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1995 – 1999

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CONTENTS

1. REFERENCE NETWORKS

1. Introduction
2. Concept of Polish Geodetic Control
3. POLREF Network – Processing and Analysis
4. Densification of the POLREF Network
5. Active GPS/DGPS Station Network in Poland
    1. Permanent GPS EUREF Stations Operating in Poland
    2. DGPS Reference Stations
    3. Some Applications of DGPS Techniques
6. Vertical Network
    1. European Unified Vertical Reference Network (EUVN)
    2. Modelling the Adjustment and Maintenance of the Polish Levelling System
    3. Baltic Sea Level Project
7. New Gravity Network

References

2. ADVANCED SPACE TECHNIQUES

1. Introduction
2. Satellite Laser Ranging
3. GPS Permanent Stations
    1. Borowa Gora (BOGO) GPS Permanent Station
    2. Borowiec (BOR1) GPS Permanent Station
    3. Jozefoslaw (JOZE) GPS Permanent Station
    4. Lamkowko (LAMA) GPS Permanent Station
    5. Wroclaw (WROC) GPS Permanent Station
4. Observations of GLONASS
5. Time Transfer and Comparison
6. Data Analysis and Orbit Determination
    1. SLR Data Analysis
    2. Activities of the EUREF WUT Local Analysis Centre
    3. Study on Influence of GPS Satellite Orbits’ Quality on Positioning Precision
7. Troposphere and Ionosphere Studies
8. Satellite Gradiometry

References

3. GEODETIC GRAVIMETRY

1. Introduction
2. Absolute Gravity Determination
3. Gravity National Surveys
4. Investigations of the Non-Tidal Gravity Changes
5. Geoid and Theoretical Studies on the Gravity Field in Poland

References

4. GENERAL THEORY AND METHODOLOGY

1. Introduction
2. Deformation Analysis
3. Least Squares – Theory And Evaluation
4. Research on GPS

References

5. GEODYNAMICS

1. Introduction
2. Geodynamic Networks in Poland
    1. Polish Geodynamic Network
    2. Geodynamics Research in the Sudety Mountains and Fore-Sudetic Block (SW Poland)
    3. Tatra Mountains Geodynamics
    4. Geodynamic Network in Wieliczka Mining Area
    5. Geodynamic Network in Copper Basin Area
3. International Geodynamic Networks
    1. Baltic Sea Level Project
    2. CERGOP Project
    3. Extended SAGET Programme
4. Earth Rotation
    1. Chandler and Free Core Nutation
    2. Free Core Nutation
    3. Variations of Semiannual and Subseasonal Oscillations of Polar Motion
    4. Prediction and Irregular Variations of Polar Motion
    5. Analysis of Polar Motion Data
    6. Theoretical Problems
    7. Regional Atmospheric Angular Momentum and its Impact on Polar Motion
    8. Atmospheric Excitation of Nutation
    9. Diurnal/Semidiurnal Atmospheric and Oceanic Excitation
    10. El Nino Impact On Polar Motion
    11. Methods
5. Earth Tide Investigations in Poland in 1995–1998
6. Variations of Sea Level

References

1. REFERENCE NETWORKS

(compiled by Lubomir W. Baran)

1.1. INTRODUCTION

This part of the Polish National Report on Geodesy is the quadrennial report on positioning works performed in Poland in a period from 1995 to 1998. It summarises the state of art of Polish national 0-order control network, its densification and link to the former geodetic control, active GPS/DGPS station network in Poland, vertical network, Polish national gravity control network, etc. The activities concerning reference networks were conducted mainly at the following research centres listed in an alphabetic order:

- Department of Planetary Geodesy, Space Research Centre, Polish Academy of Sciences in Warsaw;
- Institute of Geodesy, Olsztyn University of Agriculture and Technology;
- Institute of Geodesy and Cartography in Warsaw;
- Institute of Geodesy and Geodetic Astronomy, Warsaw University of Technology.

Complete bibliography of the related works is given in references.

1.2. CONCEPT OF POLISH GEODETIC CONTROL

According to the information given in the Polish National Report presented at the XXI IUGG General Assembly in Boulder, Colorado in 1995, the EUREF network in Poland was established in 1992. The network was created as a result of the international GPS campaign EUREF-POL'92. Data from this campaign was processed and the results, including the co-ordinates of 11 stations of EUREF-POL network in ETRS'89 were presented at the EUREF Symposium in Warsaw, June 8-11, 1994.

During data processing and analysis of EUREF-POL network its densification already started. The establishing of POLREF network was initialised in the second half of 1993. It materialised in monumentation of the sites of the network starting from south-east region of Poland (Baran and Zielinski, 1996).

1.3. POLREF NETWORK – PROCESSING AND ANALYSIS

POLREF densification network is intended to provide the ETRF reference frame for geodetic, and surveying and mapping applications. The network consists of 348 points linked to 11 EUREF-POL stations. The average distance between points equals to 25-35 km. Each POLREF point consists of two observation sites: the main one and the eccentric one, separated by 2-3 km. With the existing triangulation control points coincide 209 main sites of POLREF points and 130 eccentric sites of POLREF points. Only 10 POLREF pairs are brand new control points. The monumentation of points was adopted from existing geodetic control. Normal heights of POLREF points were determined using spirit levelling with the second class accuracy standard.

The GPS POLREF campaign was conducted in three steps. Both, the first one in July 11-27, 1994 covering 108 points in south-eastern region, and the second one in October 17-27, 1994 covering 78 points were performed by the Space Research Centre of the Polish Academy of Sciences, while the third campaign that took place in April 24–May 25, 1995 covering 208 points was carried out by the Institute of Geodesy and Cartography, Warsaw (Baran and Zielinski, 1997).

The data of the POLREF campaign was processed using three different software packages: GPPS, Trimvec and Bernese. The use of Bernese software made it possible to more thoroughly analyse the data quality and to model some perturbing effects. Separately resolved two sub-networks West and East were then joined together with use of the covariance matrix. Such a solution provided an independent estimation of accuracy. The formal precision of the solution is remarkably high. It is estimated as equal to ± 0.5 mm and ± 1.5 mm for horizontal and vertical components, respectively. The discrepancy between two independent solutions West and East obtained on joint points is, however, larger by one order of magnitude; in average it equals to ± 5 mm and ± 15 mm for horizontal and vertical components, respectively. The real accuracy of the solution could be considered as not worse then ± 1 cm, that is better than the former geodetic control based on traditional terrestrial and astronomic measurements by more than one order of magnitude.

Parameters of transformation between POLREF and the existing geodetic control were determined using the recent geoid solution for Poland (Lyszkowicz, 1996). It gave the possibility to assess the quality of the classical solutions obtained within last 30 years. Their quality was found out to be quite good; in terms of accuracy it was estimated at the level below ± 10 cm. However, some distortions from homogeneity appear. For the JSAG-83 (1942 Reference Frame) solution the northern part of the old network is visibly distorted with deformation exceeding 0.5 m in two opposite directions.

1.4. DENSIFICATION OF THE POLREF NETWORK

In 1996, the remaining points of the previous geodetic control were re-adjusted with the POLREF points admitted as fixed. All angular measurements were included in the re-adjustment while astronomical azimuths were not considered in computational process. The developed network consists of 6467 points. Average distances between the adjacent points amounts to about 8 km. The estimated accuracy of the horizontal position is better than ± 3 cm for 95% of points. For 28 points (about 5%) located mainly near the borders of Poland the estimated accuracy ranges from ± 5 cm to ± 8 cm.

Only latitudes and longitudes of these points are given in ETRS'89. Their heights take origin from different sources (spirit levelling or trigonometric levelling) and their accuracy is not uniform.

Points of the discussed network have been classified as first class but second order points of the Polish national network.

In 1997, the old Polish network of second class was also re-adjusted. It consists of 61896 points. Among them there are 4005 points surveyed with GPS. The number of observations taken to the adjustment exceeded 550000 with 48000 measured distances among them. Assuming the points of the first class as fixed, the co-ordinates of all second class points were obtained in ETRS'89. The relative accuracy of the obtained horizontal positions is estimated to be better than ± 3 cm for 92% of the points.

1.5. ACTIVE GPS/DGPS STATION NETWORK IN POLAND

The first permanent GPS stations in Poland started operating within International GPS Service for Geodynamics (IGS) in 1994. Two committees of the Polish Academy of Sciences: Space and Satellite Research Committee and Committee of Geodesy, appointed a special study group in 1995. The main goal of this group was to prepare the program of development of the active GPS station network in Poland.

In the beginning the study group worked on the EUREF permanent station network project and made an assumption to establish multifunctional stations suitable for both, precise positioning and DGPS.

The study group recognised that the number of active multifunctional permanent GPS stations in Poland should be increased in the future. The distances between stations should amount about 50 km. The stations should form a new generation geodetic network, adequate for many social and economical needs (Baran and Zielinski, 1998). The local analysis centres in co-operation with national analysis centre should be engaged in processing of the permanent GPS observations.

1.5.1. Permanent GPS EUREF Stations Operating in Poland

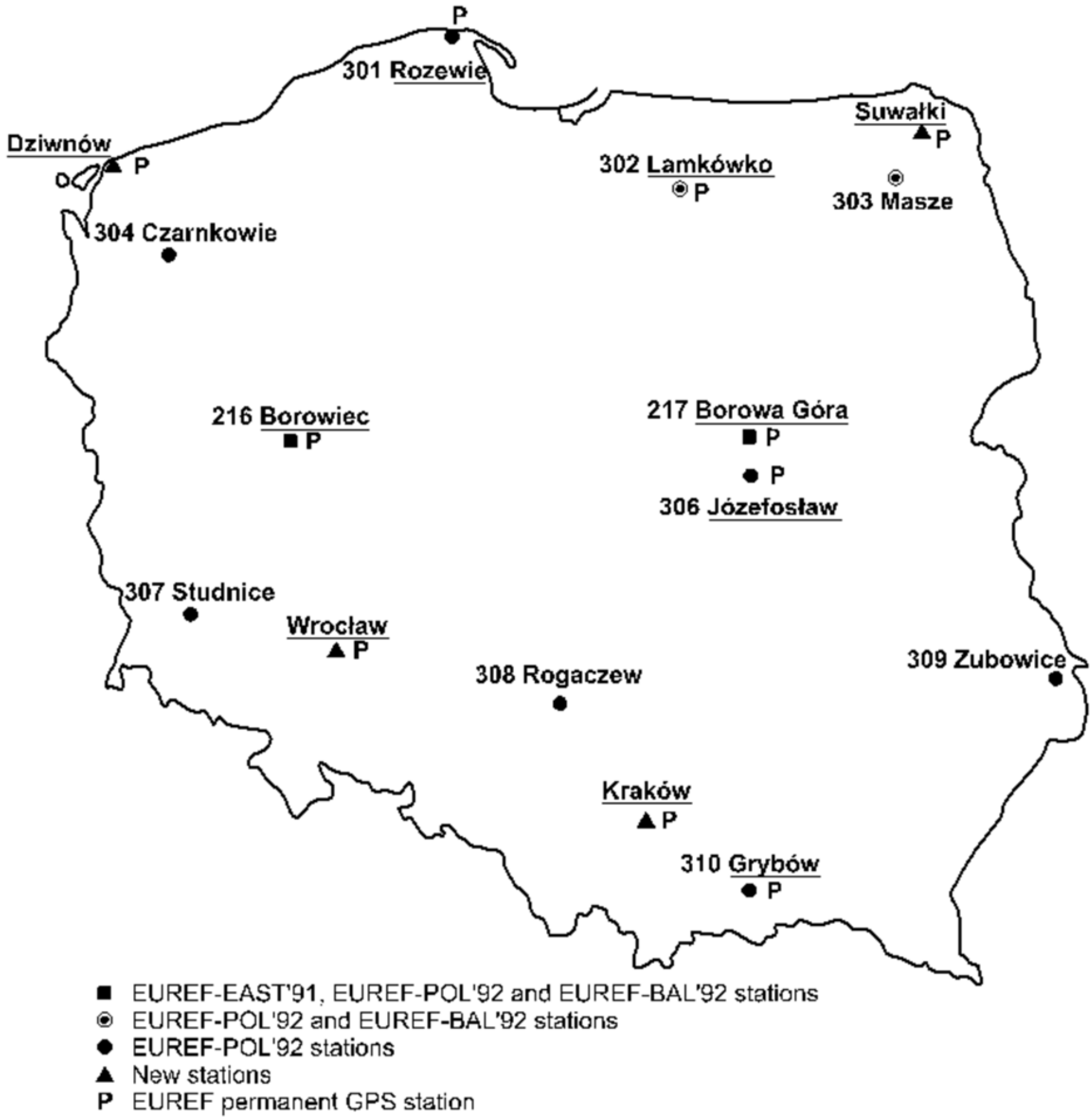

Fig. 1.1. Proposed location of the permanent EUREF GPS stations.

According to the project elaborated in 1995 by the special study group of the Polish Academy of Sciences, it was foreseen that 10 permanent EUREF stations will be set up in Poland (Fig. 1.1) (Baran and Zielinski, 1996).

Up to now 5 stations have been established (Tab. 1.1).

Table 1.1. Permanent GPS stations in Poland

Name (abbr.)	Latitude	Longitude	Status	Receiver
Borowiec (BOR1)	52°16’37’’	17°04’27’’	IGS EUREF	Turbo Rogue SNR 8000
Borowa Gora (BOGO)	52°28’33’’	21°02’07’’	EUREF	Ashtech Z-12
Jozefoslaw (JOZE)	52°05’50’’	21°01’54’’	IGS EUREF	Trimble 4000 SSE

These stations belong also to the Central European GPS Reference Network (CEGRN) and EXTENDED SAGET network.

