Basic Gravimetric Network of Republic Macedonia – a New Reality

Slaveyko GOSPODINOV, Bulgaria, Elena PENEVA, Bulgaria, Penio PENEV, Bulgaria, Kiro SECHKOV, Macedonia, Sasho DIMESKI, Macedonia, Miroslav STARCEVIC, Serbia

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SUMMARY

In the paper is presented a realization of the Basic Gravimetric Network of the Republic of Macedonia. The project and the realization are made in 2012 and 2013. This new basic gravimetric network is the first prime order gravimetric network in Macedonia. The gravity datum is defined by the absolute gravity network in Macedonia. The absolute gravity network in Macedonia consists of three points that was established in 2010. The definition and the realization of the basic gravimetric network of Macedonia, as a part of the new geodetic reference systems, was made under the authority of the Agency for Real Estate Cadastre of Macedonia. The project was supported by the World Bank project. In the project are presented network design plan, point monumentation plan, network observation schedule, and the required resources for its realization.
The main stages of the establishment of the network are presented. The measurements and processing of the data are realized in cooperation of specialists and equipments from Bulgaria, Macedonia and Serbia. In details are given the basic parameters, the method of measurements, the processing and the achieved results.

SUMMARY

В статията се представя реализацията на първокласната гравиметрична мрежа на Република Македония. Мрежата е проектирана и реализирана в периода 2012-2013 година и е първата първокласна гравиметрична мрежа на Македония. Мрежата се базира на абсолютна гравиметрична мрежа от три точки, измерена през 2010 година. Като част от единната геодезическа основа на Македония, дефинирането и реализацията на първокласната гравиметрична мрежа е под ръководството и от Агенцията по кадастър на недвижими имоти на Македония. Реализацията е осъществена по проект на Световна Банка за изготвяне на подробен проект за изграждане на мрежата. В проекта са дадени схема за проектиране на мрежата, стабилизиране на точките, начинът на извършване на измервания и необходимите ресурси за реализацията й.
Представени са основните моменти от създаването на мрежата. Измерванията и обработките са реализирани в сътрудничество на екипи и апаратура от България, Македония и Сърбия. Подробно са дадени основните параметри на мрежата, принципът на измерванията, обработките и постигнатите резултати след изравнението.

1. INTRODUCTION

The definition and the realization of the State Reference System in Republic of Macedonia (RM) is under the authority of the Agency for Real Estate Cadastre, in compliance to the provisions from the Law on Real Estate Cadastre. The State Reference System as a one unit is comprised of the following reference systems: Spatial (three-dimensional) reference system; Horizontal (two-dimensional) reference system; Vertical (one-dimensional) reference system; Gravimetric reference system and Astronomic reference system.
The Basic Gravimetric Network of RM (is a network which) has objective to establish a modern and functional Gravimetric reference system on the territory of Macedonia. Basic Gravimetric Network is developed according to European standards will be basis for a quality geo-positioning throughout the territory of Macedonia and will also serve for different scientific and geo-physical researches.
Detailed Project for realization of the Gravimetric Works in the Republic of Macedonia was prepared from Agency for Real Estate Cadastre supported by WB Project (Bidding Document for procurement of Basic Gravimetric Network of Republic of Macedonia – Establishment, Measurement and Delivering of Data ICBNo: MK-RECRP-7928MK-ICB-C5.4-14). The Gravimetric Works under this procurement include: Gravimetric Works for establishment and determination of Basic Gravimetric Network in the Republic of Macedonia, establishment of horizontal gravimetric calibration base and establishment of Microgravity Networks Points around of the each Absolute gravimetric points.
The Gravimetric Works under this project are realized by Joint Venture between "Geotechengineering" Ltd. (Bulgaria) and "Geofoto Zenit Engineering" Ltd (Macedonia) - JV Geotechengineering & Zenit. In realization of the project take part Macedonian, Bulgarian and Serbian (Republic of Serbia Geodetic Authority) specialists.
Absolute Gravimetric Network (Zero order gravity network) is part of the Basic Gravimetric Network in the Republic of Macedonia. Absolute Gravimetric Network is defining Gravimetric datum. The absolute gravity network in Macedonia was established by means of absolute gravimetric campaign that was performed in year 2010 and it consists of three points in Skopje (AGT01) (set up in the basement of the geoseismic laboratory in Skopje), Ohrid (AGT02) (set up in the vicinity of the location of IGS/EPN point) and Valandovo (AGT03) (stabilized in the geoseismic observatory).
For absolute gravimetric survey, the absolute gravimeter Micro-g-LaCoste FG5 No. 233 is used. At the locations of absolute gravimetric points, there are also made relative gravimetric measurements for the purpose of determining the vertical gradient value at each location of the absolute gravimetric point. The accuracy of gravity accelerations for three absolute points is 2.10^{-8} m/s^2 for height 1.2 m above point and 4.10^{-8} m/s^2 for point level (Engfeldt A., Odolinski R., Agren A., 2010)
For the purpose of securing the absolute gravimetric points, i.e. of measured absolute values of gravity acceleration on them, are established three Microgravity Networks (each consists from three eccentric points) in the environment of each of the absolute gravimetric points.
All of the eccentric points are newly constructed. The distance of the eccentric points from the absolute gravimetric points is from 0.5 km to 5 km.

