Gravity measurements on the territory of the Republic of Croatia – past, current and future gravity networks*

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Abstract. *The paper depicts concise historical overview on gravity measurements on the territory of the Republic of Croatia, as well as on going activities in the field of fundamental gravity works and, in the last part, outlines planned activities in same field.*
Although first gravimetric measurements on the territory of the Republic of Croatia where relative measurements performed between 1887 and 1894 in the area of Rijeka city, first activities on establishment of the Fundamental Gravity Network were done just about 1950s by the VGI (Military Geographical Institute), when Croatia was part of former Yugoslavia. In course of mentioned works, the First Order Gravity Network of Yugoslavia was established with connection of central station (Belgrade) to absolute stations in Paris. Six of 15 first order stations where on the territory of Croatia. Subsequently, work on the second order network started, by finalization of which, the Fundamental Gravity Network of former Yugoslavia was established in late 1960s.
Even though considerable part of the Fundamental Gravity Network of former Yugoslavia was on the territory of Croatia, after gaining independence, because of inability to gain data on the network that is kept in Belgrade and because of condition and layout of existing gravity stations, the Republic of Croatia had to start over with establishment of a fundamental gravity network. Hence, Croatia established 6 absolute gravity stations that form the Zero Order Gravity Network of the Republic of Croatia. Following, the First Order Gravity Network has been established that comprises 36 relative stations (including 25 stations from old fundamental network). Today, the Fundamental Gravity Network that comprises zero and first order network is completely established and there is an on going project of the Second Order Gravity Network. In addition, realisation of the gravity meter calibration line, cyclic re-surveys of the Fundamental Gravity Network, as well as its densification on land area and extension on the Croatian islands are planned.

1 Introduction

The Republic of Croatia is a small country situated on the crossroads between Central Europe and the Mediterranean, along the eastern coast of the Adriatic Sea. It stretches from the hilly sides of the Alps on the northwest to the Panonnian plain on the East. Its area comprises of 87 661 km^2, from that 56 594 km^2 is land area and 31 067 km^2 is surface area of territorial sea and interior seawaters. The population accounts of 4,442 million inhabitants (DZS 2007). Although the Republic of Croatia declared its independence not before 1991 and was recognised in December 5th 1992 as independent state, Croatia has a long history of geodetic activities. However, since major geodetic activities where carried out during the time

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when the major part of Croatia belonged to Austro-Hungarian Empire and later during the time when Croatia was one of six socialistic republics within federative Yugoslavia, established geodetic foundation was not suitable for the present territory of the Republic of Croatia. Besides, geodetic works carried out during that period is not in compliance with modern geodetic standards and requirements. Therefore, since the time when the Republic of Croatia gained its independence, a great need for re-establishment of geodetic foundation arises.

Gravity measurement works are not an exception. Moreover, as gravity measurements are concerned, there is an additional problem. Namely, major part of gravity measurements prior to independence of the Republic of Croatia has been done in time of Yugoslavia, by the *VGI*. Consequently, after the break-up of Yugoslavia, the Republic of Croatia lacks access to data on gravity survey from that time (Bašić and Markovinović 2002). Thus, the need for establishment of Croatian fundamental gravity network was more than evident. As a result, activities necessary for the establishment of the fundamental gravity network took place shortly after the Republic of Croatia gained independence. To be exact, Croatia established 6 absolute gravity stations that form the Zero Order Gravity Network of the Republic of Croatia in the course of two stages: 4 stations in 1996 and two more stations in 1999 and 2000 in the course of UNIGRACE project (CGI 2004; Medak et al. 2002). Following, the First Order Gravity Network has been established. Today, the Fundamental Gravity Network that comprises zero and first order network is completely established (Grgić et al. 2007) and there is an on going project of the Second Order Gravity Network.

2 Gravity measurements prior to the Republic of Croatia

First gravity measurements on Croatian territory were relative measurements conducted by Military-Geographic Institute (*Militärgeographisches Institut*) in Vienna. Those measurements where carried out already between 1887 and 1894 in the area of city Rijeka, and latter, between 1910 and 1912 and in 1939, in northern parts of Croatia (Bašić and Markovinović 2002; Kuhar 2006).