In September 1998 BOROWIEC station started to carry out the permanent double frequency P-code observations of GLONASS satellites in the frame of IGEX (International GLONASS Experiment) campaign. The observations are carried out with six channel 3S Navigation receiver, equipped with choke ring, temperature stabilised antenna.

1.5.2. DGPS Reference Stations

According to the mentioned programme, elaborated under supervision of the Polish Academy of Sciences, the creation of DGPS reference stations has been approached. Nowadays two permanent reference DGPS stations: Dziwnow and Rozewie (Table 1.2) are distributing RTCM corrections on radio frequency. They are located on the Southern Baltic seashore (Oszczak et al., 1996).

Table 1.2. DGPS stations in the Southern Baltic seashore

Station Name	**Geographic**	**Nominal range** (50m V/m)		**ERP**
	Coordinates	Official data (in Nm)	True data (in Nm)	(W)
Dziwnow	54^{o}01' N, 14^{o}44' E	90	55	0.1
Rozewie	54^{o}49' N 18^{o}20' E	90	100	0.4

The central station in Gdynia, controlling Dziwnow and Rozewie DGPS stations, operates at the Maritime Office.

1.5.3. Some Applications of DGPS Techniques

Space Research Centre of the Polish Academy of Sciences

DGPS test network was established at the Space Research Centre of the Polish Academy of Sciences in Warsaw. The network consist of:

- base station, located at the Space Research Centre building,
- remote station, established in mobile GPS laboratory,
- local UHF telemetry link,
- test beds, prepared for two kinds of measurements, i.e. static and kinematic.

The base station works as a permanent DGPS reference station. The differential corrections are broadcasted once a day during one-hour period. The operational range of the network depends on radio propagation conditions and reaches about 3 to 5 km from the base station.

The Space Research Centre has carried out experiments with application of DGPS/(Low Cost IMU) configuration (Vorbrich and Zielinski, 1996). In co-operation with the Institute of Navigation of the Technical University in Brunswick (Germany) a mobile GPS laboratory equipped with an integrated DGPS/(Low Cost IMU) system was constructed. The software for the laboratory is based on own algorithms and can operate both on-line and off-line. In 1997 the DGPS/IMU navigation system was tested on Poznan racing car track.

Institute of Geodesy and Cartography, Warsaw

The Institute of Geodesy and Cartography in co-operation with NAVI Company from Poznan carries out studies on NAVI_Gsm system application to distribute DGPS corrections. This system covers most of the country.

A permanent DGPS base station is operating at the Astro-Geodetic Observatory in Borowa Gora since May 1998. The base station is equipped with Ashtech G-12 receiver with a NAVI_Gsm software. Preliminary tests show the horizontal DGPS positioning precision level below 1 m and vertical positioning precision slightly above 1m (Cisak et al., 1999).

Institute of Geodesy and Geodetic Astronomy of the Warsaw University of Technology

The Institute of Geodesy and Geodetic Astronomy in co-operation with other Polish institutions is engaged in following DGPS applications (Bogusz et al., 1998):

- bathymetric measurements,
- water flow measurements,
- ships manoeuvrability,
- photogrammetry with video camera.

Astro-Geodetic Observatory in Jozefoslaw is involved in mentioned above experiments. Trimble 4000 SSE receivers record GPS observations with 10 and 30 seconds sampling rate, corrections are transmitted in RTCM format. The Observatory is also equipped with CBS base station and has carried out experiments on DGPS correction transmission to the roving GARMIN 12XL receiver.

Institute of Geodesy, Olsztyn University of Agriculture and Technology

Since 1997 the Institute of Geodesy of the Olsztyn University of Agriculture and Technology has been engaged in experimental works on application of DGPS service for the needs of Gdansk agglomeration. Three multifunctional DGPS and RTK reference stations were established in Gdansk, Sopot and Gdynia.

The first aim of the studies is to obtain operational range of the reference stations.

Numerous experimental works on accuracy of real-time DGPS and RTK positioning were carried out in co-operation with Naval Academy in Gdynia, Maritime University in Gdynia and Maritime Office (Oszczak et al., 1996; Rzepecka et al., 1997).

In 1997, the first Ashtech GG-24 receivers in Poland were put into operation and the field DGPS/GLONASS tests were undertaken. Intensive works on application of DGPS/GLONASS methods in navigation, positioning and bathymetric surveys are continued (Baran and Oszczak, 1998).

1.6. VERTICAL NETWORK

1.6.1. European Unified Vertical Reference Network (EUVN)

The main objectives of the EUVN Project are: contribution to the unification of the European height systems with an accuracy of some centimetres, providing fiducial points for the European geoid determination, connecting the European tide gauge stations at different coastlines for the investigations of sea level variations and establishing a fundamental network for further geokinematic height reference system.

The Polish part of the Project was worked out in the Department of Planetary Geodesy Space Research Centre. It consists of ten points. Some of the points are EUREF stations (Rozewie), some are geodetic observatories (Borowa Gora, Borowiec, Jozefoslaw, Lamkowko) and some of the points are UPLN (Unified Precise Levelling Network) benchmarks (Prostki, Sanok, Brudzowice, Chelmsko). The reconnaissance and the monumentation of Polish part of EUVN network were performed in autumn 1996. The campaign was carried out with TRIMBLE SSE receivers from May 21st to May 29th, 1997.

The responsibilities for the data management and data processing were distributed among the various institutions. The Department of Planetary Geodesy prepared site documents and session logs, converted raw data to RINEX, and checked RINEX headers for GPS observations for territory of Poland. As a Pre-processing Centre, the Department of Planetary Geodesy collected data and documents from Poland and United Kingdom, checked filenames for standard naming, compared file contents with logs, checked file contents for completeness, run UNAVCO’s quality Check for each file and sent data and QC output to EUVN Data Centre in Leipzig.

The entire EUVN net has been divided into eight sub-networks. Department of Planetary Geodesy processed the network, which covers the territory of Hungary, Slovakia, Poland, Latvia and Ukraine. Loosely constrained solutions according to processing standards were delivered to the EUVN Data Centre in Leipzig.

1.6.2. Modelling the Adjustment and Maintenance of the Polish Levelling System

The Polish national levelling system consists of 1st and 2nd class precise levelling networks and amounts to over 43 thousand benchmarks. The international EUVN programme assumes, among others, its integration with the ETRS'89 system, the last one realised through GPS measurements of the EUREF network. The above task is considered to be solved by adjustment of both classes of the network linked to a number of GPS reference points, as well as by its possible further systematic maintenance through repeated GPS, precise levelling and gravimetric measurements. This causes certain numerical problems reflected in the evident ill conditioning and large dimensions of matrices, cumulating round off errors, possible instability of the solution, and others. To overcome the problems it was suggested to use the so called sequential adjustment algorithm applying the sparse matrix technique.

1.6.3. Baltic Sea Level Project

The Baltic Sea Level Project was initiated already in 1989 at the IAG General Meeting held in Edinburgh to co-ordinate the vertical datum of the counties around the Baltic Sea. In order to fulfil the above goal, three Baltic Sea Level GPS Campaigns were conducted since 1990. The Third Campaign was made simultaneously with the EUVN in May, 1997. In the campaign, 35 tide gauges and 12 fiducial station were observed. Additionally, several permanent GPS stations were included in the network of the third BSL campaign.

Three Polish tide gauges (Swiniujscie, Ustka, Wladyslawowo) and four GPS permanent stations (Borowa Gora, Borowiec, Jozefolaw and Lamkowko) took part in the last BSL campaign.

1.7. NEW GRAVITY NETWORK

New Polish gravity network was established in 1994-1998. It consists of 352 gravity point with 12 absolute gravity stations (Fig. 1.2). All network points used for relative gravity measurements were monumented with the concrete pillars of size 80´ 80´ 100 cm.

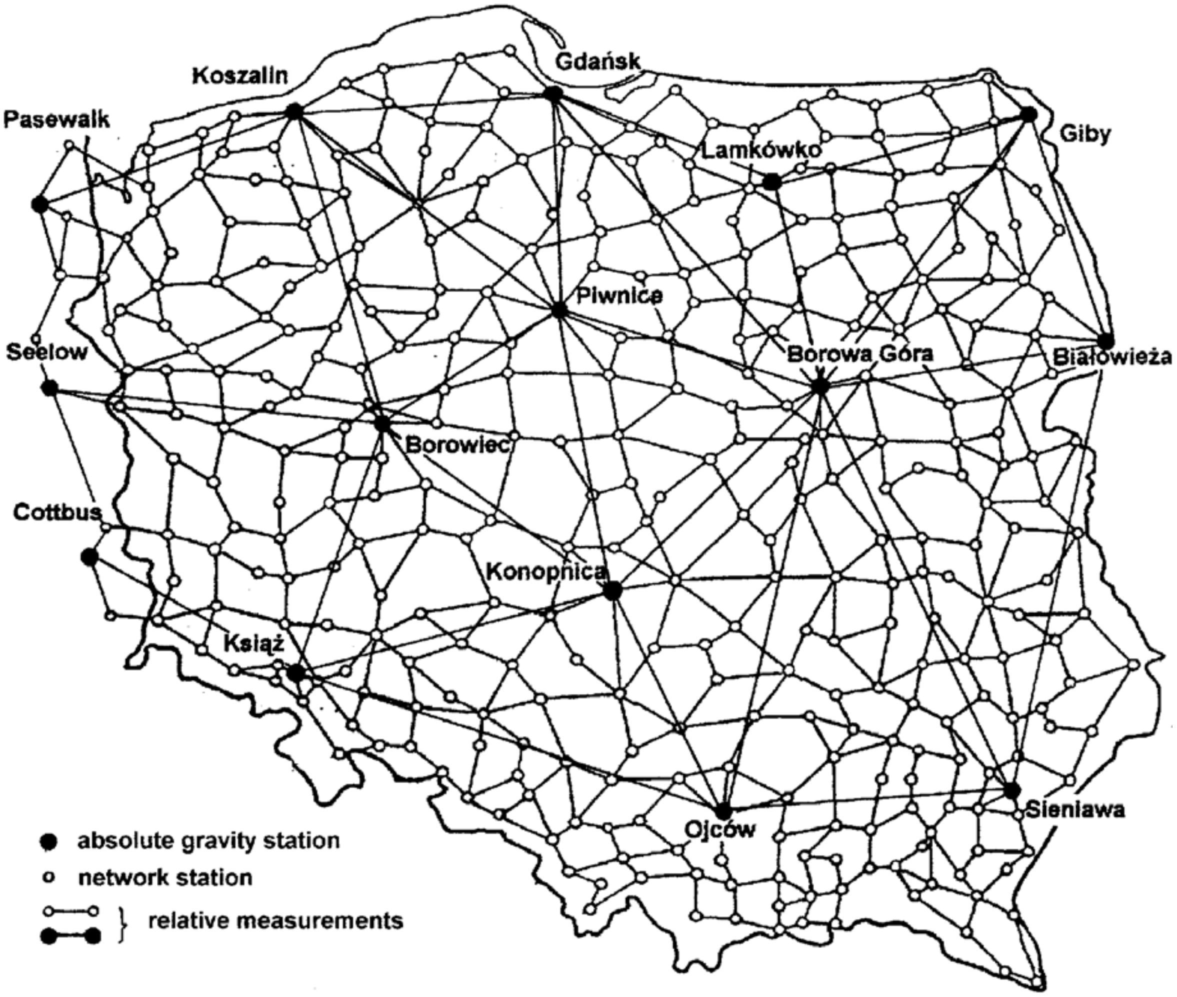

Fig. 1.2. The new Polish gravity network

Borowa Gora station, located in the Astronomic-Geodetic Observatory of the Institute of Geodesy and Cartography, was chosen as a fundamental point of the gravity network. The absolute gravity stations were located in cellar rooms of public buildings with stable geological conditions. The list of the absolute gravity stations and the description of the conducted absolute gravity measurements are given in Chapter 3 of this report.

All relative gravity measurements were carried out as independent spans. Double looping (ABAB) was completed in a day for a span between the network stations. Each span was measured simultaneously with 3 LaCoste & Romberg gravimeters. In addition 19 long spans between absolute stations were measured. Single looping (ABA) was completed in a day for a span between absolute gravity stations. It was repeated during three consecutive days with 3 LaCoste & Romberg gravimeters simultaneously. The observations were made on 720 spans between field stations. They compose 317 closed figures, of 3-5 spans each. The average length of the span in Polish national network is 35 km.

Most of the relative gravity measurements were carried out by the Institute of Geodesy and Cartography in co-operation with the Topographic Service of the Polish Army General Staff. The survey was partially performed by the Institute of Geodesy and Geodetic Astronomy, Warsaw University of Technology. The spans along and across Polish western border, measured by a German team, connected the Polish gravity network to the German absolute gravity stations at Pasewalk, Seelow and Cottbus.

Relative gravity measurements as well as the results of absolute gravity measurements were adjusted together. The gravity on 6 absolute stations (those which compose two calibration base lines: Koszalin – Borowiec – Ksiaz and Gdansk –Borowa Gora – Ojcow) was assumed to be fixed. On 90% field stations the rms of adjusted gravity ranges from ± 4 m Gal to ± 10 m Gal, (on 99% it does not exceed ± 12 m Gal).

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2. ADVANCED SPACE TECHNIQUES

(compiled by Janusz B. Zielinski)

2.1. 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 1995 to 1998. It summarises investigations such as operational activity of SLR and GPS permanent stations, achievements in GLONASS observations, time transfer and time comparison, data analysis and orbit determination, modelling of ionosphere and troposphere, satellite gradiometry, etc. These activities were conducted mainly at the following research centres listed in an alphabetic order:

- Department of Geodesy and Photogrammetry, Agricultural University in Wroclaw;
- Department of Mining Geodesy and Environmental Engineering, Academy of Mining and Metallurgy in Cracow;
- Department of Planetary Geodesy, Space Research Centre, Polish Academy of Sciences in Warsaw;
- Institute of Geodesy, Olsztyn University of Agriculture and Technology;
- Institute of Geodesy and Cartography in Warsaw;
- Institute of Geodesy and Geodetic Astronomy, Warsaw University of Technology.

