PREGLED ZNANSTVENIH IN STROKOVNIH PROJEKTOV NA PODROČJU OSNOVNIH GEODETSKIH DEL NA OZEMLJU REPUBLIKE HRVAŠKE V OBDOBJU 1991–2009

AN OVERVIEW OF SCIENTIFIC AND PROFESSIONAL PROJECTS IN THE FIELD OF BASIC GEODETIC WORKS AT THE TERRITORY OF REPUBLIC OF CROATIA IN PERIOD FROM 1991–2009

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IZVLEČEK

V članku je opisana kronologija vseh osnovnih geodetskih del z glavnimi projekti in dobljenimi rezultati, ki so bila izvedena, odkar je mednarodna javnost priznala Hrvaško kot suvereno in neodvisno državo do leta 2009, kar je obdobje 18 let. Predstavljeni so tudi podedovani (HDKS, AVD1875 in HVRS1875) in novi, uradno sprejeti (HTRS96, HVRS71 in HGRS03) geodetski referenčni sistemi Republike Hrvaške ter tudi razvoj starega (DAT_ABMO z modelom geoida HRG2000) in novega (T7D2006 in T7D2009 z modelom geoida HRG2009) transformacijskega modela za Republiko Hrvaško.

ABSTRACT

The article describes chronology of all basic geodetic works through main projects details and obtained results in period from recognition of Croatia as a sovereign and independent state by the international public to 2009 that is in period of 18 years. Article also describes inherited geodetic reference systems of Republic of Croatia (HDKS, AVD1875 and HVRS1875) and the new adopted official ones (HTRS96, HVRS71 and HGRS03) as well as development of old (DAT_ABMO with HRG2000 geoid model) and new coordinate transformation models (T7D2006 and T7D2009 with HRG2009 geoid model) of Republic of Croatia.

KLJUČNE BESEDE

kronologija, osnovna geodetska dela, geodetski referenčni sistemi, transformacijski modeli

KEY WORDS

chronology, basic geodetic works, geodetic reference systems, transformation models

1 INTRODUCTION

"Consequences" of Croatia's existence as a part of former Austrian-Hungarian Monarchy (1901) are seen in geodetic aspect as well. Republic of Croatia has historically inherited horizontal (2D) coordinate reference system as colloquially called "HDKS" (cro. *Hrvatski državni koordinatni sustav*), "Hermannskögel", "HR1901" or "MGI1901". HDKS was realized by astro-geodetic measurements of Military Geodetic Institute (MGI) in 1st order triangulation network, inhomogenously adjusted in 7 separate blocks (Figure 1) by conditional measurements (Bašić et al., 2000). Fundamental point (origin) (P_0) of HDKS was situated at *Hermannskögel* hill, near Vienna ($H = 542\ m$). Coordinates of the origin ($\varphi_0 = 48°16'15''.29$, $\lambda_0 = 33°57'41''.06$ from *Ferro*) and the orientation to the nearby hill *Hundesheimer Berg* ($A = 107°31'41''.70$) were determined by astro-geodetic measurements as well (Bašić et al., 2000). HDKS represents local (non-geocentric) geodetic datum, defined by 5 parameters: 2 for surface definition (ellipsoid semi-major axis - a; flattening - f) and 3 position parameters (φ_0, λ_0, h_0 or vertical deflection components - ξ_0, η_0 with geoid undulation - N_0) (Bašić, 2005a). Surface parameters define the mathematical approximation of Earth's shape - ellipsoid. For HDKS *Bessel 1841* rotation ellipsoid was selected. Position parameters, defining the fundamental point (origin) are indexed with "0" (zero) because its initial values must be *a priori* known or arbitrarily selected. If arbitrary position parameters are selected, equality follows: $\xi_0 = \eta_0 = N_0 = 0$. This equality causes superposition of geodetic and astronomical coordinates ($\varphi_0 = \Phi_0$; $\lambda_0 = \Lambda_0$) that is superposition of normal and vertical at P_0. Equality $N_0 = 0$ causes the superposition of ellipsoidal and orthometric height ($h_0 = H_0$) that is coincidence of ellipsoid and geoid surfaces at P_0. Above described procedure of absolute orientation of 1st order triangulation network for local geodetic datum definition is the fundament of astro-geodetic measuring technique (Čubranić, 1972). Transformation to projection plane is ensured using *Gauss-Krüger* vertical cylindrical projection (adopted in 1924) (Borčić, 1976) with division of the territory of Republic of Croatia in two meridian zones (5th and 6th). Looking from historical point of view to height component as indispensable part of compound coordinate reference system (CCRS), Republic of Croatia has inherited two reference height systems/datums, based on two levelling networks of highest order: Austrian Precise Levelling (cro. *Austrijski precizni nivelman* – APN) and 1st High Accuracy Levelling (cro. *I. nivelman visoke točnosti* – INVT) (Figure 2).

