GEODESY AND CARTOGRAPHY
Vol. 64, No 2, 2015, pp. 147–176

DOI:10.1515/geocart-2015-0011

Reference frames and reference networks

Jaroslaw Bosy[1], Jan Krynski[2]

[1] Wroclaw University of Environmental and Life Sciences
Institute of Geodesy and Geoinformatics
53 Grunwaldzka St., 50-357 Wroclaw, Poland
e-mail: jaroslaw.bosy@igig.up.wroc.pl

[2] Institute of Geodesy and Cartography
Centre of Geodesy and Geodynamics
27 Modzelewskiego St., 02-679 Warsaw, Poland
e-mail: jan.krynski@igik.edu.pl

Received: 17 March 2015 / Accepted: 20 April 2015

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

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

1. Introduction

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

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

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

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

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

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

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

2. Implementation of IUGG2011 and IAU2012 resolutions on reference systems

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

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

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

the resolution of the IAU XXVI General Assembly in Prague in 2006 precessional part of the IAU2000A precession-nutation model was replaced with the P03 starting from the 2009 edition of the Astronomical Almanac. The 2010 edition of the Astronomical Almanac, following resolutions of the IAU XXVII General Assembly in Rio de Janeiro in 2009, implemented a new set of astronomical constants named IAU2009 as well as ITRF2 as fundamental astrometric realization of ICRS (Krynski, 2011b). The resolution of IAU XXVII General Assembly in Rio de Janeiro in 2009 has been adopted by IUGG XXV General Assembly in Melbourne in 2011. The 2011, 2012, 2013 and 2014 editions the Astronomical Almanac contain all updates to the previous editions (Krynski and Sekowski, 2010, 2011, 2012, 2013). The resolution of the IAU XXVIII General Assembly in Beijing in 2012 concerning the new definition of the astronomical unit has been implemented in the Astronomical Almanac starting from 2013 edition. Works on modification of presentation methods of high precision astrometric and geodetic data in view of the latest achievements in the field of reference systems are in progress (Sekowski and Krynski, 2011).

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

3. Implementation of the ETRS89 in Poland

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

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

In 2012 the Head Office of Geodesy and Cartography (GUGiK) that represents surveying and mapping authority in Poland has completed tasks related to the definition of new reference frame for Poland. The frame was established basing on two extended GNSS campaigns conducted between 2008 and 2011 and their cumulative adjustments performed independently by the teams of the Space Research Centre of the Polish Academy of Sciences and the Warsaw University of Technology. Following the resolution No. 2 undertaken by the sub-committee EUREF on EUREF Symposium

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

2010 in Gavle, Sweden (2–5 June 2010) ETRF2000 has been approved by GUGiK as the new realization of ETRS89 in Poland. The frame named PL-ETRF2000 (epoch 2011.0) was also introduced into Polish legal act <*Regulation of Council of Ministers for National Spatial Reference System* (*pl. Rozporządzenie w sprawie Państwowego Systemu Odniesień Przestrzennych z dnia 15 października 2012 r.*)> as a primary frame for a high accuracy geodetic surveying (Fig. 3).

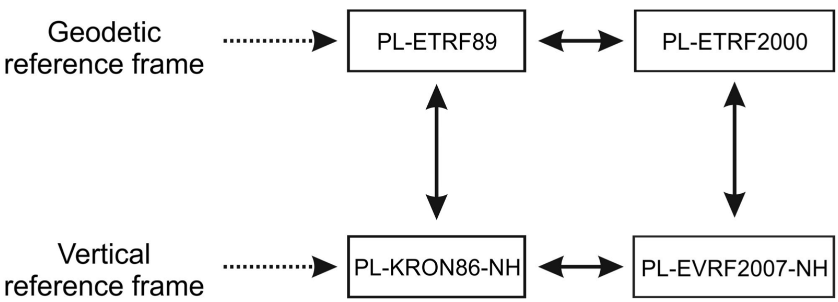

Fig. 3. Polish National Spatial Reference System

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

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

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

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

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

4.1. Operational work of GNSS permanent stations in Poland

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

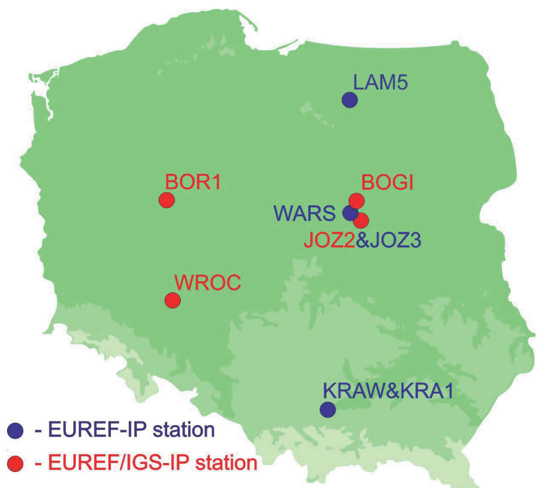

Fig. 4. EPN/IGS permanent GNSS stations in Poland (2014)