2. BASIC GRAVIMETRIC NETWORK

2.1 Main characteristics of First Order Gravimetric Network Net design, Measurements

The First Order Gravity Network of the Republic of Macedonia is defined by 25 points (Fig. 1). Eleven points of the First Order Gravity Network are chosen to be the same with points from GNSS Network (Passive GNSS Network of Macedonia). Ten points of the First Order Gravity Network are chosen to be the same with nodal points from Leveling Network of Macedonia. There are four new stabilized points - GT 103, GT 111, GT 113 and GT114. The positional coordinates are given in the datum ETRS89, epoch 1989.0 and the heights are orthometric.

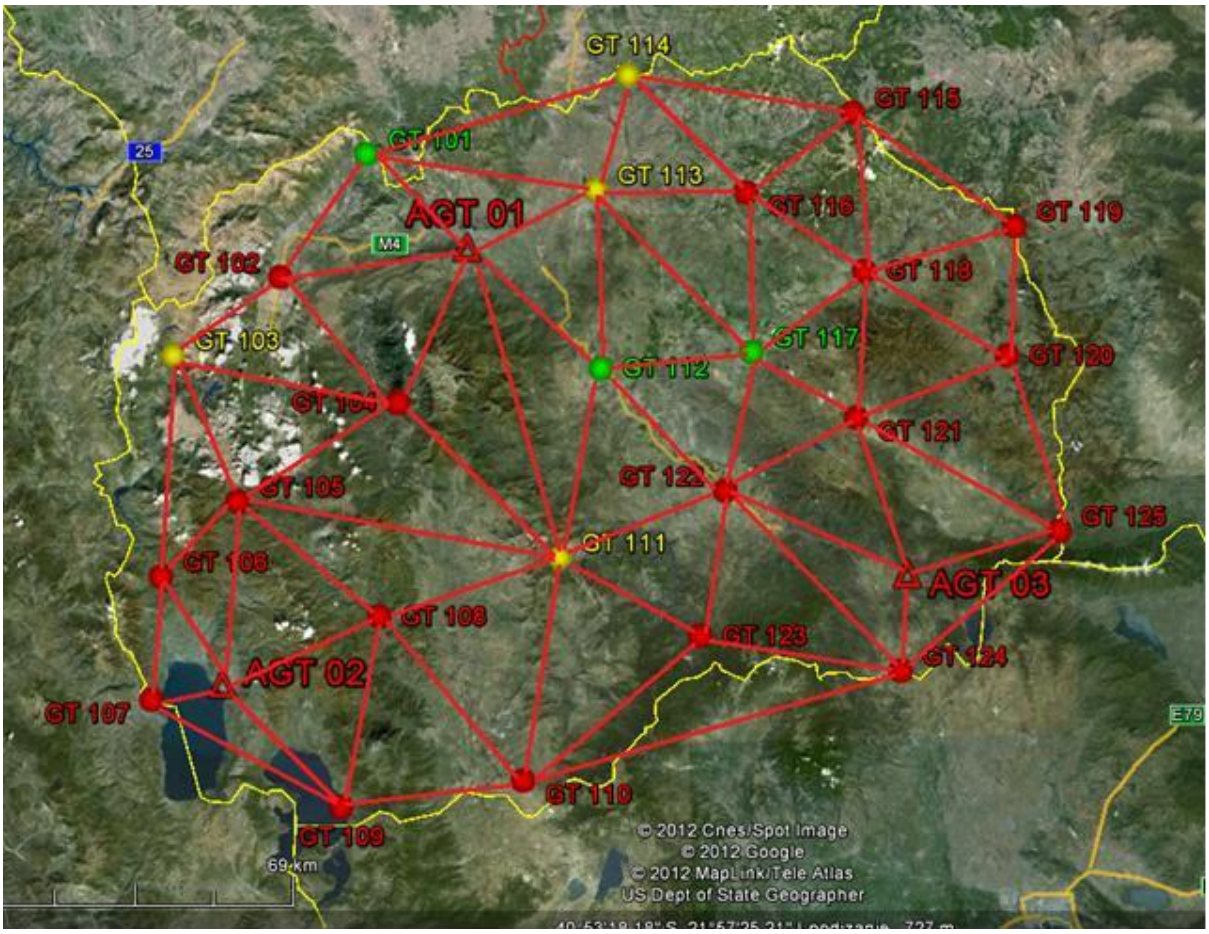

Figure 1. First Order Gravity Network of RM

The points from First Order Network are regularly covering the territory of Macedonia. The density of the set up points in the First Order Network is approximately 1 point per 1070 km2. Gravity differences (connections) between points are 68 lines, which are closing 41 triangles. The average distance between points is 39 km.

The positions and heights of each First Order gravimetric point is determined by applying GNSS measurements with dual frequency GNSS receivers, using MAKPOS system, with 3D accuracy of 2-4 cm. The ellipsoid coordinates are determined in global and local geodetic datum, and plane Gauss-Krüger coordinates and orthometric heights should be calculated by applying the transformation parameters (supplied by AREC).

Gravimetric measurements are realized with two gravimeters models Scinterx CG3+ (Ser.No. 120140052) and Scintrex CG-5 (Ser. No. 73). Measurements are made simultaneously with both gravimeters according to Measurement plan in Technical documentation. In time of gravimetric measurements are registered air pressure and temperature with two instruments (barometers) of type PHB-318.

2.2 Calibration base measurements

Horizontal calibration base of the Republic of Macedonia is defined within two absolute gravimetric points – AGT01 (Skopje) and AGT02 (Ohrid). Calibration measurements are made three times over period of gravimetric campaign – before, in the middle and at the end of measurements. For each calibration measurements are calculated gravity differences with real and normal vertical gradient for both instruments. Calibration coefficients are calculated for each gravimeter from the three calibration measurements. Mean linear calibration coefficients calculated with real vertical gradient are used for calibration of gravity differences from each gravimeter.

2.3 Gravimetric measurements

Gravimetric measurements in **First Order Gravity Network** are carried for 23 gravimetric days. Measurements are made simultaneously with both gravimeters. The used scheme of measurements is by Star method or known as Difference method (Fig. 2). Connection between every two points is measured in scheme 1-2-1. The main closing figures of measurements are triangles.