Complete bibliography of the related works is given in references.

2.2. SATELLITE LASER RANGING

The Astro-Geodynamic Observatory (AGO) of the Space Research Centre, Polish Academy of Sciences in Borowiec is participating in the determination of the International Terrestrial Reference Frame by Satellite Laser Ranging (SLR), as the station # 7811.

The SLR Station performs regular laser observations of 29 satellites in the frame of international co-operation. In the period 1995-1998, 2248 observations were completed. Borowiec AGO is a member of the International Laser Ranging Service (ILRS) and EUROLAS Consortium, group of European SLR stations. The observations were carried out within the following international programs: NASA Dynamics of the Solid Earth, Working Group of European Geo-scientists for the Establishment of Networks for Earth-science Research (WEGENER), GeoForschungsZentrum, European Space Agency Remote Sensing Satellite, US Naval Observatory, International GLONASS Experiment (IGEX'98). The results of the satellite observations were delivered on a regular basis to Eurolas Data Centre (EDC) and Crustal Dynamics Data Information System NASA (CDDIS). The main activity of SLR team was focused on increase of the quality and quantity of data and system automation. The overall accuracy of the system was increased to 10 mm in the end of 1998 due to the reduction of random errors and biases. Number of observed satellite passes increased from 1995 by a factor two mainly due to the automation of the SLR system. From 1997 Borowiec SLR participates in observations of high orbiting satellites like GPS and GLONASS. The data from Borowiec SLR were analysed by several centers: NASA, Center for Space Research of Texas University at Austin, Delft University of Technology, Royal Greenwich Observatory, US Naval Observatory, GeoForschungsZentrum, Mission Control Centre in Russia, Communication Research Laboratory in Tokyo and the Space Research Centre in Warsaw.

2.3. GPS PERMANENT STATIONS

Five GPS permanent stations operating in Poland are listed in Table 2.1:

Table 2.1. GPS permanent stations operating in Poland

Station	Program	Host Institution
Borowa Gora (BOGO)	EUREF	Institute of Geodesy and Cartography

Borowiec (BOR1)	EUREF, IGS	Space Research Centre, Pol. Acad. of Sci.
Jozefoslaw (JOZE)	EUREF, IGS	Warsaw University of Technology
Lamkowko (LAMA)	EUREF, IGS	Olsztyn University of Agriculture and Technology
Wroclaw (WROC)	EUREF	Agricultural University in Wroclaw

2.3.1. Borowa Góra (BOGO) GPS Permanent Station

A GPS permanent tracking station BOGO at Borowa Gora operates within EUREF permanent tracking station network from 9 June 1996. The station is equipped with the Ashtech Z-12 GPS receiver with the external rubidium atomic standard and the choke-ring Dorne Margolin antenna.

Data collected at the station is transmitted (fully automatically since mid of 1997) to the Local Data Centre at the Technical University at Graz, Austria. The entire batch of daily set of data is transmitted to Graz each day right after midnight GMT. The reliability of the station performance is estimated at the level of 0.3%.

From 17 November 1998 the permanent GPS station at Borowa Gora is taking part in the international experiment of hourly data download and transfer to the computing centre at Graz. Downloading the data, its pre-processing and transferring is set up to be fully automatic. Recently the electronic meteorological sensor is being installed at Borowa Gora and the software to download, format and hourly transfer the meteorological data to the computing centre at Graz is tested.

2.3.2. Borowiec (BOR1) GPS Permanent Station

Borowiec, since 1994 is a permanent station of IGS and EUREF services. The observations are especially important for determination of co-ordinate system for International Earth Rotation Service (IERS). GPS station participated in international and national campaigns and projects: EUREF, SAGET, Baltic Sea Level, CERGOP, POLREF, EUVN’97. The GPS observations were carried out with TurboRogue SNR 8000 receiver. The data was transmitted to the Local Data Centre in Graz (Austria) and to NASA/CDDIS on regular basis. Presently the process is fully automatic. According to the JPL Reports, a systematic increase of accuracy, particularly concerning the receiver clock stability is observed. The accuracy of phase measurements was increased and presently equals to 3 to 4 mm. The data from the BOR1 station was analysed at the Centre for Orbit Determination in Europe (CODE), JPL, EUREF, ESA/ESOC to determine Earth rotation parameters and satellite orbits.

2.3.3. Jozefoslaw (JOZE) GPS Permanent Station

The IGS permanent GPS station Jozefoslaw (JOZE) is located at the Astro-Geodetic Observatory of the Institute of Geodesy and Geodetic Astronomy of the Warsaw University of Technolology, 14 km south from the Warsaw city centre. The Observatory was established in 1959; GPS permanent service is maintained there since August 1993. Trimble 4000SSE receiver with antenna Trimble Geodetic L1/L2 are used as a basic GPS equipment. Three rubidium frequency standards are available at the station; one of them is used as an external standard for IGS service. On January 1, 1995 the second GPS receiver, a TurboRogue SNR8000 with the antenna type Dorne Margolin T was set up at the station. The permanent GPS IGS service is maintained by both receivers (Trimble 4000SSE and TurboRogue SNR8000). Trimble 4000SSE serves as the main receiver and the observations collected by this receiver are transmitted to the international data centres. The observations from Jozefoslaw are used for IGS service and for maintenance of the EUREF system. The observations from the TurboRogue SNR receiver are available upon request. Also other types of GPS receivers, i.e. Asthech Z-12, Leica and Zeiss were temporarily installed at the station Jozefoslaw in 1996 and 1997. The observations were performed to study some instrumental effects, multipath and atmospheric influences. JOZE station takes part in the works of the IGS Ionosphere Working Group.

The Jozefoslaw station is located at the distance of a few kilometres from the Warsaw airport (Warszawa-Okecie). Thus, meteorological service maintained at the station can be supported by nearby permanent meteo service of the Warsaw airport. In some periods the observations of atmospheric electricity are made at the Observatory by the team of the Polish Academy of Sciences.

The monumentation of the reference point for IGS GPS observations was made according to the IGS standards. Due to the geological conditions the pillar could not be monumented on the bedrock. Jozefoslaw station is the reference point of several international GPS networks, e.g. EUREF (European Reference Frame), EXTENDED SAGET (Satellite Geodetic Traverses), CEGRN (Central Europe GPS Reference Network realised in the frame of the project CEI CERGOP (Central European Initiative Central Europe Regional Geodynamics Project) and BSL (Baltic Sea Level

Project). The eccentricity of the EUREF point with respect to that of other campaigns is X = 0.079 m, Y = 0.030 m, Z = 0.108m.

2.3.4. Lamkowko (LAMA) GPS Permanent Station

The first permanent GPS observations at Lamkowko Satellite Observatory were carried out on early 1994. First results were used to test the new TurboRogue SNR 8000 receiver. Because of lack of access to Internet the Observatory has taken a part in IGS (International GPS Service for Geodynamics) only since 1 December 1994. Observations have been transmitted to the Local Data Centre in Graz (Austria) and then to global centres of collecting and analysing data.

There are four observational pillars (LAMA, LAM1, LAM2 and LAM3) in the Observatory. LAMA is a point of global IGS network. It is also a point number 302 of the EUREF-POL network. LAMA became a point of EUVN (European Unified Vertical Network) as a result of participation in observational campaign carried out in May 1997.

In 1998 a new observational point (LAM5) was established. It is placed on the roof of Observatory building and plays a role of a reference station in experiments with RTK.

Observations are carried out by two receivers. One of them is Turbo Rogue SNR 8000. Ashtech Z-12.3 can replace it in case of its malfunction (which has taken place twice since 1994). Observatory has got its own rubidium frequency standard and meteo-station HTPL 3A made by NAVI.

The results of permanent GPS observations, obtained in Lamkowko and other Polish and European IGS stations, are used for following studies:

- monitoring the Lamkowko-Borowiec vector that is perpendicular to Teisseyre-Tornquist’s Zone,
- monitoring the vectors connecting Lamkowko with other European stations situated on different geological structures,
- analysis of the influence of GPS satellite orbits’ quality on positioning,
- analysis of spatial and temporal variations of ionosphere.

The research is conducted in co-operation with Polish research institutions and also with Western Department of the Institute of Geomagnetism, Ionosphere and Radio Waves Propagation, Russian Academy of Sciences in Kaliningrad (Russian Federation).

2.3.5. Wrocław (WROC) GPS Permanent Station

The permanent GPS station "Wroclaw" has been established in November 1996 and is working within the EUREF network. It is equipped with Ashtech Z-12.3 receiver and the Dorne Margolin antenna.

2.4. OBSERVATIONS OF GLONASS

In September 1998, AGO Borowiec started, as one of the first stations in the world, permanent, double frequency, P-code observations of GLONASS satellites. The observations are carried out with six channel 3S Navigation receiver equipped with choke ring temperature stabilised antenna. Participation of Borowiec in the International GLONASS Experiment (IGEX) campaign is a very important task for permanent determination of coordinates and time comparison using GLONASS.

2.5. TIME TRANSFER AND COMPARISON

The Astro-Geodynamic Observatory in Borowiec is participating in the realization of the international atomic time scale (TAI) coordinated by the International Bureau of Measures and Weights (BIPM) by measuring the connections of local atomic standards with the use of GPS time receivers. The accuracy of connection of the local time scale, generated by the EUDICS 3020 cesium frequency standard, to the global time scale is maintained at a precision level of ± 2 ns. Another development is the time comparison by GLONASS system which enables accuracy better than one ns. Together with US Naval Observatory, BIPM, Van Swinden Laboratory in Holland and Royal Observatory in Brussels, Borowiec participates in the development of this new very precise method of clock comparisons. The expected results will be by an order of magnitude better than the measurements available with GPS. In the near future Borowiec will participate in time comparison by Satellite Laser Ranging in the frame of Atom Clock Ensemble in Space (ACES) project.

2.6. DATA ANALYSIS AND ORBIT DETERMINATION

1. SLR Data Analysis.

The following investigations were performed at the Space Research Centre PAS, Warsaw, using SLR data:

1. Investigation on stability of network solutions estimated from satellite laser measurements in 1993-1995.

The study concentrated on the possible existence of systematic range biases, and on developing a technique to obtain optimum accuracy in geodetic network solutions. The investigated global network comprises 59 stations (see Fig. 2.1). The investigations were conducted in co-operation with the Delft University of Technology. The solutions were obtained using the software combination GEODYN II, SOLVE (NASA/GSFC), 3DMOTION (DUT).

2. Orbit improvement of low and high satellites: ERS-1, TOPEX/Poseidon, Lageos1, and determination of the Borowiec SLR station position in ITRF91. Simultaneously range biases were estimated. Investigations were performed in cooperation with ESA/ESOC/ Darmstadt. Computations were conducted using BAHN (ESOC) software.

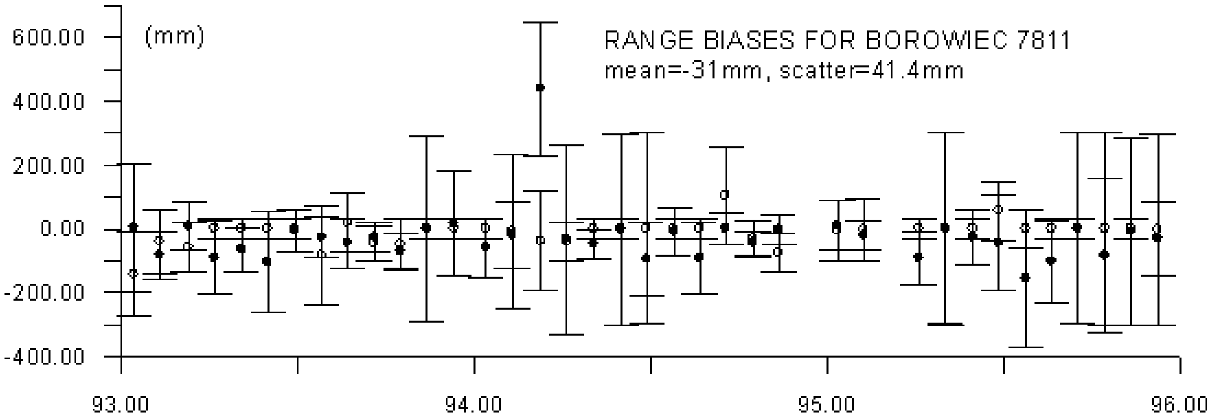

Fig. 2.1. The range bias values estimated for Borowiec

3. Orbit analysis and spin axis estimation of new low satellite WESTERN PACIFIC LASER TRACKING NETWORK “WESTPAC” launched in July 1998. The main aim is to define optimal force model for this satellite in order to ensure minimum error of orbit estimation and spin axis estimation.

2.6.2. Activities of the EUREF WUT Local Analysis Centre

Since the mid of 1996 the EUREF Local Analysis Centre in Warsaw University of Technology (WUT) has started daily processing of GPS data from EUREF sub-network. The diagram of this network is presented in Fig. 2.2.

From 919 GPS week this sub-network is extended to north-east direction. Stations JOEN, RIGA and SVTL were included to data processing. In the same time stations MATE and KOSG were excluded. Recently the network is constrained to stations WTZR, ONSA and METS. In 1997 the antenna phase centre models were changed according to IGS standards. Other parameters of data processing remained the same as in 1996. Bernese software version 4.0 with automatic data processing was used.

Data from numerous international GPS campaigns have been processed at the Centre, e.g.:

- EXTENDED SAGET 1992, 93, 94, 95, 96, 97 under the leadership of WUT;

- CEGRN 1994, 95, 96, 97 (Central European Regional GPS Geodynamic Network) conducted in the Frame CEI CERGOP Project.