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

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

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

Table 1. EPN/IGS permanent GNSS stations in Poland

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

Table 2. Characteristics of Polish EPN stations

4 char. Station ID	Domes Number	Location/ Institution	Receiver/ Antenna	Started operating/ as EPN station	Meteo Sens./ Manufacturer	Data transfer blocks	Observations performed
BOGI	12207M003	**Borowa Gora** Inst. of Geodesy and Cartography	**Javad TRE_G3T** DELTA ASH701945C_M SNOW	**03JAN2001/** since 265/2002 (GPS week No 1185)	**LB-710HB** LAB-EL Poland MET4A Paroscientific Inc.	24 h 1h	Ground water level Astrometry Gravity GPS/ GLONASS/ Galileo Geomagnetic field
BOGO	12207M002	**Borowa Gora** Inst. of Geodesy and Cartography	**TPS Eurocard** ASH700936C_M SNOW	**08JUN1996/** since 182/1996 (GPS week No 0860)	**LB-710HB** LAB-EL Poland	24 h 1h	Ground water level Astrometry Gravity GPS/ GLONASS Geomagnetic field
BOR1	12205M002	**Borowiec** Space Research Centre, PAS	**Trimble NetRS** AOAD/M_T NONE	**10JAN1994/** since 365/1995 (GPS week No 0834)	**HPTL.3A** NAVI Ltd. SKPS 800/I Skye Instr. Ltd. ARG 10/STD Skye Instr Ltd.	24 h 1h	SLR GPS/ GLONASS Time service
BPDL	12223M001	**Biala Podlaska** Head Office of Geodesy and Cartography	**Trimble NetR5** TRM55971.00 TZGD	**04DEC2007/** since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/ GLONASS
BYDG	12224M001	**Bydgoszcz** Head Office of Geodesy and Cartography	**Trimble NetR9** TRM59900.00 SCIS	**04DEC2007/** since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/ GLONASS/ Galileo/ SBAS
GWWL	12225M001	**Gorzow Wielkopolski** Head Office of Geodesy and Cartography	**Trimble NetR9** TRM59900.00 SCIS	**10DEC2007/** since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/ GLONASS/ Galileo /SBAS
JOZE	12204M001	**Jozefoslaw** Inst. of Geodesy and Geod. Astr., WUT	**Trimble 4000SSI** TRM14532.00 NONE	**03AUG1993/** since 365/1995 (GPS week No 0834)	**LB-710RHMS** LAB-EL Poland	24 h 1h	Ground water level Astrometry Gravity tidal GPS
JOZ2	12204M002	**Jozefoslaw** Inst. of Geodesy and Geod. Astr., WUT	**Leica GRX1200GGPRO** LEIAT504GG NONE	**03JAN2002/** since 257/2003 (GPS week No 1236)	**LB-710RHMS** LAB-EL Poland MET4A Paroscientific Inc.	24 h 1h	Ground water level Gravity absolute Gravity tidal GPS/ GLONASS

4 char. Station ID	Domes Number	Location/ Institution	Receiver/ Antenna	Started operating/ as EPN station	Meteo Sens./ Manufacturer	Data transfer blocks	Observations performed
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	**Krakow** AGH UST	**Ashtech µZ-12** ASH701945C_M SNOW	**01JAN2003**/ since 026/2003 (GPS week No 1203)	**LB-710** LAB-EL Poland	24 h 1h	GPS
KRA1	12218M002	**Krakow** AGH UST	**Trimble NetR5** TRM57971.00 NONE	**01JAN2010**/ since 080/2010 (GPS week No 1576)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/ GLONASS
LAMA	12209M001	**Lamkowko** UWM	**Leica GRX1200+GNSS** LEIAT504GG LEIS	**01DEC1994**/ since 365/1995 (GPS week No 0834)	**MET4A** Paroscientific Inc.	24 h 1h	Ground water level Gravity GPS/ GLONASS
LODZ	12226M001	**Lodz** Head Office of Geodesy and Cartography	**Trimble NetR9** TRM59900.00 SCIS	**03DEC2007**/ since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/ GLONASS/ Galileo /SBAS
REDZ	12227M001	**Redzikowo** Head Office of Geodesy and Cartography	**Trimble NetR9** TRM59900.00 SCIS	**07DEC2007**/ since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/ GLONASS/ Galileo /SBAS
SWKI	12228M001	**Suwalki** Head Office of Geodesy and Cartography	**Trimble NetR9** TRM59900.00 SCIS	**05DEC2007**/ since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/ GLONASS/ Galileo /SBAS
USDL	12229M001	**Ustrzyki Dolne** Head Office of Geodesy and Cartography	**Trimble NetR9** TRM59900.00 SCIS	**03DEC2007**/ since 160/2008 (GPS week No 1483)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/ GLONASS/ Galileo /SBAS
WROC	12217M001	**Wroclaw** Univ. of Env. & Life Sciences	**Leica GR 25** LEIAR25.R4 LEIT	**28NOV1996/** since 329/1996 (GPS week No 0881)	**MET4A** Paroscientific Inc.	24 h 1h	Ground water level GPS/ GLONASS/ Galileo/ BeiDouQZSS/ SBAS
ZYWI	12220S001	**Zywiec** Marsh. Off. of the Siles. Prov.	**Trimble NetR9** TRM59900.00 SCIS	**30JAN2003**/ since 222/2003 (GPS week No 1231)	**MET4A** Paroscientific Inc.	24 h 1h	GPS/ GLONASS/ Galileo/ SBAS