APN was conducted in period from 1874 to 19016 including whole southern and southeastern part of former Austrian-Hungarian Monarchy, that is territories of today's Croatia, Slovenia and Bosnia and Herzegovina (Rožić, 2001). At the 2nd Conference of Government Commissioners in 1867, APN was suggested to be a basis for height system realization. The holder and contractor was also MGI from Vienna. During levelling measurements at APN, no gravimetric measurements along levelling sides were performed, so the adopted height system was normal-orthometric. Reference surface for this height system (mean sea level – geoid) was determined using one year measurements in 1875 at tide gauge in *Trieste*, mole *Sartorio* (Feil et al., 1993) with 1 cm accuracy (Rožić, 2001). This height system was colloquially called "Austrian Height Datum 1875" (cro. *Austrijski visinski datum 1875* – AVD1875). After the World War II, the only height basis of former Yugoslavia was the one from APN which indicates that there were no levelling measurements between two World Wars. Since the long period of APN establishment has passed, Federal Geodetic Administration of Yugoslavia ordered a revision of APN benchmarks. After the revision and taking in consideration the state of preservation of APN benchmarks, in 1946 MGI from

Belgrade started levelling measurements at INVT. The configuration of INVT was mostly coincided with APN with additional benchmarks stabilizations along levelling lines. Levelling measurements lasted till 1955 with some repeating measurements till 1963. There were no gravity measurements as well so the adopted height system was again normal-orthometric with same origin at mole *Sartorio*. The main characteristic of INVT was that it didn't satisfy the conditions for levelling of high accuracy (with reference probable error $u_0 = \pm 1.33\ mm\sqrt{km}$). Reference height system based on INVT (and APN) was called "Croatian Reference Height System 1875" (cro. *Hrvatski visinski referentni sustav 1875* – HVRS1875).

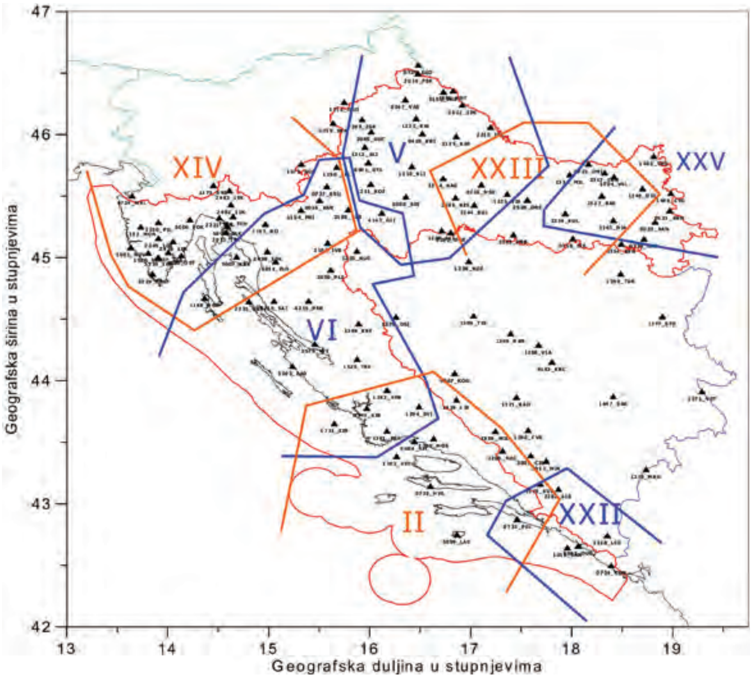

Figure 1: Adjustment blocks of Austrian-Hungarian 1st order triangulation network (Bašić et al., 2000).

