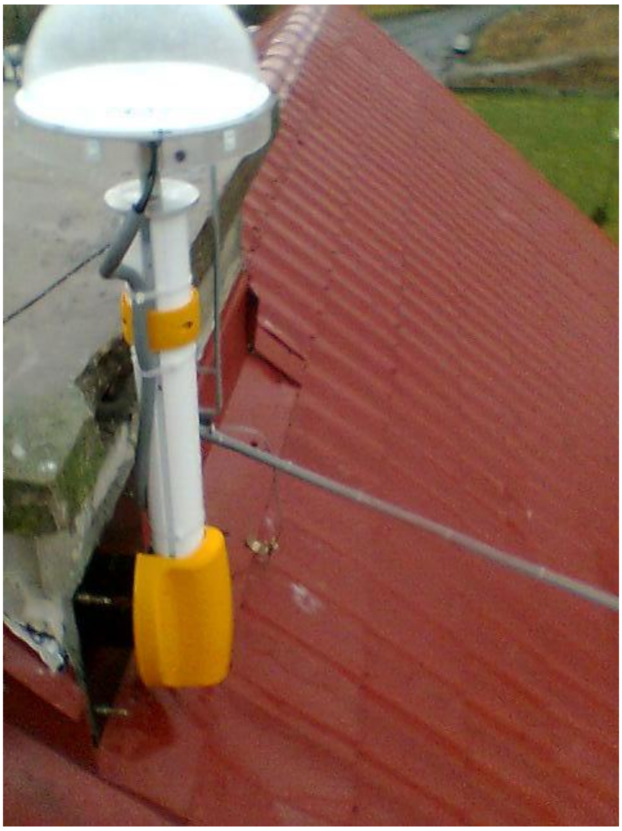


Fig. 4.3.14. REDZ antenna monumentation

4.3.15. Suwalki (SWKI) Permanent GPS/GLONASS Station

The permanent GPS/GLONASS station SWKI (IERS domes number 12228M001) operates since December 2007 in the City Office in Suwalki. The responsible agency is the Head Office of Geodesy and Cartography, Warsaw. The station is equipped with the Trimble NETR5 receiver and TRM55971.00 antenna installed on the roof of the building (Fig. 4.3.15). The station started operating as a permanent station in the EPN network in June 2008.

Data from SWKI station in 30 s rate in 24h and 1h blocks are available at BKG, and OLG GNSS Data Centres. Data in 5 s and 1 s rates are transferred to the Polish ASG-EUPOS Network Managing Centre in Warsaw**.**

Meteorological data collected in 10 min sampling interval using MET4A meteorological sensors are transferred in RINEX METEO format with GNSS data.

Fig. 4.3.15. SWKI antenna monumentation

4.3.16. Ustrzyki Dolne (USDL) Permanent GPS/GLONASS Station

The permanent GPS/GLONASS station USDL (IERS domes number 12229M001) operates since December 2007 in the City Office in Ustrzyki Dolne. The responsible agency is the Head Office of Geodesy and Cartography, Warsaw. The station is equipped with the Trimble NETR5 receiver and TRM55971.00 antenna installed on the roof of the building (Fig. 4.3.16). The station started operating as a permanent station in the EPN network in June 2007.

Data from USDL station in 30 s rate in 24h and 1h blocks are available at BKG, and OLG GNSS Data Centres. Data in 5 s and 1 s rates are transferred to the Polish ASG-EUPOS Network Managing Centre in Warsaw.

Meteorological data collected in 10 min sampling interval using MET4A meteorological sensors are transferred in RINEX METEO format with GNSS data.

Fig. 4.3.16. USDL antenna monumentation

4.3.17. Wroclaw (WROC) Permanent GPS/GLONASS Station

The permanent GPS/GLONASS station WROC (IERS domes number 12217M001) has been established in November 1996. The station is run by Institute of Geodesy and Geoinformatics of the Wroclaw University of Environmental and Life Sciences. Since November 1996 it operates as a permanent station of EPN network and since 2002 - IGS network. Originally the station was equipped with Ashtech Z-12 receiver and the ASH700936D_M antenna installed on the roof of the building (Fig. 4.3.17). In May 2000, after the receiver was damaged by the lightening, the station was equipped with the Ashtech Z-18 GPS+GLONASS receiver with the ASH701941.1 SNOW antenna. Since 13 April 2007 a new Leica GRX1200PRO receiver with LEIAT504GG antenna operates at WROC station.

The external rubidium standard FTS-74 is a source of input frequency of 5 MHz for the receiver. Data from WROC in 30 s rate in 24h and 1h blocks is available at BKG, OLG GNSS and GOPE Data Centres.

Until September 2008 data in 5 s rate in 1h blocks were provided to the ASG-PL Pilot Project Managing Centre in Katowice. Since September 2008 GNSS data from WROC station in 5 s and 1 s rate are provided to the Polish ASG-EUPOS Network Managing Centre in Warsaw. The real time data stream from WROC is also available as Ntrip within the EUREF IP project.

The meteorological sensor MET4A installed in 2008 in the station provides meteorological data in 10 min interval to the ASG-EUPOS system.

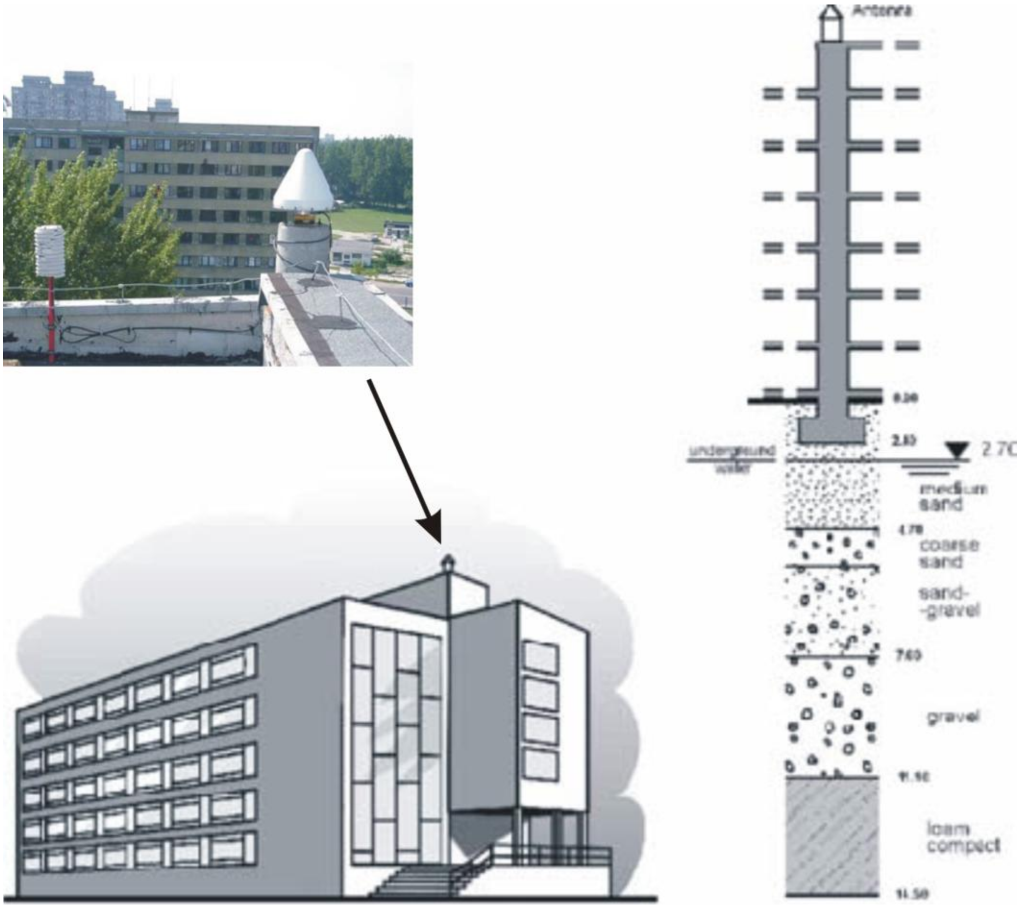


Fig. 4.3.17. WROC antenna location and monumentation

4.3.18. Zywiec (ZYWI) Permanent GPS/GLONASS Station

The permanent GPS/GLONASS station ZYWI (IERS domes number 12220M001) operates since January 2003 in the City Office in Zywiec. It became a permanent station of EPN network in August 2003. The responsible agency is the Head Office of Geodesy and Cartography, Warsaw. The original Ashtech μZ-12 receiver with ASH701945C_M SNOW antenna placed on the roof of the building was replaced in December 2007 with the new TRIMBLE NetR5 receiver with TRM55971.00 TZG antenna (Fig. 4.3.18).

Data from ZYWI station in 30 s rate in 24h and 1h blocks are available at BKG, and OLG GNSS Data Centres. Data in 5 s and 1 s rates are transferred to the Polish ASG-EUPOS Network Managing Centre in Warsaw.

Meteorological data collected in 10 min sampling interval using MET4A meteorological sensors are transferred in RINEX METEO format with GNSS data.

Fig. 4.3.18. ZYWI antenna location and monumentation

4.4. TIME TRANSFER AND COMPARISON

An extended activity in the field of time transfer and comparison was conducted at Time and Frequency Laboratory of the Astrogeodynamic Observatory (AOS) of the Space Research Centre of the Polish Academy of Sciences in Borowiec.

First of all the Laboratory has been developed by installing new frequency standards. The ensemble of clocks (Fig. 4.4.1) consists now of two hydrogen masers: 1) CH1-75A, developed by Institute of Electronic Measurements "Kvarz", Russia, currently at present master clock of the Observatory source of UTC(AOS), and 2) American Symmetricom SigmaTau, and two cesium frequency standards HP-5071A opt. 001 also from Symmetricom. The new ensemble of clocks allows for the realization of UTC(AOS) within the range of ±10 ns from UTC.

International comparisons of atomic time scales are performed from the end of 2006 based on **T**wo **W**ay **S**atellite **T**ime and **F**requency **T**ransfer (TWSTFT) method, which assures uncertainty of the measurements in the range of 200 ps. This method allows to use fully the stability of the new H-maser. In 2007 the TWSTFT equipment was calibrated using timing GPS observations carried out at the Borowiec Observatory. The satellite simulator (SatSim) installed in 2009 enables control of the equipment delay changes at the picosecond level.

New receivers, the TTS-4 (Fig. 4.4.2) observing GPS, GLONASS, and Galileo satellites were developed at the end of 2008. The receivers equipped with 116 channels receive GPS L1, L2/L2C, and L5 signals, L1/L2 GLONASS signal, and E1/E5A Galileo signal. Ionosphere-free P3 method is applied for clock comparisons. The receivers also provide real-time data in RINEX format.

In the period reported the Laboratory was completely modernized. The clocks together with measuring and distributing time and frequency equipment are now working in specially air conditioned chamber with temperature stability of 0.1 ºC. Stability of temperature and humidity at the level of 3% allows full utilization of the performances of new clocks. All of them contribute to TAI and TA(PL).

Work on the Precise Time Facility (PTF) for Galileo has passed from the design phase to realization (Achkar et al., 2007). From March 2008 the AOS team started to write final version of the software in ANSI C language. Special algorithms for the estimation and prediction of the Galileo-GPS time offset (to be broadcasted by the Galileo satellites), as well as of the PTF1 – PTF2 time offset (differences of time scales between the two Galileo control centres, Master and Slave) were developed. The work is carried on Two Way Management Software for PTF of Galileo Control Station, GPS Common View Management software for PTF Galileo Control Station, and Galileo Common View Management software for PTF Galileo Control Station.

The Laboratory continues realization and development of Polish Atomic Time Scale – now about 16 atomic clocks from Polish laboratories, Lithuania and Latvia as well as participates in the realization of UTC and TAI in cooperation with the BIPM in Sèvres.

In 2009 Baltic Time Project (6th Framework Program) on the development of international time stamping in cooperation with Lithuania, Estonia, Latvia, Ireland and Italy was completed. Application of international time stamping is now tested between Poland (AOS) and Lithuania (NSI). Also the realization of Harrison Project (6th Framework Program) on application of Galileo for precise time and frequency, as well as legal applications of Galileo Time was finished (Nawrocki and Nogas, 2010).

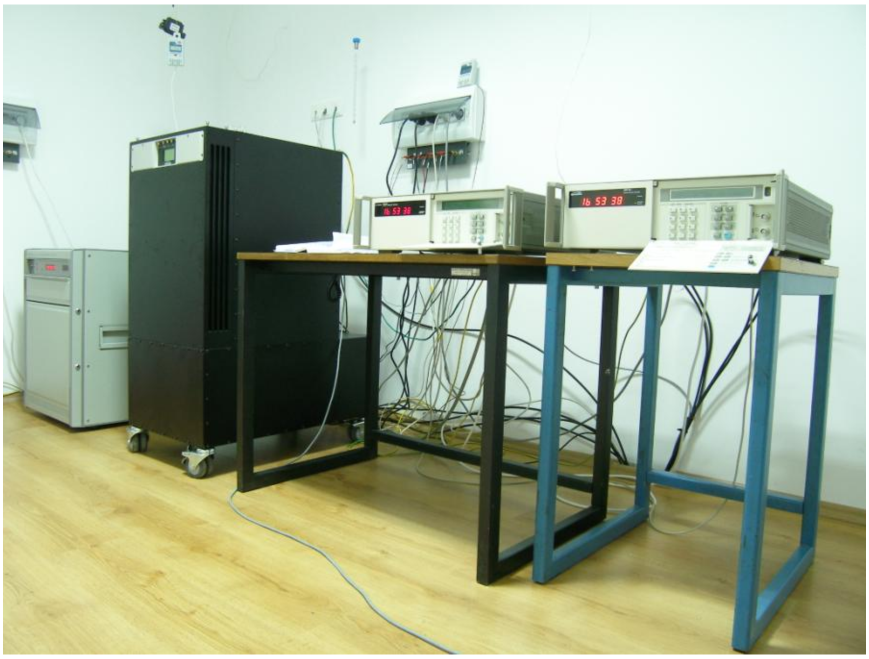


Fig. 4.4.1. Clock ensemble at AOS; from the left: Russian CH1-75A,
and then American Symmetricom SigmaTau

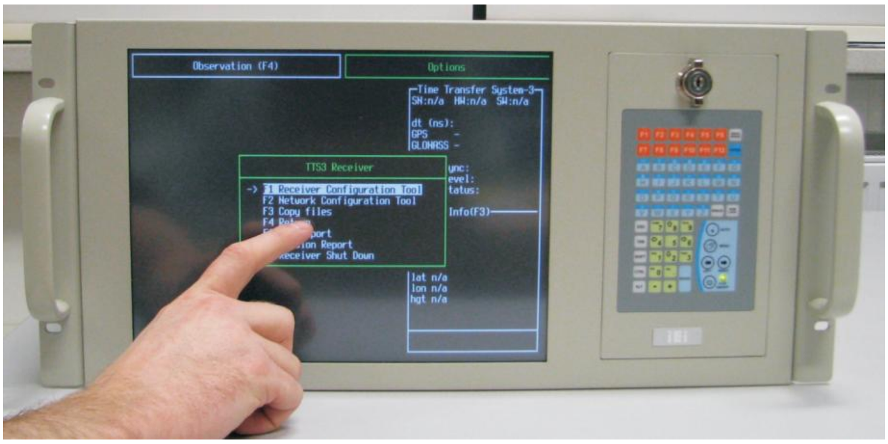


Fig. 4.4.2. New TTS-4 receiver with touch-control screen

4.5. SATELLITE DATA ANALYSIS AND ORBIT DETERMINATION

4.5.1. SLR Data Analysis

Two main tasks of the orbital analysis group of the Borowiec SLR station in 2007–2010 were comparison of SLR with GPS-derived station coordinates and the determination of station coordinates from low orbiting satellites (LEO).

