RECENZIRANI ČLANKI | PEER-REVIEWED ARTICLES

NOVA IZRAVNAVA HRVAŠKE GRAVIMETRČNE MREŽE 1. REDA

NEW ADJUSTMENT OF THE CROATIAN FIRST ORDER GRAVITY NETWORK

Marija Repanić

UDK: 528.56(497.5)
Klasifikacija prispevka po COBISS.SI: 1.01
Prispelo: 20. 4. 2017
Sprejeto: 20. 10. 2017

DOI: 10.15292/geodetski-vestnik.2017.04.630-648
SCIENTIFIC ARTICLE
Received: 20. 4. 2017
Accepted: 20. 10. 2017

SI | EN

IZVLEČEK

V prispevku je predstavljen postopek izravnave hrvaške gravimetrične mreže 1. reda kot celote. V izravnavo so vključene absolutne in relativne gravimetrične meritve, ki so bile izvedene v štirih fazah. Podan je podroben opis vseh meritev, pa tudi ponovna obdelava absolutnih meritev in predhodna obdelava relativnih gravimetričnih meritev. Opisan je funkcionalni model izravnave, kjer kot neznanke nastopajo absolutne in relativne vrednosti težnega pospeška, popravki linearne kalibracijske konstante ter popravki linearne funkcije hoda gravimetra. V modelu nastopajo absolutne meritve težnega pospeška kot opazovanja. Rezultat izravnave so vrednosti težnega pospeška, ki precej odstopajo od rezultatov predhodnih izravnav, opravljenih v štirih fazah. Razlike presegajo velikost pričakovane natančnosti, kar je posledica pogreškov kalibracijskih konstant gravimetra, ki prej niso bili dovolj obravnavani. Zaradi tega smo določili novo linearno transformacijsko funkcijo prehoda iz Potsdamskega sistema težnosti v hrvaški gravimetrični referenčni sistem.

ABSTRACT

The paper presents the new joint adjustment of the Croatian First Order Gravity Network, for the first time adjusted as a whole. The adjustment involves absolute and relative gravity measurements, latter performed in the course of four survey stages. Firstly, the measurements are concisely described. Revision of the absolute and pre-processing of the relative measurements are briefly presented. The applied adjustment model is described. Accordingly, the gravity values of all stations (absolute and relative), corrections of linear calibration coefficient and linear drift coefficients are included in the functional model as unknown parameters. The absolute measurements are included in the adjustment as observations. The new adjustment resulted in significantly different gravity values as compared to previous adjustments (of individual stages of the network). The differences in gravity values are an order of magnitude greater than the expected accuracy. It is shown that the differences are mainly due to the errors in the gravimeters' calibration constants, which were neglected in the previous adjustments. Because of the significant differences, the new linear transformation function from the Potsdam to the Croatian Gravity System is determined.

KLJUČNE BESEDE

izravnava meritev v gravimetrični mreži, osnovna gravimetrična mreža, Hrvaška, kalibracijska konstanta

KEY WORDS

gravity network adjustment, fundamental gravity network, Croatia, calibration constants

1 INTRODUCTION

In the last few decades, the availability of portable absolute gravimeters and their high accuracy made possible the establishment of national fundamental gravity networks based on absolute gravity measurements, which serve as a reference system (Wilmes, Richter, and Falk, 2003; Vitushkin, 2007). Moreover, the IAG adopted the Resolution no 2 (2015) for the establishment of the new Global Absolute Gravity Reference System based on the International Comparisons of Absolute Gravimeters (ICAG), which realisation also utilises measurements of superconducting gravimeters, in order to enable the interpolation between different epochs of measurements (Wilmes et al., 2016). Cyclic re-observations of national zero order absolute stations with properly maintained and regularly compared absolute gravimeters are usually carried out in order to provide up to date gravity values and to facilitate analysis of different geodynamic processes. Often, all available relative gravity measurements are then revised and re-adjusted but constrained with recent absolute measurements. For example, the new cycles of absolute measurements are carried out in Czech Republic, Slovakia, Hungary (Pálinkáš et al., 2013) and Slovenia (Medved et al., 2015). Re-adjustments of some fundamental networks followed (Csapó and Koppán, 2013; Lederer and Nesvadba, 2015). On the other hand, some European countries just established contemporary national gravity networks: e.g. Serbia (Odalović et al., 2012), Bosnia and Herzegovina (Abaza, 2014), or established zero-order stations which shall serve as a basis for fundamental networks: Montenegro, Kosovo and Albania (Mitterschiffthaler et al., 2016). Recently, field absolute gravimeters are also used for densification of zero order networks instead of, or as a complement to, traditionally used relative gravimeters. For example, national gravity networks of Poland and Finland are completely modernised and now comprise a smaller number of in-door stations, measured by a high precision FG5 absolute gravimeter, and a larger number of field stations measured by a field absolute gravimeter A10 (Makinen, Sękowski and Kryński, 2010; Bosy and Krynski, 2015). Field absolute gravimeters are also utilised in other European countries: Germany (Wziontek, Falk and Wilmes, 2015), France (Duquenne, Duquenne and Gattacceca, 2005), Sweden, Norway, Denmark (Krynski, 2015; Kempe et al., 2017), etc. In addition, there is a regional and global trend of integration of gravity networks with positioning and vertical networks, which is also followed on national scales.

In Croatia, a new cycle of absolute measurements is planned. However, before re-observation and re-adjustment of the Croatian Fundamental Gravity Network, significant improvement in accuracy of gravity values is possible based on existing data, which can also serve as a good basis for analysis of the two cycles of measurements and give an insight into the drawbacks of the existing measurements, which should be overcome in the future.

The Croatian Fundamental Gravity Network comprises the zero, the first and the second order networks (Pravilnik o načinu izvođenja osnovnih geodetskih radova, 2009). The Zero Order Gravity Network (ZOGN) initially comprised six stations determined by absolute gravimetry (Figure 1). The stations of the ZOGN were established in the course of two international projects in the period from 1996 to 2000. In place of the devastated station in Makarska (AGT05), its eccentric station has been included in the ZOGN (Bašić, Markovinović and Rezo, 2006).

The First Order Gravity Network (FOGN) initially covered the land part of the country and comprised 36 stations. The original network was established by the Faculty of Geodesy, University of Zagreb (FGUZ) in 2003 in the course of a project contracted with the Croatian State Geodetic Administration (CSGA) (Bašić, Markovinović and Rezo, 2006). The network was extended in three stages (in 2007, 2008 and 2009) by the Croatian Geodetic Institute (CGI) and now also covers all major Croatian islands and comprises 59 stations (Figure 1, Repanić, Grgić and Bašić, 2014).

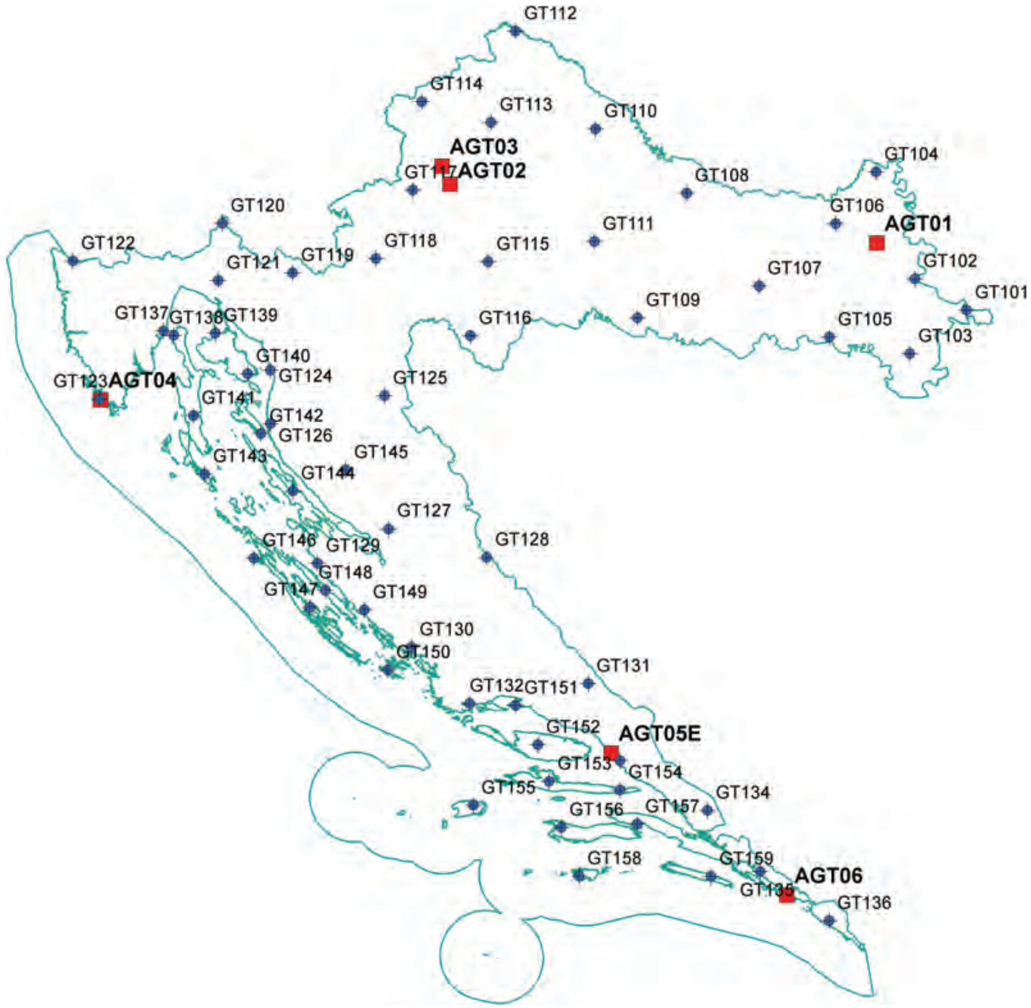

Figure 1: Stations of the Croatian Fundamental Gravity Network. Absolute gravity stations of the ZOGN are designated with AGT, while stations of the FOGN are designated with GT.