In the near future a new format for ionosphere maps and for estimated troposphere parameters (SINEX_TRO) will be included. Particular values of cut-off angle for each station are the subject of investigation in the WUT Analysis Centre.

Fig. 2.2. EUREF sub-network processed by WUT

2.6.3. Study on Influence of GPS Satellite Orbits' Quality on Positioning Precision

Study on the influence of GPS satellite orbits' quality, determined by CODE(Centre of Orbit Determination in Europe), on precision of determination of vector components was carried out at the Institute of Geodesy of the Olsztyn University of Agriculture and Technology. The following orbits were taken into account:

- CODE final orbit,
- CODE 1-day orbit (available with 3-day delay),
- CODE rapid orbit (available with 16-hour delay),
- CODE orbit predicted for 24 hours.

The results were compared with those obtained from precise IGS orbits.

The following vectors (150-1500 km long) were analysed:

Lamkowko - Borowa Gora,

Lamkowko - Borowiec,

Lamkowko - Matera,

Lamkowko - Onsala.

Data collected in January 1998 (939-942 GPS weeks) at the permanent GPS stations were processed using Bernese v. 4.0 software. The results are shown in Table 2.2.

Table 2.2. The influence of orbits' quality on vector's co-ordinates

Type of orbits	Maximum differences in co-ordinates	Maximum differences in length
CODE - IGS	2 mm	0.5 mm
CODE 1-DAY - IGS RAPID ORBIT - IGS	6 mm	2.5 mm
CODE 24-pred. - IGS (d < 300 km)	5 mm	1.0 mm
CODE 24-pred. - IGS (d < 600 km)	25 mm	10.0 mm

The analysis led to the following conclusions:

- final IGS orbits and final CODE orbits can be used for geodynamic research,

- 1-day and rapid CODE orbits can be used for high precision survey (post-processing),
- orbits predicted one day ahead can be used for real-time positioning.

2.7. TROPOSPHERE AND IONOSPHERE STUDIES

New algorithms and software for determination of tropospheric refraction were developed in the Academy of Metallurgy and Mining in Cracow (Góral, 1997). The proposed methodology does not require information on meteorological conditions in survey points. It has been indicated that the method is particularly effective for GPS projects in mountainous areas. The analysis of GPS data burdened with multi-track effect was carried out.

The research on ionospheric delay to determine Total Electron Content (TEC) and to investigate the influence of TEC changes on the precision of positioning started in the Olsztyn University of Agriculture and Technology in 1995. The TEC can be obtained on the basis of the simultaneous two frequency observations with use of the algorithm shown in (Baran et al., 1997) at the level of precision of $(2\text{-}3)*10^{16}$ el./m^2.

GPS observations from IGS and EUREFF stations were used. Changes of TEC are monitored in many directions since the GPS solution requires at least 4 GPS satellites to be simultaneously observed.

The study carried out at minimum solar activity, show that two frequency GPS observations are useful for monitoring periodical (daily and seasonal) changes of TEC and for monitoring TEC at solar storms periods (Baran and Shagimuratov, 1998).

It turned out that, at ionospheric disturbance periods at minimum solar activity, at middle latitudes the TEC could rise three times over its normal value. Changes of condition of ionosphere affect the propagation along the path between the satellite and receiver. The effect can reach up to 0.3-0.5 m.

GPS observations, carried out in 1995-1997 at the permanent IGS stations: Borowiec, Jozefoslaw and Lamkowko, were used to create regional TEC model over Poland. The model is valid at minimum solar activity. The local ionosphere models over three mentioned IGS stations were used as the bases of the model. Daily changes of the TEC were shown as expansion of Fourier series in function of local time and seasonal changes in function of number of the month. The model was checked by calculating the TEC value by back extrapolation. Differences amounted to 15-40% depending on month. The obtained discrepancies were interpreted as the result of long period changes of TEC that were not taken into consideration in this model.

2.8. SATELLITE GRADIOMETRY

Theoretical study on satellite gradiometry was conducted in the Space Research Centre, PAS, Warsaw in cooperation with the Institute of Theoretical Astronomy, RAS, St.Petersburg, Pulkovo Astronomical Observatory, RAS. St.Petersburg, the Smithsonian-Harvard Astrophysical Observatory and the Institute of Space Physics, Frascati, Italy.

Gradiometry is the technique which is still in the development phase. The gradiometer developed in IFSI, Frascati, could be applied in a balloon mission or in a free fall probe. Recently a GIZERO project has been developed, which is essentially the facility for creation of free fall conditions. The feasibility analysis of application of IFSI gradiometer for Earth gravity field investigation, Free Falling Gradiometer**,** taking into account GIZERO project, was carefully examined. The requirements for the gradiometric experiment are discussed and the possible scenario of such a mission is presented with special emphasis on the accuracy analysis and error budget of the measuring system. Much of the attention is devoted to analytical methods of the Earth gravity field modelling and model improvement (Petrovskaya and Zielinski, 1997, 1998a,b, 1999). Besides of free falling probe also orbital and airborne applications were analysed.

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3. GEODETIC GRAVIMETRY

(compiled by Marcin Barlik)

3.1. INTRODUCTION

This part of the Polish National Report on Geodesy is the quadrennial report of gravimetric works performed in Poland in a period from 1995 to 1998. It summarises investigations such as national gravity surveys, absolute and relative gravity measurements, non-tidal gravity changes monitoring, data handling and mapping, theoretical research on gravity field and modelling geoid and quasi-geoid for Poland, etc. These activities were conducted mainly at the following research centres listed in an alphabetic order:

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

Complete bibliography of the related works is given in references.

3.2. ABSOLUTE GRAVITY DETERMINATION

The first original portable and stationary ballistic gravimeters ZZG have been constructed at the Institute of Geodesy and Geodetic Astronomy (Ząbek, 1996, 1998a). The symmetrical method of observations of the test mass vertical rise and fall is applied. The stationary absolute gravimeter is equipped with the Hewlett-Packard frequency –stabilised He-Ne laser of long period (a few months) stability of 10^{-9}. The laser is periodically compared to a stationary iodine-stabilised He-Ne laser (Axis/BIPM IGL1) of stability 10^{-10} in two year period. The Rhode Schwartz XSD2 quartz oscillator serves as a time standard. The standards of length and time ensure the accuracy of 1 mGal as regards the gravity. The construction of the catapult is based on Sakuma's method of launching by means of a rubber cord. The multipoint observations are executed along the ballistic trajectory of the reflector. The height of the rise (or fall) of the reflector equals to 20 cm. Approximately 300 points along the ballistic trajectory are observed, although an arbitrary number of observations can be scheduled. Observations are repeated automatically every 15-20 seconds. In average 3000 – 4000 throws are executed within a daily series of observations. Observations are corrected for tides and reduced to the height h=20 cm above the base. The accuracy of an average gravity from 24 hour series is estimated at the level of 2 – 3 mGal (Ząbek, 1998b).

The most interesting results of gravity measurements conducted so far by use of the ZZG absolute transportable gravimeter are those carried out in the framework of two international projects. The first is the International Absolute Gravity Base-station Network (IAGBN), and the second one is the Central European Initiative Project "Unification of the Gravity Central Europe Systems" (UNIGRACE CEI Project), (Barlik, 1997b), (Reinhart et al., 1998). The measurements were conducted at the following stations: Pecny (Czech Republic), Modra and Ganovce (Slovakia), Wetzell (Germany), Jozefoslaw and Krokowa (Poland). At these stations gravity was already measured using other absolute gravimeters brought from Austria, Germany, Finland and Italy. Gravity obtained with ZZG have been in very good agreement with the measurements performed using other gravimeters, also during comparison campaign of absolute instruments in Sévres in 1998. No systematic errors between them were found.

Studies concerning the influences of seismic effects on a random error of a ballistic gravimeter have been completed.

3.3. GRAVITY NATIONAL SURVEYS

Polish national gravity network, established in the sixties, could not satisfy any more the permanently increasing needs of geodesy. The works on establishment of the new network started in 1994 and has been completed in 1998. The new gravity network consists of 352 field stations, 12 absolute stations and 2 calibration base lines. Almost each gravity field station is marked by means of concrete block, buried flush with the ground level. Only 8 old stations were included to the new network. Each absolute station is located in the lowest floor of the solid building, in accordance with IAG recommendations. The description of the Polish national gravity network is given in Chapter 1 of this report.

21 absolute measurements, using ballistic gravimeters, were performed on 12 stations. Table 3.1 contains information

on names of the stations, their co-ordinates and the type of gravimeter. As it is shown in Table 3.1, all gravimeters were used to measure gravity on the fundamental point.

Table 3.1 Absolute stations in the Polish fundamental gravity network

Absolute station	j ° ? ?	l ° ? ?	H m	Date	Type of gravi-meter
Koszalin	54 11 30	16 12 30	38.2	1995	FG-5 No 101
Borowiec	52 16 37	17 04 25	79.6	1995	FG-5 No 101
Ksiaz	50 50 36	16 17 42	399.4	1995	FG-5 No 101
Piwnice	53 05 44	18 33 22	82.2	1995	JILAg-5
Konopnica	51 21 00	18 49 20	157.8	1995	JILAg-5
Cracow-Ojcow	50 13 07	19 47 43	378.0	1996	FG-5 No 107
Gdansk	54 23 46	18 34 24	20.2	1986 1996	GABL FG-5 No 107
Białowieza	52 42 15	23 50 59	160.0	1996	FG-5 No 107
Sieniawa	50 10 16	22 36 31	177.0	1995	FG-5 No 107
Borowa Gora	52 28 32	21 02 06	106.7	1978 1995 1995 1996 1997	GABL FG-5 No 101 JILAg-5 FG-5 No 107 ZZG
Lamkowko	53 53 06	20 40 15	157.0	1997	ZZG
Giby	54 02 20	23 21 45	130.0	1997	ZZG

During a period 1995–1997 gravity surveys covered also the POLREF primary network points (see Section 1 of the Report) as well as fundamental levelling benchmarks.

In the Institute of Geodesy and Geodetic Astronomy of the Warsaw University of Technology the gravimetric group has made the calibration of static quartz gravimeters using special tilt method. In 1996 a special procedure for testing the own frequency of LCR Model G and D gravimeters and outer voltmeter was developed. Each instrument operated in Poland, especially for geophysical exploration, ought to be examined in this Institute as well as on the vertical gravimetric baseline (Dg=57 mGal) established at 1986 in the Palace of Culture and Science in Warsaw which is one of the tallest buildings in the city.

3.4. INVESTIGATIONS OF THE NON-TIDAL GRAVITY CHANGES

At the Astro-Geodetic Observatory of the Warsaw University of Technology the studies of the plumb line direction changes by use of gravimetric method were continued during the period 1995 – 1998. In 1976 a meridian gravimetric baseline, 30 km long, was established to investigate variations of the north-south component of the deflection of the vertical. Periodically (3 – 4 times a year) measurements of gravity differences were conducted. Analysis of time variations of plumb line direction simultaneously obtained from astronomical and gravity observations may suggest the meteorological and hydrological sources of the detected changes. Results of these investigations are regularly sent to the Shanghai Astronomical Observatory (the international co-ordinator of such projects) as well as in more detail to "Latitude Circular" WUT (Barlik, 1996a, 1997c) (Zheng - xin Li, 1998).

Gravimetric investigations were employed to establish the Grybów Geodetic Test Field of the Warsaw University of Technology in southern Poland, 130 km South -East from Cracow. The gravity measurements in the local network were conducted using LaCoste&Romberg Models D and G as well as the Scintrex Autograv CG-3 gravimeters (Czarnecki et al., 1997), (Kalinowska et al., 1998), (Rogowski et al., 1995, 1996). Usually both orthometric and normal levelling corrections were computed to provide precise levelling with gravity information.

Precise vertical gravity gradients were determined at the control points of the GRYBOW test network for estimation of the geoid to quasi-geoid separations (Barlik, 1997a, 1998).

Gravity and satellite measurements as employed to the investigations of gravity field geometry changes were performed on Upper-Silesia test field established near Jastrzębie Zdrój – Katowice district - SATGRAVMINE Project (Barlik, 1996c). It was found, that in some places the Poincaré-Prey's anomaly gradient is strictly correlated to the changes in inner mass distribution and topography deformations. The theory of a relation between geometric parameters of equipotential surface and horizontal gradient of these anomalies was developed. The sites of maximum horizontal gradient of gravity anomalies pointed sites with geological faults and inner stresses caused by mine exploitation.

Contribution of gravity data to geodetic investigations in the Polish part of Pieniny Klippen Belt was described. The results show a good agreement with the evaluation of mass displacement influences. They were used to the interpretation of orthometric heights obtained from precise levelling and co-ordinate changes obtained with EDM and GPS in that region.

3.5. GEOID AND THEORETICAL STUDIES ON THE GRAVITY FIELD IN POLAND

The accuracy of geoid heights calculated for Poland in the Department of Planetary Geodesy of the Space Research Centre of PAS at the beginning of the 1990s was limited to a few decimetres. The maximum spatial resolution of the geoid was at the level of some 10 km. The years 1994 – 1998 brought major changes through improved modelling techniques, the availability of high resolution gravity data, and significant advance in the computing capability. The new geoid/quasi-geoid was calculated with an accuracy improved up to one order of magnitude. Hence a combination of ellipsoidal heights from GPS with spirit levelling data is now possible.