The comparison of SLR with GPS-derived station coordinates was performed for all stations were both SLR and GPS techniques were used in the period from 1993.0 to 2009.0. The final results were obtained for 25 stations. The coordinates were determined for common SLR reference point for the epochs on the first day of each month. The SLR and GPS data analysis included estimation of the station positions stability and station velocities as well as comparison of the positions and velocities with those of ITRF2005. Generally with some exceptions, a good agreement of station positions (several mm) and velocities (below 1mm/year) obtained by both techniques was recorded. For several stations significant (2÷3 cm) differences were detected in the vertical components (Schillak and Lehmann, 2008a, 2008b, 2009). For each station N, E, U residuals referred to ITRF2005 are available on the Borowiec website www.cbk.poznan.pl.

Positions and velocities of Yarragadee (7090), Greenbelt (7105), Graz (7839) and Herstmonceux (7840) SLR stations were determined from 5-year (2001-2005) SLR data of Ajisai, Starlette and Stella LEO satellites. The orbits of these satellites were computed by means of NASA Goddard's GEODYN-II program using SLR data from 20 stations. The geocentric coordinates were transformed to the topocentric N-S, E-W. and Vertical components in ITRF2005. The influence of the number of normal points per orbital arc and the empirical acceleration coefficients on the quality of station coordinates was investigated. To get standard deviation of the coordinates determined below 1 cm, the number of the normal points per site had to exceed 50. Computed positions and velocities were compared with LAGEOS-1/LAGEOS-2 data in terms of station coordinates stability and differences from ITRF2005 positions and velocities. The stability of coordinates of LEO satellites is significantly worse (17.8 mm) than those of LAGEOS (7.6 mm); better results were obtained for Ajisai (15.4 mm) than for Starlette/Stella (20.4 mm). Difference in positions between the computed values and ITRF2005data were slightly worse for Starlette/Stella (6.6 mm) than for LAGEOS (4.6 mm); the results for Ajisai were five times worse (29.7 mm) probably due to centre of mass correction of this satellite (Lejba et al., 2007). Station velocities were on the same level ca. 1 mm/year for all satellites. Data from LEO satellites, especially Starlette and Stella, can be applied for the determination of the SLR station coordinates but with twice lower accuracy than when using LAGEOS data (Lejba and Schillak, 2009, 2010).

Spin axis orientation and spin period of the fully passive geodynamic satellites are influenced by forces and torques caused by gravitational field, magnetic field and non-gravitational effects like solar radiation and relativistic effects. Designed for SLR measurements LAGEOS satellites have completely passive construction (Fig. 4.5.1a) ensuring that the orbital motion and the spin parameters of the body cannot be affected by any artificial torques – coming from engines or active nutation dumpers. They are spherical, heavy bodies (60 cm in diameter, more than 400 kg), equipped with 426 Corner Cube Reflectors (CCR) for range measurements by laser stations. They are placed on near-circular orbits with perigee of 5860 km (LAGEOS-1, launched 4 May 1976) and 5620 km (LAGEOS-2, launched 22 October 1992).

Fig. 4.5.1a. LAGEOS-1, courtesy of NASA

The laser range measurements between the ground station and the satellites allow for calculation of the ground station position with precision of 1÷3 cm. Long term data set can be used for monitoring motion of the Earth's tectonic plates, measuring the Earth's gravitational field, position of the geocenter and the wobble of the Earth's axis of rotation, and better determination of the length of the day.

Precise Orbit Determination allows for position calculation of LAGEOS satellites with accuracy of several mm. Such accuracy can be achieved thanks to the high, very stable orbits of the satellites as well as the advanced, very accurate perturbation models applied. Perturbations depend on attitude of the satellite's body in the space, thus it is necessary to know its spin parameters while calculating precise orbits.

LAGEOS-1 was launched with spin period of 0.61 s (Kucharski et al., 2009), and since the beginning is exponentially slowing down. From the launch till year 1997, while the satellite was spinning relatively fast (spin period up to 500 s), the spin parameters were measured by photometric systems. After this time photometry could not deliver enough information for the spin parameters determination. In 2003 the first kHz SLR system was developed in Graz (Space Research Institute, Austrian Academy of Sciences). While the standard SLR systems operate with lasers of 1÷15 Hz repetition rate, the SLR in Graz operates with the laser of 2 kHz fire rate. This advantage allows for collecting up to 1 million range measurements to the LAGEOS satellites during a single pass. Very short laser pulse (10 ps) together with the single photon detection system allows for identification of range measurements to the single CCRs of the satellite (Fig. 4.5.1b).

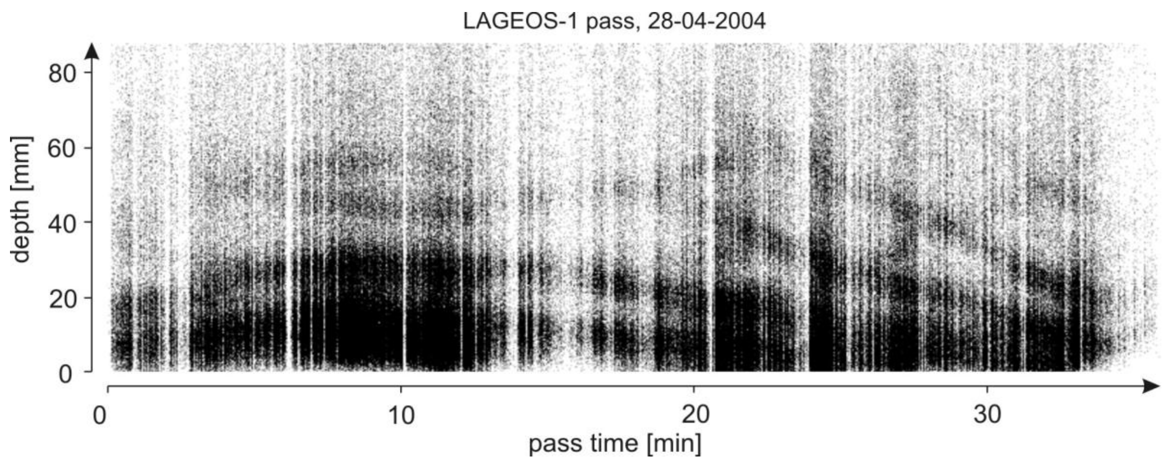


Fig. 4.5.1b. Range residuals of LAGEOS-1 pass, measured by Graz kHz SLR system, 28-04-2004, 2 a.m

Fig. 4.5.1b presents range residuals of a LAGEOS-1 pass measured by Graz 2 kHz SLR system. During 35 minutes of the pass, more than 500 000 returns were measured. The majority of the returns comes from the nearest retro-reflectors; the detection probability for returns from more distant CCRs on the satellite's sphere is decreasing. The reason for this effect is the geometry between the incident laser beam and the CCR. The dark lines and curves indicate the range measurements to the single retroreflectors of LAGEOS-1. By analysing the geometry of the lines and curves it is possible to determine the spin period and the spin axis orientation of LAGEOS-1.

33 passes measured by a kHz SLR system in Graz during 178 days of year 2004 were analysed. The determined spin axis orientation of LAGEOS-1 is shown in Figures 4.5.1c and 4.5.1d.

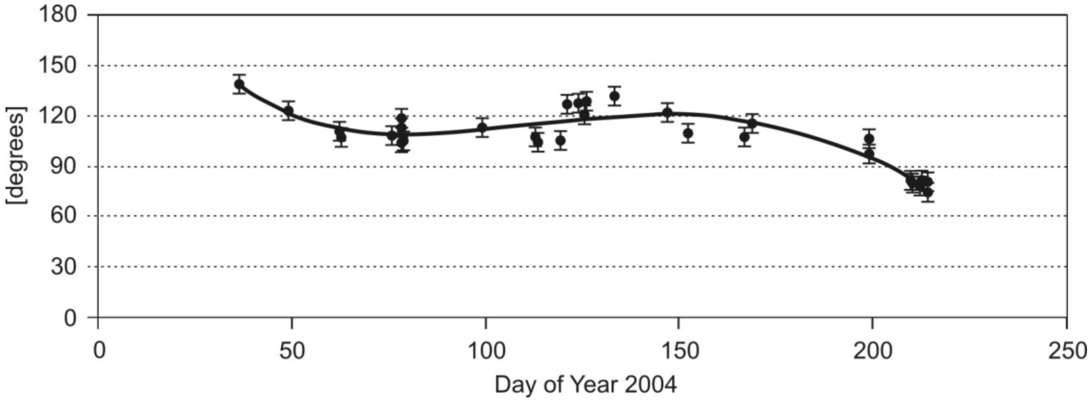


Fig. 4.5.1c. Spin axis of LAGEOS-1 – co-latitude component and the trend function

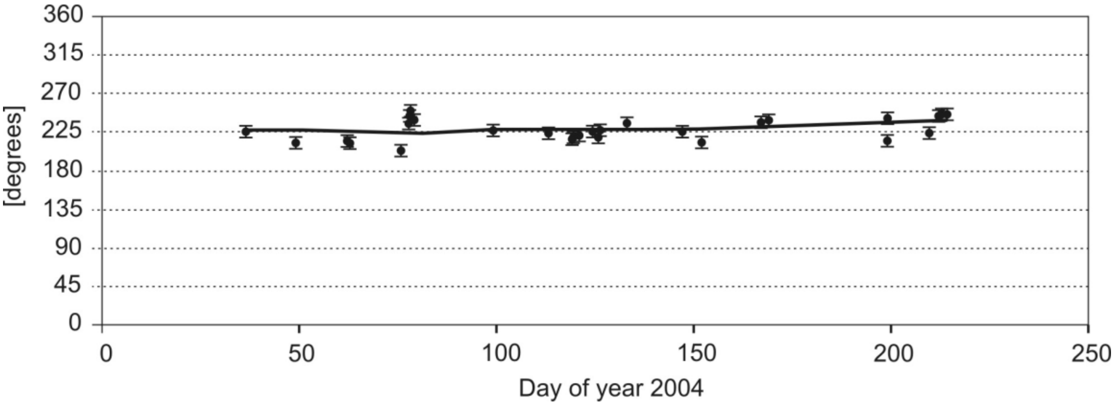


Fig. 4.5.1d. Spin axis of LAGEOS-1 – longitude component and the trend function

The spin period of LAGEOS-1 during investigated part of year 2004 was T = 5775 s (clockwise rotation, RMS = 296 s). For the spin axis orientation the spread of the determined values around the trend function expressed in RMS equals to 6˚ and 7˚ for longitude and colatitude, respectively. For the both angles the scatter around the fitted trend function is visible and has similar magnitude. This may be caused by inaccuracy of the used method or even by chaotic, small changes of the spin axis precession. The trend function of co-latitude values shows sinusoidal decreasing during the investigated part of the year, while the longitude angle is more stable.

The obtained results (Kucharski et al., 2007) agree with the theoretical predictions. At present, only a kHz SLR technique makes possible to measure the spin parameters of very slowly spinning LAGEOS-1. A kHz SLR system can also be used for measuring the spin parameters of the active satellites equipped with CCRs like Gravity Probe – B (Kirchner et al., 2009). Analysis of the spin axis precession of LAGEOS-1 allows a more accurate determination of the forces perturbing orbital motion of the satellite. It is expected that this will help to quantify the effects of the small magnitude perturbations, which have been modelled up to now by empirical accelerations only.

4.5.2. Orbit Determination

Investigations in the area of satellite orbit determination were continued at the University of Warmia and Mazury, Olsztyn. They mainly concerned dynamics of GOCE satellite motion. Spectral analysis of selected accelerations and orbital elements for the GOCE satellite orbit was conducted (Bobojć, 2008, 2009). Also GOCE satellite orbit sensitivity under the influence of perturbing forces was determined (Bobojć and Drożyner, 2007, 2010):

4.5.3. Activities of the EUREF WUT Local Analysis Centre

The Warsaw University of Technology has been operating the WUT EPN Local Analysis Centre since 1996. The EPN subnetwork (Fig. 4.5.3a) being processed at WUT LAC consists of 80 stations (November 2010) located mainly in Central Europe. Six new stations were added to the network in 2010.

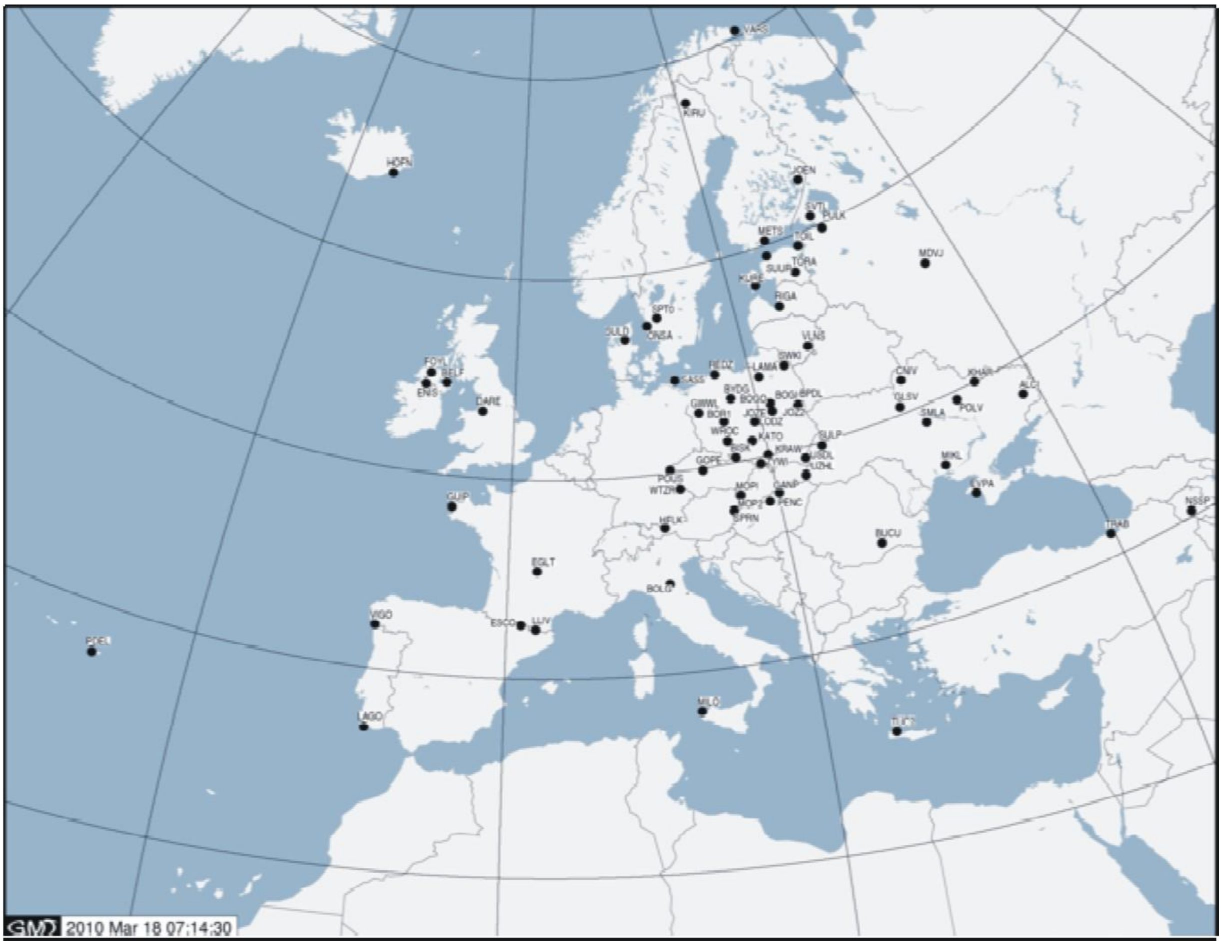


Fig. 4.5.3a. Map of EPN subnetwork processed by WUT LAC (http://www.epncb.oma.be/_dataproducts/analysiscentres/subnetwork.php?lac=WUT)

WUT LAC contributes to EUREF with weekly and daily solutions based on IGS final products, and with rapid daily coordinate solution based on IGS rapid products since December 2009. The official submission of WUT rapid daily solutions to EPN started in early January 2010 (Krynski and Rogowski, 2010).