In 2008 the CGI started the establishment of the Second Order Gravity Network (SOGN). Due to the affiliation of the CGI to the CSGA in 2010, the latter continued the activities on the establishment of the SOGN. The measurements were completed in 2015 by the final, 11th stage. The network comprises 193 second order gravity stations. The processing and adjustment of the SOGN are in progress.

Up to now, the adjustment of the FOGN has been carried out separately for each of the four stages. The adjustment models applied for different stages are presented in Bašić, Markovinović and Rezo (2004;

2006); Markovinović (2009) and Repanić et al. (2010). Since the gravity values at the FOGN stations have been obtained from adjustments of the four individual parts of the network (corresponding to the four stages of the FOGN establishment) and because of different adjustment models applied, the need for a uniform joint adjustment of the whole network emerged. Thereby applied adjustment model should account for already perceived instrumental error influences. This paper presents the method and results of the new joint adjustment of the FOGN and comparison of its results with results of the previous adjustments.

2 MEASUREMENTS

2.1 Absolute gravity measurements in the Zero Order Gravity Network

The stations of the ZOGN were established in the course of two projects: the Connection of the Republic of Croatia to International Absolute Gravity Basestation Network in 1996 and the Unification of Gravity Systems in Central Europe (UNIGRACE). The projects in Croatia were coordinated by the FGUZ. Absolute gravity measurements, determination of vertical gravity gradients and relative connections to eccentric stations were carried out by the former German Institut for Applied Geodesy (IfAG), later German Federal Agency for Cartography and Geodesy (BKG) and French School and Observatory of Earth Sciences (EOST) (Table 1). The measurements have been documented in a number of technical reports, publications and other materials, which have been reviewed and summarised in the Report on data of the Croatian Absolute Gravity Network (compiled in the CGI by Ž. Hećimović). The vertical gravity gradients on stations AGT02 and AGT03 were also determined by the CSGA in 2013 and 2014 (Repanić, Kuhar and Malović, 2015).

Table 1: Overview of absolute gravity measurements at the ZOGN stations. For AGT01, the second measurement and AGT06, both measurements the data for actual height of measurement is not available.

Station	Measured by	Date of measurement	Instrument	g [nms^{-2}]	σ_g [nms^{-2}]	Reference height [m]
AGT01	BKG	7.-8.8.2000.	FG5-101	9806582866	27	1.3038
AGT01	EOST	27.-29.11.2000.	FG5-206	9806583739	13	1.00
AGT02	IfAG	4.-5.6.1996.	FG5-101	9806618330	37	1.3148
AGT03	IfAG	6.-7.6.1996.	FG5-101	9805099032	10	1.3148
AGT04	IfAG	9.-10.6.1996.	FG5-101	9806070091	20	1.3107
AGT05	IfAG	11.-13.6.1996.	FG5-101	9804069258	27	1.3190
AGT06	EOST	26.-29.8.1999.	FG5-206	9803693491	24	1.00
AGT06	BKG	6.-8.4.2000.	FG5-101	9803692759	75	1.25

2.2 Relative gravity measurements in the First Order Gravity Network

The FOGN comprises 59 stations established in four stages (Figure 1). Stations GT101 to GT136 were established in stage 1, which covers the land part of the country and stations GT137 to GT145, GT146 to GT150 and GT151 to GT159 in stages 2, 3 and 4, which cover the north, the central and the south Adriatic islands, respectively. More detail information on the selection of locations, network design and measurement practice applied in the course of the FOGN survey is available in Bašić, Markovinović and Rezo (2004; 2006); Markovinović (2009) and Repanić et al. (2010). Below, only the data relevant for the network adjustment is given.

Measurements in all four stages were carried out using the same three Scintrex gravimeters (Table 2). Every station was connected to adjacent points by at least two connections, each measured twice. However, all three stages of the extension to the Adriatic islands significantly differ from the initial land part of the network as regards distances between stations and means of transportation. Specifically, besides car transportation, the extensions involved transportation by ferry boat and, in case of stage 2, even fast boat (catamaran) and speedboat. Furthermore, although stages 1 and 2 have been designed as a network of triangles, due to specific terrain configuration, available ferry lines and financial resources, network configurations of stages 3 and 4 have been much weaker. All three gravimeters were transported together and, if the station monumentation allowed, the readings of all three gravimeters were taken simultaneously. Stage 1 of the survey comprised 37 days of measurements, each involving from three to nine station occupations. Thereby, from one to five station occupations have been redundant to provide for at least linear daily drift determination. Stages 2, 3 and 4 involved 14, 5 and 9 days of measurements, respectively. In each day there have been two or three redundant station occupations.

Table 2: Relative gravimeters used for the survey of the FOGN.

Owner	Manufacturer	Model	Serial number
CSGA	Scintrex	CG-3M	4373
CSGA	Scintrex	CG-3M	4372
FGUZ	Scintrex	CG-5	10012

The calibration of the relative gravimeters was usually carried out before and after each stage of the survey on the auxiliary vertical calibration line (comprising only two stations AGT02 and AGT03) with the gravity range of approximately 1500 μms^{-2} and the height difference of almost 850 m. An exception is the calibration of gravimeter CG-5 in stage 1, which was calibrated on the calibration line in Orangeville, Canada (Markovinović, 2009). Thus, for each gravimeter, a different calibration constant was used for every stage (Table 3). For the CG-5 gravimeter, the data on processing method and reached precision of calibration constants is unavailable. Figure 2 depicts all determinations of the calibration constants for the two CG-3M gravimeters on the auxiliary vertical calibration line. The measurement scheme, duration of the observation series, data processing and consequently reached accuracy significantly differs for different determinations. In general, the last six determinations can be considered the most accurate. Nevertheless, given a long time span, Figure 2 provides a good insight into the behaviour of the calibration constants for the two gravimeters. One can observe that the calibration constants were significantly changing during the first three years. Since about a year elapsed between the determination of the calibration constants of gravimeters 4372 and 4373 and stage 1 of the FOGN survey, the measurements could be significantly affected by the change in the calibration constants. Estimated relative change of about $3.5 \cdot 10^{-4}$ year^{-1} during the corresponding period could result in significant errors in the range of

1.52 μms^{-2} over the range of the FOGN of 4335 μms^{-2}. In addition, there is a question of accuracy of the determined calibration constants. The standard deviations for determinations used during the FOGN survey amount up to 6 μms^{-2}/CU (CU stands for counter units), or relatively 10^{-4}. In addition, because of relatively small calibration range with respect to the range of the FOGN, even the environmental effects can significantly affect the calibration constants determined on the auxiliary vertical calibration line (Repanić and Kuhar, 2017). Therefore, the corrections of the calibration constants have been included in the adjustment of the FOGN as unknown parameters (see section 3).

Table 3: Calibration constants used for specific stages of the FOGN survey in μms^{-2}/CU.

Campaign	**Gravimeter**				
	4372		**4373**		**10012**
	GCAL1	σ_{GCAL1}	*GCAL1*	σ_{GCAL1}	*GCAL1*
Stage 1 (2003)	60553.42	0.41	61828.17	0.62	84272.88
Stage 2 (2007)	60623.34	1.32	61905.03	0.61	84255.93
Stage 3 (2008)	60620.94	6.35	61910.84	4.93	84285.76
Stage 4 (2009)	60627.12	5.63	61919.15	1.06	84280.17

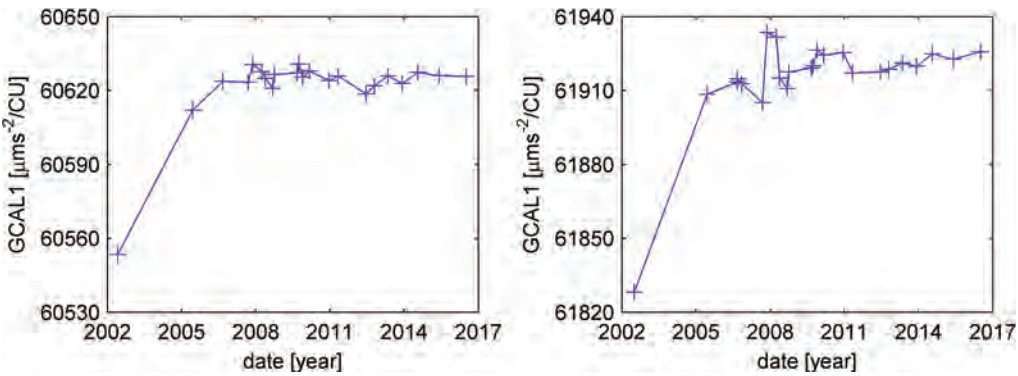

Figure 2: Determined values of linear calibration constants for gravimeter 4372 (left) and 4373 (right).