Experience with comparison of GPS ellipsoidal heights on levelling benchmarks (POLREF-96 network) against the new quasi-geoid model have shown the evidence of systematic offset and tilts. The technique of computing the latest QUASI97b quasigeoid height model uses gravity data to calculate high frequency corrections to the EGM96 model (Lyszkowicz, 1996a,b). For the evaluation of Stokes integral by the FFT the gravity anomalies were gridded by a fast collocation prediction procedure (KMS GEOGRID program). Next, high frequency geoid grid was combined with EGM96 geoid heights and corrections derived from digital terrain data (Lyszkowicz and Forsberg., 1995) providing final geoid heights. At last, computed geoid heights were converted into the quasi-geoid heights using Bouguer anomalies.

The final results for geoid and quasi-geoid are available in the graphical and also in computer applicable form of FORTRAN subroutine with enclosed the input grid files. The input files contain geoid/quasigeoid heights for a 1.5' x 3.0' grid (Lyszkowicz, 1998). Similar procedure was used to compute geoid heights for Libya (Lyszkowicz and Wahiba, 1997).

An attempt to use balloon gradiometry to determine height anomalies and geoid heights was undertaken in the Space Research Centre of the PAS (Petrovskaya and Zielinski, 1998a,b).

Local determination of height anomalies in the vicinity of Cracow was the field of research of the Department of Mining Geodesy and Environmental Engineering of the Academy of Mining and Metallurgy. The quasi-geoid was determined with use of spirit levelling and GPS data. The survey was carried out in two areas close to Cracow and the Wieliczka salt mine. It was pointed out that the ellipsoidal model (quadratic) of quasigeoid ensures the required accuracy of quasi-geoid approximation.

In the city of Cracow the average deflections of the vertical were determined using the astro-geodetic method. Deflections of vertical were also determined on the basis of differences of orthometric heights and differences of ellipsoidal heights obtained from GPS measurements. The comparison of both methods shows no important differences. Practical use of information on local shape of quasi-geoid for processing GPS measurements was discussed.

One project in reported period was devoted to the investigations of the Earth's shape parameters as a consequence of its inner structure taking into account a theory of the gravity field of rotating fluid body (Barlik, 1996c).

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4. GENERAL THEORY AND METHODOLOGY

(compiled by Wojciech Pachelski)

4.1. INTRODUCTION

This part of the Polish National Report on Geodesy is the quadrennial report of works on theory, evaluation and methodology performed in Poland in a period from 1995 to 1998. It summarises investigations such as deformation analysis, least squares theory and evaluation, research on GPS, etc. These activities were conducted mainly at the following research centres listed in an alphabetic order:

- Department of Geodesy, University of Agriculture in Cracow;
- Department of Geodesy and Photogrammetry, Agricultural University in Wroclaw;
- Department of Mining Geodesy and Environmental Engineering, Academy of Mining and Metallurgy in Cracow;
- Department of Planetary Geodesy, Space Research Centre, Polish Academy of Sciences in Warsaw;
- Institute of Geodesy, Olsztyn University of Agriculture and Technology;
- Institute of Geodesy and Geodetic Astronomy, Warsaw University of Technology.

Complete bibliography of the related works is given in references.

2. DEFORMATION ANALYSIS

New procedures for modelling and processing kinematic and quasi-kinematic networks in application to deformation analysis were presented (Kadaj and Plewako, 1996). An examination of the problem led to a definition of kinematic vector fields as 4D deformation models for investigated objects.

A generalised algorithm for direct determining displacement components by the method of differences was presented (Beluch, 1997). It consisted also of a critical analysis of previous presentations of the method.

Electronic measurements allow for station positioning by means of the so-called free station technology. Equations for determination a covariance matrix for two separate cases of intersection were derived (Beluch, 1998). The obtained average errors differ from their expectations resulting from the geometry of the intersection.

Two kinematic models of adjustment of a vertical control network in areas of intensive vertical movements were investigated (Beluch and Plewako, 1995). In order to overcome the singularity of the system the authors introduced the Meissl’s condition of free adjustment, as well as an additional pseudo-observation equation. It was shown that an improper assumption of the point motion might cause a significant blunder in the results.

A generalised model of displacements and deformations was given (Czaja, 1996). Minimisation of the quadratic form is executed for random deviations, as well as for the constraints preserving continuity of deformations. An extended theoretical basis of the problem was given (Czaja, 1997).

3. LEAST SQUARES – THEORY AND EVALUATION

An algorithm for processing observations with the use of a generalised matrix inverse was presented (Pietruszka, 1995). It allowed a free choice of an optimal co-ordinate system. The analysis of accuracy was based on the matrix eigenvalues.

General concept of the adjustment method using Edgewood series was presented (Dumalski and Wiśniewski, 1995). The series approximates a certain class of probability distributions and the proposed method can then replace the set of adjustment methods derived with application of specific probabilistic model observation errors.

Definitions of the reduced vectors of the second, third and fourth order moments were given (Wiśniewski, 1995, 1996a). The vectors concerned mutually independent random variables. Also, the propagation laws of the defined vectors were given. The major goal of the study was to present an estimation method of the moment vectors after the LS adjustment. The estimation was carried out under the assumption that the preliminary estimations of the third and fourth order moments were known. Implementation of the proposed method would facilitate practical applications of such adjustment methods in which knowledge of values of the higher order moments (besides of the variances) would be required.

Relationship between the variance estimate and the matrix of excess coefficients was given (Wiśniewski, 1996b). It made it possible to assess the effectiveness of the analysed estimate with respect to the excess values of the set of observations to be adjusted. There were also derived the relationships to determine critical and admissible values of the excess. Moreover, some optimisation problems connected with the determination of the variance in the class of the ?-locally minimum variance quadratic unbiased invariant estimators were investigated (Wi?niewski, 1998).

The method of estimation according to Henderson was applied to determine local variances (Duchnowski, 1996). The main purpose of the study was to estimate local variances in 3D networks.

The alternative forms of commonly used adjustment algorithms were elaborated (Oszczak, 1996) taking advantage of the introduced by author symbols of generalised Kalman weighting matrices.

The sequential estimation algorithm has a compact and simple form and can be used both for batch and sequential processing procedure of GPS observations.

Matrix expressions for minimum semi-norm least-squares solutions and the related inverse were investigated (Prószyński and Sosnowski, 1995). The expressions had initially been derived for the needs of data analysis in geodetic monitoring of relative movements in engineering structures. The mathematical models used there were linearised rank–deficient systems solved by least squares method. The solutions are often required to be of minimum l^2 – norm for a specified sub-vector of unknowns.

The initial approach was later expanded into a more general problem of seeking the minimum *N* – semi-norm *M* – least squares solutions (with the matrices *N* and *M* positive semi-definite) and determining an inverse to generate those solutions.

The derivations were based on the Moor–Penrose inverse, providing a clearly interpretable structure of the matrix expressions as well as enabling a prior analysis to detect areas of non-unique solutions. With the auxiliary assumption of minimum l^2 – norm for the full solution vectors a unique minimum *N* – semi-norm *M* – least squares inverse was defined.

An algorithm for calculating the rms of a function *C* of two sets of variables: (1) the set of *s* unknowns *x* calculated from the system of observation equations with known rms *m*, and (2) the set of *r* known variables *w*, for which some of rms were also known was derived (Skórczyński, 1997a). The idea of the solution consisted in the assumption that all *w* variables are observations. Hence *r* additional observation equations $l_j = w_{s+j}$ with appropriate weights were obtained. Then the inverse of the (regular) matrix $(s+r)\times(s+r)$ of parametric normal equations allows for calculating the rms of *C*.

The exact practical formula for the rms of a linear misclosure of a traverse with initial azimuth calculated from co-ordinates was derived (Skórczyński, 1997b). It was used to show substantial influence of the misclosure's azimuth onto misclosure's rms.

The robustness potential of the least-squares estimation with geodetic illustration was investigated (Prószyński, 1997). The structure of the projection operator transforming the vector of standardised observations onto the vector of standardised residuals was analysed. On this basis the properties of the model responses to observational disturbances (i.e. blunders) were derived. A final outcome of the research was: (1) suggesting characteristic quantities of the robustness of a given model and linking them to the local measures of internal reliability, and (2) determining the internal reliability levels satisfying the specified requirements for the robustness (i.e. possibility of detecting at least one of the *k* observational disturbances). The theory and a numerical example showed that a system properly designed, with respect to a given level of internal reliability, could provide accordingly high level of robustness.

A comparative analysis of several approaches to reliability measures for correlated observations was given (Prószyński, 1998). The approaches were compared on the basis of numerical examples used in recent publications. An attempt was made to explain the discrepancies in the results. The conclusions contained possible directives for future investigation of the problem.

A perspective modelling of the adjustment and maintenance of the Polish levelling system was studied (Pachelski, 1998). The Polish national levelling system consists of 1st and 2nd class precise levelling networks and amounts to over 43 thousand benchmarks. The international EUVN programme assumes, among others, its integration with the ETRS'89 system, the last one realised through GPS measurements on the EUREF network.

The above task was considered to be solved by a simultaneous (“single batch”) adjustment of both classes of the network linked (constrained) to a number of GPS reference points, as well as by its possible further systematic maintenance through repeated GPS, precise levelling and gravity measurements. That caused certain numerical problems reflected in the evident ill conditioning and large dimensions of matrices, cumulating round-off errors, possible instability of the solution, and others. To overcome the problems it was suggested to use the so-called sequential adjustment algorithm applying the sparse matrix technique. Its basic properties consisted in high numerical stability (no matrix inversion performed), possible on-line control of the covariance matrix in the course of the one-by-one processing of observation equations, and possible augmenting (as well as reducing) the number of unknowns.

The study gave a basic idea of the sequential algorithm for this task. It also presented results of its tests on a simulated levelling system, including its performance in the course of updating the system and estimating possible inaccuracies due to the used sparse matrix technique. Positive results indicated possible application of the approach also in other types of geodetic control systems.

4. RESEARCH ON GPS

A concept of single epoch ambiguity and slip resolution applied to undifferenced GPS phases was presented (Pachelski, 1996). According to it an observation equation of the GPS carrier phase contains a bias $\gamma_r^s = \psi^s(t_0) - \psi_r(t_0) + N_r^s$ independent of epoch and specific for a station-satellite pair, in which N_r^s is an integer ambiguity and $?^s(t_0)$, $?_r(t_0)$ are transmitter and receiver initial phases. Through sequential processing of phases we update γ_r^s estimates in each epoch, provided specific minimal configurations of satellites, stations and already processed epochs are satisfied. All second differences of the phases with respect to a given reference satellite and reference receiver, $\nabla\Delta\gamma_r^s = \nabla\Delta N_r^s$, should be then integers on each L1 and L2 band. These conditions can be solved for all N_r^s 's (thus implying new γ_r^s -values) about current estimates of the γ_r^s 's as soon as the integer values are found by means of a proper search procedure.

Cycle slips come into view as outliers of observations caused by rapid changes of particular γ_r^s values. In that case a new observation sequence is created, for which new ?-parameters are estimated, and then consequently constrained for ambiguities.

A series of works concerning integration of the total station and GPS measurements in real time were published (Osada, 1996, 1998; Osada and Trojanowicz, 1998; Osada et al., 1997: Bosy, 1996; Bosy and Osada, 1997).

Problems of the GPS levelling, updating and optimal designing were investigated (Osada, 1998). Height and local gravity models in GPS network were discussed (Osada and Trojanowicz, 1996; Osada, 1997; Osada and Bosy. 1995).

A strategy of GPS data evaluation for local geodynamic polygons was presented (Bosy and Kontny, 1998).

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next

5. GEODYNAMICS

(compiled by Barbara Kolaczek)

5.1. INTRODUCTION

This part of the Polish National Report on Geodesy is the quadrennial report of geodynamic works performed in Poland in a period from 1995 to 1998. It summarises investigations such as establishment, maintenance and analysis of geodynamic networks of continental, regional and sub-regional scale, theoretical research and analysis of Earth rotation data, Earth tides monitoring, investigations of sea level variations, etc. These activities were conducted mainly at the following research centres listed in an alphabetic order:

- Department of Geodesy and Photogrammetry, Agricultural University in Wroclaw;
- Department of Mining Geodesy and Environmental Engineering, Academy of Mining and Metallurgy in Cracow;
- Institute of Geodesy, Olsztyn University of Agriculture and Technology;
- Institute of Geodesy and Cartography in Warsaw;
- Institute of Geodesy and Geodetic Astronomy, Warsaw University of Technology;
- Space Research Centre, Polish Academy of Sciences in Warsaw.

Complete bibliography of the related works is given in references.

5.2. GEODYNAMIC NETWORKS IN POLAND

5.2.1. Polish Geodynamic Network

In the period of 1991-96 the full modernisation of the primary Polish control network was completed. Consulting geologists, 33 points of this network (including all 11 Polish 0-order EUREF points) were selected as well as 3 additional ones, setting up a repetitive Polish Geodynamic Network. The network points are nearly evenly spread all over Poland and comprise all main and secondary geological block structures. They are especially located and marked for safety with a sophisticated construction. Repetitive measurements on this network, besides other geodynamic tasks, should make possible investigations of coherency and stability of the primary control network. Distribution of the network points is presented in Fig. 5.1.

0-epoch GPS campaign on the Polish Geodynamic Network was carried out from 6 to 24 September 1997. Observations were taken over 3 days at each point (6 days at sessions joining points). However, temporary malfunctioning of two GPS receivers (lack of L2 signals, interruptions of both L1 and L2 signals) made it necessary to make supplementary observations, carried out in early October 1997 and April 1998. Eight Leica SR299, SR399 and SR9500 GPS sensors were used in the observation campaign on the network. Amending sessions were performed with the Ashtech Z-12.3 receivers.

The network was processed and adjusted in co-operation with WUT sub centre of “Permanent EUREF Network” program, using Bernese version 4.0 software, according to presently valid standards. All five Polish GPS permanent stations (BOGO, BOR1, JOZE, LAMA, and WROC) as well as stations in neighbouring countries (METS, ONSA, WTZR, GOPE and GRAZ) were used as reference points. The whole operation, designed and completed in the Institute of Geodesy an Cartography (IGiK).