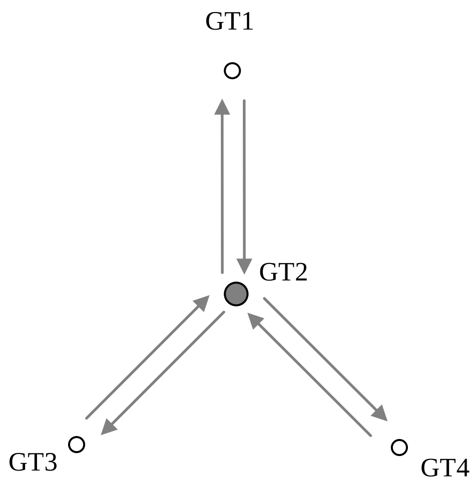

Figure 2. Difference method (star method) for First Order Gravity Network

On absolute points instruments are stationing side by side at the surface of point (Fig. 4). On points from **First Order Gravity Network** was adopted gravimeter CG-5 to be set on the point, and CG-3 to be set at the base of the point (Fig. 5). Height of the instruments was measured very carefully with accuracy of 1 mm. In order to achieve correct instrument height according to surface, height is measured at 3 different sides of instrument. End instrument height is formed from mean arithmetical values from 3 measurements. Atmospheric pressure and temperature are measured too in time of measurement

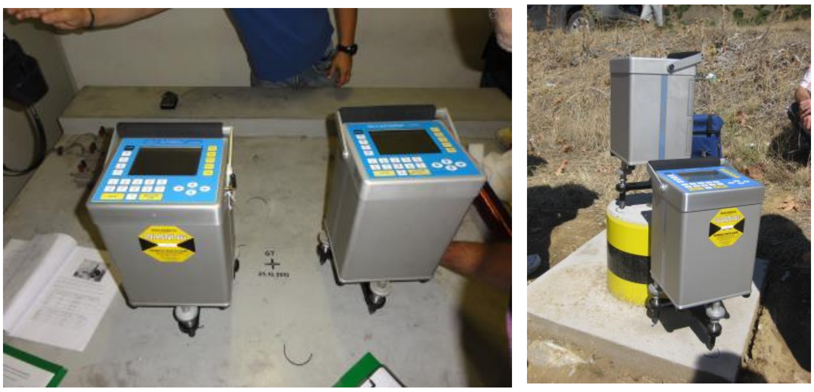

Figure 3. a) Stationing at absolute gravimetric point; b) stationing at points from First Order Gravity Network

In every station are presented 6 cycle measurements in order to have at least 5 reliable cycle measurements if there are disturbances in period of measurement. Duration of measurement each cycle measurement is 60 seconds with applied Tide correction, Seismic filter, Continuous tilt correction and Auto-rejection of bad measurements.
Gravimetric measurements in each gravity station are processed separately to achieve the reading in and SD of reding in each station. Gravity readings with their SD from raw files with measurements are processed in MS Excel worksheet. All records are analyzed together with information from Field books. Two criteria are used for estimation of data: 1) standard deviation of arithmetical mean from 6 readings to be less than 0.005 mgal and 2) difference from maximal and minimal reading to be more than 10 microgal (0.010 mgal). From all measurements with CG-3+ and CG-5 are excluded 4 readings.

2.4 Corrections to gravimetric measurements

Tidal corrections – earth tide correction is introduced automatically in the time of measurement (CG-5 Scintrex Operational Manual, 2006). The corection is is calculated in the Scintrex software via the Longman formula (Longman I.M., 1959) by entering of the latitude, longitude and UTC time. The time used in the tidal computation is the midpoint between the start and the end of a reading session. The accuracy of introduced correction is ± 3 microgal, because of accepted mean gravimetric factor 1.16 in Longman formula and existents of variations in it. Ocean loading effect is not taken into account.
Atmospheric corrections - atmospheric pressure correction is introducing error from pressure variations in period of measurement. Pressure is measured in each gravity station in *hPa* units. For computation of correction is used empirical formula