WUT LAC uses Bernese GPS Software v5.0 to analyse GPS observations. Data are processed according to EPN AC guidelines. All WUT products are available at the EPN regional data centre located at BKG (ftp://igs.bkg.bund.de/EUREF/products).

Warsaw University of Technology acts also as one of GPS Analysis Centres in the frame of CERGOP-2 project (Central European Regional Geodynamic Project). WUT has analysed 9 CERGOP campaigns conducted in 1994–2007. Within the Project, velocity vectors of stations were computed (Hefty et al., 2009) using data from campaigns 1994–2006. In 2007 a new CERGOP campaign was reprocessed at WUT. Stations participating in this campaign are presented in Figure 4.5.3b. Also in 2007 all previous campaigns were reprocessed with consistent orbit products from PDR (Potsdam – Dresden Reprocessing), recent models and methodology using Bernese GPS Software v5.0.

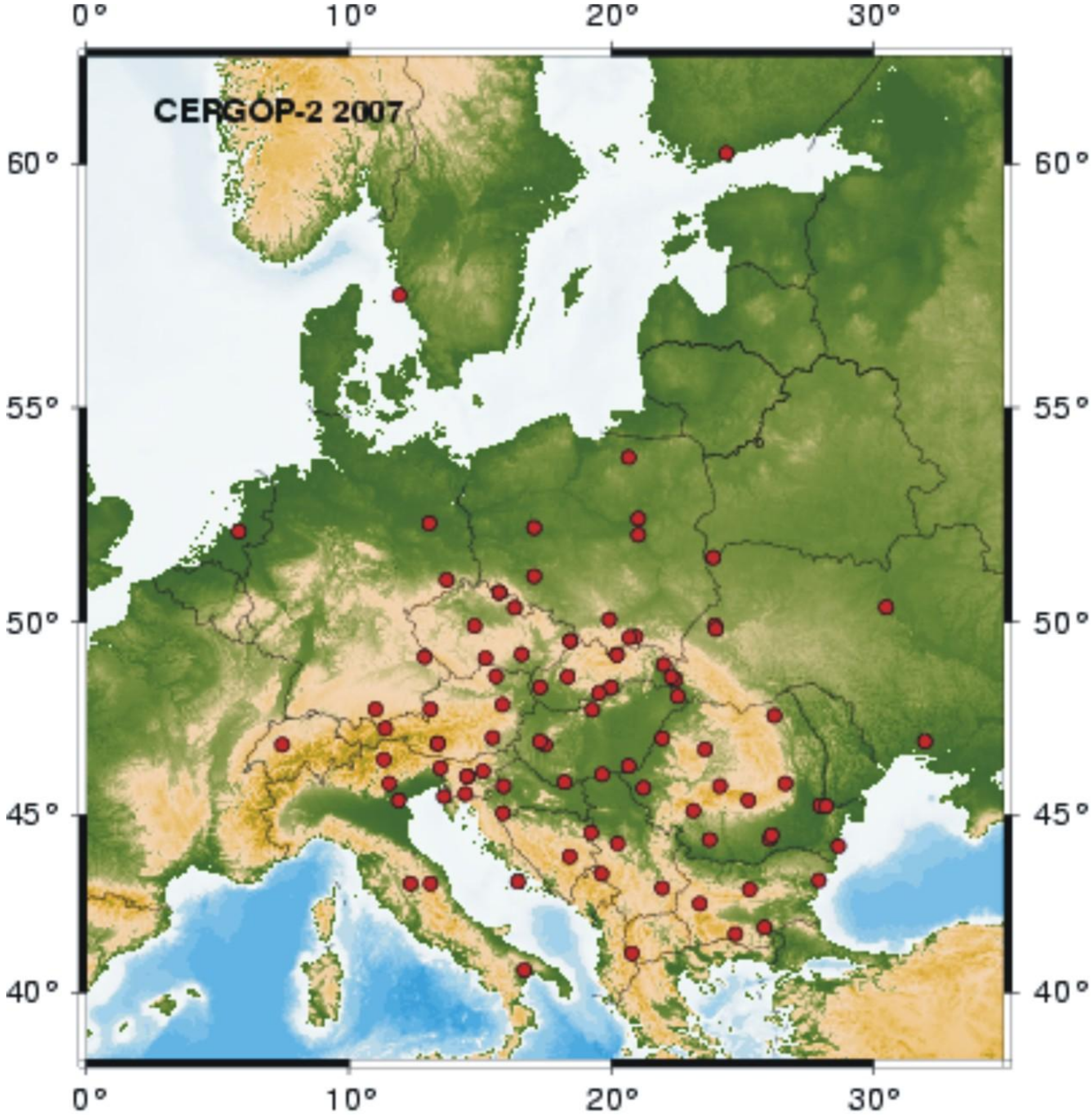


Fig. 4.5.3b. Stations participating in CERGOP-2 2007 campaign

4.5.4. Activities of the EUREF MUT Local Analysis Centre

EUREF Working Group established in December 2009 the 17th Local Analysis Centre LAC MUT, which operates at the Faculty of Civil Engineering and Geodesy of the Military University of Technology. The body responsible for operating LAC MUT is the Centre of Applied Geomatics. MUT LAC evaluates satellite data from 114 EPN reference stations (Fig. 4.5.4). The starting point for the computations is 1560 GPS week.

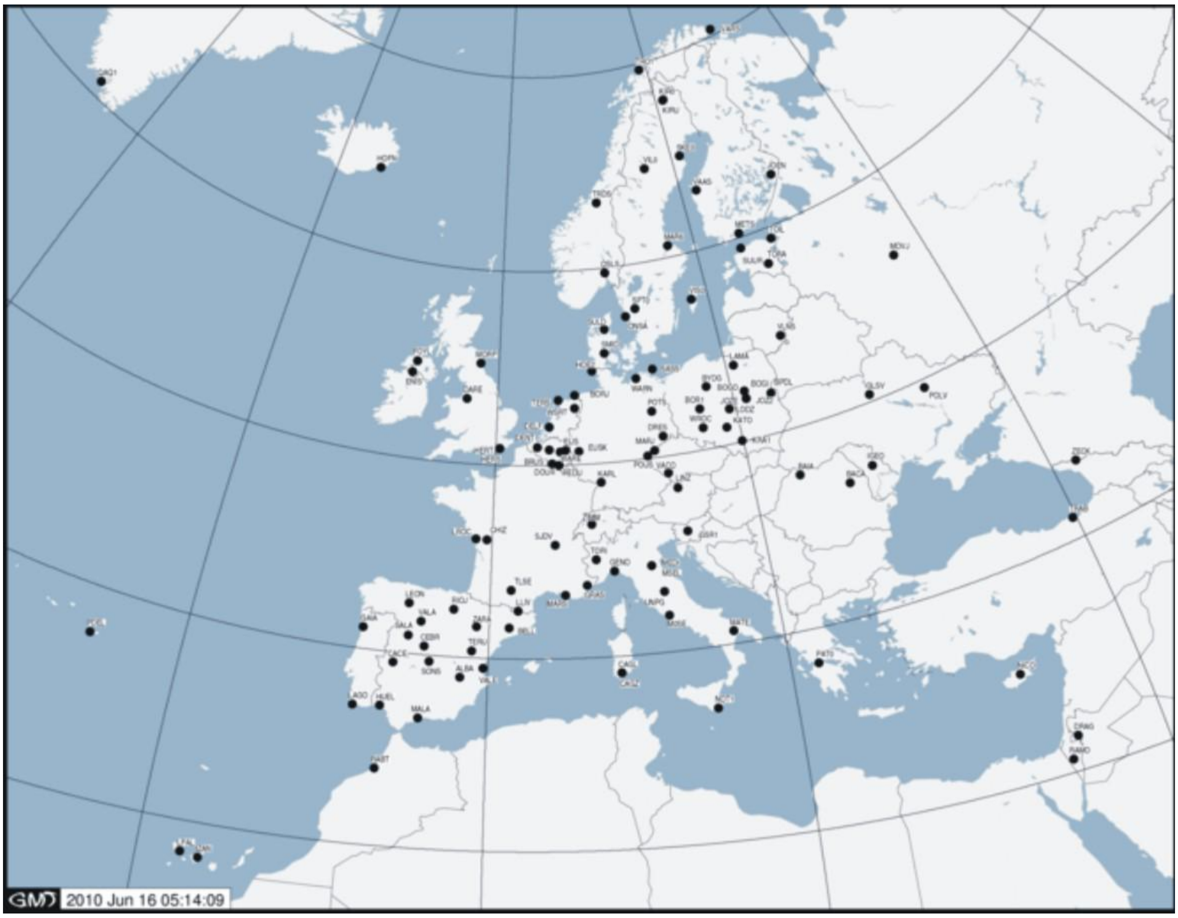


Fig. 4.5.4. Subnetwork processed by MUT (www.epncb.oma.be)

4.5.5. Re-processing of EPN Data

The team of the Military University of Technology, Warsaw, as well as the team of the Warsaw University of Technology participate in the EPN Reprocessing Project (http://epn-repro.bek.badw.de/), that is another form of processing of the archive GNSS data using the newest computing strategies, products and models. The main purpose of the project is to obtain homogenous time series of sites' coordinates and to provide the realization of the ETRS89 using cumulative weekly solutions obtained with the highest possible accuracy. The results of the reprocessing in the form of daily and weekly coordinates time series give a comprehensive set of data for a variety of geodetic, geodynamic and geophysical analyses.

The test reprocessing of the whole EPN data was done simultaneously by two centres: Centre of Applied Geomatics of MUT (Figurski et al., 2009a) and the Royal Observatory of Belgium (where global IGS stations were taken into consideration). The results of the tests gave rise to a new strategy for official EPN reprocessing, which is under preparation (Kenyeres et al., 2009).

4.5.6. GNSS Antenna Calibration

A simple, portable prototype of the device for antenna calibration was constructed at the Institute of Geodesy and Cartography, Warsaw, in co-operation with the "Metrologia" Institute, Kharkiv, Ukraine (Cisak and Zanimonskiy, 2007; Krynski, 2007). Phase centre offset (PCO) is being measured with the use of a reference site, whose antenna does neither need a precise nor absolute calibration. On the other hand, phase centre variations (PCV) may be measured in single site mode with the use of satellite-satellite carrier differences. Numerous test measurements were performed at Borowa Gora and Lamkowko Observatories in Poland as well as in the Ukrainian Antarctic "Akademik Vernadsky" station (Cisak and Zanimonskiy, 2008). The example of variations of phase centre offset averaged over observed satellite passes in one minute intervals is shown in Figure 4.5.6.

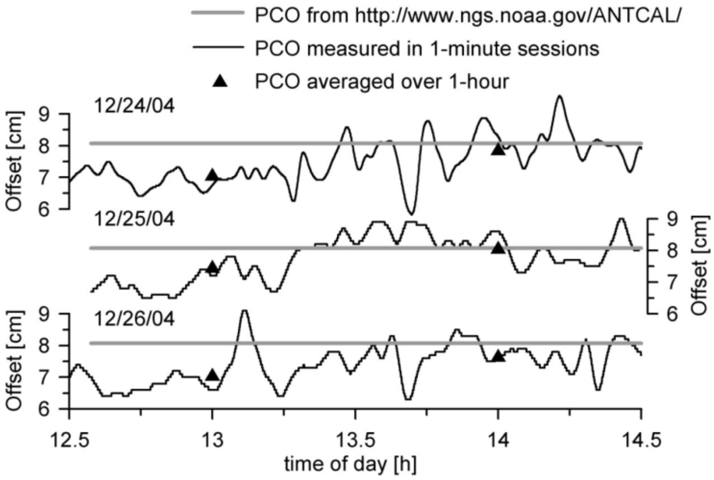


Fig. 4.5.6. Comparison of the results of the mean phase centre offset obtained from the observations with the results of NGS calibration

The research on the antenna calibration device and elaboration of the calibration method at the Institute of Geodesy and Cartography, Warsaw, was completed in 2008.

Tests on the certification of GPS measurements were performed at the University of Warmia and Mazury (Oszczak et al., 2007; Ciecko et al., 2008). Also quality control and quality assurance of satellite navigational systems was investigated (Oszczak et al., 2010).

4.5.7. Study on Accuracy and Reliability of Precise GPS Positioning

Extensive studies on efficiency and reliability of ambiguity resolution in network-based RTK GPS were conducted in cooperation of the University of Warmia and Mazury, Olsztyn, with the team of the Ohio State University (OSU).

4.5.7.1. Studies on Efficiency and Reliability of Ambiguity Resolution in Network-based RTK GPS

Fast and reliable ambiguity resolution (AR) is particularly challenging in long-range real-time kinematic (RTK) GPS, since the effects of spatially-correlated atmospheric or orbital errors increase with growing distance between the base stations and the roving receiver, effectively reducing the success rate of integer AR. In order to account for these error sources, and ultimately, to increase the success rate of integer fixing, external information is required. Four state-of-the-art methods of ionosphere modelling were used as a source of external information, and their impact on the speed and reliability of AR and the rover positioning accuracy were analysed and discussed. The following ionospheric models MPGPS-NR, IGS GIM, ICON, and MAGIC were tested. The first three models assume that the ionosphere is an infinitesimal single layer, while the last one considers the ionosphere as a 3D medium. Recent updates to ICON and MAGIC that improved the quality of these models, and ultimately, enabled faster on-the-fly (OTF) AR were also discussed.