Yet, according to Stefanović (1958) and Grašić (1958; 1970), fundamental gravimetric activities on Croatian territory started after 1951, when former Yugoslavia begun with establishment of the First Order Gravity Network, with connections of central station in Belgrade (airport Zemun) with absolute stations in Paris (airport Orly in 1951 and airport Le Bouget in 1953). According to same sources, both connections were realized with relative gravity meter Worden No 63 in the ownership of the *VGI*, calibrated on French calibration lines prior to both campaign, though connection in 1951 was also measured with relative gravity meter North American No 124. Apart from central station in Belgrade, the First Order Gravity Network of former Yugoslavia had comprised 14 more gravity stations, and thus formed 14 closed figures, i.e. triangles (Figure 1). Six first order gravity stations where on the territory of Croatia: station in Borovo, Zagreb, Pula, Zadar, Sinj and Gruda (ibid; Bašić and Markovinović 2002; Bašić et al. 2006b). Measurements of the First Order Gravity Network were conducted in 1952 and 1953 (whole network was measured twice in two independent stages) with same gravity meter, i.e. Worden No 63, and adjusted by least square method (Stefanović 1958; Grašić 1958; Grašić 1970). Unfortunately, among old first order stations on Croatian territory, only the station in Borovo (today part of Vukovar city) is not destroyed.

According to the same sources, along with above described works, on the basis of relative gravity measurements with gravity meters calibrated on French calibration lines, calibration lines where established for the purposes of further gravity measurements. Calibration line for large circle Belgrade – Skoplje was withal line of the First Order Gravity

Network, while calibration line on hill Avala was of smaller range, and therefore used only for calibration of small circle. However, none of these calibration lines where on the territory of the Republic of Croatia.

In 1954, with measurements from Zagreb through Ljubljana and Sežana to Italy, the First Order Gravity Network of former Yugoslavia was connected to Italian gravity network for the purposes of definition of unitary mGal. By mentioned connection, figure that runs from Paris through Frankfurt, Belgrade, Zagreb, Sežana, Trieste, Padova and Milan, again to Paris, was closed. Miss closure of the figure was 0.22 mGals (2.2 μms^{-2}) that indicates of relative high quality measurements and good consistency of networks of different states for that time. (Stefanović 1958; Grašić 1958; Grašić 1970)