$$\delta O_{pressure} = 0.3(p - p_n), \quad (microgal),$$

where

$p = measured\ pressure\ at\ station\ in\ hPa;$

$p_n = normal\ pressure\ at\ station\ in\ hPa;$

Normal atmospheric pressure (p_n) for station is calculated upon orthometric height of point for International Standard Atmosphere (ISA). After IAG (International Association of Geodesy) resolutions is used formula for Normal Atmosphere DIN 5450 (Schuler, 2000)

$$p_n = 1013.25\left(1 - \frac{0.065\,H^{ort}}{288.15}\right)^{5.2559}$$

Seismic effects – possible seismic processes are filtered in time of measurement with seismic filter options in time of measurements.
Tilt effect – introduced in time of measurement with automatic readings of x-level and y-level. Preliminary set criteria is inclination of x- and y-levels to be less than 10 arcseconds.
Temperature effects – variations in air temperature are calculated and introduced automatically in time of measurement.
Magnetic field – possible influences of Earth's magnetic field to gravity measurements are eliminated with same orientation of instrument in each station. To assure same orientation in all measurements in each gravity stations legs of instrument are marked in first measurement.
Drift - After introduction of the corrections in measurements linear drift correction for every connection (gravity difference) is calculated. The value of linear drift is calculated from double measurements in every gravity connection.
Calibration - Measured gravity differences are calibrated according to calculated calibration coefficient for each instrument.
All these computations are made in one MS Excel worksheet for each gravimetric day, where every gravity difference is calculated separately.

2.5 Data models for estimation and adjustment

Two data models are formed: (1) arithmetical mean of six readings and arithmetical mean SD of readings ("s" model) and (2) mean proportional of six readings and mean proportional SD of readings ("t" model).
For each data model are applied three stochastic models: (1) equal weights (p1=1); (2) weights proportional to the duration of measurement (Δt) of gravity connection (p2 = 1/Δt); (3) weights calculated upon standard deviations for each gravity connection (p3 = c/mΔg2, c=constant).
Combined models for measurements with two gravimeters CG3 and CG5 are formed for arithmetical ("s" models – 35sp1, 35sp2 and 35sp3) and mean proportional ("t" models – 35tp1, 35tp2 and 35tp3) models for each gravimeter, according to weight model (p1, p2 or p3). For mean proportional models are formed and "scaled models" calculated with scaled weight with value for posteriori RMS after free network adjustment of each gravimeter data (35_mtp1, 35_mtp2 and 35_mtp3). For model with good quality after analysis is chosen mean proportional scaled model "35_mtp2". For this model is applied an active robust estimation method - Danish method (Krarup, 1967; Krarup T., J. Jul, K. Kubik, 1980). Danish method is performed as a variant of application with modifying function given by Caspary (2000). Result model after Danish method is assigned as "35_dtp2".

Used models are performed in Figure 4.