Besides the uncertainty of the calibration constants, additional weaknesses of the relative gravity data are the significant hysteresis effects after transport in the upright position in the measurements of the two CG-3M gravimeters (Repanić and Kuhar, 2017), presence of the tilting effects caused by the transport in tilted position (Reudink et al., 2014) and insufficient drift control. The analysis of the long observations series used for the purposes of calibration of the two CG-3M gravimeters from 2012 revealed significant and not completely uniform hysteresis effects, but surprisingly uniform daily drift behaviour through all days (Figure 3). Because relative gravity measurements of the FOGN comprise only five 60-second readings for each occupation, which were taken after the instruments were stabilising for 10 minutes, it is not possible to model or eliminate hysteresis effects, which are still significant and not completely homogenous. Consequently, the hysteresis and even more inhomogeneous tilting effects are superimposed to nonlinear drift. Specifically, because of practical reasons, the two CG-3M gravimeters during stage

1 and gravimeter 10012 at least during stages 2, 3 and 4 were not transported in the upright position, but on the back seat of the car, which caused the tilting effects in readings. The analysis of the hysteresis effects for gravimeter 10012 is not available, but the data of the FOGN suggest that this instrument is not so sensitive to the hysteresis effect after transport in the upright position and that it often exhibits a linear drift. Still, there are indications of the tilting effects.

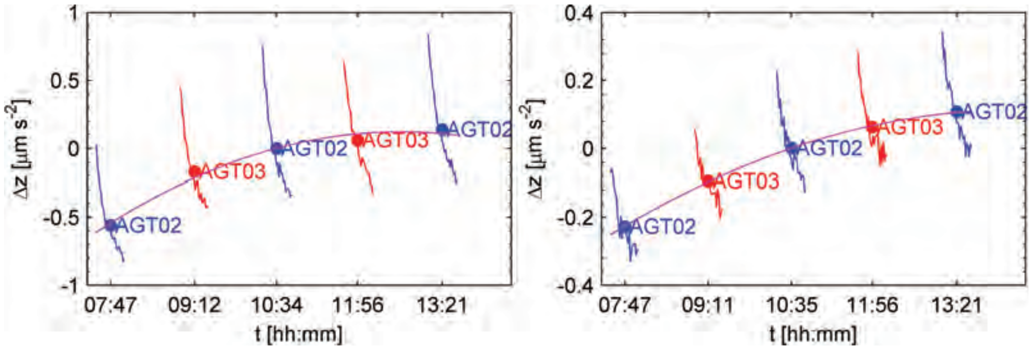

Figure 3: Typical hysteresis effects after transport in the upright position and daily drift approximated based on the mean value of observation series for gravimeters 4372 (left) and 4373 (right) for 30-minutes observation series.

3 NEW JOINT ADJUSTMENT OF THE FIRST ORDER GRAVITY NETWORK

In order to carry out the joint adjustment of the FOGN, available data on absolute gravity measurements has been revised again. For certain stations, new gravity values at the ground level have been calculated. Furthermore, uniform pre-processing of all four stages of the relative gravity measurements have been carried out.

3.1 Revision of the absolute gravity measurements

The revision of the absolute gravity measurements comprised all materials on basis of which the Report on data of the Croatian Absolute Gravity Network was compiled, as well as the report itself. Since the measurements at stations AGT01 and AGT06 for the purpose of vertical gravity gradient determination were carried out at three heights (0.3, 0.8 and 1.3 m), the vertical gravity gradient has been determined using the second order polynomial. Accordingly, new gravity values at the ground level have been calculated for each absolute gravity measurement at the two gravity stations as well as the linear vertical gravity gradient between the ground level and the height of 0.25 m for the purpose of reduction of relative measurements (Table 4). The differences between the new mean gravity values at the ground level and the values given in the Report on data of the Croatian Absolute Gravity Network are significant and amount to -67 and 68 nms^{-2}, for stations AGT01 and AGT06, respectively. Such significant differences are probably due to the fact that, in the report, the gravity values were reduced from the height of 1 m to the ground level using linear gravity gradients corresponding to the heights of 0.3 and 1.3 m. Furthermore, new gravity values at the ground level have been calculated for stations AGT02 and AGT03 based on more precise vertical gravity gradients determined by Repanić, Kuhar and Malović (2015). However, the differences between these values and the previous values are not significant and amount to 11 and -5 nms^{-2}.

Table 4: Revised data on absolute gravity stations.

Station	Instrument	g(h) [nms^{-2}]	h [m]	$\sigma_{g(h)}$ [nms^{-2}]	g(0) [nms^{-2}]	W_{zz} [ns^{-2}]	$u_{g(0.25)}$ [nms^{-2}]
AGT01	FG5-101	9806582866	1.3038	27	9806586587	-2967	58
	FG5-206	9806583739	1.00	13	9806586622	-2967	53
	mean	-	-	-	9806586605	-2967	39
AGT02	FG5-101	9806618330	1.3148	37	9806622579	-3232	59
AGT03	FG5-101	9805099032	1.3148	10	9805104402	-4084	47
AGT04	FG5-101	9806070091	1.3107	20	9806073900	-2906	51
AGT05	FG5-101	9804069258	1.3190	27	9804072611	-2542	54
AGT06	FG5-206	9803693491	1.00	24	9803696363	-2786	56
	FG5-101	9803692759	1.25	75	9803696379	-2786	91
	mean	-	-	-	9803696371	-2786	53

Besides the new gravity values at the ground level, the uncertainties of gravity values at the height of 0.25 m have been determined for all absolute measurements (Table 4). Although all adjusted gravity values refer to the ground level, the height of 0.25 m, which is an average sensor height of Scintrex CG-3M and CG-5 gravimeters, represents the effective height for the network adjustment. Specifically, the relative measurements at the absolute stations have been reduced using the same vertical gradients. Thus, the errors caused by the height reduction between 0.25 m and the ground level have been cancelled out. The uncertainties were determined analogously to Vitushkin et al. (2002) according to the following expression:

$$u_{g(0.25)}^2 = \sigma_{g(h)}^2 + u_{ins}^2 + u_{dg(h)}^2, \tag{1}$$

where $\sigma_{g(h)}$ represents the standard deviation of absolute gravity measurement (at the height of measurement), u_{ins} the instrumental uncertainty of the absolute measurement due to systematic errors (value of 40 nms^{-2} is taken as determined by Vitushkin et al. (2002)) and $u_{dg(h)}$ is the uncertainty of the reduction to the height of 0.25 m.

In order to evaluate the instrumental uncertainties and check for existence of significant offsets in the absolute measurements, an analysis of the deviations of measurements of gravimeters FG5-101 and FG5-206 from the reference values of the ICAGs have been made based on the results of the ICAGs from 1994 to 2013 (Marson et al. 1995; Robertsson et al. 2001; Vitushkin et al., 2002; Jiang et al., 2011; Jiang et al., 2012; Francis et al., 2015). The deviations presented in Figure 4, in most cases, are not significant for gravimeter FG5-101 with respect to their uncertainties, while for both gravimeters the deviations are not consistent in time. In addition, the deviations are in accordance with the applied value of u_{ins} (equation (1)). One can draw the same conclusion from available data on regional and bilateral comparisons close in time to the absolute measurements in Croatia (Wilmes, Richter and Falk, 2003; Van Camp et al., 2003). Therefore, the corrections for the deviations have not been reduced from absolute gravity measurements. In addition, neither global nor local hydrological influences have been reduced.

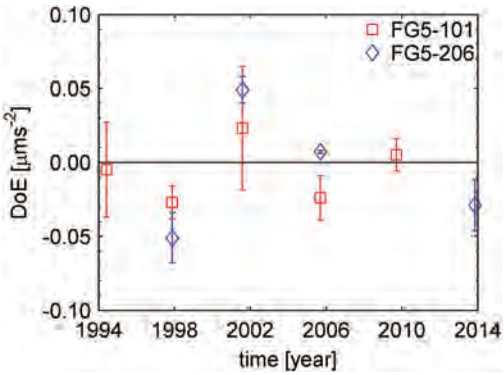

Figure 4: Deviations from the reference value (DoE) of respective ICAG for gravimeters FG5-101 and FG5-206 with their uncertainty (1 σ).