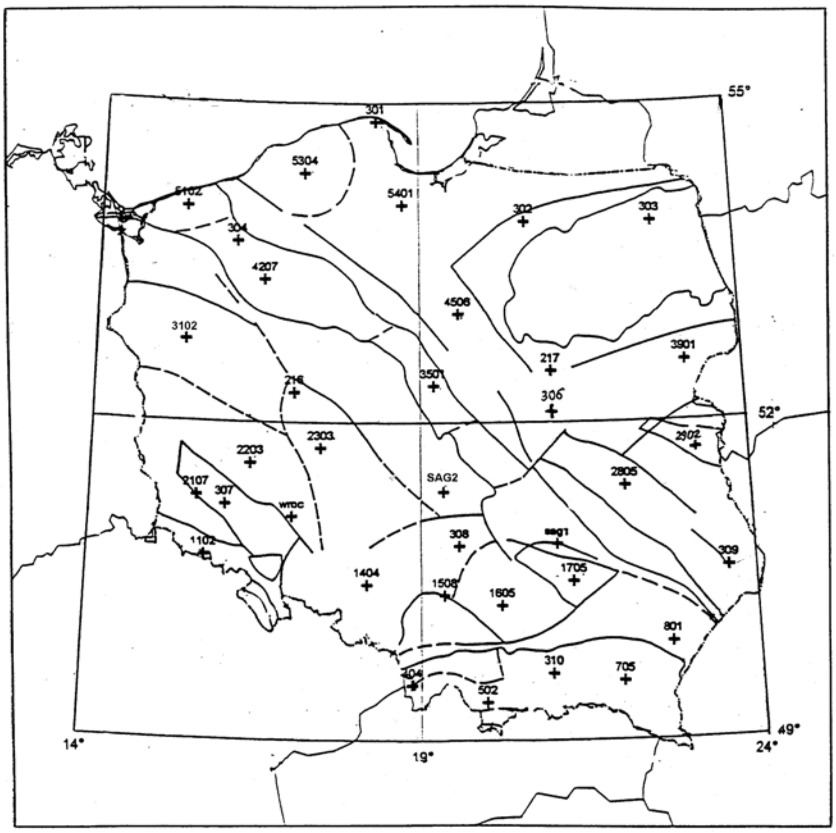

Fig. 5.1. Structure of geological blocks and distribution of points in Polish Geodynamic Network

5.2.2. Geodynamics Research In The Sudety Mountains And Fore-Sudetic Block

(SW Poland)

The research is conducted on three geodynamic polygons: “Snieznik Massif”, “Paczkow Graben”, “Stolowe Mountains”. The control networks of the mentioned polygons are integrated by a regional control network “Geosud” (Fig. 5.2). The network was established in 1996 as the geodynamic network in the Eastern Sudety Mountains and in Fore-Sudetic Block (Cacoń, 1996; Cacoń, 1998). Fig. 5.2 shows the "Geosud" network points distribution with Wrocław permanent station. In the Stołowe Mountains National Park the geodetic network was established and surveyed by GPS (Kontny and Mąkolski, 1996). Since then the GPS and terrestrial geodetic measurements are periodically repeated (Cacoń, 1998). Results obtained confirm that neo-tectonic movements are not finished yet. It indicates the potential hazard for water dams of the Lower Silesia (Cacoń and Dyjor, 1995) as well as for the other objects (Cacoń, 1998a). Recent mobility of the upper crust is also confirmed by investigations of geodynamic polygons in Snieznik Massif (Cacoń et al., 1996; Jamroz, 1997), Paczkow Graben (Cacoń and Deeb, 1995, 1996) and in the Stolowe Mountains (Cacoń, 1996a). Similar results were obtained for the Eastern Sudety and Fore-Sudetic Block (Cacoń, 1996b, 1998b; Cacoń et al., 1998). Concept of spatial database for geodynamics was presented (Kontny et al., 1997).

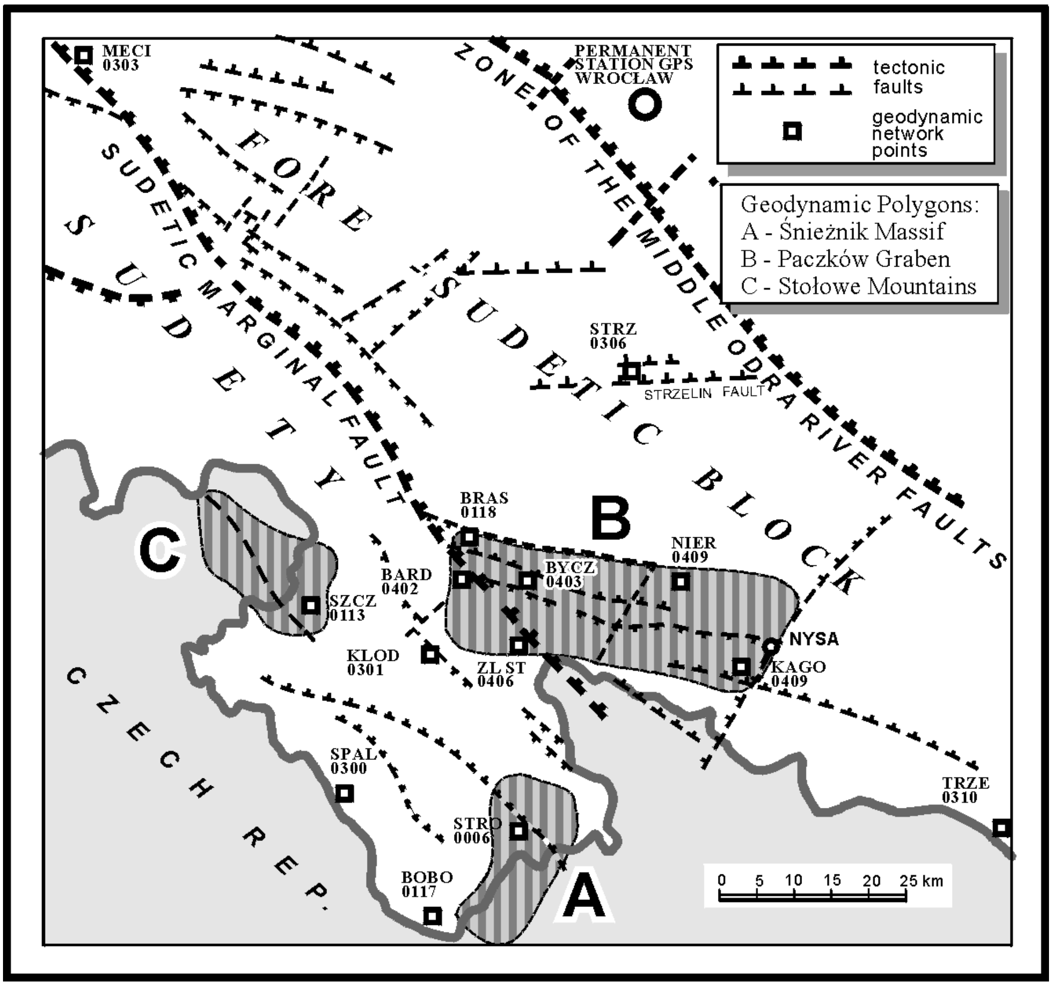

Fig. 5.2. "GEOSUD" geodynamic network

In 1997 the "GEOSUD" regional network was integrated with the "SILESIA" network in the northern part of Morava (Czech Republic) into the new network named "SUDETY" (Schenk et al., 1998).

5.2.3. Tatra Mountains Geodynamics

Geodynamic research in the Tatra Mountains Geodynamic Test Area has been initialised in mid 1980 and is carried on since. The network of well stabilised control points has been extended over a part of Slovakian Tatra Mountains. Three GPS observation campaigns were conducted in 1995, 1996 and 1998 respectively. Numerous relative gravity measurements were also conducted at the fiducial points of the control network. The final analysis of the data is being elaborated (Makowska and Cisak, 1997).

5.2.4. Geodynamic Network In Wieliczka Mining Area

An integrated geodynamic network was established in 1944-1966 within a project financed by the State Committee of Scientific Research, to monitor displacements and to analyse the sources of these displacements over Wieliczka salt mine and its surroundings. There are movements of the rock body due to seven hundred years of mining as well as due to land sliding movements and neo-tectonic movements. Geodetic network consists of numerous points stabilised on the mining area as well as intermediate points located outside this area. These points were connected to the 0-order GPS POLREF network and to a Tatra Mountains geodynamic network. GPS, levelling and gravity measurements were used for determination of a local quasi-geoid. The analysis of the results showed high effectiveness of GPS technology while monitoring displacements.

A new concept of the universal observation network for monitoring 3D displacement in mining areas and on land slide areas was described including guidelines how to carry out measurements. The concept has been verified in practice.

Verification of various hypotheses concerning the behaviour of a rock body under the influence of mining on the basis of geodetic measurements carried out periodically is presented together with a strategy of using the verified hypothesis in a kinematic model adjustment of vertical control (Beluch and Piwowarski, 1996). In areas with quick vertical dislocations a project on observation control and technology of measurements become important. Problems of collecting data from altimetry with use of technology of modular sequences located among points positioned with GPS were described. Based on finite elements a numerical model of a rock body is used. It allows to determine a deformation index at arbitrary point of the area being investigated. It is found to be an efficient tool for prediction changes and dangers caused by mining.

Application of the finite elements method for calculation of local changes of Earth gravitational field caused by a dislocation of huge masses of a rock body in open pit mines was discussed. It was proved that local changes of Earth gravitational field might have a major influence on the accuracy of precise levelling.

5.2.5. Geodynamic Network in Copper Basin Area

Polish Copper Basin is located in south-western Poland, between two towns: Lubin and Glogow. In this area the following influences of mining exploitation on the surface and the rocks mass can be established:

- direct influences caused by displacement of the rocks filling free space created as a result of mining activity,
- indirect influences caused by water draining action in the mines.

From the very beginning of mining activity in this area, i.e. since 1960, investigations and classical measurements aiming to determine factors shaping the deformation process have been carrying out.

The precise levelling network covers the area of about 2300 km^2. The study of horizontal displacements in this area was carried out using spirit levelling measurements of control points repeated every 2-3 years.

Since 1992 the new concept of 3D control network measured with GPS was developed. The primary GPS control network in the Copper Basin area consisting of 53 new points was established. The classical horizontal control network has been integrated with GPS determined one and tied to the POLREF'92 points (Wasilewski et al., 1996a; Wasilewski et al., 1996b; Baran et al., 1998).

The accuracy of co-ordinates determination, using GPS technique, of the network points was shown to be not worse than 3 mm. Performed analysis shows also high reliability of GPS measurements.

The finite elements method for deformation analysis and prediction of displacement is just under development.

5.3. INTERNATIONAL GEODYNAMIC NETWORKS

5.3.1. Baltic Sea Level Project

The Baltic Sea Level Project was initiated already in 1989 at the IAG General Meeting held in Edinburgh. The purpose of the project was to co-ordinate the vertical datums of the counties around the Baltic Sea.

In order to fulfil the above goal, three Baltic Sea Level GPS Campaigns were conducted since 1990. The first one was a two-week campaign held in October 1990, called the First Campaign. The results of the First Campaign were not as good as hoped for. The estimated accuracy of ellipsoidal height is not better than ± 4.6 cm.

As the First Campaign took place at the time of political unrest in the Baltic States and Russia, these counties were not able to take part in it. As soon as it was politically possible, contacts were made with the authorities of the newly independent states in order to plan and arrange the Second Baltic Sea Level Campaign. The Second Campaign conducted in June 7 -13, 1993 was performed under more favourable measurement conditions than the First Campaign, and a large volume of good data was collected (Zielinski and Zdunek, 1995). The estimated accuracy of ellipsoidal height was found to be at the level of ± 2.0 cm, which is essentially better than that in the First Campaign. The Third Campaign took place simultaneously with the EUVN, i.e. in May 1997. In the campaign 35 tide gauges and 12 fiducial stations were observed. Additionally, several permanent GPS stations were included into the network of the Third Campaign.

5.3.2. CERGOP Project

The main objectives of the project are: to integrate the geodynamic research in the Central European region based on high accuracy spatial geodetic measurements, to investigate the most profound geotectonic features in the Central European region, the Teisseyre-Tornquist zone, the Carpathians, the Bohemian Massif, the Pannonian Basin and the Alpine-Adria region as well as to provide a stable Central European GPS Reference Network (CEGRN) for sub-regional, local or across the borders investigations and deformation studies. In 1994 Austria, Croatia, Czech

Republic, Germany, Hungary, Italy, Romania, Poland, Slovakia, Slovenia and Ukraine joined the Project headed by Hungary and Poland. As associated country Bulgaria joined the project in 1996.

Since 1994 four epoch monitoring GPS campaigns have been carried out on this network in yearly intervals. The CERGOP Data Centre established in 1994 in the Lustbühel Observatory at Graz, Austria. The data of the CEGRN campaigns were processed in the CERGOP Processing Centres. Originally 3 processing groups were formed (Graz, Austria; Penc, Hungary and Warsaw, Poland). A number of processing centres increased later to 8 (Bratislava, Slovakia; Frankfurt, Germany; Matera, Italy; Pecny, Czech Republic and Zagreb, Croatia. A major role in the project was played by CERGOP Study Groups (CSGs) formed by the scientists from two or more member countries. Nine of them remained active during the whole project period. The proceedings of semi-annual CERGOP Working Conferences were published in Reports on Geodesy, by the Warsaw University of Technology. The results obtained within the project were presented at the biannual International Seminar on "*GPS in Central Europe*", organised by the FÖMI Satellite Geodetic Observatory, Penc, in Hungary. The proceedings of these conferences were also published in the Reports on Geodesy series.