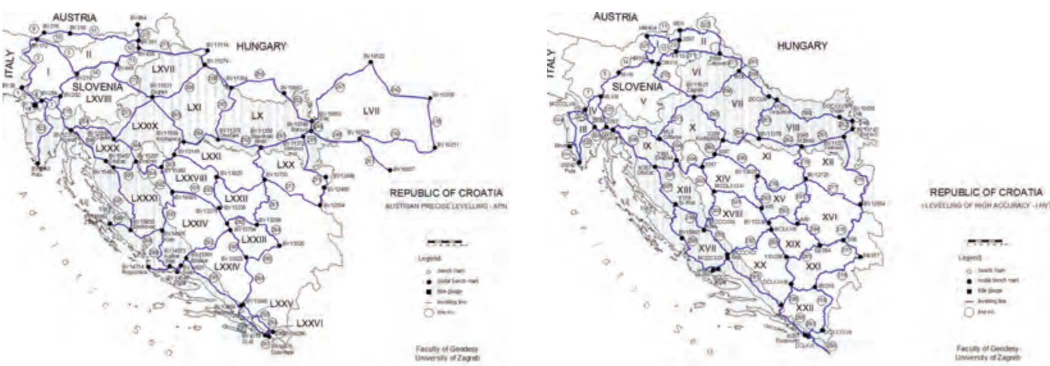

Figure 2: Configuration of APN (left) and INVT (right) networks at territories of Croatia, Slovenia and Bosnia and Herzegovina (Rožić and Razumović, 2009).

2 CHRONOLOGY OF STATE SURVEY IN CROATIA FROM 1991 TO 2004

The application of satellite surveying techniques (GPS) in Croatia started in late 80's and in the beginning of 90's of 20th century (Bilajbegović et al., 1989). In 1991 former Croatian Ministry of Science and Technology financed scientific project "Basic geodetic works of Croatian spatial information system" (cro. *Osnovni geodetski radovi informacijskog prostornog sustava Republike Hrvatske*), with Full Professors Asim Bilajbegović and Miljenko Solarić as main researchers. Under the mentioned project, first dual frequency *Ashtech* GPS receivers with possibility of registration of C/A code were obtained. Despite the war conditions, the adoption of GPS measuring technique resulted with first domestic and international GPS measuring campaigns in period from 1991 to 1993 (Solarić M. et al., 1996): CROATIA'91 – 3 stations in collaboration with Austria, Italy and Slovenia, inclusion in international project TYRGEONET'91 – 3 stations in Croatia (*Hvar*, *Pula* and *Zadar*) in collaboration with Italy and Slovenia, TYRGEONET'92 – 4 stations in Croatia (*Hvar*, *Pula*, *Zadar* and *Kozjača*) in collaboration with Italy and Slovenia with goal of determining crustal movements at area of Tyrrhenian and Adriatic Sea, inclusion in scientific project AGREF'92 – 10 stations in Croatia with goal of determining crustal movements at area of Austria, Slovenia and northern part of Croatia, ZAGORJE'92 - 10 stations in Croatia in collaboration with Slovenia, IGS'92 – 5 stations in Croatia in collaboration with 40 countries worldwide, BRZA PRUGA '93 – 10 stations in Croatia for the purposes of former State Hydrographic Institute, SLAVONIJA'93 – 8 stations in Croatia for the purposes of Croatian Ministry of Defense and inclusion in international scientific project ADRIATIC MICROPLATE '93 - 1 station in Croatia (*Hvar*).

The period from 1991 to 1993 was of particular importance for Croatian geodesy. The recognition of Croatia as a sovereign and independent state by the international public, influenced on its provisional membership in International Union of Geodesy and Geophysics (IUGG) in 1992 (and later in 1995 at IUGG XXI General Assembly held in Boulder full membership) and opened the door to international scientific collaboration.