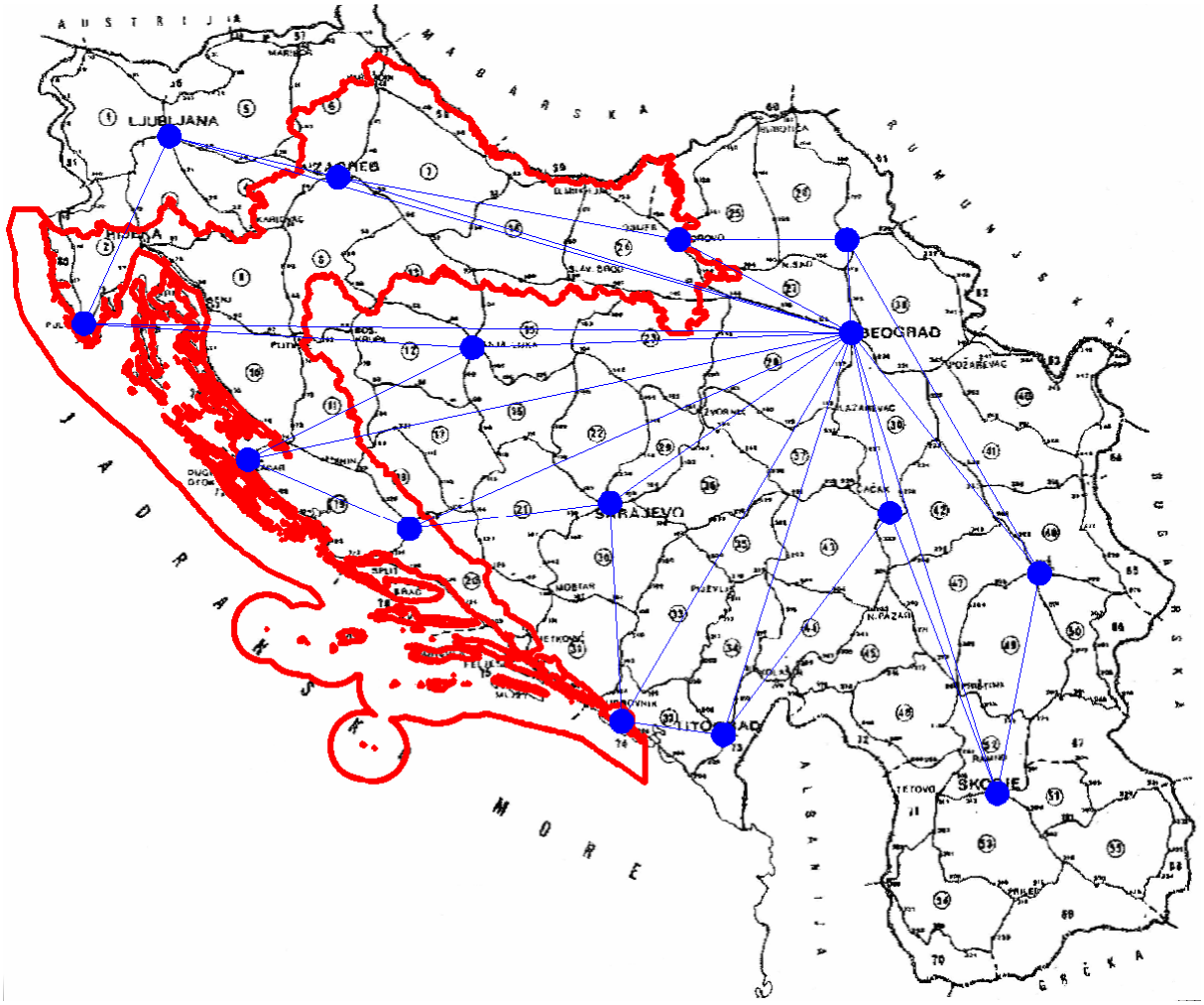

Figure 1: The First Order and Fundamental Gravity Network of ex-Yugoslavia

In period from 1958 to 1960 the *VGI* and Institute for Geological and Geophysical Researches have been carrying out the measurements of the Second Order Gravity Network of former Yugoslavia (Bašić et al. 2006b; Grašić 1958). The second order gravity stations were settled out every 10 km or more, for the purpose of: control of gravity measurements along levelling lines of high accuracy levelling; gravity anomaly charts drafting; determination of the deflection of the vertical; and other (Stefanović 1958). Detail station descriptions of gravity stations of second order where compiled and filed in register managed by the *VGI* in Belgrade (Grašić 1958).

In the period from 1964 to 1967, the *SGU* (Federal Geodetic Administration), have established the Fundamental Gravity Network of former Yugoslavia (Figure 1) (Bašić et al. 2006b). Gravity stations of first and second order were included in the network (Kuhar 2006, Grašić 1970). According to Bašić et al. (2006b), the network "…comprised 55 closed figures with 350 main stations (station separation 30 km) and 1150 minor stations (station separation 10 km). … After the brake up of former state, the Republic of Croatia does not have the access to that data, for now (the matter of succession), with exception of station description for 84 main stations, which are situated on its territory".

According to Grašić (1970), in 1969, old Fundamental Gravity Network was connected to Italian network by two connections: between I. order station in Gruda (near Dubrovnik) and Italian station at Fiumicino airport near Rome; and between II. order station in Kopar and station at the Experimental Geophysics Observatory in Trieste. As a result, a figure that runs from Gruda through Koper, Trieste and Rome, and again to Gruda was closed. The connections where done in the course of gravimetric works for the purpose of validity evaluation of old fundamental network and calibration lines, since, in middle 1950s, European fundamental network with central point in Potsdam was established and French calibration lines, on which Yugoslavian network and calibration lines where lined on, have changed. Mentioned works proved relatively good consistency of the network, since mentioned figure closed in 0.13 mGals (1.3 μms^{-2}).