CERGOP project was partially financed by the Programme COPERNICUS of the European Commission co-ordinated by the Institut für Angewandte Geodäsie (now Bundesamt für Kartografie und Geodäsie), Frankfurt/Main, Germany. First phase of the Project was concluded on 30 June 1998. Lately the proposal for the second phase of the CERGOP-2 Project was submitted to the European Commission with the request for financial support from the 5th Framework EU Programme.

The main achievements of the CERGOP-1 Project are as follows:

* Establishment and maintenance of the Central European GPS Reference Network consisting of 31 sites in 11 countries. The sites satisfy the strict requirements for repeated GPS monitoring on the highest accuracy level (2-4 mm in horizontal co-ordinates and 4-8 mm in vertical co-ordinates have been achieved).

* Eleven CEGRN stations are permanent GPS stations providing continuous monitoring capabilities for tectonic studies. The remaining 20 sites are so called "epoch stations' that provide positioning at the measurement epochs.

* The Central European Terrestrial Reference Frame (CETRF) has been established, which suits best for geophysical and geotectonic studies of the region. The yearly monitoring of CETRF provided already significant kinematic results about intraplate tectonic motions in Central Europe. 22 stations from CEI countries (eleven CEGRN stations) are involved in permanent monitoring of the European Reference Frame (EUREF).

* The five monographs of five particular regions in Central Europe produced by CSG.8 "Geotectonic analysis of the region of Central Europe" can be considered as major scientific outputs of CERGOP Study Groups. The following volumes of geotectonic monographs were published in Reports on Geodesy series: The Pannonian Basin (ed. Grenerczy), The Bohemian Massif (ed. Vyskočil), The Teisseyre-Tornquist Zone (ed. Liszkowski), The Northern Carpathians (ed. Zablotskij), and The Southern Carpathians (ed. Ioane). The monographs summarise the latest geoscience results, available on these regions, with particular emphasis on the project's objectives. There is also a sixth volume (eds. Vyskočil & Sledzinski) which contains general characteristics of all regions, list of performed studies and a summary indicating proposals for future investigations.

The second phase of the CERGOP-2 Project will include three new member countries (Albania, Bosnia&Hercegovina and Bulgaria); extension of the CEGRN will result in accepting in total more than 60 CERGOP (CEGRN) sites. Thus the extension of the geographic area of the project will conclude in establishing the Central European Extended GPS Reference Network (CEEGRN). The existing network of permanent satellite stations will play the crucial role in maintenance of the Central European Terrestrial Reference Frame (CETRF), which is best suited for regional tectonic investigations; it is also envisaged to introduce CEEGRN network as a sub-network of the EUREF permanent network. The calculation and interpretation of the 3D tectonic velocity field covering the Central European Region will be continued; the geodynamic investigations in Central and Southern Europe will be extended.

According to the requirements of the EC, the proposal must be expressed in terms of work-packages. The following work-packages for CERGOP-2 are proposed:

WP1: Enhancement of the Permanent CEEGRN Network, WP2: Maintenance and Extension of CEEGRN,

WP3: Central European Terrestrial Reference Frame,

WP4: Tropospheric Delay Estimation,

WP5: Ionospheric Modelling,

WP6: Real Time GPS Applications,

WP7: Local Deformation Studies in Central Europe.

5.3.3. Extended SAGET Programme

For technical reasons the number of sites of the Central European GPS Reference Network (CEGRN) was limited to 31. It is successfully supplemented by the EXTENDED SAGET programme (initiated in 1991 by the Institute of Geodesy and Geodetic Astronomy of the Warsaw University of Technology as an extension of the Polish SAGET Project launched at this Institute in 1986). There is a significant coincidence of scientific aims of both CEGRN and EXTENDED SAGET projects. However, there are also very essential differences. The EXTENDED SAGET network covers much more extended area and an unlimited number of points can be incorporated to this network. This gives an excellent opportunity to all participating institutions to connect new points to the ITRF. EXTENDED SAGET campaigns are thought as long-term action and will be performed every year at least in the whole of current decade. The EXTENDED SAGET campaigns took place in the following periods:

No.	**Campaign**	**Date**
1.	EXTENDED SAGET'1992	1992, September 7-11
2.	EXTENDED SAGET'1993	1993, August 2-6
3.	EXTENDED SAGET'1994	1994, May 2-6
4.	EXTENDED SAGET'1995	1995, May 29 - June 3
5.	EXTENDED SAGET'1996	1996, June 10-15
6.	EXTENDED SAGET'1997	1997, June 4-10
7.	EXTENDED SAGET'1998	1998, June 27 - July 1
8.	EXTENDED SAGET'1999	1999, June 14 - June 19

In order to increase a number of points related to the same observation epoch, the four campaigns of EXTENDED SAGET 1994-1997 fully overlapped with CEGRN campaigns. This will also be a case of 1999 campaign. The following conclusions may be pointed out when comparing both projects: (1) The same standards of GPS observations are used in both CEGRN and EXTENDED SAGET campaigns, (2) EXTENDED SAGET network includes stations of Scandinavia and Mediterranean Region. CEGRN is limited only to CEI countries; only some regions of Germany, interesting from tectonic point of view, are included, (3) EXTENDED SAGET campaigns give the possibility to connect new points to ITRF, (4) Both networks (projects) can coexist. Campaigns of both projects may supplement each other.

5.4. EARTH ROTATION

5.4.1. Chandler and Free Core Nutation

The Chandler and semi-Chandler oscillations were studied. The semi-annual oscillation and the semi-Chandler wobble were separated using the Fourier Transform Band Pass Filter (FTBPF), (Kolaczek et al., 1996; Kosek, 1995a;

Kosek et al., 1997), (see Fig.5.3). Long period variations of their amplitudes with periods of 11-14 years were demonstrated. The correlation coefficient between the change of amplitude of the semi-Chandler wobble and the Wolf numbers is significant at the 90% confidence level. It was found out that the temporal variations with the period of 3-4 years of the amplitude of the semi-annual oscillation filtered using a wide band pass filter are simply beats from the two oscillations. Polhody of the semi-annual oscillation is a left-handed ellipse with the major axis almost parallel to the Greenwich meridian. Its amplitude is of the order of 6 mas. The polhody of the semi-Chandler wobble is circular but irregular and its amplitude does not exceed 3 mas (Kosek and Kolaczek, 1995R; 1997).

IERS C04 B270 lambda=0.0005

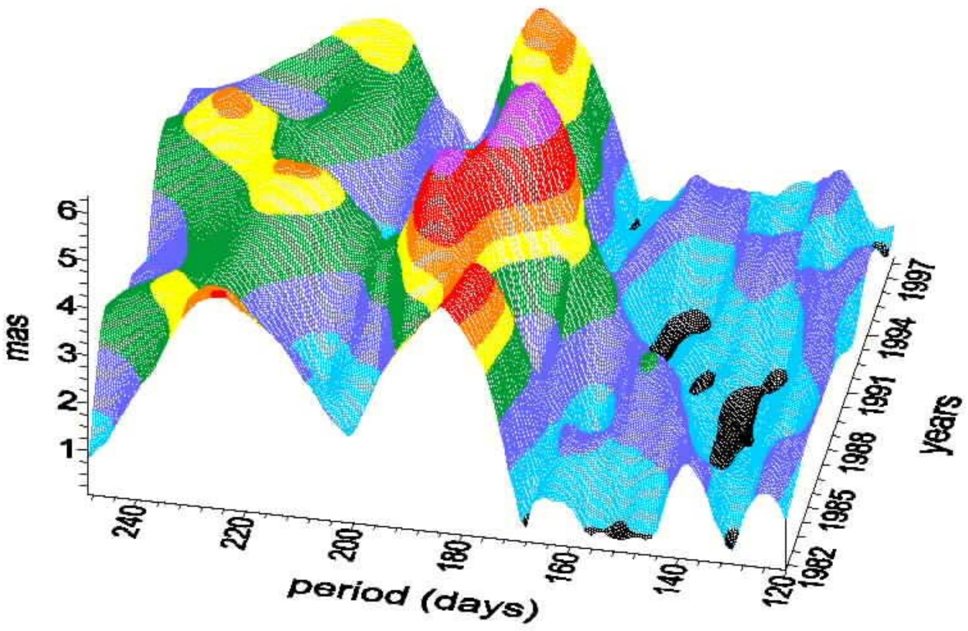

Fig. 5.3. Amplitude variations of the semi-Chandler (218 days) and the semi-annual

(182 days) oscillations of polar motion computed from the IERS C04 data

filtered by the Butterworth High Pass Filter with the cut-off period of 270 days

Variations of amplitudes of the Chandler nutation have been analysed. Oscillations with periods of 75, 40, 30, 20 years were detected by the Maximum Entropy Spectral Analysis in variations of the Chandler nutation amplitude. The oscillation with the period of 40 years is the most energetic and suggests the influence of variations of the Earth magnetic field which have the similar oscillation.

Predictions of Chandler nutation amplitude variations using the least squares and auto-regression methods show a deep minimum of the Chandler nutation amplitude at the beginning of the 21 century. Similar minimum took place at end of the 1920's/beginning of the 1930's (Kolaczek and Kosek, 1998).

5.4.2. Free Core Nutation

A maximum likelihood method (MLM) algorithm for direct determination of the Free Core Nutation (FCN) parameters was developed. It consists in tracking the freely excited variable FCN signal in the celestial motion of the pole observed by VLBI technique, and fitting the resonance parameters. The VLBI observations yield the FCN period estimate T=425.9± 7.9 days which confirms earlier claims that its true value is significantly shorter than 460 days theoretically predicted; on the other hand this estimate is also by about 5 days shorter than previous results from indirect estimation. The MLM estimate of the FCN quality factor is Q=40280 with 1-s confidence interval (13710,?), that is up to one order of magnitude higher than previous indirect estimates. Comparison with the atmospheric angular momentum data shows that nearly diurnal variations of the surface pressure have enough power to excite the FCN oscillation to the observed level of 0.2 to 0.5 mas, while the wind contribution is negligible (Brzeziński, 1996b; Brzeziński and Petrov, 1998).

Application of the FTBPF to the series of nutation corrections EOP 97C04 determined by the IERS allows to determine time variable spectrum of the FCN amplitude in 1984-1996. The amplitude of the FCN is of the order of 0.2-0.3 mas at maximum and decreases since 1984. The short time-span of the data does not allow to state whether this amplitude is diminishing or it has long period variations (Kosek et al., 1998R).

5.4.3. Variations of Semiannual and Subseasonal Oscillations of Polar Motion

Time variations of amplitudes of semi-annual and short period oscillations with periods of about 30, 50-60, 90-100, 120 days of polar motion and Atmospheric Angular Momentum were determined using the FTBPF (Kolaczek, 1995; Kolaczek and Kosek, 1996; Kosek et al., 1998a), (see Fig. 5.4).

5.4.4. Prediction And Irregular Variations Of Polar Motion

The auto-covariance method of polar motion prediction was elaborated (Kosek, 1997). Prediction of polar motion was computed using the least squares model of the Chandler circle and annual ellipse together with the auto-covariance prediction of the residuals obtained after removing the least squares model. The accuracy of polar motion prediction was increased by a factor two with respect to the current prediction model for about 60-250 days in the future (Kosek et al., 1995a, 1998a).

Irregular variations of short period oscillation of the polar motion containing oscillation with periods ranging from 20 to 150 days were detected. The least squares method along with the auto-covariance prediction method were applied to determine variations of amplitudes and phases of these oscillations The largest irregular variations of amplitudes of short period variations of polar motion took place at the beginning of 1985, 1988 and 1990, which correspond to the epochs of El Nino events (Kosek and Kolaczek, 1995b). Similar irregular variations occurred in the atmospheric angular momentum variations of polar motion.

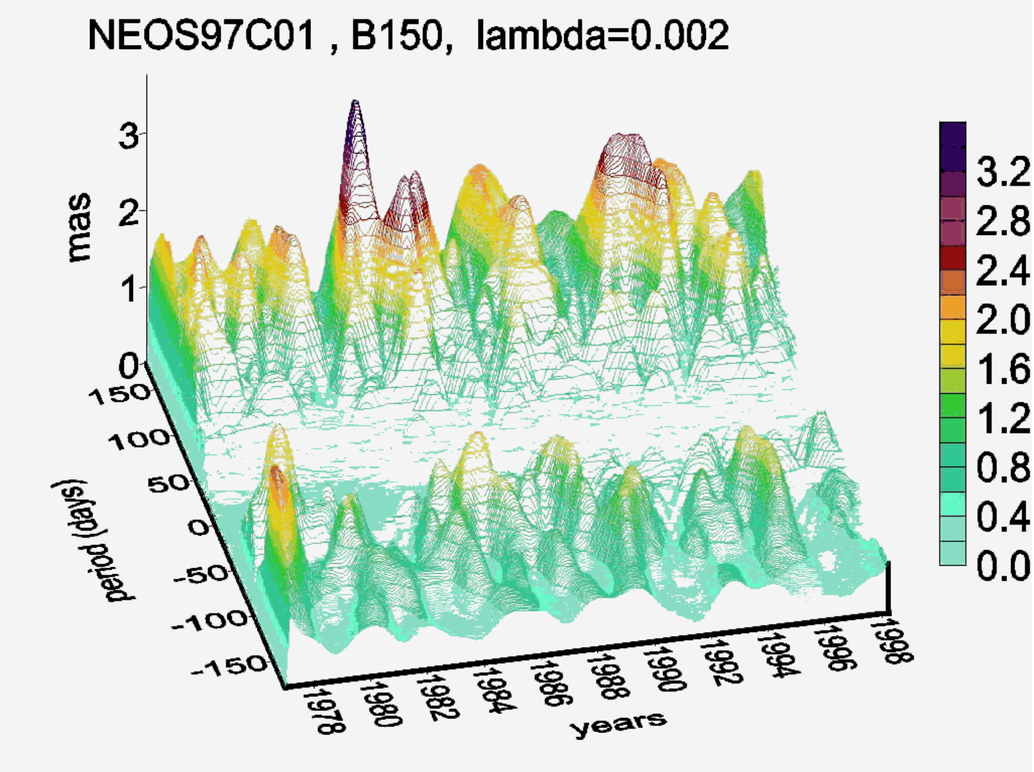

Fig.5.4. Amplitude variations of short period oscillations of polar motion with periods ranging from 30–150 days computed from the NEOS C01 polar motion data filtered by the Butterworth High Pass Filter with the cut-off period of 150 days

5.4.5. Analysis of Polar Motion Data

An application of the stochastic models of polar motion in algorithms of processing and interpreting Earth orientation data (Kalman filter, least squares collocation) was investigated in detail. It includes both theoretical studies and numerical experiments proving clearly a superiority of the stochastic modelling over classical methods (Petrov et al., 1995; 1996). One particular phenomenon studied in detail concerns the atmospheric normal modes which have considerable effects on Earth rotation (Petrov and Brzeziński, 1996; Petrov et al., 1997; Petrov, 1998).