3.2 Pre-processing of the relative gravity measurements

Prior to the adjustment of the gravity network, the observation data files from all stages have been uniformly analysed and processed. Firstly, the errors in the data were corrected, such as incorrect calibrations constant applied during a day, stationary drift constant or time parameters. Thereby, if applied, the corrections of gravity readings were made based on the formulas for signal processing given in CG-3/3M Autograv Automated Gravity Meter Operator Manual (1989) and CG-5 Autograv System Operational Manual (2006). Analysis of the simultaneous measurements of the three gravimeters revealed significant clock drift for gravimeter 10012 (CG-5). The clock drift amounted to about 14 s day^{-1} during 2003 and September 2007, while during November 2007, 2008 and 2009 it amounted to about 4 s day^{-1}. Hence, the start time of each reading of gravimeter 10012 was corrected for the clock drift to provide for the accurate calculation of the Earth tide reduction. For comparison, the clock drift of gravimeter 4373 with respect to gravimeter 4372 amounted to 0 s day^{-1}, during all four stages.

Since field records for gravimeter 10012 have not been available for 16 days of measurements from stage 1, it was necessary to approximate the instrument heights. Firstly, the average differences of instrument heights of each of the two CG-3M gravimeters and gravimeter 10012 were determined for the days with field records. Then, two sets of heights for gravimeter 10012 were calculated, each from the average height difference and the heights of corresponding CG-3M gravimeter. The final heights were determined as the mean values of the two sets, between which a good agreement has been reached (average difference amounts to 2 ± 3 mm).

The Scintrex gravimeters automatically apply certain instrument corrections (for a stationary drift, a tilt of the sensor and a change of the sensor temperature) as well as the Earth tide reductions according to Longman (1959) formula. After the corrections of the data, the Earth tide reductions were recalculated using the PREDICT software (Wenzel, 1996) based on synthetic tidal parameters interpolated from Timmen's and Wenzel's (1995) regular grid with utilization of Tamura's (1987) tidal potential catalogue. Also, the polar motion reductions were calculated using the PREDICT software. Next, the mean readings were calculated as the weighted mean of the five readings taken during each occupation, with weights inversely proportional to the readings' variances. In addition, the reduction for the variation in atmospheric pressure and reduction to the ground level have been applied.

Although the analysis of the daily drift has been performed in the phase of pre-processing, the drift is determined in the course of the adjustment. Because of a small number of redundant occupations during a day and due to the superimposed hysteresis and tilting effects (see section 2.2), which sometimes yield unrealistic quadratic drift coefficients, only the linear drift coefficients have been included in the adjustment model as parameters.

3.3 Network adjustment

The absolute gravity measurements at the ZOGN stations have been introduced in the network adjustment as observations (or quasi-observations, since derived from original observations of time and distance) with associated uncertainties (Torge, 1989). There are a few examples in the literature of introduction of absolute measurements (or a priori given gravity values) as pseudo-observations in gravity network adjustment, e.g. Hwang, Wang and Lee (2002) and Medved et al. (2009). The model applied in this study is somewhat different and represents a generalisation of the adjustment with pseudo-observations, since more than one absolute measurement per station can be introduced.

3.3.1 Adjustment model

The network adjustment comprises the relative gravity measurements from the four stages of the FOGN survey, as well as the absolute gravity measurements, which define the network datum. For relative measurements, the following functional model has been applied:

$$\begin{aligned} z_i^c + v_i &= g^T - N_0^{d,gr} - y'^{gr,k}_1\, z_i \cdot 10^{-4} + d_1^{d,gr}(t_i - t_0) \\ y'^{gr,k}_1 &= y_1^{gr,k} \cdot 10^4 \end{aligned} \tag{2}$$

where z_i^c is ith relative gravity observation (the weighted mean, corrected and reduced as described in section 3.2), v_i its residual and z_i the raw reading (uncorrected and unreduced); g^T, $N_o^{d,gr}$, $y_i^{gr,k}$ and $d_i^{d,gr}$ are the adjusted unknown parameters (the gravity value at a station T, instrument level, correction of linear calibration coefficient and linear drift coefficient, respectively, for day d, gravimeter gr and stage k); and finally t_i and t_0 are the time of ith reading and reference time, respectively. Substitution for the correction of calibration coefficient ($y'^{gr,k}_i$) has been introduced to provide for computations' numerical stability.

Absolute measurements have been represented by the equation (Torge, 1989):

$$L_j^c + v_j = g^T, \tag{3}$$

where L_j^c is corrected and reduced jth absolute gravity measurement.

Thus, the observation equations have been compiled from two sets: relative and absolute observations:

$$\begin{aligned} \begin{bmatrix} \mathbf{L}_\mathrm{R} \\ \mathbf{L}_\mathrm{A} \end{bmatrix} + \begin{bmatrix} \mathbf{v}_\mathrm{R} \\ \mathbf{v}_\mathrm{A} \end{bmatrix} = \begin{bmatrix} \mathbf{A}_\mathrm{R} \\ \mathbf{A}_\mathrm{A} \end{bmatrix} \mathbf{x} \quad \ldots \quad \begin{bmatrix} \mathbf{P}_\mathrm{R} \\ \mathbf{P}_\mathrm{A} \end{bmatrix} \\ \mathbf{L} + \mathbf{v} = \mathbf{A}\ \mathbf{x} \quad \ldots \quad \mathbf{P} \end{aligned} \tag{4}$$

where **L** and **v** are vectors of observations and their corrections, **A** the design matrix, **x** the vector of unknowns and **P** associated diagonal weight matrix. Weights for ith relative and jth absolute measurements have been defined according to (Feil, 1989):

$$p_i = \frac{c_R}{\sigma_i^2},$$
$$p_j = \frac{c_A}{u_j^2}, \tag{5}$$

where c_R and c_A are appropriate constants, σ_i^2 is the variance of the relative and u_j^2 squared uncertainty of the absolute gravity measurement.

Such observation model represents a combined adjustment by parameters of indirect and direct observations (Feil, 1989), but if for every station no more than one absolute measurement is introduced, it also corresponds to adjustment with pseudo-observations (e.g. Fan, 1997; Niemeier, 2002).

3.3.2 Adjustment course and results

In order to estimate the accuracy of the relative measurements and to screen the measurements for outliers, firstly the adjustment of only relative measurements was carried out. Thereby, the weights were defined according to the equation (5), with σ_i^2 and c_R equal the variance of the weighted mean (see section 3.2) and the mean value of all variances, respectively. The gravity values at two ZOGN stations: AGT01 and AGT06 were held fixed in order to define the network's origin and scale. All other unknown parameters were free for determination. Outlier detection was carried out according to Pope's Tau-test (Pope, 1976; Kavouras, 1982). Only two outliers were detected, both form stage 2, one with gravimeter 10012 and one with gravimeter 4373 from measurement days involving transportation by fast boat (catamaran) and speed-boat, respectively. The a posteriori reference standard deviation of 0.17 μms^{-2} was obtained.

In addition to the described stochastic model, adjustment with equal weights (**P** = **I**) was carried out. However, such stochastic model resulted in more outliers (six) and larger standard deviations of the adjusted gravity values and corrections of calibration coefficients. The differences of the gravity values between the results of the two applied stochastic models are in the range from -0.18 to 0.24 μms^{-2}. The reasoning for choosing a stochastic model with weights inversely proportional to observations' variances, besides experimental results, was that the observations' variances rather well reflect the influence of hysteresis effect after transport, which is considerable for the two CG-3M gravimeters, especially gravimeter 4372 (Figure 3). However, due to the same hysteresis effect, the observations' variances do not provide reliable information on accuracy, but only on the relative ratios among them.

After the adjustment of the relative measurements and elimination of outliers, the combined adjustment of relative and absolute measurements was carried out. The absolute measurements comprised 7 measurements at 5 stations (without AGT05, devastated before relative campaigns). All unknown parameters were free for determination. Weights of the relative measurements were defined same as in the first adjustment. In order to balance the weights of absolute measurements with respect to the relative ones, the constant c_A in the equation (5) was set to the a posteriori variance from the adjustment of only relative measurements. The adjustment resulted in the reference standard deviation of 0.17 μms^{-2} and the standard deviations of gravity values from 0.03 to 0.05 μms^{-2} for the absolute stations, and from 0.05 to 0.18 μms^{-2} for the relative stations. However, analysis of the results reviled poor accuracy of the adjusted corrections of calibration coefficients for stage 3 (due to the limited gravity range of involved stations, Table 5), but a rather good agreement among the obtained calibration coefficients for the last three stages. In addition, frequent calibration of the two CG-3M gravimeters on the auxiliary calibration line (stations AGT02 and AGT03), indicated that apparent variations in the calibration constant from 2007, are mostly caused by instrumental error effects and external hydrological and barometric influences (Figure 2). Therefore, the mean calibration constant was determined for each gravimeter for the period comprising the last three stages and the observation data files were re-calculated to correspond the common calibration constants.