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

Location	St. ID	Observations	Latitude [deg]	Longitude [deg]	Receiver	RTCM type – message types (update rate [s])
Borowa Gora	BOGI	GPS+GLO	52.48	21.04	Javad TRE_ G3T DELTA	RTCM 3.0 – 1004(1), 1006(10), 1008(10), 1012(1)
Borowiec	BOR1	GPS+GLO	52.28	17.07	TRIMBLE NetRS	RTCM 2.3 – 1(1),3(10), 18(1),19(1), 22(10)
Jozefoslaw	JOZ2	GPS+GLO	52.02	21.03	Leica GRX1200 GGPro	RTCM 3.0 – 1004(1), 1006(60), 1008(60), 1012(1)
Jozefoslaw	JOZ3	GPS+GLO	52.02	21.03	Leica GRX1200 GGPro	RTCM 3.0 – 1004(1), 1006(15), 1008(15), 1012(1), 1033(15)
Krakow	KRAW	GPS	50.01	19.92	Ashtech μZ-12	RTCM 2.2 – 1(1),3(60), 16(60), 18(1), 19(1),22(60)
Krakow	KRA1	GPS+GLO	50.01	19.92	TRIMBLE NetR5	RTCM 3.0 – 1004(1), 1006(10), 1008(10), 1012(1), 1013(10), 1033(10)
Lamkowko	LAMA	GPS+GLO	53.89	20.67	Leica GRX1200 GGPro	RTCM 3.0 – 1004(1), 1006(15), 1008(15), 1012(1), 1019, 1020, 1033(15)
Warsaw	WARS	GPS+GLO	52.00	21.00	Leica GRX1200 +GNSS	RTCM 3.0 – 1004(1), 1006(15), 1008(15), 1012(1)
Wroclaw	WROC	GPS+GLO	51.11	17.06	Leica GR 25	RTCM 3.0 – 1004(1), 1006(15), 1008(5), 1012(1), 1013(15), 1033(15)

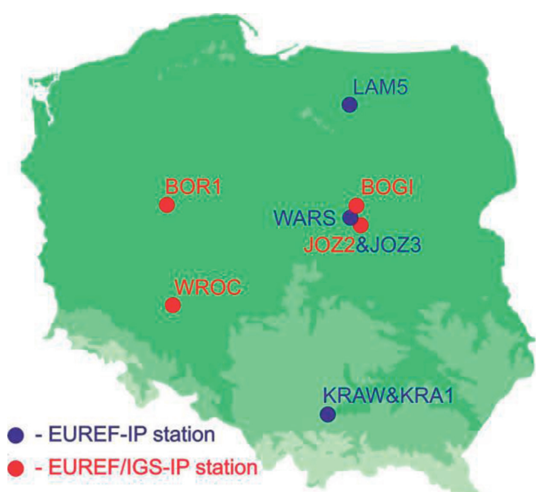

Fig. 5. Polish EPN stations participating in the EUREF-IP project (2013)

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

4.2. Operational work of ILRS laser ranging station in Poland

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

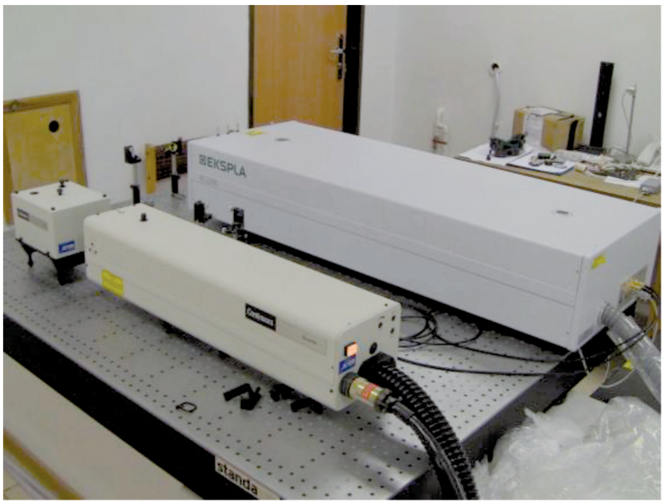

Fig. 6. New laser at the Borowiec Observatory

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

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

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

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

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

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

Time series of GNSS solutions can provide information for detection of some internal problems affecting SLR station, e.g. the station Wettzell (Germany) (Fig. 8b). The agreement in both horizontal components of GNSS WTZR and SLR 8834 is