Although the Fundamental Gravity Network of former Yugoslavia was in old Potsdam Gravity System, 3 stations (1 in Zagreb and 2 in Belgrade) where included in the International Gravity Standardization Net 1971, IGSN71 (Bašić et al. 2006b).

Unfortunately, as mentioned above, Croatia does not have the access to data on gravimetric works on its territory gathered in former state, with exception of station description for 84 gravity stations compiled by the former *SGU*. Moreover, of those 84 stations, only 35 stations are found in the course of revision of old Fundamental Gravity Network on territory of the Republic of Croatia, carried out in 2000 (Bašić and Markovinović 2002). What is more, in 2003 it is determined that two more stations are destroyed (Bašić et al. 2004; Bašić et al. 2006b). Hence, one can conclude that gravimetric works on the territory of Croatia performed in former state, although comprehensive and significant, do not provide much of a legacy to Croatian scientists.

3 Gravity measurements in the Republic of Croatia

Since the Republic of Croatia lacks access to data on old gravity network, it was necessary to undertake extensive works on the establishment of new fundamental gravity network. One of the first tasks was setting up a number of absolute stations on Croatian territory. Unlike positional and height datum, gravity datum is directly determined by absolute gravity measurements at each absolute gravity station. A modern gravity network is hence based on several absolute gravity stations, which constitute absolute gravity network or a zero order gravity network. In line with that, the absolute gravity network that comprises 6 stations uniformly distributed on entire territory of the Republic of Croatia was established (Figure 2).

In the course of the project *Connection of the Republic of Croatia to International Absolute Gravity Basestation Network* during June 1996 in collaboration with experts of the former German *Institut für Angewändte Geodäsie* (*IfAG*), today the *Bundesamt für Kartographie und Geodäsie* (*BKG*), measurements with the absolute gravity meter FG5-101 at four newly established absolute stations: Zg-Maksimir, Zg-Puntjarka, Pula and Makarska where performed (Table 1).

In the course of the international project *UNIfication of GRAvity systems in Central Europe* (UNIGRACE) that started in 1998 two new absolute stations: Dubrovnik and Osijek where established in Croatia. The measurements where carried out in two stages by the French *Ecole et Observatoire des Sciences de la Terre* (*EOST*) and German *BKG*. The first measurement at station Dubrovnik was performed by the *EOST* in August 1999 with FG5-206 gravity meter, whereas the BKG team performed the second measurement in April 2000 with FG5-101 gravity meter, which was also used in previous campaign in 1996. The first measurement at station Osijek was carried out by the *BKG* in August 2000, while the second measurement performed the *EOST* team in November same year with same gravity meters as for previous measurements (CGI 2004).

Table 1: Absolute gravity measurements in the Zero Order Network

	1. measurement			2. measurement		
Station	Date	Institution	Gravity meter	Date	Institution	Gravity meter
AGT02 Maksimir	Jun. 1996	*IfAG*	FG5-101	-	-	-
AGT03 Puntjarka	Jun. 1996	*IfAG*	FG5-101	-	-	-
AGT04 Pula	Jun. 1996	*IfAG*	FG5-101	-	-	-
AGT05 Makarska	Jun. 1996	*IfAG*	FG5-101	-	-	-
AGT06 Dubrovnik	Aug. 1999	*EOST*	FG5–206	Apr. 2000	*BKG*	FG5-101
AGT01 Osijek	Aug. 2000	*BKG*	FG5-101	Nov. 2000	*EOST*	FG5–206

In addition to mentioned works, because of significance of the absolute stations in addition to bad experiences regarding the destruction of the absolute station in Makarska, at zero order stations the works for the purpose of its security were conducted. In the course of mentioned works at every absolute station three gravimetric eccentres were established. Monumentation was carried out in 2004, while the gravity connections of eccentres to each absolute station have been measured in stages in 2005 and 2006 (Bašić et al. 2006a). After establishment of the Zero Order Gravity Network, that took four years, the preconditions for further development of the network in lower order networks are fulfilled.