A 24-hour data set, collected by selected four stations of the Ohio Continuously Operating Reference Station (CORS) network on 31 August 2003, was presented and analysed with a special emphasis on varying ionospheric conditions during the course of the day, and their impact on the AR speed and reliability in rover positioning over baselines of 100 km. One CORS station was selected as simulated rover with known reference coordinates. Subsequently, the AR and the rover position estimation were performed using each above-mentioned ionospheric model in order to study their applicability to high-accuracy RTK GPS. In particular, the time required to fix the ambiguities (i.e. time-to-fix), the level of AR success, and the quality of the resulting rover position were analysed. The analyses were performed using in the post-processing mode the Multi Purpose GPS Processing Software (MPGPS™) developed in cooperation with OSU.

Based on the obtained results it was concluded that the local model, MPGRS-NR, usually requires 3÷7 epochs to fix the ambiguities with 5 cm stochastic constraints imposed on the ionosphere. Of the two regional models, MAGIC, needs 3÷12 epochs and 3÷18 epochs, for 5 cm and 10 cm constraints, respectively, and ICON requires 11÷68 epochs with the constraint of 20 cm. ICON may require longer times with tighter constraints. Once the ambiguities are fixed to their integer values, the rover positioning algorithm provides the coordinate accuracy at the centimetre-level for the horizontal and vertical coordinates (Grejner-Brzezinska et al. 2007b).

The influence of the double-difference (DD) ionospheric corrections latency on the instantaneous (one-epoch) AR in long-range RTK under typical ionospheric conditions was investigated (Kashani et al., 2007). Atmospheric corrections are used in order to obtain a high quality RTK position over long distances. DD ionospheric correction prediction derived from the previous correctly resolved epoch was applied. Yet, at the beginning of the session, a short initialization period is still required in order to produce the initial prediction. After the initialization the method is based on single epoch solution. This method assures a high success rate of the instantaneous AR for long baselines (over 100 km). Since the previous-epoch ionospheric delay is used, and instantaneous mode is applied in the algorithm, the method proposed is robust against cycle slips and data gaps, and still capable of producing centimetre-level RTK positions. The RTK solution was simulated in the post-processing mode. Namely, different DD ionospheric delay correction latencies were simulated in 10 s increments and sent to the (simulated) rover in order to test the AR performance. The AR results were compared and analysed, and the performance of the RTK positioning was assessed based on the static true solution. Several hours of GPS data, collected by the State of Israel permanently tracking network, were processed. The analyses show that about 90 s latency may exist while the instantaneous ambiguities could still be resolved correctly.

4.5.7.2. Network Calibration for Unfavorable Reference-Rover Geometry in Network-Based RTK: Ohio CORS Case Study

The impact of the reference network–rover geometry on the GPS kinematic rover coordinate solution derived using the network-generated atmospheric corrections was investigated. Two different geometries were considered: (1) pentagonal, uniform reference receiver geometry, with the rover inside the network of five reference stations (Case 1); and (2) simulated shore-bound reference receiver geometry for a rover moving away from the shore line (Case 2). The latter case was of primary interest here. The analysis of these two scenarios enabled the quantification of the growth of the error in the generated ionospheric corrections, resulting in the lower success rate and lower reliability of AR in the case of rovers moving away from the network, in comparison to the case of a rover located within the reference receiver network (Grejner-Brzezinska et al. 2009).

4.5.7.3. Studies on the Application of a Predicted Ionosphere Model to Medium Range RTK Positioning

RTK positioning over longer distances requires a support of atmospheric (ionospheric and tropospheric) corrections, since the atmospheric errors decorrelate with the growing distances and cannot be completely eliminated by double differencing of the satellite observations. Currently, the most commonly used approach is to derive the atmospheric corrections at the reference station network and provide them in real time to the roving receiver. Another solution, proposed, is to use predictive atmospheric models in order to derive the atmospheric corrections. The test results of the performance assessment of the predictive ionosphere model (UWM-IPM) application to medium-range RTK positioning were presented (Wielgosz et al. 2007). The rover data collected within 25 to 67 km from the closest reference station were processed in the kinematic mode with the support of the ionospheric corrections derived from the UWM-IPM model. The RTK solution was derived in both single- and multi-baseline modes. All numerical tests were carried out using the MPGPS™ software; a recent extension to the software, developed at the University of Warmia and Mazury, introduces the predictive ionosphere model to the RTK solution.

The application of a predictive ionosphere model to the kinematic positioning provides very promising results. The model's performance is comparable to that of the IGS final or JPL ionospheric models obtained for the quiet and moderate ionosphere. The predicted corrections may be successfully applied to the processing of 25÷50 km baselines in a single-baseline mode, and up to ~70 km baselines in a multi-baseline mode, when a longer baseline is combined with 1÷2 shorter baselines. It is expected, however, that when the base and the predicted models improve then this methodology may be successful for even longer baselines. It was shown that cm-level horizontal kinematic position can be achieved using the proposed methodology with dual-frequency GPS data over distances of tens of kilometres with short initialization time (less than 15 s for short baseline or multi-baseline solutions) (Wielgosz et al. 2008a).

4.5.7.4. Studies on the Troposphere Modelling for Precise GPS Rapid-Static Positioning in Mountainous Areas

This study performed by the team of the University Warmia and Mazury, Olsztyn, presents an evaluation of different approaches to the tropospheric delay modelling in rapid static applications when using 10-minute long observing sessions of dual-frequency pseudorange and carrier phase GPS observations. Several permanent GPS stations of the EUPOS (European Position Determination System) active geodetic network located in the Carpathian Mountains were selected as a test reference network. The distances between the reference stations ranged from 64 to 122 km. KRAW station served as a simulated user receiver located inside the reference network. User receiver ellipsoidal height is 267 m and the reference station heights range from 277 to 647 m. Four 66÷72 km baselines connecting rover and the reference stations were selected and processed in the rapid-static mode using the MPGPS™ software.

A 13h data set collected on 3 July 2008 (from 6:00 to 19:00 UT, LT = UT + 1h) was divided into 78, 10-minute long, sessions. Each session was processed independently. Three different approaches to the troposphere modelling were applied and tested: a) neglecting the troposphere, b) using a standard atmosphere model, c) estimating tropospheric delays at the reference station network and providing interpolated tropospheric corrections to the user. All these solutions were repeated with various constraints imposed on the tropospheric delays in the least squares adjustment. The quality of each solution was evaluated by analysing the residual height errors calculated by comparing the estimated results to the reference coordinates.

It has been confirmed that over distances of tens of km double differencing of the GPS observations is not sufficient to remove tropospheric delays. The remaining tropospheric residuals clearly hamper the AR process and corrupt the position quality. The best results were obtained by applying TZD interpolated from the reference network (network-derived TZD), regardless of using the constraints or not. This approach is feasible anywhere where reference station networks are established. The Modified Hopfield model (or any standard atmosphere model) may by applied in the absence of the network-derived TZD, and the results may be improved by constraining the user TZD to, e.g. ±5 cm in the LS adjustment. The solution with no a priori knowledge of the tropospheric delays may also give acceptable results, at least for applications that do not require highest accuracy. The results obtained for baselines with low and high ΔH give very similar results when applying network derived TZD or the Modified Hopfield model (Wielgosz et al. 2008b).

4.5.7.5. Studies on a New Network-Based Rapid-Static Module for the NGS Online Positioning User Service

The National Geodetic Survey (NGS) operates the On-line Positioning User Service (OPUS) as a means to provide the GPS users with easier access to the National Spatial Reference System (NSRS). Standard OPUS service accepts a minimum of 2h of GPS data, with a recommendation of submitting at least 4h to improve the solution. In order to reduce the required user session duration, a rapid-static module (OPUS-RS) has been implemented, in collaboration with the Satellite Positioning and Inertial Navigation Laboratory at OSU. The OPUS-RS is based on the Wide Area Rapid-Static (WARS) module of the MPGPS™ software. The new OPUS-RS module reduces the required session duration to 10÷15 minutes while centimetre-level accuracy is still achievable.

The analyses consist of a subnetwork of the State of Michigan CORS network with station separations of 247÷292 km, and base-rover distances of 135÷162 km. An example 24h data set was post-processed in 144 10-minute sessions with 30-second data sampling rate. The AR success ratio, speed and reliability, along with the positioning results were analysed. The results show that 97% success ratio was achieved. Applying a second iteration to the unresolved cases improved the success ratio to 100%. The analyses were performed under unfavorable ionospheric conditions when a minor geomagnetic storm took place with maximum Kp = 6+. The resulting coordinate accuracy is better than 1 cm for the horizontal components and better than 3 cm for the vertical one. On 31 January 2007, after 15 months as an Operational Prototype, OPUS-RS was promoted to Initial Operational Capability Status (http://www.ngs.noaa.gov/OPUS/OPUS-RS.html) (Kashani et al., 2008).

4.5.7.6. Studies on Multipath Impact on Precise GNSS Positioning

The effect of multipath on the determination of coordinates of control network stations was analysed at the Warsaw University of Technology (Szpunar et al., 2008).

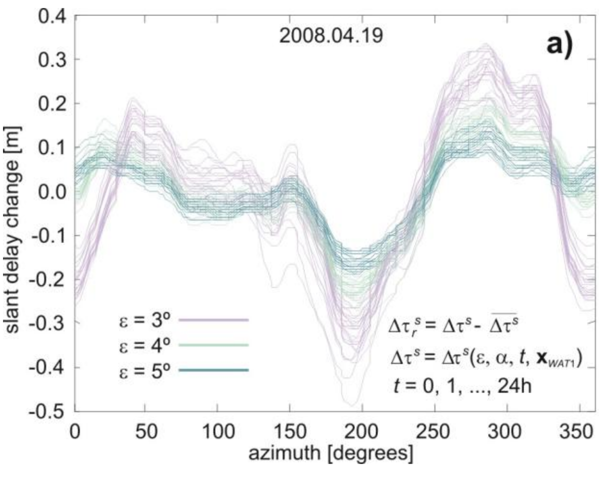
4.5.7.7. Studies of the RTK Performance Under Severe Conditions

Research on the RTK performance in the forested area was conducted at the University of Warmia and Mazury, Olsztyn, (Bakuła et al., 2009c).

4.6. TROPOSPHERE STUDIES

The significant one week period variations of aerosol content are mentioned in some publications. There are no natural cycles with 7 days period, except those of anthropogenic source. The car traffic and industrial activity changes on global scale with weekly period cause the corresponding variations of the released aerosol amount. The total amount and anthropogenic/natural related aerosol changes causes variations in water cycle dynamics in the atmosphere. As a consequence the regular cloud height and activity changes are observed as well as a sequence of the powerful atmospheric processes takes place. Besides well-known and widely discussed consequence of the aerosol variations, the geodynamic phenomena, i.e. the Earth rotation velocity variations with 7 days period are observed, that can be the result of periodic changes of the moment of inertia of the atmosphere due to the redistribution by height of the aerosol amount and atmospheric water. This weekly cycle was investigated on the basis of the Kiev AERONET site aerosol measurements data, the GNSS tropospheric water data and other long-term aerosol data available and an attempt if its interpretation was made. The obtained periodic variations were compared with 7-days Earth rotation velocity oscillations (Zanimonskiy et al., 2009).

Investigations of neutral atmosphere slant delay based on the analysis and forecast fields from mezoscale weather model are conducted by the Centre of Applied Geomatics (CAG) of the Military University of Technology, Warsaw. The Coupled Ocean / Atmosphere Mesocale Prediction System, Naval Research Laboratory, Monterey Marine Meteorology Division (COAMPS - NRL) was used (Figurski and Kroszczynski, 2007a, 2007b; Figurski et al, 2009). Refraction fields required for calculation were interpolated from the model grid with the spatial resolutions of 13, 4.3 and 1.44 km for every hour in the 24-hour range. Slant delays were determined using ray tracing procedure – a numerical realization of the eikonal equation solution. Spatial distribution of delays was obtained in the process of atmosphere scanning for the ASG-EUPOS sites positions (Fig. 4.6.1). The scanning was performed in topocentric frames for the elevations and azimuths within the range of 3º – 15º and 0º – 360º, respectively. The results enabled preliminary estimation of temporal and spatial slant delay fields changes and their dependencies on mezoscale model grids resolution. They also helped to determine the anisotropy characteristics of their local spatial distributions.



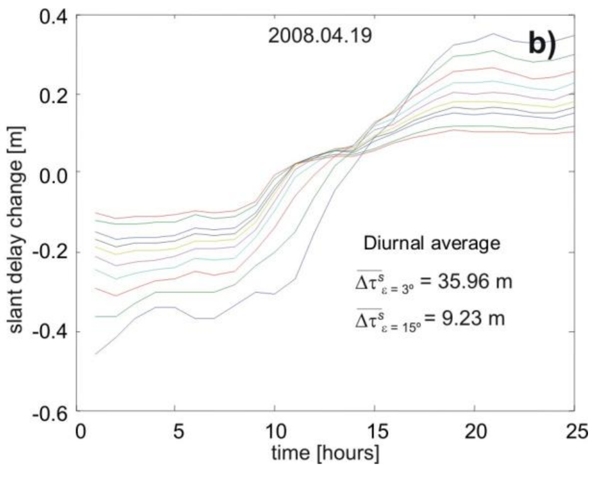


Fig. 4.6.1. Slant delay differences and their azimuth average values for each hour COAMPS forecast a); azimuthally averaged differences of hourly and diurnal slant delays b)

An important area of research of the team of the Warsaw University of Technology is to estimate and analyse ZTD estimation results as well as Integrated Precipitable Water (IPW) and Integrated Water Vapour (IWV) time series derived from GPS solutions. One of main objects of WUT LAC is thus a standard ZTD estimation, monitoring of the results and research on IPW time series. Both, IPW – derived from GPS tropospheric solutions as geophysical data – and ZTD itself derived from WUT LAC solutions and EPN combination are investigated. Most important conclusion from EPN ZTD series monitoring is a dramatic decrease of ZTD differences between individual LAC solutions in 2007 (solutions after GPS week 1400 showing best conformity since 2003) (Fig. 4.6.2). Results from 2005, when a new Bernese software v5.0 was introduced, show greater discrepancies in some LACs only. The cause of excellent conformity starting from the GPS week 1400 is most probably a cumulative effect of using almost exclusively the Bernese v5.0, absolute antenna PCVs and a new reference frame ITRF2005/IGS05 (Kruczyk et al., 2010).