In 1992 for the first time at the territory of Republic of Croatia (northwestern part) astro-geodetic relatively orientated geoid was computed (Čolić et al., 1993). Furthermore, in 1993 the first geoid model for Adriatic Sea, based on satellite altimetry missions' data (Bašić, 1993) and first gravity geoid using FFT method (Bašić and Čolić, 1993) were computed as well. During 1993 2nd High Accuracy Levelling (cro. *II. nivelman visoke točnosti* - IINVT) levelling data started to sort, which 11 years later would be a basis for the new reference height system. In 1994 with the help of IfAG (ger. *Institut für Angewandte Geodäsie;* todays *Bundesamt für Kartographie und Geodäsie* - BKG), for the first time Republic of Croatia was included in EUREF (Regional Reference Frame Sub-Commission for Europe) GPS measuring campaigns (EUREF'94) with collaborating measuring campaign with Slovenia called CROSLO'94 (Figure 3) at 15 1st order trigonometric points using dual frequency GPS receivers *Trimble 4000 SSE*, which later would be a basis for the new horizontal reference system (Čolić et al., 1996; Marjanović and Bačić, 2001). Relying on CROSLO'94 measuring campaign, first series of measurements in Croatian Geodynamic Project - CRODYN (CRODYN'94) were obtained. CRODYN'94 (Figure 3) included 17 stations (4 EUREF permanents stations, 5 tide gauges and 8 geodynamic stations) with the goal of monitoring crustal movements at the area of Adriatic Sea (Bašić et al., 2000).

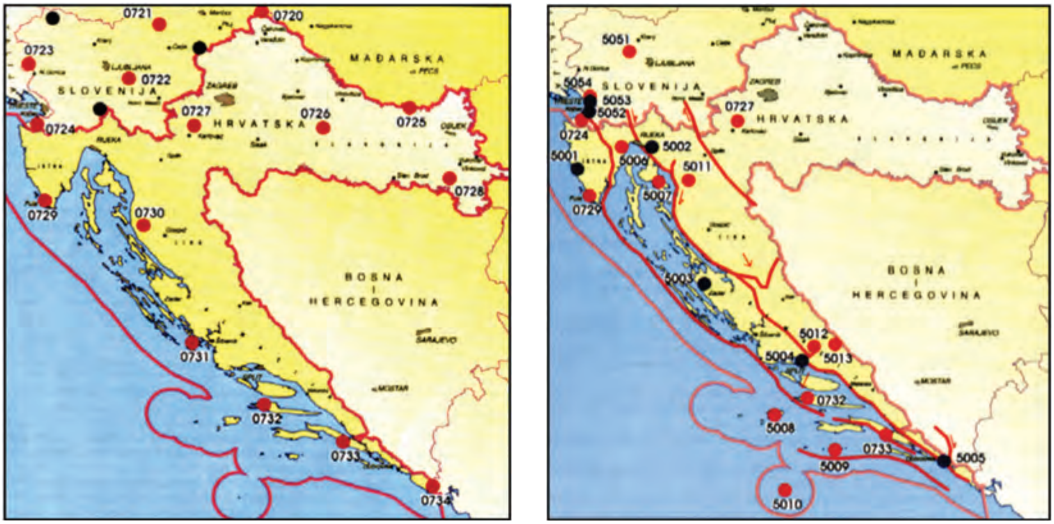

Figure 3: CROSLO'94/EUREF'94 (left) and CRODYN'94 (right) GPS measuring campaigns (Bašić et al., 2000).

In 1994 Republic of Croatia was included in Central Europe Regional Geodynamics Project (CERGOP) project that is in Central European GPS Geodynamic Reference Network (CERGN) with GPS measurements at 1st order trigonometric point *Brusnik* (near Jastrebarsko), which continues in 1995 with GPS measurements at same location (Čolić, 1996; Medak et al., 2002). Furthermore, in same year, Croatia continued its participation in TYRGEONET project with TYRGEONET'95 GPS measuring campaign at station *Hvar*. In effort of Republic of Slovenia to establish reference GPS network, in September 1995 Slovenia and Croatia organized GPS measuring campaigns SLOVENIA'95 (47 stations) and CROREF'95 (14 stations) (Marjanović and Bačić, 2001).

Significant progress in the field of gravity determination was inclusion of Croatia in project "Unification of Gravity Systems in Central Europe" (UNIGRACE) in 1996 with absolute gravity measurements at four absolute gravity stations (part of today's Croatian "Zero-order gravimetric network"): *Zagreb-Puntijarka*, *Zagreb-Maksimir*, *Pula* and *Makarska* (Bašić and Markovinović, 2002). Absolute gravity measurements were obtained using *FG5-101* absolute gravimeter in collaboration with IfaG. The second EUREF GPS campaign - CROREF'96 (Figure 4) was held in period of 29th August to 12th September 1996. Project was divided in four phases with last phase as CRODYN'96 geodynamic measuring campaign (Bašić et al., 2000).