Outbreak of works on the First Order Gravity Network occurred in 2000, when, as mentioned above, detail analysis of the condition of inherited fundamental network of former state was performed. The results of the analysis that was carried out on the basis of old station descriptions, which are the only available data on former network, as well as later examination of stations, have shown that, of totally 84 old stations, 51 station is buried or destroyed, 2 stations are damaged, while only 31 station is in adequate state (Bašić and Markovinović 2002; Bašić et al. 2004).

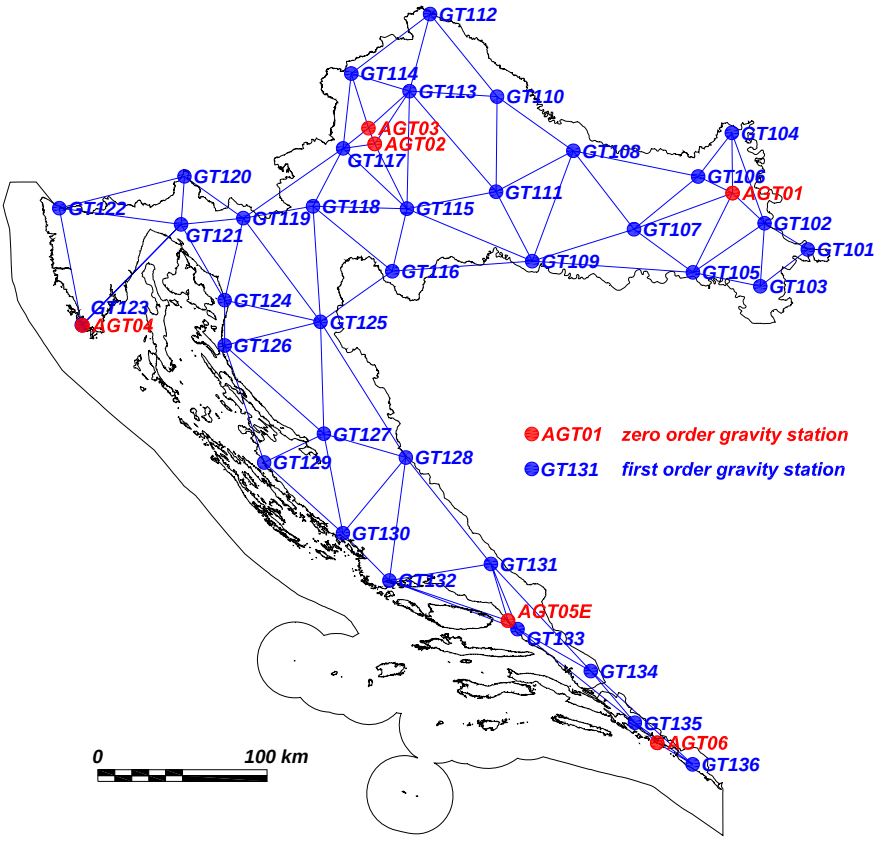

Figure 2: The First Order Gravity Network connecting the zero and first order stations

New First Order Gravity Network (Figure 2) comprises totally 36 stations, of which 25 stations are taken over from old network (Figure 3), whilst 11 stations are newly monumented (Figure 4) (Bašić and Markovinović 2002). After defining the locations for the network stations, in the period from June to August 2003, the zero cycle of the measurements have been conducted. After the measurements processing, preliminary gravity values at the stations of new First Order Gravity Network where obtained. The measurements are performed with two relative gravity meters Scintrex CG-3M by the experts from the Faculty of Geodesy, University of Zagreb (Bašić et al. 2004). At the measurements three basic methods are combined: star (Figure 5), profile (Figure 6) and figure closure (Figure 7).