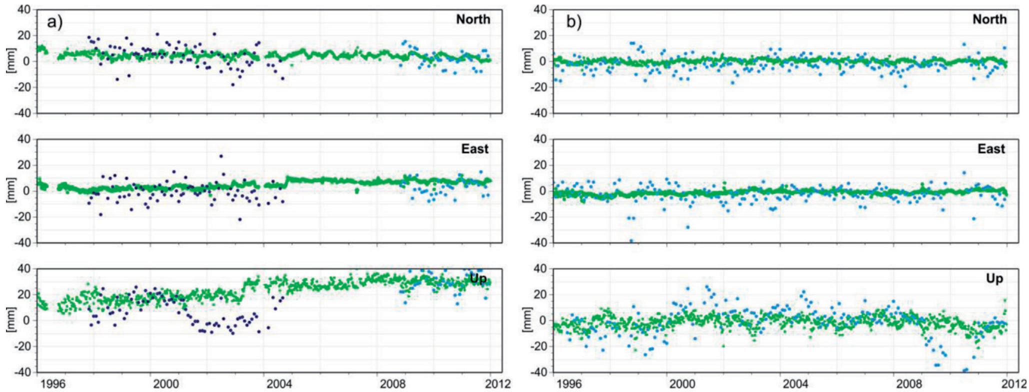

Fig. 8. Time series of *N*, *E*, *U* components of the GNSS station GRAS (green) and SLR stations 7835 (navy blue) and 7845 (blue) – on the left (a); time series of the WTZR (green) and SLR station 8834 (blue) – on the right (b)

observed, while some disturbances at the level of 40 mm can be noted in SLR solutions for *Up* component in 2009–2010.

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

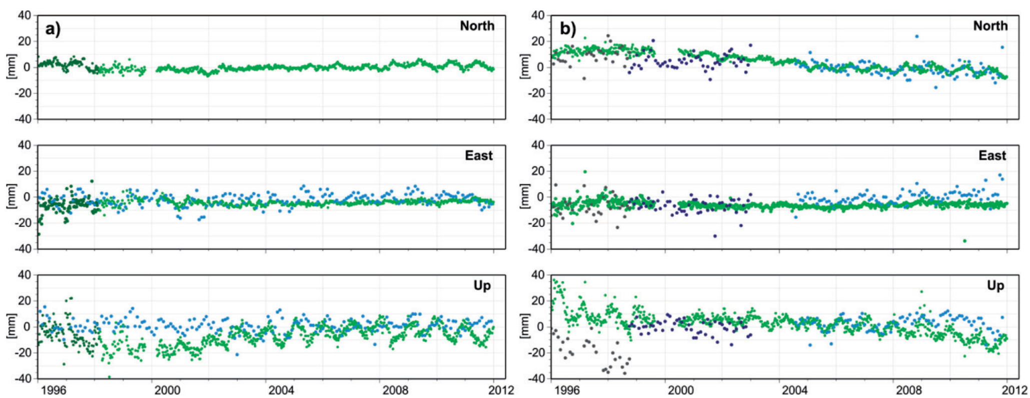

Fig. 9. Time series of *N*, *E*, *U* components of the GNSS stations YAR1 (grey) and YAR2 (green) and SLR station 7090 (blue) – on the left (a); time series of the GNSS station TIDB (green) and SLR stations 7843 (grey), 7849 (navy blue) and 7825 (blue) – on the right (b)

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

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

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

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

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

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

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

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

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

5.2. Validation of ETRS89 realization in Poland

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

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

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

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

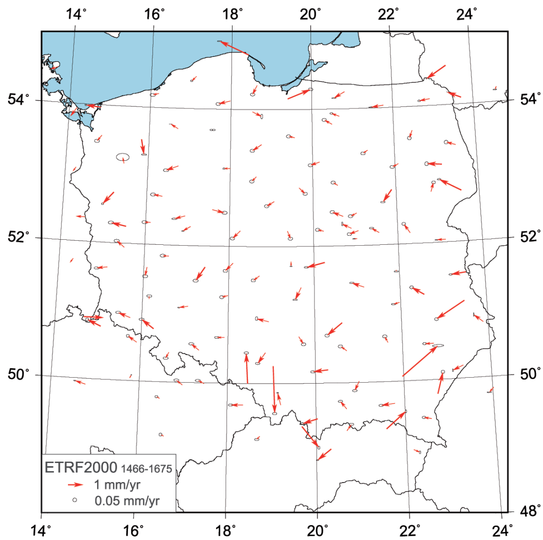

Fig. 11. Horizontal velocities of ASG-EUPOS stations in ETRF2000 determined by CAG MUT