Table 5: Gravity range at stations involved in the specific campaign.

Campaign	Stations with the extreme values (min – max)	Gravity range [μms^{-2}]
Absolute measurements	AGT06 – AGT02	2926
Stage 1 (2003)	GT127 – GT112	4335
Stage 2 (2007)	GT145 – GT122	2342
Stage 3 (2008)	GT123 – GT129	719
Stage 4 (2009)	GT131 – GT132	1715
Stages 2–4 together	GT131 – GT122	3481

Finally, the adjustment of relative and combined adjustment of absolute and relative measurements were repeated. The final adjusted gravity values are presented in Table 6. The repeated adjustments resulted in no significant difference as regards the outliers and accuracy assessment of measurements. The reference standard deviation again amounts to 0.17 μms^{-2}. However, moderate improvement has been obtained in the precision of the adjusted gravity values for the stations involved in stage 4 and considerable improvement in the precision of adjusted corrections of calibration coefficients for the last three stages together. Specifically, the standard deviations of the adjusted gravity values are now up to 0.16 μms^{-2} for relative stations (Table 6). However, the standard deviations for the majority of stations are up to 0.10 μms^{-2}. The higher values generally correspond to stations with extremely small gravity values (GT127 and GT131) or to the stations determined in stage 4 with sparse connections. The differences in the gravity values after the repeated adjustment are not significant (up to 0.06 μms^{-2}). The differences over 0.02 μms^{-2}, in general, correspond to the stations determined in stage 4.

The values of adjusted corrections of calibration coefficients and corresponding calibration constants are given in Table 7. Although the gravity range of the ZOGN stations is almost double the range of the auxiliary calibration line, it is evident that the precision of calibration constants (and other adjusted parameters) is impaired by the weakness of the relative gravity measurements. In addition, since the range of the FOGN stations exceeds that of the ZOGN for 1400 μms^{-2}, the uncertainty of the calibration constants, which in fact reflects the uncertainty of the scale of the network, is propagated over the whole network. Consequently, the gravity stations with extreme gravity values have the largest standard deviations.

Table 6: Final adjusted gravity values with their standard deviations.

Station	g [μms^{-2}]	σ_g [μms^{-2}]	Station	g [μms^{-2}]	σ_g [μms^{-2}]
AGT01	9806586.642	0.034	GT127	9802841.24	0.13
AGT02	9806622.513	0.048	GT128	9803822.45	0.09
AGT03	9805104.365	0.041	GT129	9805366.48	0.06
AGT04	9806073.898	0.045	GT130	9804952.13	0.07
AGT06	9803696.384	0.044	GT131	9802934.03	0.11
AGT05	9804067.33	0.10	GT132	9804649.09	0.07
AGT05E	9804058.35	0.09	GT133	9803430.43	0.09
GT101	9806427.05	0.08	GT134	9803978.73	0.08
GT102	9806433.43	0.06	GT135	9803201.30	0.09
GT103	9806145.15	0.08	GT136	9803557.84	0.09
GT104	9806809.04	0.07	GT137	9805797.10	0.07
GT105	9806072.71	0.06	GT138	9806003.29	0.07
GT106	9806512.82	0.06	GT139	9805794.43	0.07
GT107	9806261.67	0.05	GT140	9805686.77	0.08
GT108	9806577.79	0.06	GT141	9805626.92	0.07
GT109	9805927.54	0.06	GT142	9805582.74	0.07
GT110	9806819.81	0.07	GT143	9805706.99	0.07
GT111	9806572.41	0.06	GT144	9805472.07	0.07
GT112	9807176.44	0.08	GT145	9804073.03	0.11
GT113	9806893.01	0.06	GT146	9805315.03	0.10
GT114	9806826.59	0.07	GT147	9805241.22	0.09
GT115	9806421.74	0.05	GT148	9805290.73	0.09
GT116	9805621.29	0.06	GT149	9805160.37	0.09
GT117	9806584.17	0.06	GT150	9805023.61	0.09
GT118	9806386.89	0.06	GT151	9804399.71	0.11
GT119	9805157.44	0.06	GT152	9803733.51	0.12
GT120	9804874.32	0.08	GT153	9804299.24	0.14
GT121	9804932.83	0.06	GT154	9803933.28	0.13
GT122	9806415.18	0.06	GT155	9804604.69	0.13
GT123	9806085.23	0.06	GT156	9804500.39	0.14
GT124	9805632.58	0.06	GT157	9804274.26	0.10
GT125	9804638.32	0.07	GT158	9804608.89	0.16
GT126	9805078.36	0.07	GT159	9804247.68	0.12

Table 7: Adjusted corrections of linear calibration coefficients (y_1), calibration constants applied on data before adjustment ($GCAL1$) and corrected calibration constants after adjustment ($\overline{GCAL1}$) with corresponding standard deviations.

Campaign	Gravimeter	$y_1 \cdot 10^4$	$\sigma_{y_1} \cdot 10^4$	$GCAL1$ [μms^{-2}/CU]	$\overline{GCAL1}$ [μms^{-2}/CU]	$\sigma_{\overline{GCAL1}}$ [μms^{-2}/CU]
1 (2003)	4372	4.260	0.448	60553.42	60579.22	2.71
	4373	6.287	0.497	61828.17	61867.04	3.07
	10012	4.251	0.410	84272.88	84308.70	3.45
2–4	4372	0.033	0.880	60626.60[1]	60626.80	5.34
(2007– 2009)	4373	0.029	0.702	61908.98[1]	61909.16	4.35
	10012	0.098	0.632	84291.26[1]	84292.08	5.33

[1] *Average calibration constants determined in the course of preliminary adjustment.*

4 COMPARISON WITH PREVIOUS ADJUSTMENTS

The final adjusted gravity values: A (Table 6) have been compared with the results from previous adjustments of separate stages, which also comprise the measurements of all three gravimeters:

B: Bašić, Markovinović and Rezo (2006) for stage 1 and separate adjustments of stages 2, 3 and 4 carried out in the CGI according to the model described in Repanić et al. (2010), which lean on the gravity values of the FOGN stations from Bašić, Markovinović and Rezo (2006);

C: Markovinović (2009), involving separate adjustments of stages 1 and 2.

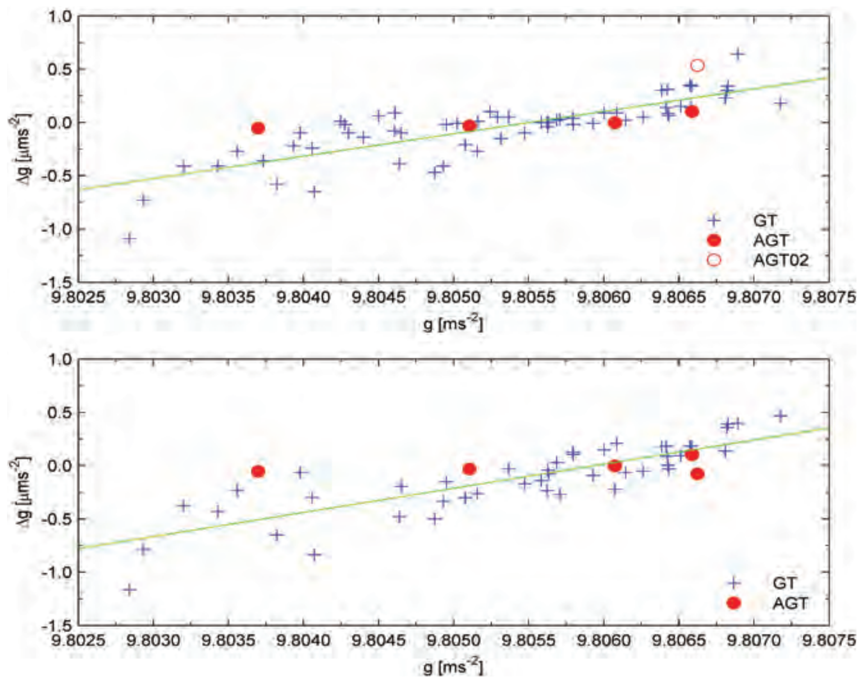

Figure 5: Differences of the gravity values between the result of adjustment B and A (top) as well as C and A (bottom) against the gravity values. Differences for the ZOGN stations with gravity values form B or C fixed in the adjustment are designated as red disks, and for the absolute station with free gravity value as a red circle.