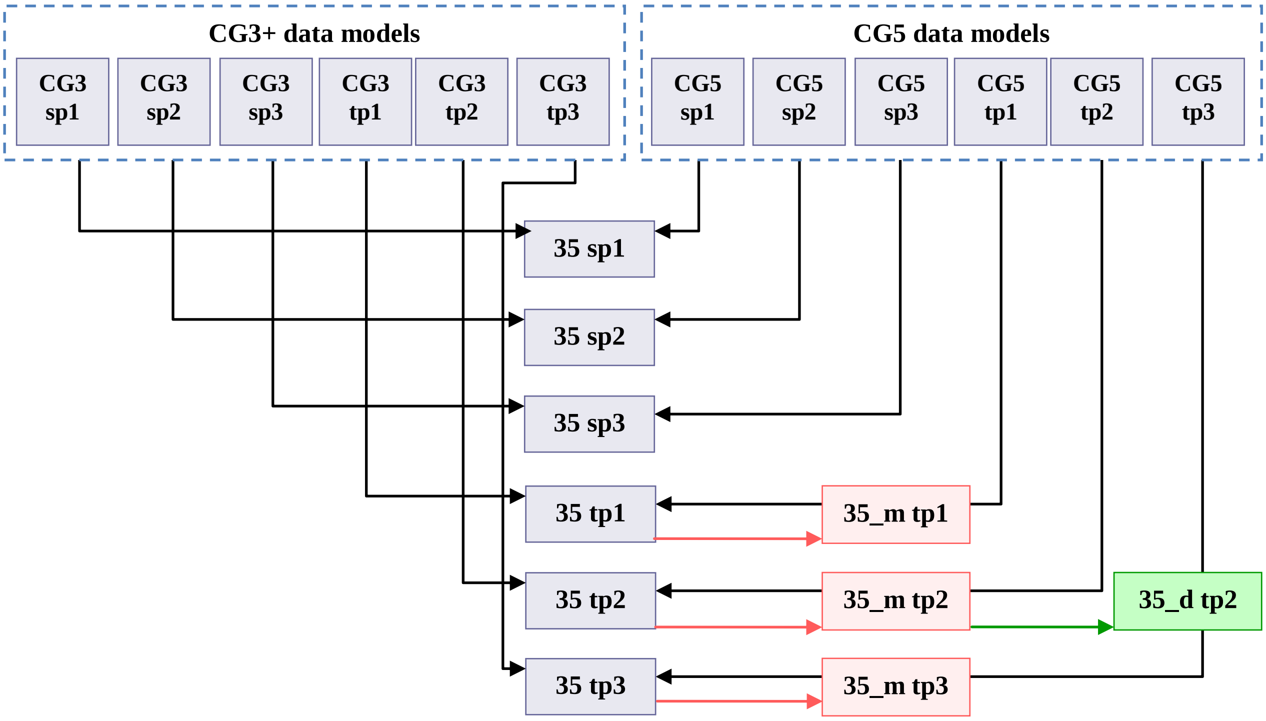

Figure 4. Data models for CG3+, CG5 and combined models

2.6 Preliminary accuracy estimation

According to realized gravimetric measurements simultaneously with two gravimeters CG3 and CG5 could be performed two type preliminary accuracy estimations.

(1) Preliminary accuracy estimation of network upon closures of triangles in gravity network;

(2) Preliminary accuracy estimation of network upon to differences in acceleration between gravity connections achieved with each gravity meter CG3 and CG5.

For statistical rows with values for closers of triangles and differences between two gravimeters are performed statistical tests for:

- **availability of gross errors** with confidence level of probability 0.997;
- **availability of systematical errors** – applied for non-calibrated and calibrated data. Calibrated data gives insignificant values for systematical errors ;
- **hypothesis for normal distribution** - applied for non-calibrated and calibrated data. Results for calibrated data show that hypothesis is not rejected, so data are not in contradiction with hypothesis for normal distribution.

2.7 Least squares adjustments and Least squares adjustments analysis

Adjustments of gravity measurements and data analysis are made with program

GRAVI_P. This applied program is written on Visual Studio C++ language and is especially made for precise gravity measurements least squares adjustment and least squares adjustment analysis. Program is made by Prof. Penio Penev from Geodetic Faculty of University of Architecture, Civil Engeneering and Geodesy UACEG (Sofia, Bulgaria).

With program GRAVI_P are made free and constrained adjustments for the different composed models. Free adjustments are used for estimation of accuracy of observations, beside preliminary made estimations of observations. Results from preliminary estimations and from free network adjustment show very good agreement. In free adjustments with program GRAVI_P are made statistical tests - Tau test and Chi square test. Tau test is applied after Pope's techniques (Pope, 1976) to detect outliers in observations. Chi square test is a global test on residuals (variance factor test) (Walpole R.E. and R.H. Myers, 1989). The two tests are applied with global significance level 5%.

2.7.1 CG3 models

For CG3 models (Figure 4) better results are achieved for mean proportional observation data. Free networks RMS of weight unit are for p1 – 9.59 microgal, p2 – 5.62 microgal, p3 – 10.64 microgal. Connections with biggest residuals are 117-122 and 114-101. Chi square test is satisfied – a-priori RMS of unit weight is in agreement with achieved posteriori value. Connections with bigger residuals are the same as connections find as outliers in applied robust estimation with Danish method.