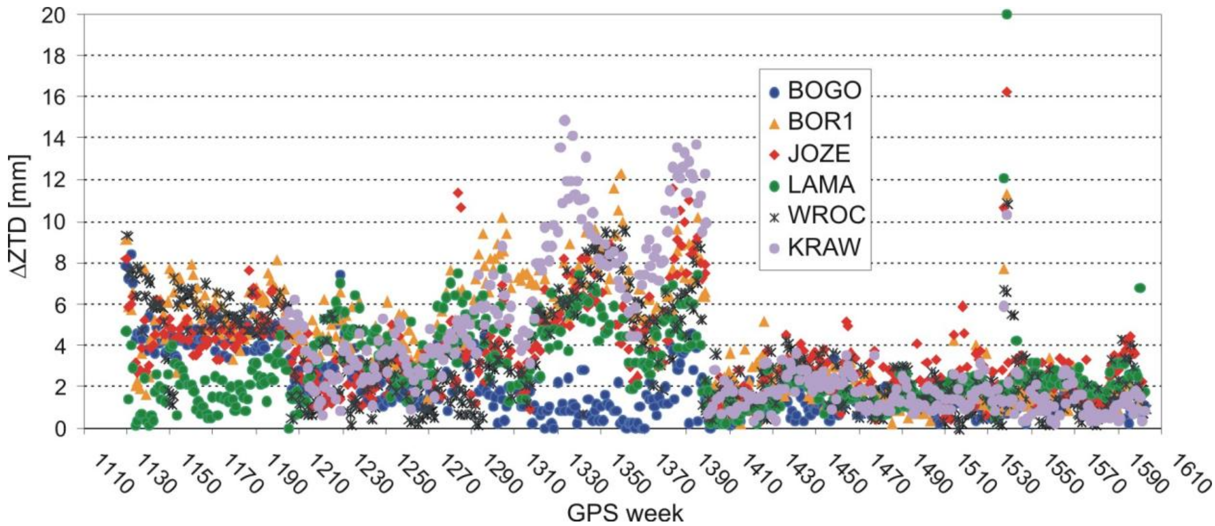


Fig. 4.6.2. ZTD weekly mean absolute differences: EUR combined product - individual LAC for all EPN stations in Poland

WUT LAC ZTD series monitoring is a proof of good tropospheric solution quality. Decrease of differences between WUT LAC solutions and EPN combination after 2007 is shown in Figure 4.6.3 (Kruczyk, 2010).

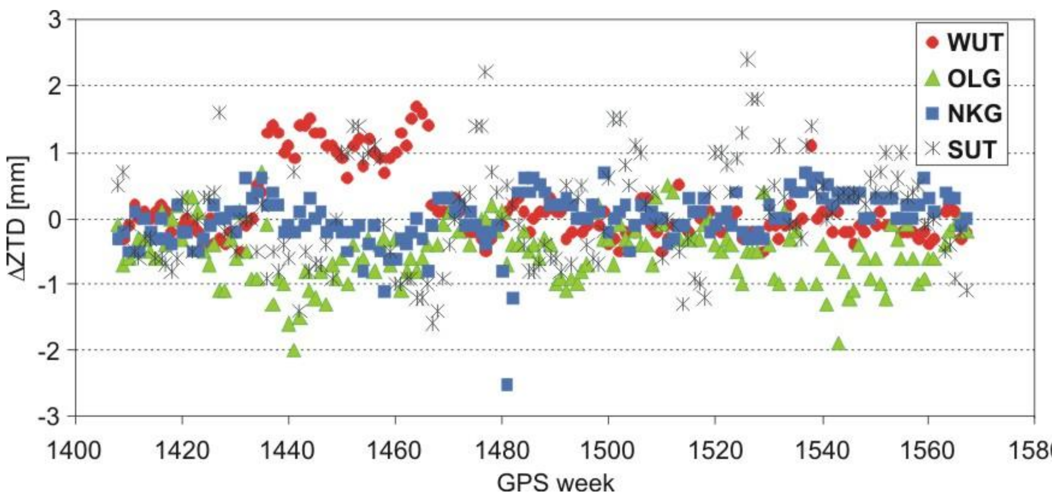


Fig. 4.6.3. ZTD weekly mean biases: EUR combined product - individual LAC for all EPN stations in the Center's solution

IPW is an important meteorological parameter easily derivable from GPS tropospheric solutions (ZTD's from different EPN solutions and combination). IPW values from other sources can be much more problematic due to various technical shortages. Numerous comparisons of different static solutions (mainly EPN) with three meteorological water vapour data sources: radiosoundings, sunphotometer (CIMEL, Central Geophysical Observatory of the Polish Academy of Sciences, Belsk) and input data of operational numerical prediction model (NWP) COSMO-LM (maintained by the Polish Institute of Meteorology and Water Management data made accessible by Mr. A. Mazur) treated as meteorological database. All analyses indicate high quality of IPW data coming from GPS (Kruczyk, 2009).

CIMEL-318 sunphotometer seems the most genuine source of the IPW data. Multichannel radiometer measures many air properties (mostly aerosoles) registering also water vapour absorption lines of solar spectra (e.g. 440 nm, 870 nm) and provides IPW values (precisely – slant values in the direction to the Sun). The major disadvantage of the technique is a poor time coverage of sunphotometer data (and small number of instruments of course) (Kruczyk 2007, 2008).

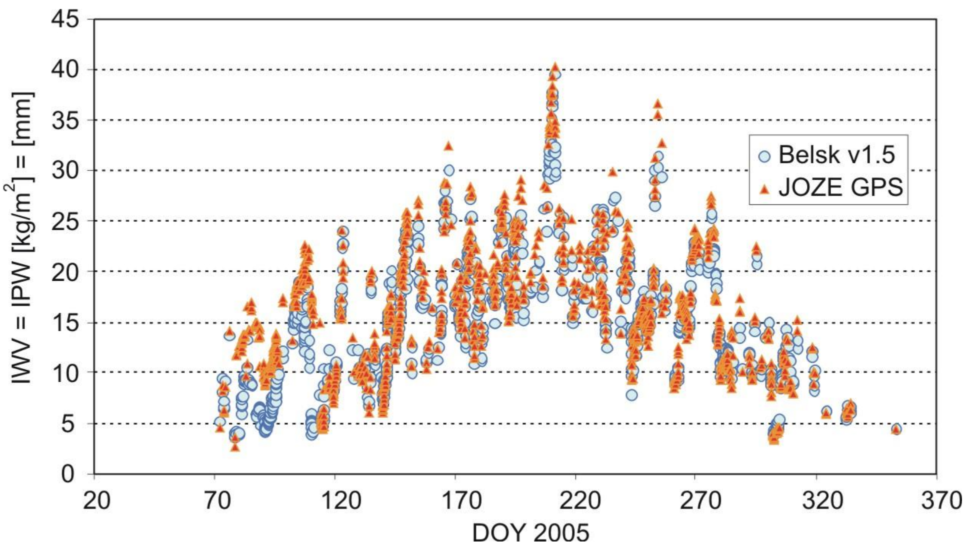


Fig. 4.6.4. Integrated Precipitable Water values validated by independent technique: sunphotometer CIMEL CF-318 (Central Geophysical Observatory, Belsk near Warsaw, 33 km from JOZE) – results shown for 2005

Earlier results indicated a possibility for direct collocation of GPS and sunphotometer measurements. In May 2009 JOZE station GPS receiver Trimble 4000 SSE – one of the oldest in the EPN network – was replaced by more a recent model. The Trimble 4000 SSE receiver was then installed at the Central Geophysical Observatory in Belsk and works permanently thereafter; its antenna has been located on the roof of the Observatory main building. Data was analysed in the manner very similar to the EPN standard tropospheric solution but in smaller network (27 stations). Results from September 2007 are presented in Figure 4.6.5. Decreasing data conformity with increase of GPS receiver distance can easily be seen (Kruczyk and Liwosz, 2010).

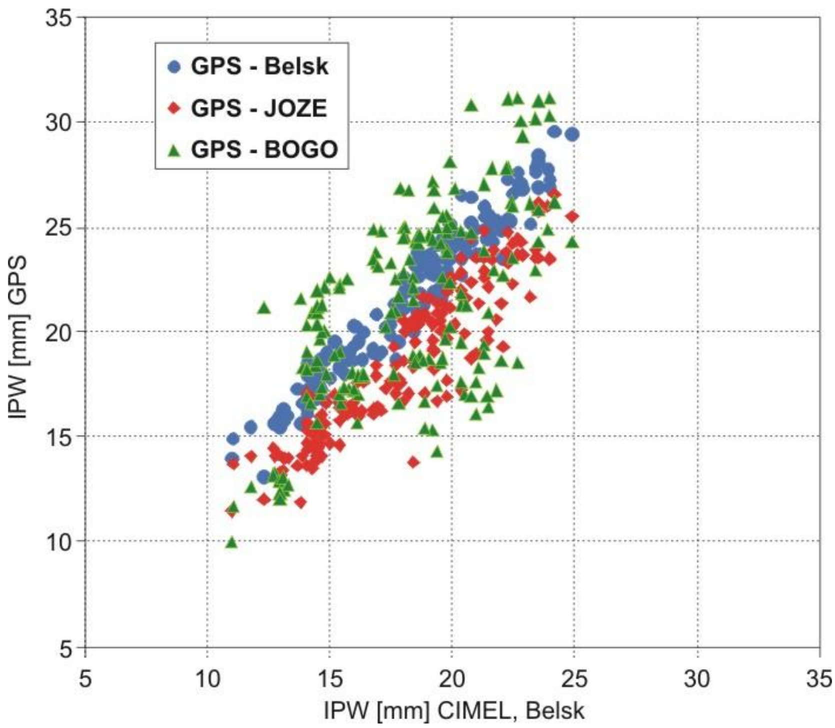


Fig. 4.6.5. IPW from sunphotometer in Belsk and GPS data 'in situ', JOZE (33 km distance) and BOGO (73 km) in September 2009

Two techniques of direct measurements of IPW, i.e. CIMEL – 318 sunphotometer at Belsk and radiosounding data from Legionowo, both considered as independent IPW source were compared to verify GPS tropospheric solutions for two GPS stations BOGO and JOZE (Table 4.6.1) (Kruczyk et al., 2010).

Table 4.6.1. Comparison of radiosounding (RAOB) and CIMEL sunphotometer (CSPHOT) as a mean to verify GPS solution (EPN tropospheric combination) in 2009

GPS	Aerological data	Bias [mm]	Mean absolute bias [mm]	Difference RMS [mm]	Correlation
BOGO	RAOB Legionowo	-1.05	3.43	4.43	0.87
JOZE	RAOB Legionowo	-0.72	1.42	2.28	0.96
BOGO	CSPHOT Belsk	1.47	3.33	3.82	0.88
JOZE	CSPHOT Belsk	0.58	1.16	1.74	0.97

Results of radiosoundings can be problematic due to various technical shortages, e.g. sparse RAOB network, accuracy of humidity sensor, various heights attained by sounding systems, etc. Thus sunphotometer seems more genuine source of IPW (Kruczyk, 2010).

It has been proved that the Numerical Weather Prediction model (COSMO-LM) treated as meteorological database can produce ZTD and IWV for all stations independently from sparse RAOB network. Unfortunately the procedure is not clearly straightforward. It has been found that NWP model topography is greatest concern for the proper ZTD derivation (Kruczyk, 2008).

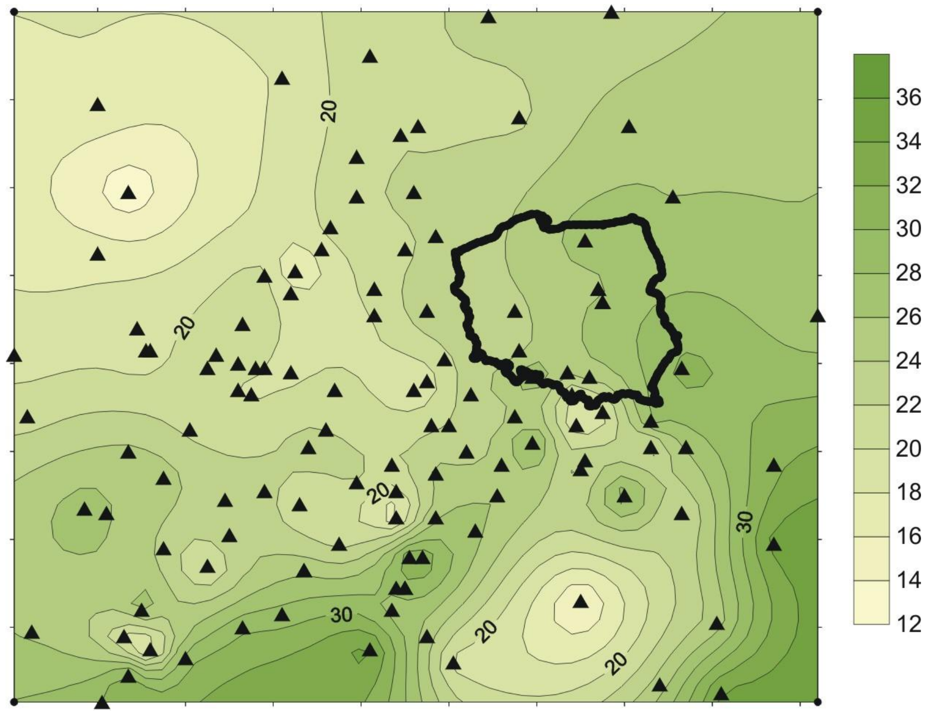


Fig. 4.6.6. ZTD differences RMS [mm] map in 2007 (EPN combined tropospheric product minus COSMO-LM input fields derived ZTD), model grid map

Deficiency of surface humidity data to model IPW extremely encourages to investigate information exchange potential between Numerical Model and GPS network derived values – crucial for future development of weather prediction but also for developing less laborious methods of GNSS precise positioning.

Value of GPS IPW as a geophysical parameter has been demonstrated by finding clear physical effects depending on station location (e.g. height, and ZTD series correlation coefficient as a function of distance) and weather pattern (Kruczyk, 2007). Especially intriguing are long series of daily averaged IPW which can serve as climatological information. A sinusoidal model adjusted using LS method to the IPW series derived for JOZE from IGS CODE ZTD solution, every year separately, for 5 year period, is shown in Figure 4.6.8. It can be noted that not only amplitudes but also phases differ. The IPW trend obtained equals to +0.6 mm/year. For the following years such trend was not observed (Kruczyk, 2009).

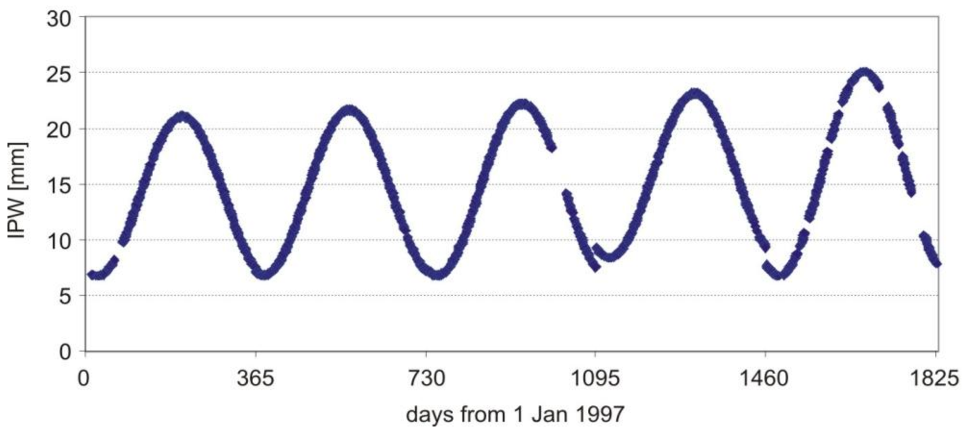


Fig. 4.6.7. Simple model of daily IPW values series (sinusoid + constant) derived from IGS CODE ZTD solution for JOZE 1997–2001

Local weather pattern is quite consistent in long series of daily averaged IPW. This is the acknowledged climatological parameter. In Figure 4.6.8 The sinusoidal model has been adjusted using LS method to the one year IPW data series of selected set of EPN stations. Different climate characteristics are seen not only in amplitudes but also in phases (Kruczyk, 2010).