Year 1997 was a turning point that is the beginning of modernization at the field of basic geodetic works in Croatia. In May 1997 Croatia was included in EUVN'97 project with 8 official stations (*Bakar-tide gauge*, *Busnik-EUREF*, *Dubrovnik-tide gauge*, *Gradište-EUREF*, *Split-tide gauge*, *Zagreb-benchmark*, *Rovinj-tide gauge*, *Plitvička jezera-benchmark*) and 5 additional stations (not part of EUVN'97: benchmarks in *Kostajnica*, *Livno*, *Metković*, *Virovitica* and station *Institute for Photogrammetry, Geodetic Services, Design and Implementation in Zagreb-ZZF)* (Marjanović and Rašić, 1999). The goal of EUVN project was unification of different height systems of European countries. During April and May 1997 Republic of

Croatia started one of the biggest geodetic projects at its territory - establishment and survey of so called "10-km GPS network" (Bašić et al., 2002a). The first phase of establishment and survey of "10-km GPS network" included: northwestern part (Istra and Gorski Kotar), middle part and eastern part (Slavonija) of Croatian territory (Figure 5).

Figure 4: CROREF'96/CRODYN'96 GPS measuring campaigns (Bašić et al., 2000).

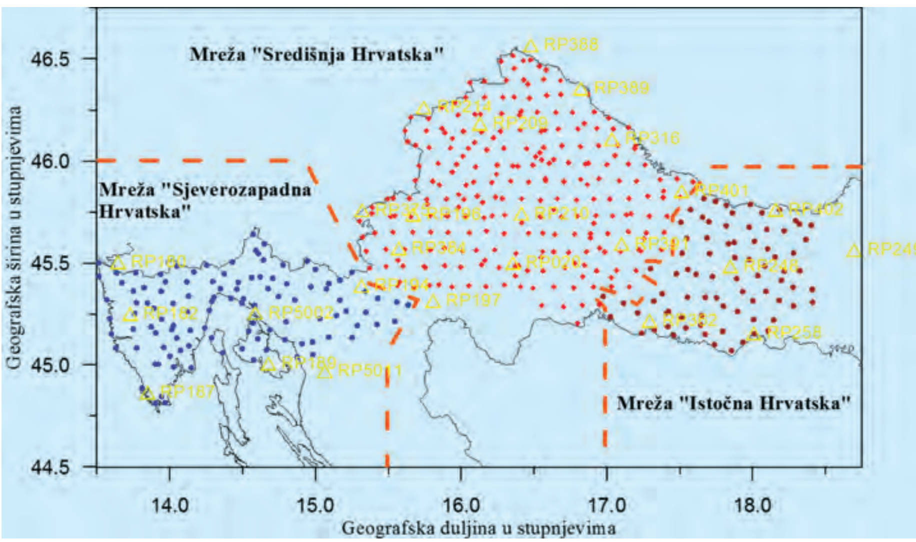

Figure 5: Part of "10-km GPS network" established in 1998 (Bašić et al., 2002a).

In first phase of project total number of 377 new stations were established, while survey besides new points included 62 existing trigonometric points and 25 reference stations. The goal of "10-km GPS network" project was the establishment of unique homogenous field of geodetic basis of Croatia that is homogenization of inherited horizontal reference system (HDKS). For the study of local tectonic activity in October 1997 the first series of measurements at "Basic GPS network of City of Zagreb" (cro. *Temeljna mreža Grada Zagreba* - TM ZG) (established during June 1997) (Figure 6) were performed.

Figure 6: "Basic GPS network of City of Zagreb" (TM ZG) (Markovinović et al., 2011).