5.4.6. Theoretical Problems

Theoretical investigations concerning geophysical interpretation of modern Earth rotation observations and the related geophysical data have been continued. This subject includes the definition of the Celestial Ephemeris Pole (Brzeziński and Capitaine, 1995; Brzeziński, 1998) and the equation of polar motion (Brzeziński, 1996a; Zharkov et al., 1996).

5.4.7. Regional Atmospheric Angular Momentum And Its Impact On Polar Motion

The regional values of the effective atmospheric angular momentum had been obtained from the Japanese Meteorological Society data (Nastula, 1995, 1997; Nastula et al., 1998b; Nastula and Kotreleva, 1998Ra) and from NCEP/NCAR Reanalysis Project a nearly 40 years long data series (Nastula and Salstein, 1998a, 1999). In co-operation with Atmospheric and Environmental Research Inc. (AERI), Cambridge, MA, USA, ways in which different regions are responsible for excitations of high frequency polar motions were explored using a much longer and more reliable data set than it was previously available (Nastula and Salstein, 1998a, 1999). The earlier results of Salstein and Rosen from the AERI, who found maxima in the atmospheric excitation function over the extra-tropical South Pacific, North Pacific, and North Atlantic, and Nastula, who showed that short period oscillations of polar motion excitation are mainly coherent with pressure variations over northern mid-latitude land, were expanded. Here, the Eurasian region was isolated, as particularly important for exciting high frequency polar motion (Nastula and Salstein, 1998a, 1999). The propagation of signals with these periods into Eurasia from areas west of that region was also documented. One of the most interesting results is the discovery that at northern mid-latitudes the coherence between short period variations of atmospheric excitation and polar motion depends only weakly on the inverted barometric correction.

It is clear, however, that the atmospheric data do not explain all origins of the observed high frequency polar motion signals. This lack of full agreement is likely due to the existence of other forcing mechanism. With regards to the latter, a candidate for such forcing is the ocean. The addition of oceanic excitation to atmospheric excitation, leads to a substantial improvement in the agreement between observed polar motion at seasonal and intraseasonal periods (Nastula et al., 1998Rb; Nastula and Ponte, 1999). To estimate equatorial excitation functions for the ocean the velocity and mass fields from the constant density ocean model by R.M. Ponte AERI) was used.

Analysis of the influence of shallow seas (with depth not exceeding 500m) and shelf areas on the variations of atmospheric angular momentum was performed. It was concluded that for the range from 10 to 150 days the maximum contribution from seas to standard deviation of atmospheric angular momentum could be about 40% (Nastula and Manabe, 1997). This region does not have, however, any significant influence on the change of the correlation coefficient between atmospheric angular momentum and polar motion excitation. The changes of the amplitude of atmospheric angular momentum function are 100 to 300 times smaller than the changes of the shallow and shelf sea regions (Nastula and Manabe, 1997).

5.4.8. Atmospheric Excitation of Nutation

A 29-year time series of 6-hourly atmospheric angular momentum estimates has been used to study the atmospheric influence on nutation. The most important contributions are found for the pro-grade annual (0.077 mas), retrograde annual (0.053 mas), pro-grade semi-annual (0.045 mas) nutation waves, and for the constant offset of the pole (0.115 mas). These are significant results from the point of view of both the accuracy of geodetic determinations (about 0.030 mas) and the assumed accuracy of the new non-rigid Earth theory of nutation (0.005 mas). A comparison of the atmospheric excitation and VLBI nutation data yields high correlation after 1989, which is an important confirmation of the derived results (Bizouard et al., 1997; 1998).

5.4.9. Diurnal/Semidiurnal Atmospheric and Oceanic Excitation

The estimation of the atmospheric contribution to the nutation amplitudes has been extended to the whole diurnal and semi-diurnal bands in polar motion and length of day (LOD) (Petrov, 1998; Petrov et al., 1998a). The first estimation of the non-tidal oceanic influence on nutation has been completed, where "non-tidal" means fluctuations of the oceanic angular momentum driven by the observed variations of the surface atmospheric pressure and winds. Comparison with the VLBI nutation data shows that the global ocean circulation model used in the analysis is not realistic within the diurnal band, nevertheless such a comparison provides important information on how to improve this model (Petrov et al., 1998b).

5.4.10. El Nino Impact On Polar Motion

The influence of El Nino phenomena on variations of LOD have been studied by many authors. El Nino influence on polar motion has not been studied but the correlation of El Nino phenomena with the influence of Atmospheric Angular Momentum (AAM) on the polar motion was analysed. Correlation coefficients between two El Nino parameters, differences of sea surface temperatures and sea surface atmosphere pressure in different regions of Pacific Ocean and variations of correlation coefficients between (AAM) and polar motion were computed for several El Nino phenomena. El Nino phenomena disturbs correlation coefficients between the AAM and polar motion and causes also impulsive irregular variations of short period oscillations in polar motion (Kosek et al., 1995c; Kolaczek et al., 1998a, 1998b; Nuzhdina at al., 1997R).

5.4.11. Methods

The method of time variable spectrum was developed using a band bass filter (Kosek et al., 1995c). This method enables to compute the instant amplitudes of oscillations as a function of time and oscillation periods. The application of the FTBPF enables fairly good frequency resolution of an amplitude spectrum. The time and frequency resolutions of such time variable spectrum can be changed by only one lambda parameter (Kosek, 1995a; Popiński and Kosek, 1995a, 1995b). It is also possible to determine polarisation of oscillation in complex valued time series. Such analysis revealed that short period oscillations of polar motion have variable amplitudes and they are mostly counter-clockwise (Kosek et al., 1995c, 1998a).

The new auto-covariance prediction method was developed and the computation program was written. This method enables the prediction of stationary time series without any a-priori information (Kosek, 1997).

The Maximum Entropy Method (MEM) of spectral analysis has been developed for the purpose of interpretation of the observed changes in Earth orientation (Brzeziński, 1995a). This method allows to extract new information from the series of observations analysed so far and to better interpret recent, highly accurate measurements of UT1 and polar motion. A self-contained package of FORTRAN programs for the MEM spectral and cross-spectral analysis together with its description has been made available (Brzeziński, 1995b).

5.5. EARTH TIDE INVESTIGATIONS IN POLAND IN 1995–1998

Space Research Centre is carrying out tide gauge observations at the Ksiaz station (horizontal components) and at the Warsaw station (vertical component). At the Ksiaz station observations are made using Blum's pendulum and the observational series is already 25 years long. In Warsaw observations are made with the LaCoste&Romberg gravimeter and observed data are collected for 17 years (up to 1995 with the Askania Gs-11 gravimeter).

Annual series of tidal observations is analysed and then the results are published. At the same time the observations are delivered to International Centre for Earth Tides in Brussels. On the basis of existing observations the following works have been done:

- determination of the seasonable modulation of tidal waves since 1973 up to 1993,

- determination of the recent vertical crustal movement at the Ksiaz station. The results of investigations show oscillating character short time vertical movement and linear character long time vertical movement.

Additionally in collaboration with various groups the following works have been done:

- with the Institute of Geophysics in Budapest the tidal movement of the underground waters in Hungary was determined,
- with the Institute of Earth Physics in Paris the new Blum’s construction compact clinometre was tested,
- with the Institute of Geodesy and Geodetic Astronomy, Warsaw University of Technology and the Institute of Geodesy and Cartography in Warsaw and their tidal stations in Jozefoslaw and Borowa Gora the investigation of Teisseyre-Tornquist zone has began.

In 1997 at Ksiaz station new tidal device “Long Water Tube” was constructed. It is based on the newest optic and registration technology and is now extensively tested.

5.6. VARIATIONS OF SEA LEVEL

Short period oscillations with periods of 182, 120, 90, 60 and 30 days of sea level anomalies determined from altimetry measurements of TOPEX/Poseidon were detected using the FTBPF. These oscillations have amplitudes ranging in maxima from 7 cm in case of the semi-annual oscillation to 2-3 cm for the shortest ones (Kolaczek et al., 1997R). Amplitudes of these oscillations vary with geographic latitudes, longitudes and time (Kosek and Kolaczek, 1998; Kosek 1998R), (see Fig. 5.5). Time variable spectra of these variations for all oceans were computed. A correlation of these oscillations with the atmospheric pressure variations was also found (Nastula et al., 1998R)

The spectral analysis and filtration of the sea surface topography was conducted using the 2D Fourier transform. The analysis enables detection of the most energetic waves in sea surface topography and estimation of sea surface correlation along parallels and meridians. Results show that the sea surface waves along the parallels have larger periods than those along the meridians all over the oceans (Popiński and Kosek, 1998R).

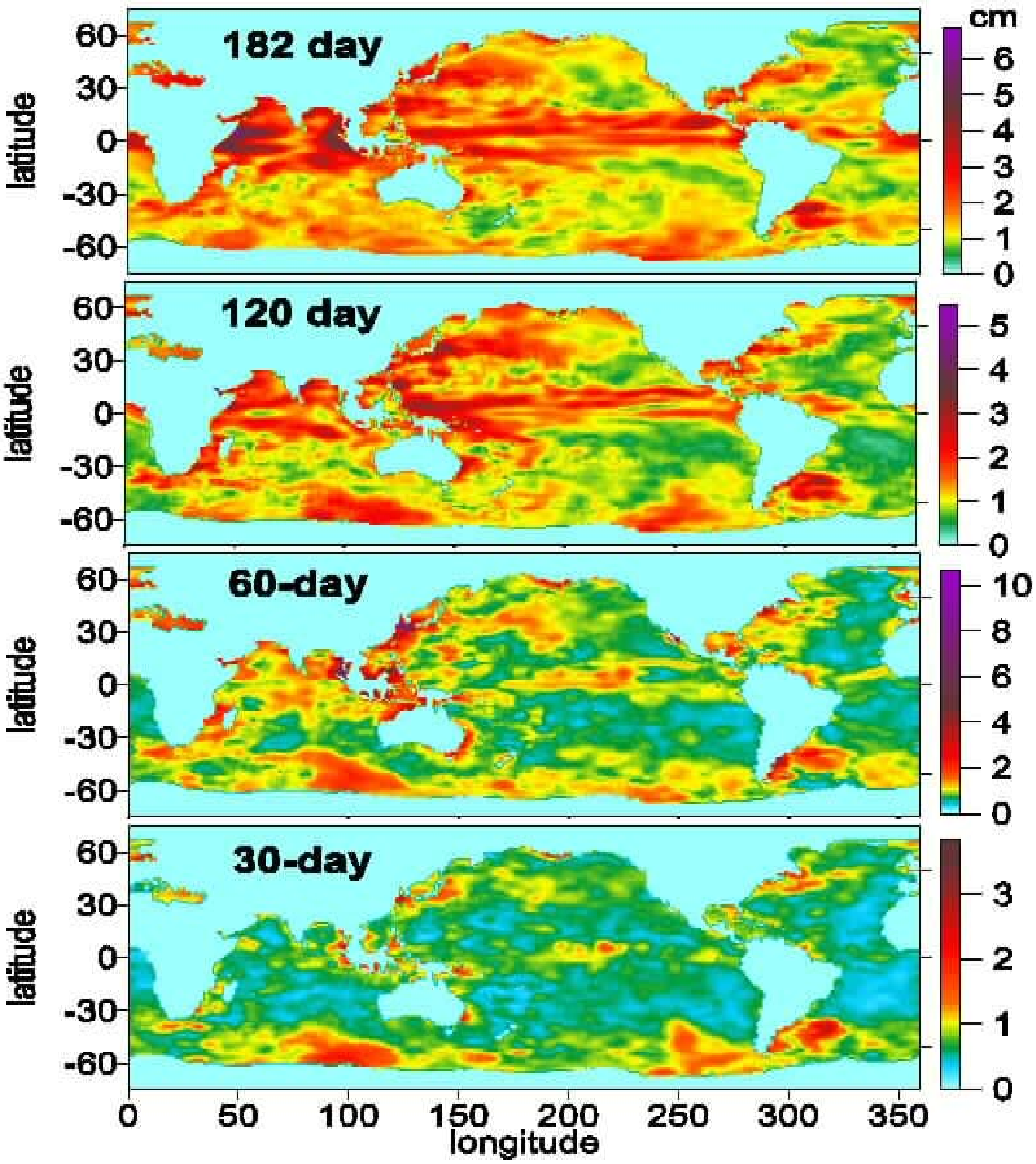

Fig. 5.5. Mean amplitudes of semi-annual and short period oscillations with periods of 120, 60, 40 days computed by Fourier Transform Band Pass Filter from 167 cycles of sea level anomalies determined from TOPEX/Poseidon altimetry data

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