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

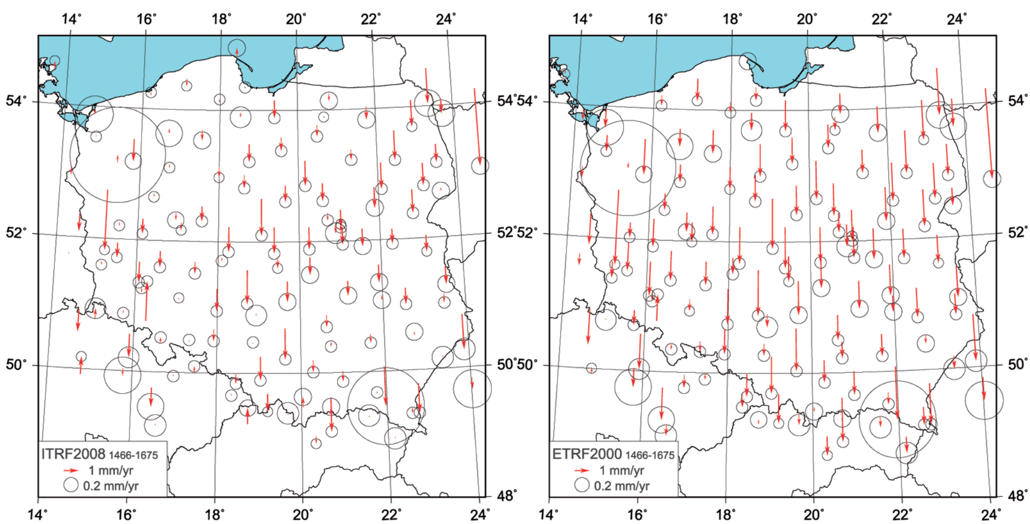

Fig. 12. Vertical velocities of ASG-EUPOS stations in ITRF2008 and ETRF2000 determined by MUT

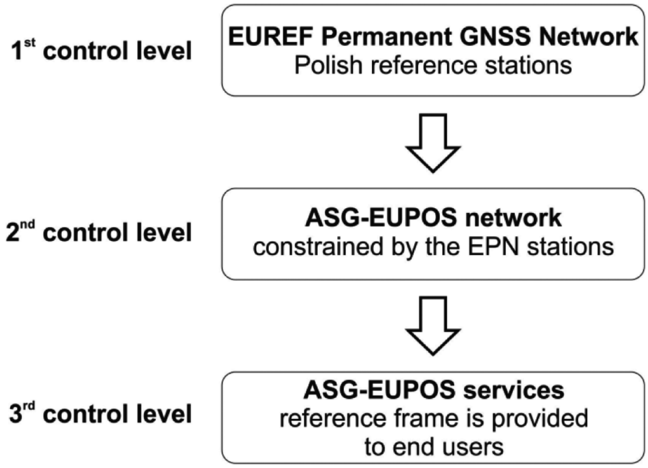

Fig. 13. ETRS89 realization and control via the ASG-EUPOS system

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

6. Maintenance of vertical control in Poland

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

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

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

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

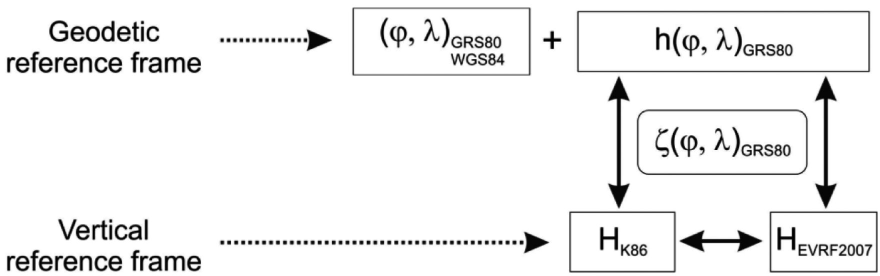

Fig. 14. The relationship between geodetic and vertical reference frame realizations of the Polish National Spatial Reference System

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

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

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

In practice, however, Kronstadt60 vertical reference system is still in use in many places in Poland and the transformation of heights to PL-KRON86-NH is done locally. The results of the analyses of local transformations between Kronstadt60 and Kronstadt86 (PL-KRON86-NH) in the area of Krakow's district using polynomial regression (Fig. 16) (Ligas and Banasik, 2012) and a continuation of this study with the