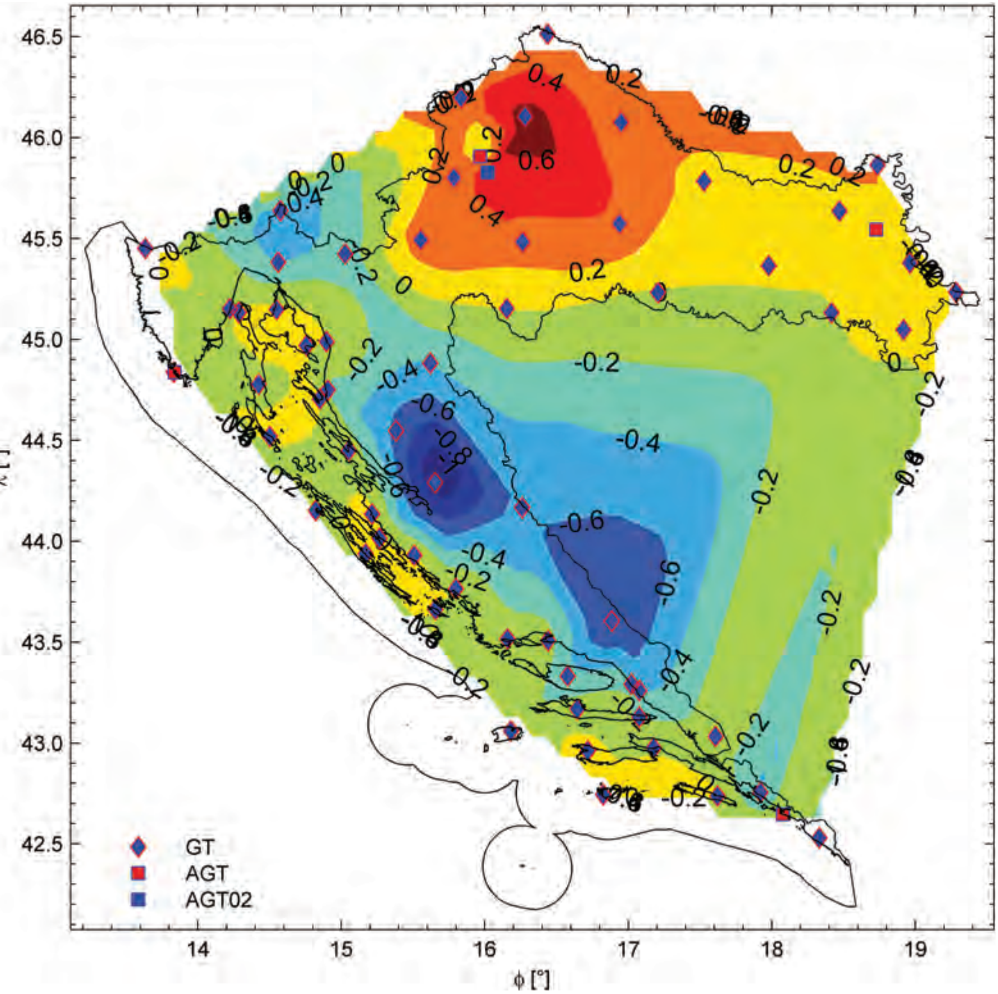

Figure 6: Spatial distribution of differences of gravity values between B and A in μms^{-2}. The extreme negative differences are in the Dinaric Alps region with higher altitudes, for which the closest fixed gravity values are close to the sea level, while the extreme positive differences are in the northern part, where the closest fixed gravity value is at AGT03 on the mountain Medvednica.

The differences between the results form B or C and the results A are substantial and amount to form -1.09 to 0.64 μms^{-2} or from -1.16 to 0.47 μms^{-2}, respectively (Figure 5). The results from B and C are in considerably better agreement. The differences are in the range of ±0.29 μms^{-2}, with exception of the gravity value at station AGT02 (0.61 μms^{-2}), which was not held fixed in Bašić, Markovinović and Rezo (2006) adjustment. Given the declared accuracy of Scintrex gravimeters of 0.05 μms^{-2} and estimated standard deviations of gravity values from all three adjustments, the comparisons imply considerable systematic influences, obviously the errors in the calibration constants, which were neglected in Bašić, Markovinović and Rezo (2006) and Markovinović (2009). Indeed, there is a significant correlation between the differences and the gravity values itself (Figure 5). The correlation coefficient amounts to 0.8 and the regression coefficient 2.104·10^{-4} for both comparisons. The received regression coefficients are significantly smaller than the adjusted corrections of calibration coefficients, since, in the previous adjustments, the network scale was partially adjusted by fixing the gravity values at the absolute stations. However, if corrections of the calibration coefficients are not included in the functional model, such procedure can introduce distortions. One can notice that the extreme values of the differences are for the gravity values, which are out of the range of the fixed gravity values. Though, there are also gravity values within this range with considerable differences, what can be explained with considerable difference in the gravity values as compared to the closest stations with fixed gravity values (Figure 6).

5 TRANSFORMATION FROM THE POTSDAM SYSTEM

Because of the considerable differences of the new gravity values of the FOGN stations as compared to the previous adjustments, parameters of the linear transformation has been determined again. The parameters of the linear transformation function according to Torge (1989):

$$g_{\mathrm{HRGS03}} = g_{\mathrm{Potsdam}} + a + b\,(g_{\mathrm{Potsdam}} - g_0) \tag{6}$$

have been determined based on 25 identical stations with the gravity values in Potsdam and the Croatian Gravity System (HGRS03). In equation (6) g_{HRGS03} is a gravity value in HGRS03, g_{Potsdam} in Potsdam system and g_0 the average value in Potsdam system of 9805584.01, all in μms^{-2}. Determined parameters of the linear transformation with their accuracy estimates are $a = -151.314 \pm 0.249$ μms^{-2} and $b = (-1.254 \pm 0.201) \cdot 10^{-3}$ (Figure 7). The reference standard deviation is 1.27 μms^{-2}. The values in the Potsdam system for the 25 stations of fundamental gravity network of former Yugoslavia, which are now included in the FOGN, are taken form Bašić, Markovinović and Rezo (2006) and Markovinović (2009).

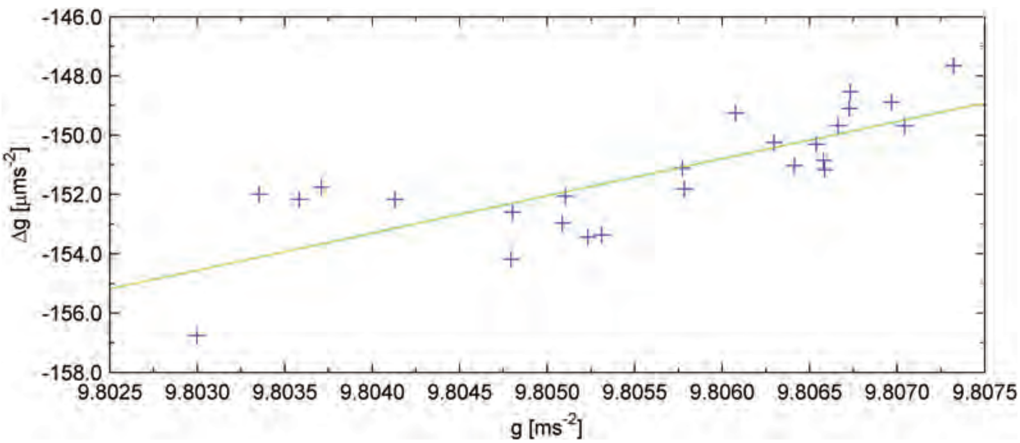

Figure 7: Differences between the gravity values in the Potsdam system and the new gravity values with the linear transformation function.

6 CONCLUSION AND OUTLOOK

For the first time, the Croatian First Order Gravity Network has been adjusted as a whole, according to the adjustment model, which accounts for the corrections of linear calibration coefficients. Prior to the adjustment, revision of the absolute and uniform pre-processing of the relative measurements has been carried out. The adjustment resulted in significantly different gravity values, as compared to the previous adjustments. Accordingly, the differences are an order of magnitude greater than the expected accuracy. It is shown that the differences in gravity values are mainly due to the errors in gravimeters' calibration constants, which were neglected in the previous adjustments. Therefore, it is advisable to include the correction of the linear calibration coefficients in the functional model at least in the first iteration of the fundamental gravity network adjustment. In contrary, adjusted gravity values could be significantly biased and their estimated precision too favourable.

In addition, it is not advisable to change gravimeter's calibration constant for every campaign, but rather only to check their stability on suitable calibration line. That is especially important if the calibration constant cannot be determined with sufficient accuracy and if the initial period of several years have been passed, during which calibration constant of a gravimeter significantly changes (CG-3/3M Autograv Automated Gravity Meter Operator Manual, 1998).

In the Croatian FOGN, there is an evident problem of the scale of the network. Neither the existing auxiliary calibration line nor the ZOGN sufficiently covers the range of the FOGN. To overcome this problem, several options can be employed. For example, the relative gravimeters can be calibrated on foreign calibration lines of sufficient range, e.g. the German or Swiss with gravity ranges of more than 5000 and 6000 μms^{-2}, respectively (Timmen et al., 2006; Marti et al., 2015). Alternatively, a calibration line of greater range than the present auxiliary line can be established in Croatia. In addition, at least several first order stations could be observed with a field absolute gravimeter, e.g. in Dinaric Alps on the south where the extremely small gravity values occur and where the establishment of in-door zero order stations is not possible. Also, connections to absolute stations of neighbour countries could be realized.