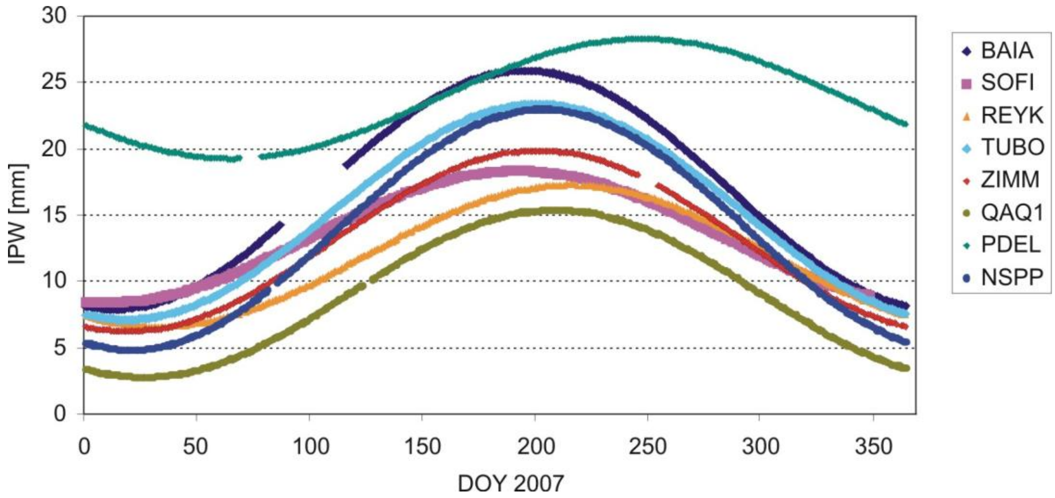


Fig. 4.6.8. Simple model of daily IPW values series (sinusoid + constant) EPN ZTD combination in 2007 for 8 EPN stations representing diversity of European climates

The GNSS meteorology group from the Institute of Geodesy and Geoinformatics of the Wroclaw University of Environmental and Life Sciences, has been studying the impact of the troposphere on the GNSS signal since 2005. The first stage of the investigations concerns the usage of meteorological parameters from selected EPN stations to model ZTD. To compare and calibrate meteorological data from meteo packs with the use of data from synoptic stations, special procedures have been applied (Rohm and Bosy, 2007). First results show the problem of accuracy deficiencies on some of tested meteorological EPN stations. To investigate actual accuracy of all meteorological stations mounted close to EPN sites previously developed methodology (comparison with reference World Meteorological Organization WMO stations) with one year of observations was utilized. The results obtained show a number of stations with corrupted or malfunctioning sensors; the stations administrators were informed about these issues (Bosy and Rohm, 2009).

The next stage of the research was the use of ZTDs from GNSS observations to develop a tomographic model of the troposphere, its most changeable part – water vapour. The investigations concerned theoretical testing of the model, its optimal size, temporal and spatial resolution, scanning rays reconstruction techniques, effective numerical inversion (Rohm and Bosy, 2009). In the GNSS tomography **SWD** is linked with the wet refractivity $\mathbf{N}_W$ as follows

$$\mathbf{SWD} = \mathbf{A} \cdot \mathbf{N}_W \tag{1}$$

where **A** is the design matrix. The basic information contained in the **A** matrix is a distance that signal travels through each voxel (Fig. 4.6.9).

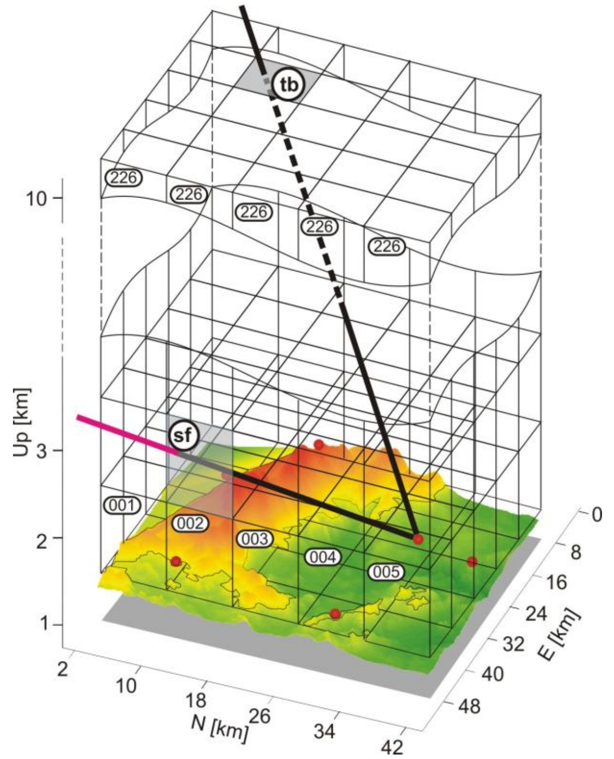


Fig. 4.6.9. The ray path in consecutive voxels. Two cases are considered, the first when the ray is coming out of the model's side face (sf), and the second, when ray is coming out of the model top boundary (tb). Model presented here has 25 voxels in 10 layers (Rohm and Bosy, 2009, 2010)

The original author's solution of equation (1) was applied (Rohm and Bosy, 2009, 2010). To find the voxels' refractivities one needs to invert the equation (1), using the More-Penrose pseudoinverse ($^+$)

$$\mathbf{N}_W = (\mathbf{A}^T \cdot \mathbf{P} \cdot \mathbf{A})^+ \cdot \mathbf{A}^T \cdot \mathbf{P} \cdot \mathbf{SWD}^T \quad (2)$$

where the **P** is a weighting matrix which is constructed as an inversion of covariance matrix of observations $\mathbf{P} = \mathbf{C}_{\mathbf{SWD}}^{-1}$. The design matrix **A** contains the distances and especially tuned horizontal constraints whose impact together with model voxel's size has been studied (Rohm and Bosy, 2009). The **A** matrix was modified according to latest findings in the field of flow analysis (Rohm and Bosy, 2010). The method presented uses the minimum constraint conditions imposed on the system of observation equations (1) and the design matrix **A**. The pseudoinverse of ($\mathbf{A}^T \cdot \mathbf{P} \cdot \mathbf{A}$) is based on Singular Value Decomposition (SVD).

The results of numerical simulations show that the voxel height should be at least 3÷5 times smaller than the horizontal size to solve the system with currently available GPS satellites. The use of minimum horizontal constraints proved to be robust and sensitive.

After testing the model against simulated values, it was tested against real values. The proposal of methodology to compute IWV not only over the GNSS receiver but also to investigate the water vapour distribution in space and time, a 4-Dimensional Water Vapour Distribution (4DWVD) model was constructed using GNSS tomography method (Bosy et al., 2010a). The input data of GNSS tomography are tropospheric signal delays, results of GNSS data processing and additionally ground meteorological observations. Different sources of ground meteorological data have heterogeneous character but give a broad spectrum of information. The meteorological observations obtained from synoptic stations and meteorological sensors located near the GNSS antenna need integration and error quantification. The procedure of verification of meteorological and NWP data for GNSS tomography were described (Bosy et al., 2010a).

Next the GNSS tomography model was modified to resolve the problems with numerical stability, according to latest findings in the field of flow analysis (Rohm and Bosy, 2010). The analysis of the flow derived from radio sounding and NWP as well as the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) model, shows that the actual correlation between consecutive voxels in the model is weaker in the bottom part and grows with increasing height. Thus, the model constraints scheme was changed to stick closer to the reality. The results of tomographic model solution fed with GNSS derived SWDs are presented in Figure 4.6.10. Previously calculated refractivities from COAMPS model served as a reference.

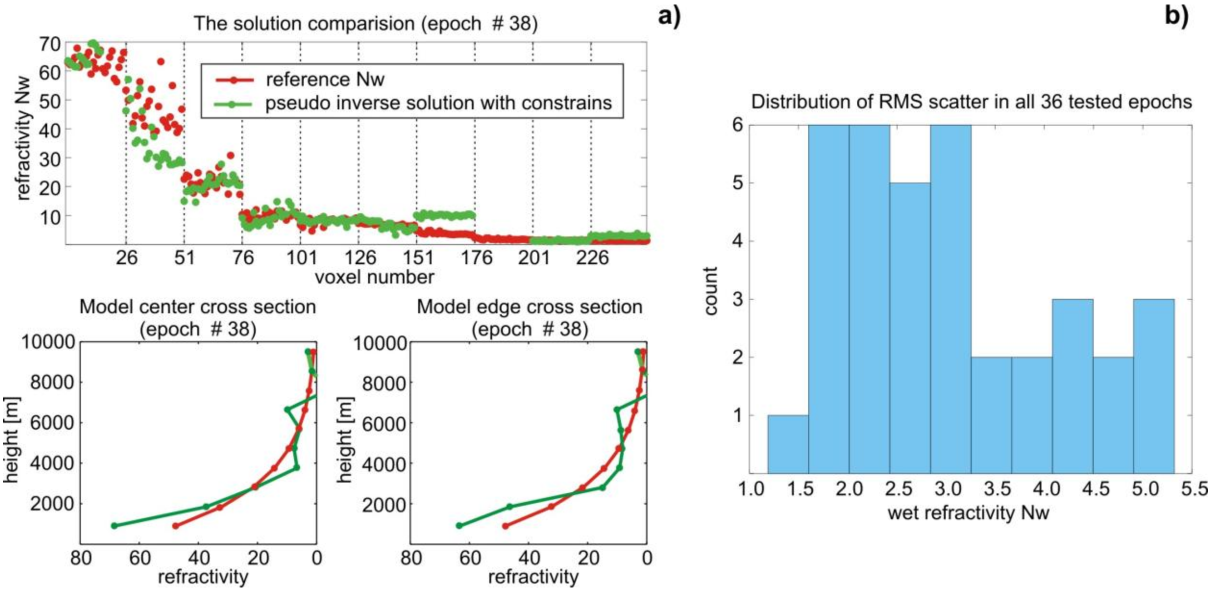


Fig. 4.6.10. a) The intersection through the model, real observed SWDs were used (tomographic solution - grey line, COAMPS reference data – black line); b) The histogram of the RMS of the real data solution with respect to COAMPS reference data (Rohm and Bosy, 2010)

Despite the extensive use of the NWP model COAMPS (mainly for verification purposes), the tomographic solution does not use any additional parameters other than derived from GNSS or ground meteorological stations. It is a main advantage of this method that can be regarded as complimentary to NWP models in case of the water vapour partial pressure estimation. Another advantage of the tomographic solution is that it still stays closer to the observation side of science and does not go deeply into the modelling (Rohm and Bosy, 2010).

The most recent investigations were directed into Near Real-Time application of the tomographic model (Bosy et al., 2010b). The GNSS tomography method will be used to create NRT models of water vapour NRT 4DWVD and meteorological parameters: temperature and pressure NRT 4DTPD in atmosphere. Meteorological observations from ASG-EUPOS (www.asgeupos.pl) and IMGW synoptic stations after mutual validation and integration procedure will be used for Slant Wet Delay (SWD) computation. The above meteorological observations, radiosoundings observations and NWP COAMPS model outputs will also be used for verification of GNSS tomography model. The NRT atmosphere model created from meteorological and GNSS data, could be competitive to NWP model, especially for nowcasting. The improvement in positioning is that tropospheric delays will be calculated directly from observations, not like now from deterministic models (Bosy et al., 2010b).

4.7. IONOSPHERE STUDIES

The Geodynamic Research Laboratory (GRL) of the University of Warmia and Mazury in Olsztyn in collaboration with West Department of the Institute of Geomagnetism, Ionosphere and Radio-Wave Propagation of the Russian Academy of Sciences, Kaliningrad continues the analysis of long time series of GNSS data from European Permanent Network (EPN) stations since 1994, to study the Earth's ionosphere. In the last year simultaneous GPS observations from about 150 stations of EPN have been used for studying the development of the severe geomagnetic storms of October 2003 (Krankowski et al., 2007a; Jakowski et al., 2008) and 7-12 November 2004 (Krankowski et al., 2007b), in the total electron content (TEC) on a global scale and dynamics of latitudinal profiles and structure of mid-latitude ionospheric trough (MIT) (Krankowski et al., 2009, Rothkaehl et al., 2008).

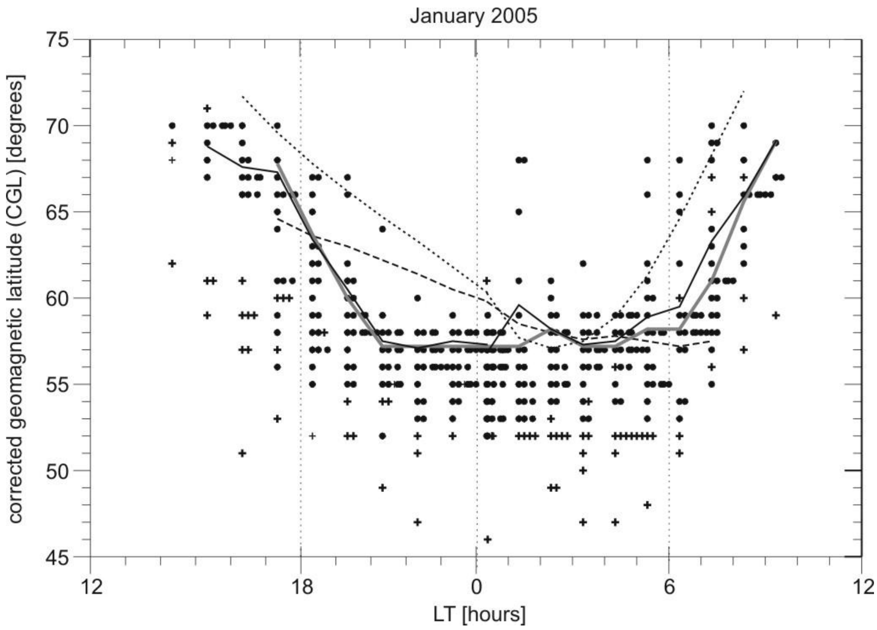


Fig. 4.7.1. Day by day position of the trough minimum for January 2005 (in CGL and LT). Dots – daily values, crosses – disturbed days with $\Sigma K_P \geq 20$, grey solid line – median with $\Sigma K_P \leq 20$, thin black solid line – presented model, dotted line – Werner and Prolss (1997) model, dashed line – Benkova et al. (1993) model (Krankowski et al., 2009)

In 2009 simultaneous GPS observations from about 150 stations of EPN have been used for studying dynamics of latitudinal profiles and structure of the MIT (Krankowski et al., 2009). For the analyses, the TEC maps over Europe were created with high spatial and temporal resolution. The latitudinal profiles were produced from TEC maps with 1h interval for latitude range 35ºN–75ºN. The structure of latitudinal profiles relates to the occurrence of the ionospheric trough. The location of the trough depends on season, local time, and both geophysical and geomagnetic conditions. The trough occurrence as a distinguished structure is more distinct during winter.