Within TM ZG project total number of 33 new stations were established (32 stations with special built pillars and 1 station with underground stabilization - *1028 Trg Kralja Tomislava*). TM ZG consists of 43 stations (33 new + 1st order trigonometric point-*1041 Kozjača*, 2 former city permanent stations-*1038 GZAOP* and *1043 Katastar Sesvete*, 2 stations at buildings-*1039 ZZF* and *1036 Medvedgrad*, 2 stations with quality stabilization-*1014 GTŠ* and *1021 Kalibracijska baza* with 3 adjustment fixed 1st order trigonometric points-*210 Kloštar Ivanić*, *196 Samoborska Plješevica* and *514 Sljeme*, which coordinates were obtained from CROREF'96 GPS measuring campaign) (Čolić et al., 1996; Medak and Pribičević, 2002; Bašić, 2006). The establishment of TM ZG had a double goal: basis for establishment of homogeneous filed of points and basis for tectonic activity monitoring at the area of City of Zagreb (from 2001 TM ZG takes over a function of/becomes "Geodynamic network of City of Zagreb").

Significant efforts in regional gravity field research, establishment of local GPS homogeneous fields and regional monitoring of tectonic activity were made in 1998. For the first time at the territory of Republic of Croatia absolutely orientated geoid surface HRG98 (Figure 7) was calculated with internal accuracy of ±5 cm over whole territory of Croatia (Bašić et al., 1999; Bašić et al., 2000). Shortly after, improved solution HRG98A was calculated as well (Bašić and Brkić, 1998). In calculation of HRG98, for the first time, gravity point data, recalculated to free air anomalies at GRS80 level-ellipsoid were used. Furthermore, 200 astro-geodetic points with known vertical deflection components (recalculated from HDKS to global geodetic datum), ERS-2 satellite altimetry data and 28 GPS-levelling points (for absolute orientation of geoid surface) were taken into calculations as well (Bašić et al., 2000).

In the field of establishment of local GPS homogenous fields it's important to highlight the project

"Establishment of GPS homogeneous field of points of City of Zagreb". Whole project was divided in eastern and western part (Bašić, 2006). Measurements were taken in period from February to December 1998 at 4128 new established points. In September 1998 CRODYN project was continued with third measuring campaign - CRODYN'98 (Altiner et al., 2006) with GPS observations at 34 stations. Second part of UNIGRACE project in Croatia was conducted during 1999 and 2000 and included absolute gravity measurements at absolute gravity stations *Dubrovnik* and *Osijek* using *FG5-206* and *FG5-101* absolute gravimeters (Medak et al., 2001; Bašić and Markovinović, 2002). After UNIGRACE project, Republic of Croatia has established "Zero-order gravity network" (Figure 7).

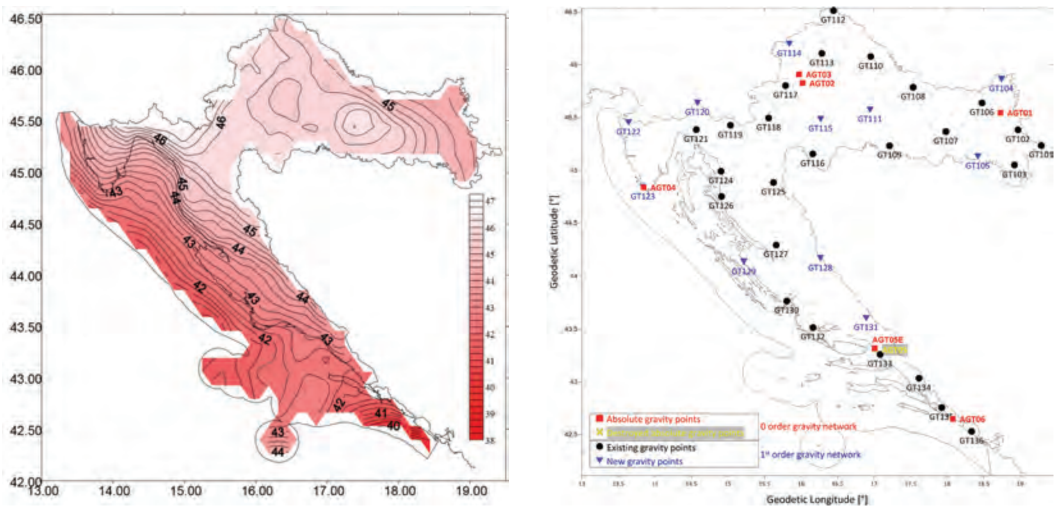

Figure 7: HRG98 geoid model in meters (left) (Bašić et al., 2000) and "Basic gravimetric network of Republic of Croatia" (right) (Bašić and Markovinović, 2002).