Furthermore, treatment of other significant instrumental error influences in Sintrex' measurements, such as hysteresis effect and transportation drift, in pre-processing and adjustment model should be further analysed in order to minimise their effects on results of the adjustment.

Since the adjusted gravity values are significantly different from the previous, the author proposed to make the results of the new adjustment official.

Acknowledgments

The author would like to thank two anonymous reviewers for their valuable comments which helped to significantly improve the manuscript. M. Kuhar and P. Pavlovčič Prešeren are gratefully acknowledged for help and advice concerning the manuscript revision. The author would also like to thank M. Kuhar for the help with the PREDICT software and a fruitful discussion on gravity network adjustment.

Literature and references:

Abaza, H. (2014). Kampanje mjerenja apsolutnog i relativnog ubrzanja sile teže u „Osnovnoj gravimetrijskoj mreži BiH". Geodetski glasnik, 48 (45), 74–81.

Bašić, T., Markovinović, D., Rezo, M, (2004). Osnovna gravimetrijska mreža Republike Hrvatske. In I. Landek (Ed.), Izvješća Državne geodetske uprave o znanstvenostručnim projektima iz 2002. godine (pp. 51–65). Zagreb: Državna geodetska uprava.

Bašić, T., Markovinović, D., Rezo, M. (2006). Osnovna gravimetrijska mreža Republike Hrvatske, Geodetski list, 60 (2), 73–91.

Bosy, J., Krynski, J. (2015). Reference frames and reference networks. Geodesy and Cartography, 64 (2), 147–176. DOI: http://dx.doi.org/10.1515/geocart-2015-0011

CG-3/3M Autograv Automated Gravity Meter Operator Manual (1998). Concord, Canada: Scintrex Limited.

CG-5 Autograv System Operational Manual, revision 2 (2006). Concord, Canada: Scintrex Limited.

Csapó, G., Koppán, A. (2013). The results and works of the latest adjustment of Hungarian Gravimetric Network (MGH-2010). Acta Geodaetica et Geophysica, 48 (1), 9–16. DOI: http://dx.doi.org/10.1007/s40328-012-0001-5

Duquenne, F., Duquenne, H., Gattacceca, T. (2005). Gravity measurements of the French geodetic network: toward an integrated network. EUREF symposium 2005. http://www.euref.eu/symposia/Symposium2005-Vienna.html, accessed 25. 9. 2017.

Fan, H. (1997). Theory of Errors and Least Squares Adjustment. Stockholm: Royal Institute of Technology.

Feil, L. (1989). Teorija pogrešaka i račun izjednačenja – prvi dio. Zagreb: Faculty of Geodesy, University of Zagreb.

Francis, O., Baumann, H., Ullrich, C., Castelein, S., Van Camp, M., Andrade de Sousa, M., Lima Melhorato, R., Li, C., Xu, J., Su, D., Wu, S., Hu, H., Wu, K., Li, G., Li, Z., Hsieh, W. C., Pálinkás, V., Kostelecký, J., Mäkinen, J., Näränen, J., Merlet, S., Pereira Dos Santos, F., Gillot, P., Hinderer, J., Bernard, J.-D., Le Moigne, N., Fores, B., Gitlein, O., Schilling, M., Falk, R., Wilmes, H., Germak, A., Biolcati, E., Origlia, C., Iacovone, D., Baccaro, F., Mizushima, S., De Plaen, R., Klein, G., Seil, M., Radinovic, R., Sekowski, M., Dykowski, P., Choi, I.-M., Kim, M.-S., Borreguero, A., Sainz-Maza, S., Calvo, M., Engfeldt, A., Agren, J., Reudink, R., Eckl, M., van Westrum, D., Billson, R., Ellis, B. (2015). CCM.G-K2 key comparison. Metrologia, 52 (Technical Supplement), 07009.

Hwang, C., Wang, C., Lee, L. (2002). Adjustment of relative gravity measurements using weighted and datum-free constraints. Computers & Geosciences, 28 (9), 1005–1015. DOI: http://dx.doi.org/10.1016/S0098-3004(02)00005-5

IAG Resolution No. 2 (2015). http://iag.dgfi.tum.de/fileadmin/IAG-docs/IAG_Resolutions_2015.pdf, accessed 15. 6. 2016.

Jiang, Z., Francis, O., Vitushkin, L., Palinkas, V., Germak, A., Becker, M., D'Agostino, G., Amalvict, M., Bayer, R., Bilker-Koivula, M., Desogus, S., Faller, J., Falk, R., Hinderer, J., Gagnon, C., Jakob, T., Kalish, E., Kostelecky, J., Lee, C., Liard, J., Lokshyn, Y., Luck, B., Mäkinen, J., Mizushima, S., Le Moigne, N., Origlia, C., Pujol, E., Richard, P., Robertsson, L., Ruess, D., Schmerge, D., Stus, Y., Svitlov, S., Thies, S., Ullrich, C., Van Camp, M., Vitushkin, A., Ji, W., Wilmes, H. (2011). Final report on the Seventh International Comparison of Absolute Gravimeters (ICAG 2005). Metrologia, 48 (5), 246–260. DOI: http://dx.doi.org/10.1088/0026-1394/48/5/003

Jiang, Z., Pálinkáš, V., Arias, F. E., Liard, J., Merlet, S., Wilmes, H., Vitushkin, L., Robertsson, L., Tisserand, L., Pereira Dos Santos, F., Bodart, Q., Falk, R., Baumann, H., Mizushima, S., Mäkinen, J., Bilker-Koivula, M., Lee, C., Choi, I. M., Karaboce, B., Ji, W., Wu, Q., Ruess, D., Ullrich, C., Kostelecký, J., Schmerge, D., Eckl, M., Timmen, L., Le Moigne, N., Bayer, R., Olszak, T., Ågren, J., Del Negro, C., Greco, F., Diament, M., Deroussi, S., Bonvalot, S., Krynski, J., Sekowski, M., Hu, H., Wang, L. J., Svitlov, S., Germak, A., Francis, O., Becker, M., Inglis, D., Robinson, I. (2012). The 8th International Comparison of Absolute Gravimeters 2009: the first Key Comparison (CCM.G-K1) in the field of absolute gravimetry. Metrologia, 49 (6), 666–684. DOI: http://dx.doi.org/10.1088/0026-1394/49/6/666

Kavouras, M. (1982). On the Detection of Outliers and the Determination of Reliability in Geodetic Networks, Technical Report no 87. Fredericton, Canada: University of New Brunswick.

Kempe, C., Jivall, L., Norin, D., Steffen, H., Ågren, J., Engfeldt, A., Ning, T., Alm, L., Jämtnäs, L., Lilje, M., Lindberg, M., Wiklund, P. (2017). National Report of Sweden to the EUREF 2017 Symposium. http://www.euref.eu/symposia/2017Wroclaw/Symposium2017-Wroclaw.html, accessed 25. 9. 2017.

Krynski, J. (2015). Gravity field modelling and gravimetry. Geodesy and Cartography, 64 (2), 177–200. DOI: http://dx.doi.org/10.1515/geocart-2015-0012

Lederer, M., Nesvadba, S. (2015). A new realization of the Czech Gravity System. EUREF symposium 2015, Leipzig. http://www.euref.eu/symposia/2015Leipzig/Symposium2015-Leipzig.html, accessed 25. 9. 2017.

Longman I.M. (1959). Formulas for computing the tidal accelerations due to the moon and the sun. Journal of Geophysical Research, 64 (12), 2351–2355. DOI: http://dx.doi.org/10.1029/JZ064i012p02351.

Makinen, J., Sękowski, M., Kryński, J. (2010). The use of the A10-020 Gravimeter for the Modernization of the Finnish First Order Gravity Network. Geoinformation Issues, 2 (1), 17–29.

Markovinović, D. (2009). Gravimetrijski referentni sustav Republike Hrvatske. Unpublished PhD Thesis. Zagreb: Faculty of Geodesy, University of Zagreb.

Marson, I., Faller, J. E., Cerutti, G., De Maria, P., Chartier, J.-M., Robertsson, L., Vitushkin, L., Friedrich, J., Krauterbluth, K., Stizza, D., Liard, J., Gagnon, C., Lothhammer, A., Wilmes, H., Makinen, J., Murakami, M., Rehren, F., Schnull, M., Ruess, D., Sasagawa, G. (1995). Fourth International Comparison of Absolute Gravimeters, Metrologia. 32 (3), 137–144. DOI: http://dx.doi.org/10.1088/0026-1394/32/3/001

Marti, U., Baumann, H., Bürki, B., Gerlach, C. (2015). A First Traceable Gravimetric Calibration Line in the Swiss Alps. In: S. Jin (Ed.), R. Barzaghi (Ed.) IGFS 2014. International Association of Geodesy Symposia, vol 144 (pp. 17–25). Springer, Cham. DOI: http://dx.doi.org/10.1007/1345_2015_52

Medved, K., Kuhar, M., Stopar, B., Koler, B. (2009). Izravnava opazovanj v osnovni gravimetrični mreži Republike Slovenije. Geodetski vestnik, 53 (2), 223–238.