GPS observations from the EPN network were used to observe the response of TEC to the total solar eclipse on 3 October 2005 under quiet geomagnetic conditions of the daytime ionosphere (Fig. 4.7.2) (Krankowski et al., 2008; Altadill et al., 2009). The effect of the eclipse was detected in diurnal variations and more distinctly in the variations of TEC along individual satellite passes. The trough-like variations with a gradual decrease and followed by an increase of TEC at the time of the eclipse were observed over a large region. The depression of TEC amounted to 3÷4 TECU.

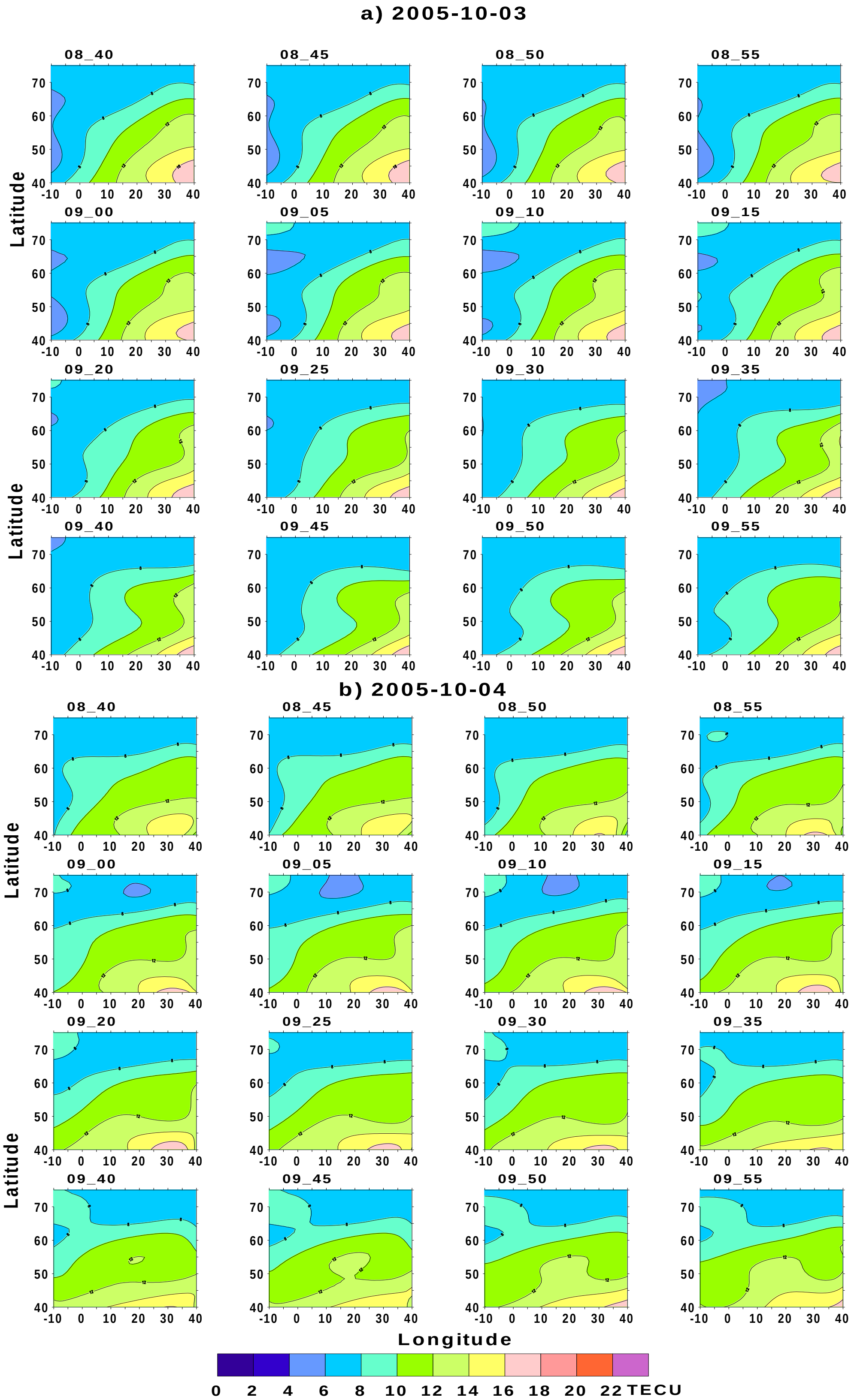


Fig. 4.7.2. The detailed TEC maps over Europe with 5-minute resolution during the eclipse day on 3 October 2005 (a) and one day after the solar eclipse on 4 October 2005 (b) (Krankowski et al., 2008)

GPS measurements of global IGS network were used to study the occurrence of TEC fluctuations at the northern (>55ºN) and southern high latitude ionosphere during severe geomagnetic storms (Shagimuratov et al., 2008, 2009). The rate of TEC (ROT) was used as a measure of fluctuation activity, and fluctuation intensity was evaluated using ROTI index. Using daily dual-frequency GPS measurements for individual satellite passes from all selected stations, the images of spatial and temporal behaviour of TEC fluctuations were formed (in Corrected Geomagnetic Coordinates – CGC and geomagnetic local time - GLT). Similarly to auroral oval, these images demonstrate an irregularity oval. The occurrence of the irregularity oval relates with the auroral oval, casp and polar cap. During a storm the intensity of TEC fluctuations essentially increased. The irregularity oval expands equatorward with increase of the magnetic activity. The studies showed that the existing high-latitudes GPS stations can provide a permanent monitoring tool for the irregularity oval in near real-time. The features of the development of phase fluctuations at the geomagnetic conjugate points and inter-hemispheric differences and similarities during winter and summer conditions were discussed.

A new mechanism for explaining unusual wave-like disturbances of a period of 4–6h with amplitudes increasing from high to low latitudes, observed frequently in TEC observations was proposed (Shagimuratov et al., 2010). The phase of the perturbations is weakly depended on latitude, so in observations they can be detected as a standing wave. The unusual structures can be explained by ionospheric effects of Poincare wave. Planetary Poincare waves propagate along longitudes westward and eastward and can generate standing waves with corresponding scales. The preliminary calculations show that spatial and temporal features of the observed TEC disturbances can be qualitatively explained by standing Poincare waves.

The features of pre-earthquake ionospheric anomalies in the TEC data obtained on the basis of regular GPS observations from the IGS network were investigated (Zakharenkova et al., 2007a, 2007b, 2008). For the analysis of the ionospheric effects of the Kythira 2006 earthquake (Fig. 4.7.3), the 25 September 2003 Hokkaido earthquake and 26 September 2005 Peru earthquake, respectively Global Ionospheric Maps (GIMs) of TEC were used. Analysis of the TEC maps has shown that modification of the equatorial anomaly occurred few days before the earthquake. In previous days, during the evening and night hours of local time (LT), a specific transformation of the TEC distribution had taken place.

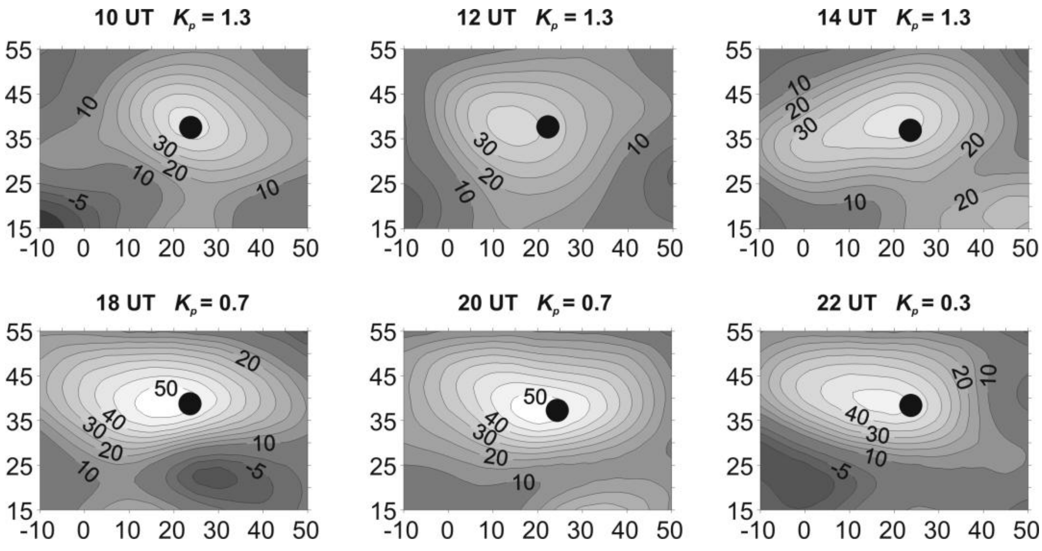


Fig. 4.7.3. Differential percentage TEC maps over European region calculated for fixed moments of universal time for 7 January 2006. The vertical and horizontal axes show geographical latitude and longitude. The epicenter position is marked by black dot (Zakharenkova et al., 2007a)

Nowadays, the Ionosphere Working Group of IGS generates three types of ionospheric products: final, rapid and predicted, respectively (Hernandez-Pajares et al., 2009). There are currently four IGS Associate Analysis Centres (IAACs) for the ionospheric products: CODE (Centre for Orbit Determination in Europe, University of Berne, Switzerland), ESA/ESOC (European Space Operations Centre of ESA, Darmstadt, Germany), JPL (Jet Propulsion Laboratory, Pasadena, USA) and gAGE/UPC (Technical University of Catalonia, Barcelona, Spain). These centres provide ionosphere maps computed using different approaches. Their maps are uploaded to IGS Ionosphere Product Coordinator, who computes official IGS combined products. Since January 2008, this coordination is carried out by the GRL/UWM (Geodynamics Research Laboratory of the University of Warmia and Mazury in Olsztyn, Poland).

Study on the impact of severe ionospheric conditions on the GPS hardware in the Southern Polar Region was conducted. It quantified the differences in tracking abilities among a number of geodetic-grade GPS receivers deployed in Antarctica, under disturbed ionospheric conditions (data collected under two ionospheric storms with significantly different magnitudes were tested). Substantial differences were found among the hardware types, indicating the importance of a careful selection of GPS receivers deployed in Antarctica, where the ionosphere is more active, as compared to mid-latitudes.

Differences in receiver performance are a result of several factors. Apart from the L2 tracking technique, tracking loop bandwidth, firmware version, the in-receiver processing algorithms, and the antenna gain pattern make a significant difference in the overall performance of a given receiver. The antenna environment is a contributing factor, too. For example, different antenna settings and types might be a reason for a considerably different performance of the same receiver type.

Semi-codeless receivers investigated showed very good performance, even under very severe ionospheric disturbances, while one of the semi-codeless receivers displayed the worse performance among the receivers tested. Several codeless receivers demonstrated a very good performance during both storms. On average, however, the performance of the codeless receivers was worse, as compared to the semi-codeless ones.

The comparison was performed for receivers significantly spread in latitude and longitude, and thus, the effects of the ionospheric storms analysed might not have been identical in space and time for all receivers tested. A better approach would be to test the receivers connected to the same antenna, or at least, antennas located in a close vicinity to each other, to assure no time and space dependency as a function of the storm evolution. In such a case, the data loss and reacquisition times could be compared (Grejner-Brzezinska et al., 2007a).

4.8. GNSS POSITIONING OF THE MOVING OBJECTS

Investigations of the results of RTK measurements using data transmission by internet and mobile phones for precise positioning for inshore navigation were conducted at the Warsaw University of Technology (Kujawa et al., 2007). The rover user is equipped with a GPRS modem in a GSM phone, which is connected to a notebook or receiver controller with RTCM Client software that receivs the RTCM data stream from the server via the TPC/IP protocol and transmits it via the serial port to the rover GNSS receiver. Practical aspects of common use of GPS and GLONASS observations in precise navigation were also investigated (Kujawa et al., 2009). Also the application of the autoregression algorithm for moving objects' track prediction was investigated (Woźniak et al., 2008).

The team of the University of Warmia and Mazury, Olsztyn, investigated application of GNSS techniques to the development of vehicles traffic model in urban area, specifically in the city of Olsztyn (Łukaszczuk et al., 2009).

4.9. OTHER GNSS APPLICATIONS

The team of the Institute of Geodesy and Cartography, Warsaw, takes part in the international geodynamics projects for Antarctica as well as in the projects of mapping some regions of Antarctica of special interest. The state-of-art of research in the several fields of geodesy and geophysics investigations based on GPS observations in Ukrainian Antarctic Vernadsky station area on the basis of the results of the Atmospheric Impact on GNSS Observations project has been presented (Cisak et al., 2008). The examples of the specific errors of the GNSS-solutions for Antarctic continent and of the troposphere-ionosphere coupling research were presented. The necessity of application of the new precision measurement methods is caused by complexity of the local geodynamic processes. This complication was illustrated by the examples of sea level data and results of the glaciers GPS-photogrammetry monitoring of the small ice caps dynamics of Argentine Islands Archipelago. The sea level changes as a consequence of climate change and geological processes were discussed. The present ice cap GPS-photogrammetry observations showed a reduction in volume of around several percent of Galindez ice cap in eight years, suggesting that it could disappear within a century.

An advanced research on theory of GNSS data processing was conducted at the Institute of Geodesy of the University of Warmia and Mazury in Olsztyn. A new method of Integer Least Square Adjustment (ILSA) was developed (Cellmer, 2009; Cellmer et al., 2010). Modified Ambiguity Function Approach (MAFA) algorithm ensures the condition of parameter “integerness“ without the necessity for the additional stage of the integer search (Cellmer et al., 2010). It is based on the LS adjustment algorithm with condition equations in the functional model. In order to derive such functional model an appropriate formula for function of the condition equation was derived. The method was implemented in GPS data processing. Because of relatively weak model of carrier phase data, different linear combinations of L1 and L2 GPS carrier phase observables were applied in the cascade adjustment in order to assure the appropriate convergence of the computational process.

The research on the use of the pseudolites to augment GPS positioning was continued at the University of Warmia and Mazury, Olsztyn. Differences in mathematical models of GPS and pseudolite observation equations were discussed (Rzepecka et al., 2007). GPS augmented with pseudolites can be used in various engineering surveys. Pseudolite observations with EDM survey influence on GPS vector estimation were compared (Rapiński and Zapert, 2007). The use of pseudolite as only navigation system for rapid deformation detection was investigated (Rapiński and Bond, 2008). Also the use of pseudolite in any place, when no GPS signal is available was discussed. One of the major issues in pseudolite surveys is linearization problem. The problem is in neglecting second terms of Taylor series expansion in GPS baseline processing software. An impact of linearization process on the results of positioning on the basis of pseudolite’s signals was estimated (Cellmer and Rapinski, 2010). The investigations of the possibility of monitoring the superficial deformation located on the unstable foundation with the use of GPS technology were also conducted (Kamiński, 2008a, 2008b).

In the paper (Bakuła et al., 2009b) two GPS Ashtech Z-Xtreme receivers were tested in very severe conditions in terms of reliability of determined coordinates using RTK technology. Results of experiments showed that RTK survey in the forest can result in centimetre accuracy of positioning with the use redundant independent RTK solutions based on repeated independent ambiguity reinitializations. Although gross errors might occur, the RTK technique can be a very helpful technology for positioning in woodland areas at cm-level of accuracy.