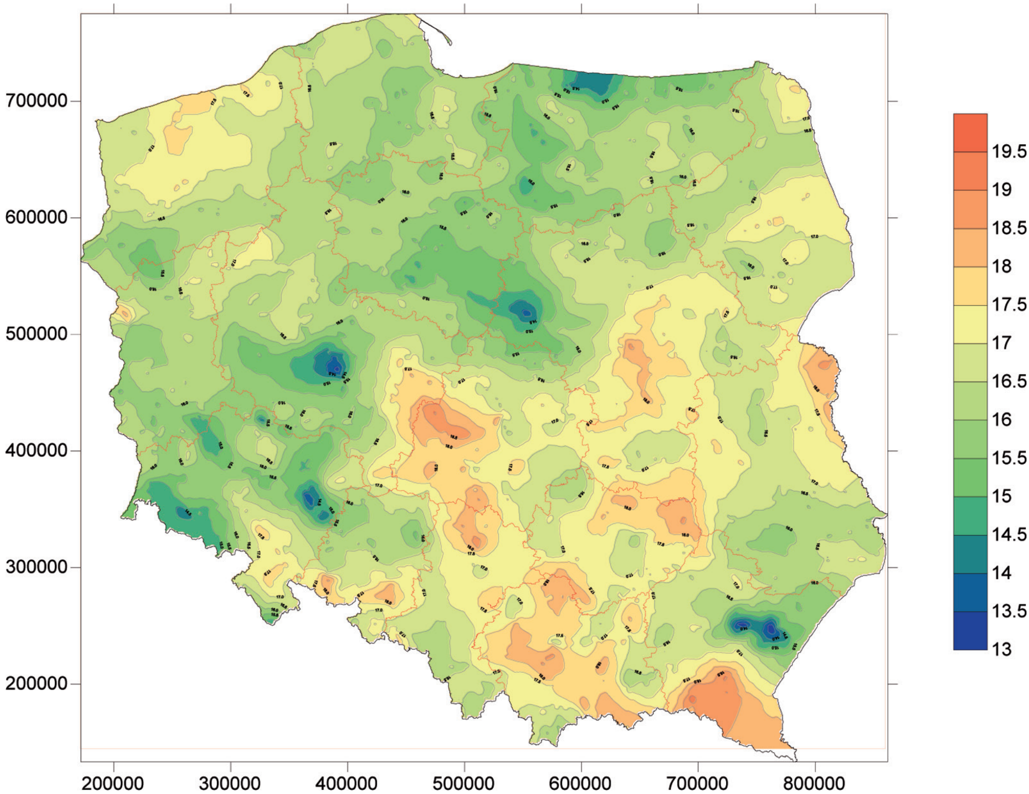

Fig. 15. Differences of heights between vertical datums PL-EVRF2007-NH and PL-KRON86-NH [cm]

use of kriging approach (Ligas and Kulczycki, 2014). have been published. Differences between heights the those systems within the study area vary from 2.5 cm to 5.5 cm. They have been modelled using a polynomial regression model. The model uncertainty has been estimated at the level of 1–4 mm; it depends on the location (Fig. 13). The uncertainty of the newly predicted heights (benchmarks that were not used in model developing) measured by confidence intervals was estimated at the level of 5–8 mm.

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

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

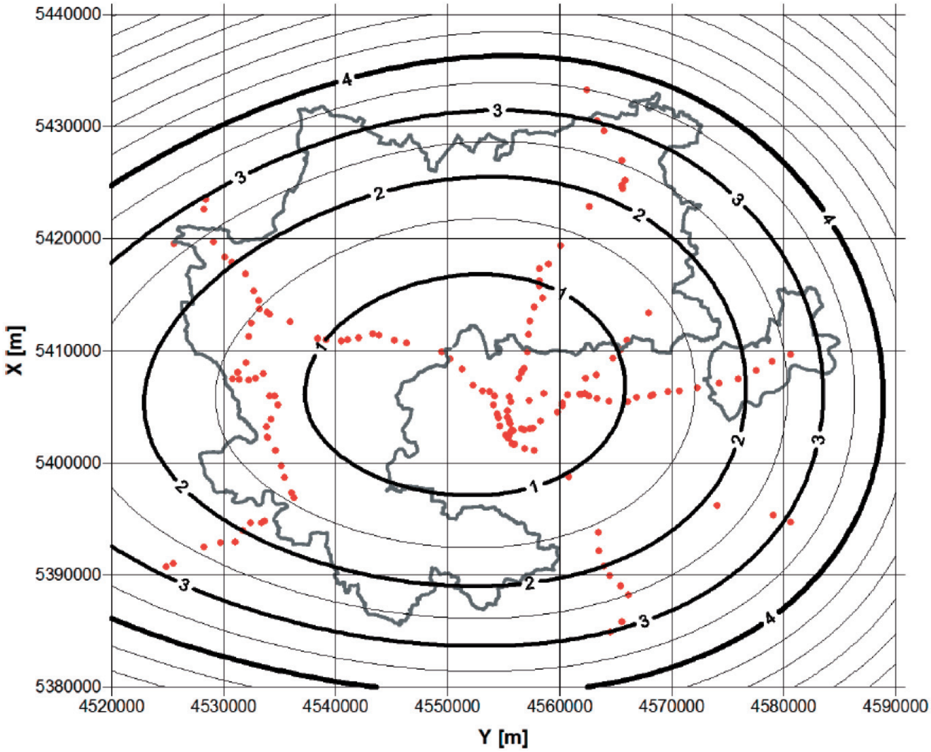

Fig. 16. Half of the confidence interval for the quadratic transformation function (confidence level of 0.95) [mm]

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

7. Maintenance and modernization of gravity control

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

7.1. Maintenance and modernization of gravity control in Poland

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

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

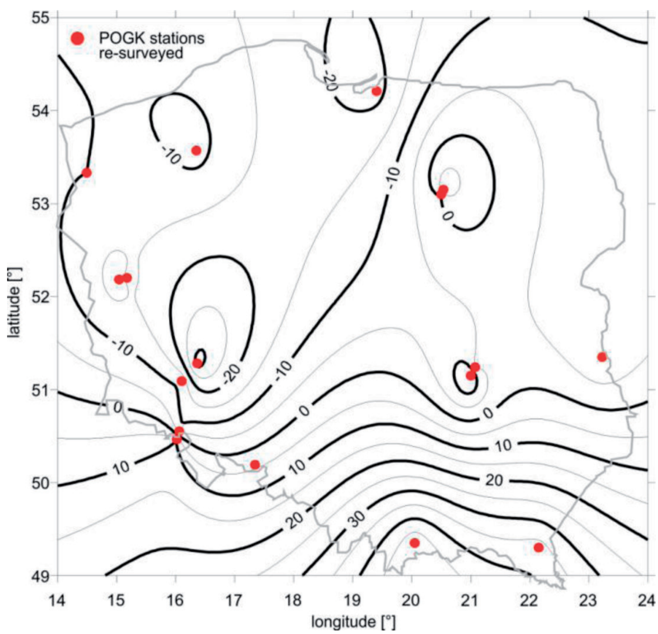

Fig. 17. Difference dg between gravity measured in 2007–2008 on chosen POGK stations and the corresponding one in POGK98 system [µGal]