Medved, K., Berk, S., Koler, B., Komadina, Ž., Kuhar, M., Oven, K., Pavlovčič Prešeren, P., Režek, J., Strele, O., Stopar, B. (2015). National Report of Slovenia to the EUREF 2015 Symposium in Leipzig. http://www.euref.eu/symposia/2015Leipzig/Symposium2015-Leipzig.html, accessed 25. 9. 2017.

Mitterschiffthaler, P., Ruess, D., Stangl, G., Titz, H., Ullrich, Ch., Zahn, E. (2016). EUREF National Report of Austria 2016. http://www.euref.eu/symposia/2016SanSebastian/Symposium2016-SanSebastian.html, accessed 25. 9. 2017.

Niemeier, W. (2002). Ausgleichungsrechnung. Berlin, New York: Walter de Gruyter.

Odalović, O., Starcević, M., Grekulović, S., Burazer, M., Aleksić, I. (2012). The establishment of a new gravity reference frame for Serbia. Survey Review, 44 (327), 272–281. DOI: http://dx.doi.org/10.1179/1752270611Y.0000000033

Pálinkáš, V., Lederer, M., Kostelecký, J., Šimek, J., Mojzeš, M., Ferianc, D., Csapó, G. (2013). Analysis of the repeated absolute gravity measurements in the Czech Republic, Slovakia and Hungary from the period 1991–2010 considering instrumental and hydrological effects. Journal of Geodesy 87 (1): 29–42. DOI: http://dx.doi.org/10.1007/s00190-012-0576-1

Pope, A. J. (1976). The Statistics of Residuals and the Detection of Outliers. Rockville, Md., USA: National Ocean Survey.

Pravilnik o načinu izvođenja osnovnih geodetskih radova (=The Book of Rules on the Fundamental Geodetic Works). Official Gazette of the Republic of Croatia No.87/2009.

Repanić, M., Barišić, B., Grgić, I., Liker, M., Lučić, M., Bašić, T. (2010). Extension of the Croatian Fundamental gravity network to the north Adriatic islands. Gravity, Geoid and Earth Observation GGEO 2008, 23-26 July, Chania, Greece. In T. Bašić (Ed.), Zbornik radova Hrvatskog geodetskog instituta 2006.-2009 (pp. 137–144). Zagreb: Hravatski geodetski institut.

Repanić, M., Grgić, I., Bašić, T. (2014). Prijedlog dopune gravimetrijske mreže 0. reda Republike Hrvatske. Geodetski list, 68 (1), 17–32.

Repanić, M., Kuhar, M., Malović, I. (2015). High precision vertical gravity gradient determination in Croatia. Acta Geodaetica et Geophysica, 50 (2), 151–171. DOI: http://dx.doi.org/10.1007/s40328-015-0102-z

Repanić, M., Kuhar, M. (2017). Modelling Hysteresis Effect in Scintrex CG-3M Gravity Readings. Geophysical Prospecting. DOI: http://dx.doi.org/10.1111/1365-2478.12557

Reudink, R., Klees, R., Francis, O., Kusche, J., Schlesinger, R., Shabanloui, A., Sneeuw, N., Timmen, L. (2014). High tilt susceptibility of the Scintrex CG-5 relative gravimeters. Journal of Geodesy, 88 (6), 617–622. DOI: http://dx.doi.org/10.1007/s00190-014-0705-0

Robertsson, L., Francis, O., van Dam, T. M., Faller, J., Ruess, D., Delinte, J.-M., Vitushkin, L., Liard, J., Gagnon, C., Guo You Guang, Huang Da Lun, Fang Yong Yuan, Xu Jin Yi, Jeffries G., Hopewell H., Edge R., Robinson I., Kibble B., Makinen J., Hinderer J., Amalvict M., Luck B., Wilmes H., Rehren F., Schmidt K., Schnull M., Cerutti G., Germak A., Zabek A., Pachuta A., Arnautov G., Kalish E., Stus Y., Stizza D., Friederich J., Chartier J.-M., Marson I. (2001). Results from the Fifth International Comparison of Absolute Gravimeters, ICAG97. Metrologia, 38 (1), 71–78. DOI: http://dx.doi.org/10.1088/0026-1394/38/1/6

Tamura, Y. (1987). A harmonic development of the tide-generating potential. Bulletin D'Information des Marees Terrestres 99, 6813–6855.

Timmen, L., Flury, J., Peters, T., Gitlein, O. (2006). A new absolute gravity base in the German Alps. In: Hvoždara, M. (Ed.), Kohúh I. (Ed.), Contributions to Geophysics and Geodesy, 36 (special issue): 2nd Workshop on International Gravity Field Research (pp. 7–20). Bratislava: Slovak Academy of Sciences.

Timmen, L., Wenzel, H.-G. (1995). Worldwide synthetic gravity tide parameters. In: H. Sünkel (Ed.), I. Marson (Ed.) Gravity and Geoid. Proceedings of IAG Symposium, 113 (pp. 92–101), Berlin, Heidelberg: Springer. DOI: http://dx.doi.org/10.1007/978-3-642-79721-7_11

Torge, W. (1989). Gravimetry. New York, Berlin: Walter de Gruyter.

Van Camp, M., Hendrickx, M., Richard, P., Thies, S., Hinderer, J., Amalvict, M., Luck, B., Falk, R. (2003). Comparisons of the FG5#101, #202, #206 and #209 Absolute Gravimeters at Four Different European Sites. In P. Francis (Ed.), T. Van Dam (Ed.), Proceedings of the Workshop: IMG-2002: Instrumentation and Metrology in Gravimetry (pp. 65–73). Luxembourg: European Center for Geodynamics and Seismology.

Vitushkin, L. (2007). Measurement standards in gravimetry. In V. G. Peshekhonov (Ed.), International Symposium on Terrestrial gravimetry: Static and mobile measurements: Proceedings (pp. 197-202). Saint Petersburg: Elektropribor.

Vitushkin, L., Becker, M., Jiang, Z., Francis, O., Van Dam, T. M., Faller, J., Chartier, J.-M., Amalvict, M., Bonvalot, S.,Debeglia, N., Desogus, S., Diament, M., Dupont, F., Falk, R., Gabalda, G., Gagnon, C. G. L., Gattacceca, T., Germak, A., Hinderer, J., Jamet, O., Jeffries, G., Käker, R., Kopaev, A., Liard, J., Lindau, A., Longuevergne, L., Luck, B., Maderal, E. N., Mäkinen, J., Meurers, B., Mizushima, S., Mrlina, J., Newell, D., Origlia, C., Pujol, E. R., Reinhold, A., Richard, Ph., Robinson, I. A., Ruess, D., Thies, S., Van Camp, M., Van Ruymbeke, M., de Villalta Compagni, M. F., Williams, S. (2002): Results of the Sixth International Comparison of Absolute Gravimeters, ICAG-2001. Metrologia, 39 (5), 407–424. DOI: http://dx.doi.org/10.1088/0026-1394/39/5/2

Wenzel, H. G. (1996). The nanogal software: Earth tide data processing package ETERNA 3.30, Bulletin D'Informations Marees Terrestres, 124, 9425–9439.

Wilmes, H., Richter, B., Falk, R. (2003). Absolute Gravity Measurements: a System by Itself. In I. N. Tziavos (Ed.), Proceedings of the 3rd Meeting of the International Gravity and Geoid Commission, Gravity and Geoid GG2002 (pp. 19–25). Thessaloniki, Ziti Editions.

Wilmes, H., Vitushkin, L., Pálinkáš, V., Falk, R., Wziontek, H., Bonvalot, S. (2016). Towards the Definition and Realization of a Global Absolute Gravity Reference System. In: International Association of Geodesy Symposia. Springer, Berlin, Heidelberg. DOI: http://dx.doi.org/10.1007/1345_2016_245

Wziontek, H., Falk, R., Wilmes, H. (2015). The absolute gravity reference system and its contribution to geoid determination. EUREF Symposium 2015, Tutorial Height and Gravity. http://www.euref.eu/documentation/Tutorial2015/t-03-02-Wziontek.pdf, accessed 8. 9. 2017.

Repanić M. (2017). New Adjustment of the Croatian First Order Gravity Network. Geodetski vestnik, 61 (4), 630-648.
DOI: 10.15292/geodetski-vestnik.2017.04.630-648

Marija Repanić, M.Sc.
Croatian State Geodetic Administration
Gruška 20, HR-10000 Zagreb, Croatia
e-mail: marijarepanic@yahoo.com