But when the same models are adjusted as constrained networks to three absolute points their RMSs are increased with ~ 50% - RMS of weight unit are for p1 – 18.61 microgal, p2 – 11.36 microgal, p3 – 23.70 microgal. Connections with biggest residuals are changed to connections with point AGT01 – 113-1 and AGT01-111. This shows that after fixing of networks behavior of networks is changed.

2.7.2 CG5 models

For CG5 models (Figure 4) better results are achieved for mean proportional observation data. Free networks RMS of weight unit are for p1 – 11.98 microgal, p2 – 7.60 microgal, p3 – 14.66 microgal. Connections with biggest residuals are 120-118 and 120-125. Chi square test is satisfied – a-priori RMS of unit weight is in agreement with achieved posteriori value. Connections with bigger residuals are the same as connections find as outliers in applied robust estimation with Danish method.

But when the same models are adjusted as constrained networks to three absolute points their RMSs are increased with ~ 60% - RMS of weight unit are for p1 – 31.54 microgal, p2 – 18.87 microgal, p3 – 41.10 microgal. Connections with the biggest residuals are changed to connections with point AGT01 – 1-111 and 1-104. This shows that after fixing of networks behavior of networks is changed.

2.7.3 Combined models

After free networks adjustment and preliminary estimations, mean proportional data models shows much better representation results, that is the reason for free and constrained adjustment of combined models to be used only combined formed from mean proportional separate models for CG3 and CG5. First are combined proportional mean models and second are combined proportional mean scaled models (“m” models). These models are used for free and constrained adjustments. Free adjustments are made to estimate accuracy of networks for combined models. Better results are achieved for Combined proportional mean scaled models (“m” models) - RMS of weight unit are for p1 – 9.68 microgal, p2 – 5.68 microgal, p3 – 11.15 microgal. Connection with the biggest residuals for three weight models is 120-125. Chi square test is satisfied – a-priori RMS of unit weight is in agreement with achieved posteriori value. Connections with bigger residuals are same as connections find as outliers in applied robust estimation with Danish method.

When the same models are adjusted as constrained networks to the three absolute points their RMSs are increased with ~ 60% - RMS of weight unit are for p1 – 28.64 microgal, p2 – 16.41 microgal, p3 – 34.73 microgal. Connections with biggest residuals are changed to connection with point AGT01 – 1-111 for three weight models. This shows that after fixing of networks behavior of networks is changed.

For better combined models - combined proportional mean scaled models (“m” models) are performed robust estimations in order to find and minimize eventual availability of gross errors. Found outliers in iterations processes of application of Danish method are with reduced weights. They are compared with results for combined proportional mean scaled models (“m” models). Accuracy of RMS for free network after last iteration in Danish method is getting better with 30-44% - for p1 – 5.50 microgal, p2 – 3.60 microgal, p3 – 7.88 microgal. Besides that when same models are used for constrained adjustment RMS of unit weights are almost the same. Connection with the biggest residual for three weight models for free adjustment is 120-125, and connection with the biggest residual for three weight models for constrained adjustment is 1-111.

Indicated outliers in application of Danish method for all models in iterations are corresponding with registered disturbances in time of measurements. The outlier with maximal value for all 3 models is found to be measurement between points **120-125**. Observation is made in 16.09.2013 and in field book for that day is written remark that weather is rainy, muddy, with big humidity. The next maximal value of outlier is **for model 1** – **120-118** (15.09.2013 – point 118 – strong wind) (this connection is found as outlier for model 2 and model 3), **for model 2** – **123-110** (11.09.2013 – rainy weather, muddy) (found as outlier in model 1 and model 3); **for model 3** – **124-110** (13.09.2013 – strong wind and vibrations) (this connection is found as outlier for model 1). Connection between points **124-125** is found as outlier in three models it is measured on 13.09.2013 – strong wind and vibrations. Connection between points **111-112** is found as outlier in three models, and in model 3 is third maximal value – it is measured on 01.09.2013 (autobus vibrations) and remeasured on 19.09.2013.