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

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

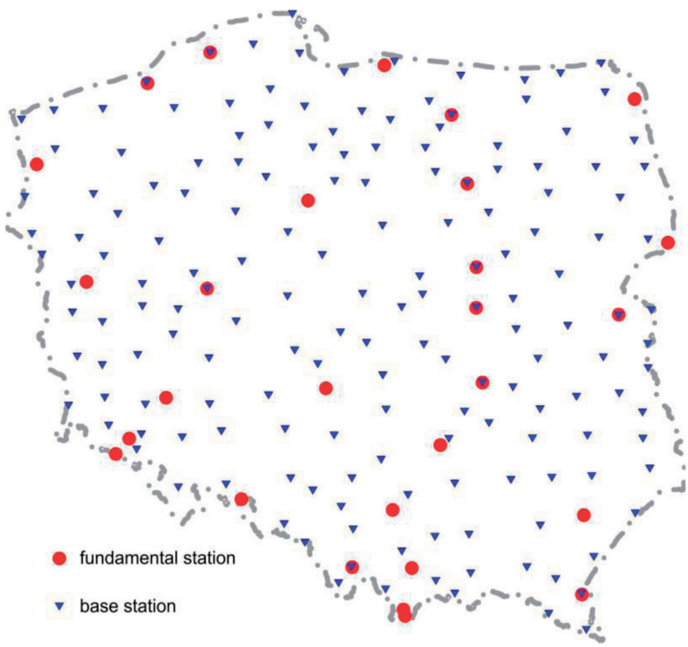

Fig. 18. Stations of new gravity control in Poland

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

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

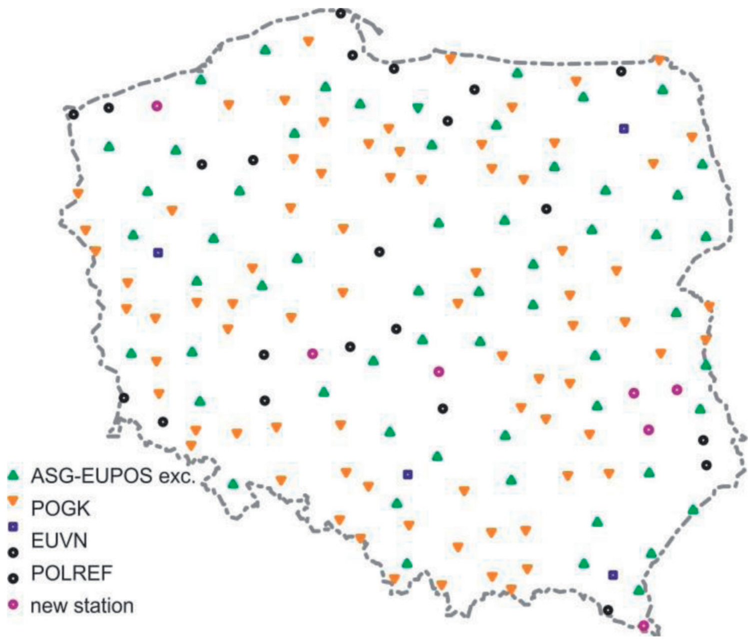

Fig. 19. Base stations of the new gravity control in Poland

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

The realization of the project of a new gravity control PBOG14 started in 2012. The team of the Institute of Geodesy and Cartography, Warsaw, conducted absolute gravity measurements with the A10-020 as well as vertical gravity gradient measurements on 168 base stations in 2012–2013 (Fig. 19) (Krynski and Rogowski, 2013, 2014). Quality of the new gravity control in Poland was preliminarily assessed. Gravity in

POGK98 on 77 stations common for POGK98 and PBOG14 was compared with the respective ones of PBOG14 (Fig. 21). The mean difference and the standard deviation are 12.3 μGal and 18.6 μGal, respectively (Krynski and Dykowski, 2014).

Alongside the establishment of the base stations of the gravity control, multiple additional activities were performed to assure and provide a reliable gravity reference level. These activities concerned regular gravity measurements on monthly basis with the A10-020 on the test network at Borowa Gora Geodetic–Geophysical Observatory (Dykowski et al., 2013a), calibrations of metrological parameters of the A10-020 gravimeter (Sekowski et al., 2012) and scale factor calibrations of LCR gravimeters, participation with the A10-020 in the international (ECAG2011, ICAG2013) and regional comparison campaigns of absolute gravimeters and local comparisons with the FG5-230. Careful analysis of the data gathered throughout the project resulted in the estimation of the Total Uncertainty budget for the A10-020 gravimeter on each of 168 base stations. It provides a reliable quality assessment of the new gravity control in Poland (Krynski and Dykowski, 2014).