Figure 3: Old gravity station monumentation

Figure 4: New gravity station monumentation

Finally, the Fundamental Gravity Network, which comprises 42 gravity stations (6 zero order stations and 36 first order stations) and represents the practical realization of IGSN71 gravity system in the Republic of Croatia, is established. Processing and adjustment of the Fundamental Gravity Network of the Republic of Croatia indicate that the measurements are conducted in conformity with international recommendations and criteria. As well, the accomplished accuracy is more than satisfactory (standard deviation of gravity values is in range from 36.0 to 67.8 nms^{-2}, i.e. 3.60 to 6.78 μGals). On top, the Fundamental Gravity Network is the foundation of new Croatian Gravity Reference Frame, abbreviated *HGRS03* (NN 2004).

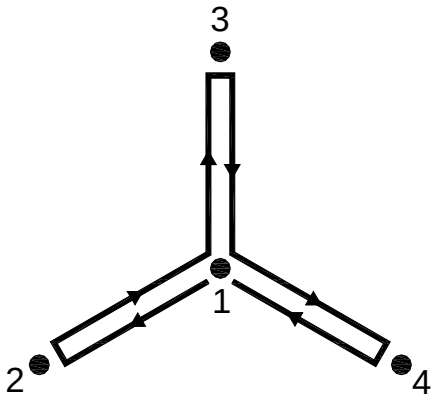

Figure 5: The star method

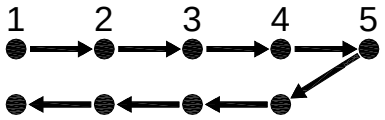

Figure 6: The profile method

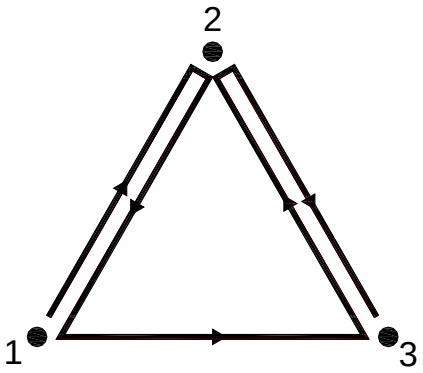

Figure 7: The figure closure method

Further densification of the network shall be realized in near future, with the activities on the Second Order Gravity Network establishment (Figure 8). For now, the locations of the second order gravity station are determined. As perceptible from the figure, the station separation shall be around 30 km. According to the plan, the network shall comprise 206 stations. The measurements of the Second Order Network shall be carried out in several stages, regarding the sectors, on which the territory of the Republic of Croatia shall be divided in. The beginning of the first stage of measurements is planned for the autumn 2007, whereas the competition of the measurements shall be reached in several following years, depending on the capacities of the Croatian Geodetic Institute that shall be carrying out the works (CGI 2007).