After fixing of networks from last iteration in Danish method the behavior of network is changed. Registered outliers in all estimations of observations and free adjustments are changed with bigger residuals for connections to absolute points.

After processing of observations, estimations and adjustments of Fundamental network we could say that relation between weights is not equal. Weights models p1 and p2 after applied Danish method for robust estimation are giving similar results and are with same behavior. As final data are suggested to be used results from constrained adjustment of proportional mean scaled “m” model for weight p2 (35_2mv), after application of Danish method for robust estimation (35_2dv).

Are used measures of accuracy of geodetic network

For combined models with weight p2 (proportional to time of measurement) are given main characteristic results from free (Table 1) and constrained adjustment (Table 2). Characteristics are: **RMS a-priory**, calculated upon closure of triangles; **RMS posteriory**; **m_{max}g** – maximal value of RMS for gravity acceleration; **Nr. of point** - number of point in which is found this maximal value; **$M_{ar.mean}$g** – average of RMS’s for gravity accelerations; **$M_{geom.mean}$g** – generalized variance of RMS’s for gravity accelerations and **[pv]** – sum of product of residuals and weights.

Table 1. Results from free adjustment of combined models with weight p2

FREE ADJUSTMENT	**Combined models with weight (p2) proportional to time of measurement**		
	Combined model	**Scaled combined model**	**Scaled combined model after Danish method**
Model name	**35_p2**	**35_mp2**	**35_dp2**
RMS a-priory [μGal]	6.42	5.41	3.95
RMS posteriori [μGal]	**6.75**	**5.68**	**3.60**
m_{max}g [μGal]	5.57	5.32	4.17
Nr. of point	GT119	GT119	GT115
$M_{ar.mean}$g [μGal]	**4.39**	**4.19**	**3.03**
$M_{geom.mean}$g [μGal]	**4.33**	**4.14**	**2.98**
[pv]	**37.8**	**21.4**	**2.8**

Table 2. Results from constrained adjustment of combined models with weight p2

CONSTRAINED ADJUSTMENT	**Combined models with weight (p2) proportional to time of measurement**		
	Combined model	**Scaled combined model**	**Scaled combined model after Danish method**
Model name	**35_v2**	**35_mv2**	**35_dv2**
RMS posteriori [μGal]	**20.19**	**16.41**	**15.12**
m_{max}g [μGal]	18.66	17.24	19.62
Nr. of point	119	119	115

M$_{ar.mean}$g [µGal]	**13.59**	**12.56**	**13.05**
M$_{geom.mean}$g [µGal]	**13.43**	**12.41**	**12.81**
[pv]	**203.5**	**141.9**	**113.3**

3. SUMMARY AND CONCLUSIONS

Presented Basic Gravimetric Network of republic Macedonia is a contemporary gravimetric network satisfying present-day standards for accuracy and realization. The network is realized with use of modern instruments and technologies. In processing of data are introduced all necessary corrections for precise relative gravimetric measurements. In main stages of processing are made all tests and analyses. The key points in processing are: control of data in time of measurement; applying of appropriate scheme of gravimetric measurements, which is leading to identical calculation of drift in all loops and securing of direct independence between measurements. The appropriate net design and scheme for gravimetric loops are giving availability to realize good preliminary estimation of accuracy. Forming of two type data models with three type weights is a base for detailed analysis of results and localization of possible mistakes in measurements or calculations. The verification for completeness and propriety of formed models is made with analyses of residuals with application of Tau-test and Chi-square test. Successfully is applied an active robust estimation method – Danish method. With use of Danish method are localized possible estimates for measurements and for them are set appropriate weights. The good qualities of network are verified with many tests, analyses, using of precise instruments and applying of suitable methods.

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