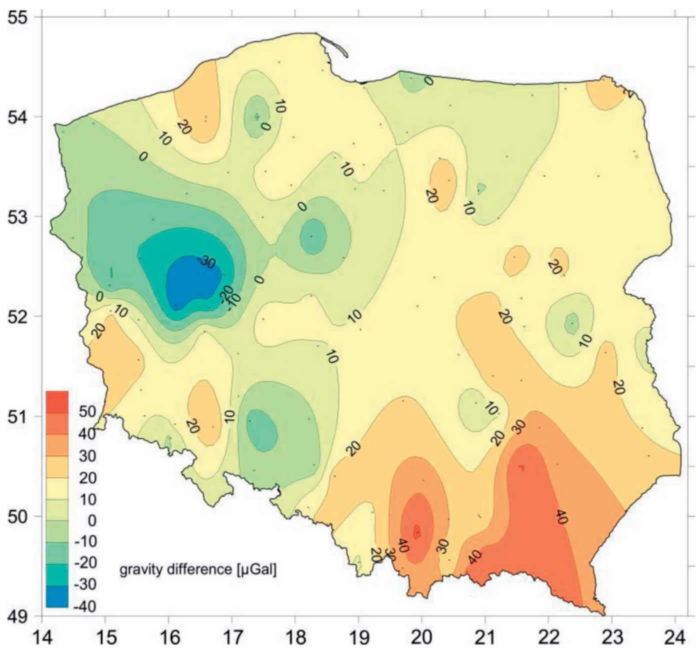

Fig. 21. Differences between PBOG14 and POGK98

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

7.2. Maintenance of gravity control in Fennoscandia

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

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

8. Maintenance of magnetic control in Poland

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

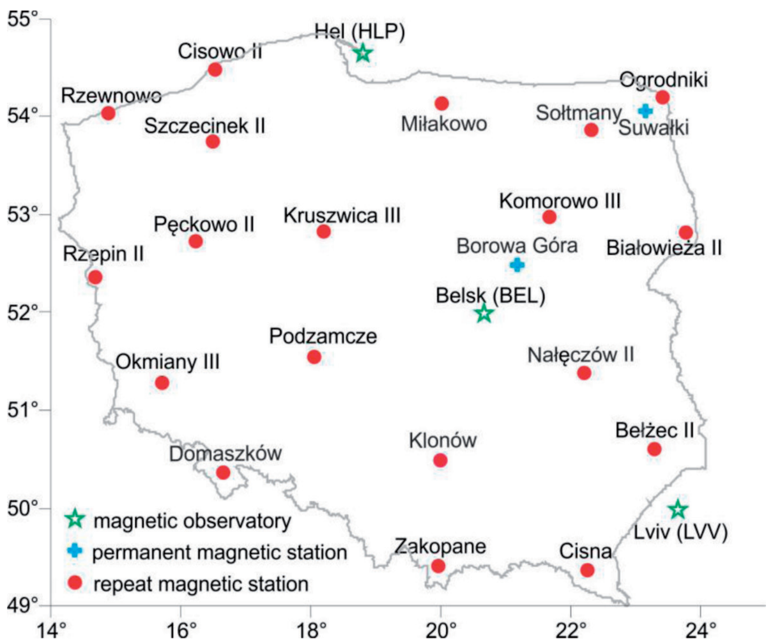

Fig. 22. Polish magnetic repeat station network

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

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

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

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

Station name	Latitude [° ' "]	Longitude [° ' "]	2011	2012	2013	2014
Cisowo II	54 26 20	16 27 39		×		×
Ogrodniki	54 08 22	23 27 06		×		
Milakowo	54 01 12	20 05 20		×		×
Rzewnowo II	53 54 20	14 58 34			×	
Soltmany	53 42 03	22 24 07		×		
Szczecinek II	53 36 36	16 34 50		×		
Komorowo III	52 50 16	21 46 18		×		×
Bialowieza II	52 42 32	23 51 04		×		×
Kruszwica	52 40 25	18 18 30			×	
Peckowo II	52 35 40	16 19 20			×	
Rzepin II	52 15 35	14 44 31			×	
Podzamcze	51 24 16	18 09 05	×		×	×
Naleczow II	51 14 15	22 11 12			×	
Okmiany III	51 07 33	15 44 26			×	
Belzec II	50 27 33	23 20 30	×		×	
Klonow	50 20 37	20 09 59	×		×	×
Domaszkow	50 13 20	16 40 05			×	×
Zakopane	49 17 22	20 01 51			×	
Cisna	49 12 44	22 19 39	×		×	

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

9. Summary and conclusions

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

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

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

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

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

Acknowledgements

The review paper was elaborated in the framework of the statutory project “Problems of geodesy and geodynamics” of the Institute of Geodesy and Cartography (IGiK), Warsaw, financially supported by the Polish Ministry of Science and Higher Education as well as the activities of Commission of Geodynamics and Geodetic Control of the Committee on Geodesy of the Polish Academy of Sciences. Valuable help was provided by Piotr Banasik, Janusz Bogusz, Wieslaw Graszka, Marcin Ligas, Adam Lyszkowicz, Stanislaw Schillak, Karolina Szafranek and Elzbieta Welker.

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