The use of integrated GNSS with hydroacoustic technologies was investigated at the University of Warmia and Mazury, Olsztyn. Its application for creation of an interactive inland underwater objects database (Popielarczyk, 2009) as well as for inventory taking of upper water reservoir in pumped-storage power station (Popielarczyk and Templin, 2009) was discussed.

Strategy of processing GNSS data and the performance of commercial GNSS softwares were analysed at the University of Warmia and Mazury, Olsztyn. A few short as well as long vectors of the test network were calculated using GPPS5.2/FILLNET3.1 and AOSS software. The results obtained confirmed the well known literature data. Namely, for short vectors better results are obtained when processing single frequency L1 measurements, while for longer baselines the use of L3 linear combination which almost completely eliminates the influence of ionosphere is recommended (Dawidowicz and Swiatek, 2008).

Satellite positioning system was used by the team of the Military University of Technology, Warsaw, to investigate displacements and deformations of engineering constructions (Figurski et al., 2007). This enables to easily detect any geometric construction changes with up to 20 Hz and sub centimetre accuracy. Past, present and real-time laboratory tests prove that there is a high efficiency of such research (Figurski et al., 2009c). The method is a strong alternative for traditional methods of surveying. At the Warsaw University of Technology the investigations on displacement monitoring of engineering objects using GPS-RTK technique were conducted (Szpunar and Walo, 2007). In particular, the use of the ASG-EUPOS system NAVGEO service in monitoring displacement was tested (Próchniewicz et al., 2009).

The GNSS group from the Institute of Geodesy and Geoinformatics of the Wroclaw University of Environmental and Life Sciences, has been studying the possibility of determining vertical component of station coordinates for both global and regional networks with a centimetre accuracy. In case of local networks, particularly those with epoch measurements, such accuracy can be obtained only when processing strategy includes specific feature of such network in terms of its location, geometry, as well as observation material used. In mountainous terrain one experiences large fluctuations of atmospheric conditions. Standard atmosphere models, used in GPS observation processing with the Bernese GPS software and other computer programmes, adequate for global and regional networks do not render these fluctuations of atmospheric conditions in the case of networks located in mountainous areas (Bosy, 2007). In the case of local networks located in mountainous terrain estimation of tropospheric delay is the most important stage of processing. It has a key influence on the determined coordinates of points, particularly the vertical component. The procedures of tropospheric delay estimation in GNSS data processing model proposed for local GNSS networks located in mountains area are shown in Figure 4.9.1 (Bosy, 2007).

The tropospheric delay estimation procedure, basing on standard atmosphere (SA) model for the KARKONOSZE network has yielded twice as high RMS error values as in the case of EPN networks. An alternative solution, estimation of delay based on local atmosphere (LT) model having large time resolution where tropospheric delay estimation procedure does not require time correction and RMS values correspond with obtained from EPN network solutions (Bosy, 2007).

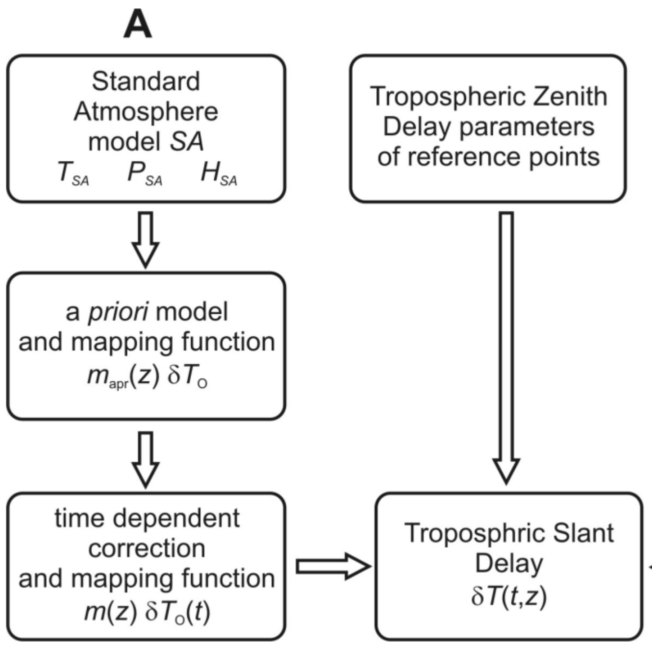


Fig. 4.9.1. The tropospheric delay estimation procedures based on the standard (A) and local (B) atmosphere models for local GNSS networks data processing models

4.10. ACTIVITIES WITHIN GALILEO PROGRAM

The Department of Planetary Geodesy of the Space Research Centre of the Polish Academy of Sciences (SRC PAS) participates in many European projects concerning the positioning and improving the navigation position of GNSS receiver. It operates the RIMS station in cooperation with ESA, the GNSS station that participated in the PERFECT project, and observing the GIOVE satellites the GESS station that participated in ESA project.

At SRC PAS in Warsaw there is located one of the RIMS stations (Ranging and Integrity Monitoring Station) of the EGNOS System (Fig. 4.10.1) which has been designed for broadcasting embedded correction signals in Europe, to improve performance with GPS.

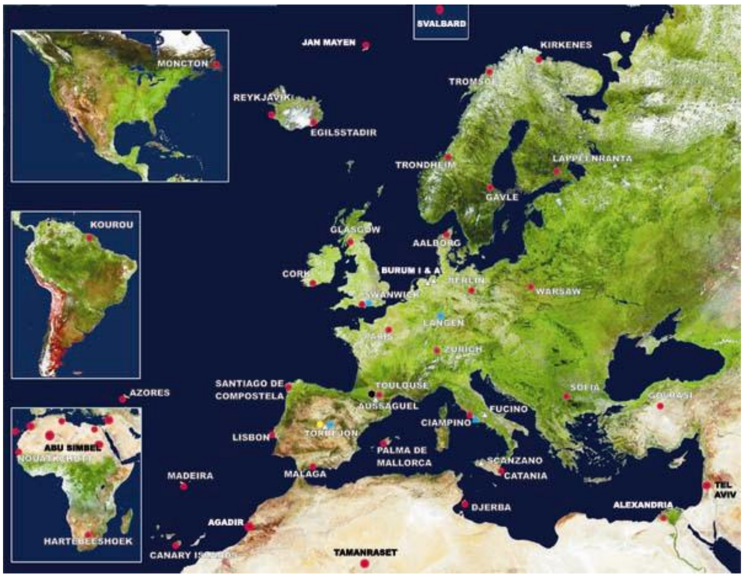


Fig. 4.10.1. The EGNOS Ground Segment (RIMS, MCC, NLES, PACF)

IMAGE project was launched in the autumn 2002 by the ESA GNSS-1 EGNOS Project Office for conducting independent SIS monitoring activities. A part of IMAGE project designed to provide continuous, near-real time information on EGNOS key performance values is called PERFECT (**PER**formance-website **F**or **E**gnos **C**ontinuous **T**racking). It consists of a set monitoring stations (Fig. 4.10.2) continuously tracking GPS satellites and EGNOS corrections. Every hour results are sent to the Web Server.

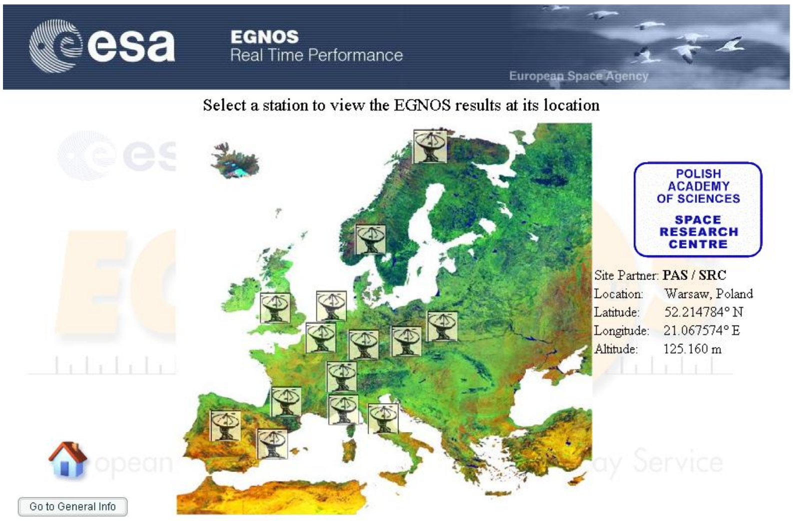


Fig. 4.10.2. PERFECT monitoring stations

Space Research Centre PAS participates in PERFECT project from June 2005. The equipment used for the project consists of Septentrio PolaRx2 GPS/EGNOS receiver, and PC with RxControl software to control the receiver as well as the WebUpdate Software to analyse observations and transfer results to the Web Server.

In 2009 a new GESS+ (Galileo Experimental Sensor Station) station GWAR (Fig. 4.10.3) was installed in the Space Research Centre PAS, Warsaw. After few months of data quality tests, the station was included as fully operational to the global network of monitoring GIOVE satellites starting from 16 December 2009 (Fig. 4.10.3).

Fig. 4.10.3. New GALILEO GESS+ station (GWAR) in SRC, Warsaw

The improvement of EGNOS corrections provided by system for Eastern Europe and especially for territory of Poland is one of the research activities of the Space Research Centre PAS. In 2007, static measurements were conducted using the Septentrio and CSI receivers, and dynamic tests were prepared. The analyses performed (Aguilar et al., 2007) showed that the EGNOS corrections improve in general the receiver position, but under some circumstances they do not (Fig. 4.10.4 and Fig. 4.10.5).

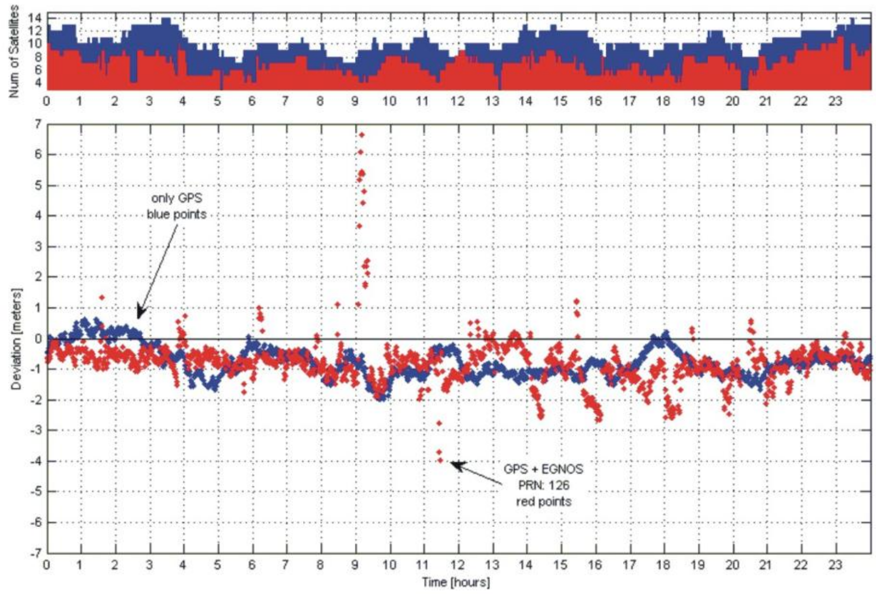


Fig. 4.10.4. The resulted values of *Y* coordinate for static measurement from 22 May 2007. The upper graph shows the number of observed satellites and the bottom one – the position of the receiver. The blue dots present GPS only measurements and red ones the GPS+EGNOS

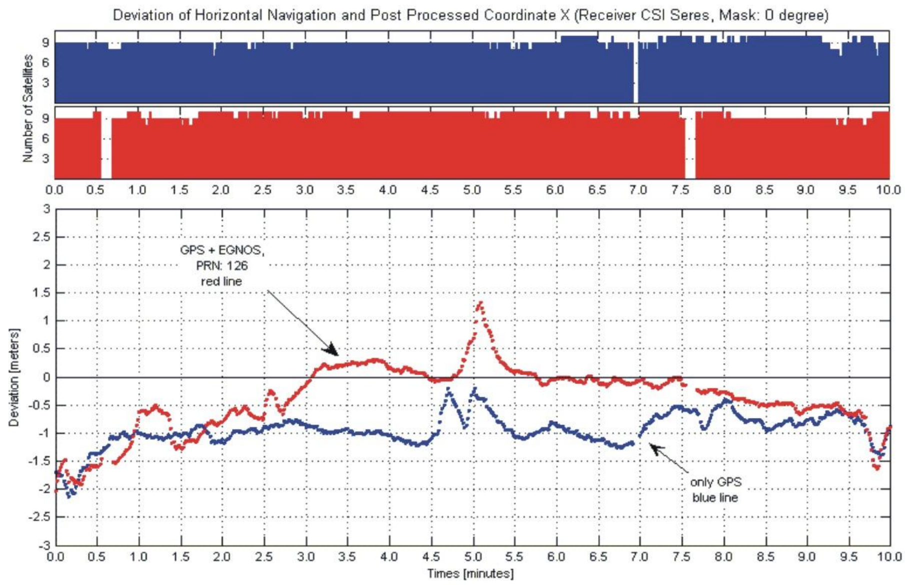


Fig. 4.10.5. The resulted values of *X* coordinate for static measurement from 17 April 2007. The upper graph shows the number of observed satellites and the bottom one – the position of the receiver. The blue dots present GPS only measurements and red ones the GPS+EGNOS

The analyses of the tests performed resulted in the proposal of the new project of EGNOS-EUPOS Integration (EEI). The EGNOS corrections are computed based on the GNSS observations, provided by 34 RIMS stations and are transmitted to the users by three geostationary satellites. In Central and Eastern Europe, including Poland, accuracy of EGNOS corrections could be improved if the distribution of RIMS stations was more regular, in particular if new RIMS stations were installed in East European countries from outside EU. At the moment accuracy and availability of EGNOS corrections are degraded there; for some GPS satellites observed no EGNOS corrections are available. The main purpose of the EEI project is to improve the effectiveness and range of applications of the EGNOS system, by achieving the full compatibility and integration with the EUPOS system. The EUPOS system installed recently in a number of countries of Central Europe will be the basis of the official legal geodetic reference system in those countries. Both systems are designed for positioning and navigation at the same territory, both are based on satellite technology but with different conceptual and technical assumptions and with different technical infrastructure (Jaworski and Swiatek, 2009).

4.11. ACTIVITIES IN THE USE OF RADAR INTERFEROMETRY

Radar interferometry technique is widely used in studies the Earth's surface using satellites (In-SAR). It also allows for detecting and monitoring displacements and deformations of engineering objects. Structures of elongated or slender shape, such as bridges or towers, are susceptible to vibration arising. Application of interferometric radar to examination of engineering objects vibration was investigated at the Department of Engineering Surveying and Civil Engineering, AGH University of Science and Technology in Cracow (Kuras et al., 2009). Ground-based interferometric radar is capable to measure the relative movement with 0.1 mm precision and 200 Hz frequency of data acquisition and enables to detect even slight vibration.

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