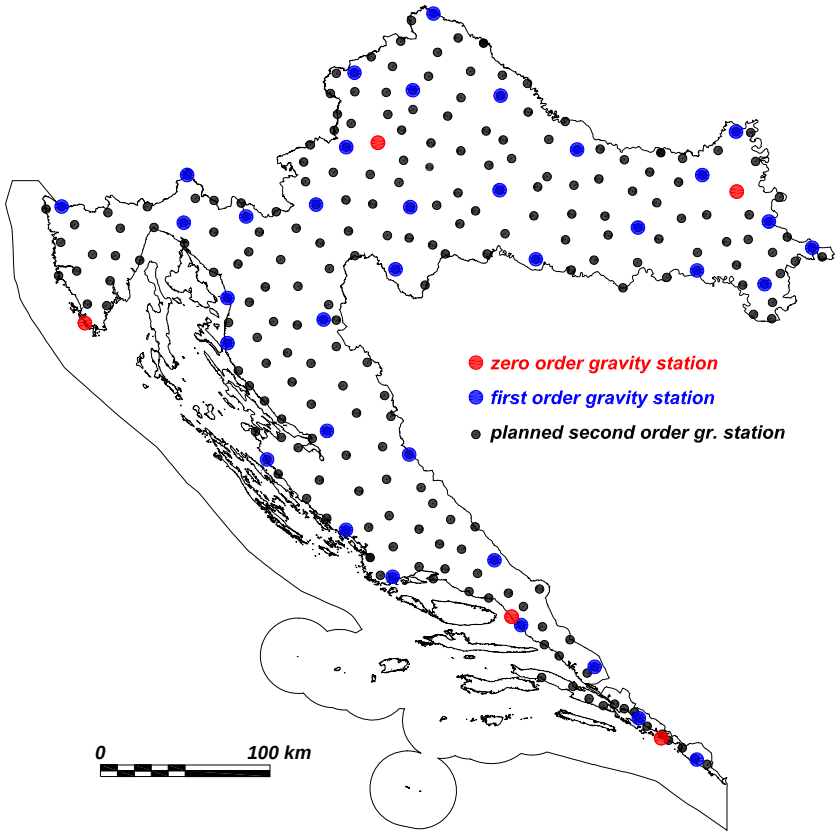

Figure 8: Plan of the Second Order Gravity Network

The measurements of the second order gravity network of the Zagreb city (Figure 9) provide useful experiences for the development of the Second Order Gravity Network. The measurements where conducted in June 2005 with relative gravity meter Scintrex CG-5 by the experts from the Faculty of Geodesy, University of Zagreb. At 34 stations that constitute the network the gravity value of adequate accuracy was reached - standard deviation of gravity values where in range from 11.5 to 48.5 nms^{-2}, i.e. 1.15 to 4.85 μGals (Bašić et al. 2006c).

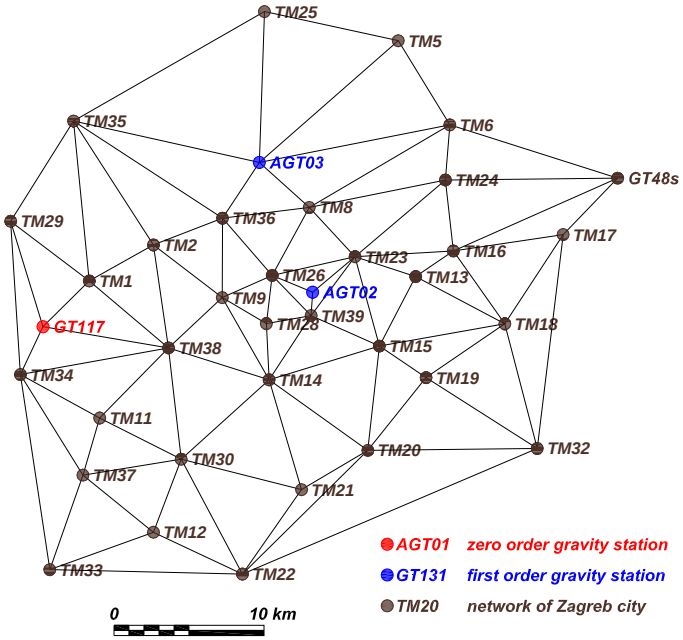

Figure 9: Gravity network of the Zagreb city

In the period form September to November 2006, together with Slovenian, the experts form the Croatian Geodetic Institute have measured the First Order Gravity Network of the Republic of Slovenia (Kuhar et al. 2007). Two national networks of first order have been connected through four common stations. Given that the same instruments (Scintrex CG-3M relative gravity meters) and measurement methods where used for the measuring both networks, one can expect that the properties of the networks shall almost similar.

4 Conclusion

Even though the Republic of Croatia had to start over from scratch with fundamental gravimetric works, it managed to realize a significant amount of work in relatively short time period, i.e. from 1996 until today. Namely, the Zero Order Gravity Network of the Republic of Croatia that consists of 6 absolute stations is established through the international cooperation. Subsequently, it is densified with the First Order Gravity Network that comprises 36 stations. The zero and first order networks are integrated in the Fundamental Gravity Network. Moreover, the activities on the establishment of the Second Order Gravity Network are already underway, and the measurements are about to begin. In addition, cyclic re-surveys of the Fundamental Gravity Networks, as well as its densification on land area and extension on the Croatian islands are planned.

One can notice that in the past as well as today a numerous fundamental gravimetric activities where carried out by different institutions. Alongside with the benefits of such case, bringing together such activities, along with related documentation, under single strong centre that could meet the upcoming challenges and put in better use gathered experiences should be strongly considered. Croatian Geodetic Institute is for shore the capable institution to fulfil that tasks.

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