In October 2000 Republic of Croatia was included in IGS network of permanent GPS stations with stations *Osijek* (DOMES No. 11901M001) and *Dubrovnik* (DOMES No. 11901M002). Initial coordinates of both stations are obtained from two micro-geodetic networks with adjustment fixed points included in CROREF'96 (for Osijek: *Valpovo*, *Tvrđa Osijek* and *Gradište*; for Dubrovnik: *Dubrovnik-tide gauge* and *Ilin Vrh*) (Medak and Pribičević, 2001).

During 2000 several important project regarding to national Croatian geodetic datums were performed. In January 2000 Croatian State Geodetic Administration (CSGA) and Faculty of Geodesy - University of Zagreb (GEOF UNIZG) signed a contract of project "Geodetic and Cartographic Datum of Republic of Croatia" with special contract addition "Suggestion of official geodetic datums of Republic of Croatia". For the preparation of this study, scientists from GEOF UNIZG were engaged: for horizontal and gravimetric datum - *Prof. dr. sc. Tomislav Bašić*, for height datum - *late Prof. dr. sc. Ladislav Feil* and for cartographic projections - *Prof. dr. sc. Miljenko Lapaine*. The analysis of inherited horizontal datum (HDKS) indicated to inhomogeneity of 1st order trigonometric network (1-2 m at state level, few dm at county levels and ~10 cm at city level), caused by separate adjustment of 7 blocks (Figure 8). For the first time, transformation parameters for the territory of Republic of Croatia between inherited horizontal datum (HDKS) and European Terrestrial Reference System 1989 (ETRS89) based on 120 identical points were computed. Height transformation was ensured using HRG98 geoid model with 3D transformation accuracy of ±*0.873 m* over the territory of Croatia (Bašić et al., 2000; Bašić and Bačić, 2000). The final result of this project was suggestion that the solution of CROREF'96 GPS measuring campaign in epoch 1996.7 would be a realization of ETRS89 for the territory of Croatia with GRS80 level-ellipsoid as mathematical approximation of Earth's shape. Parallel with the end of this project, works towards new geoid solution - HRG2000 (Figure 8) have started.

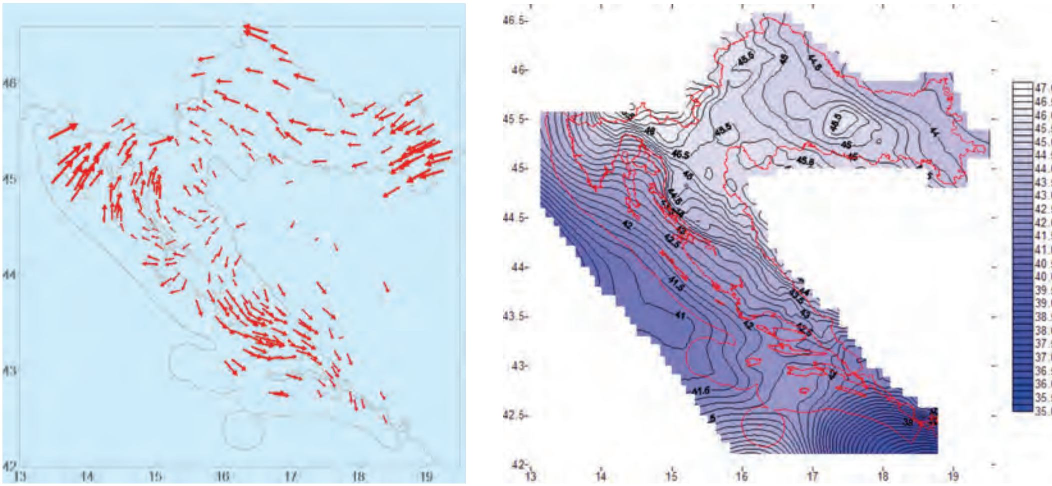

Figure 8: Inhomogeneity of 1st order trigonometric network (left) (Bašić et al., 2000) and HRG2000 geoid model in meters (right) (Bašić, 2001).

Absolute orientation of HRG2000 surface was obtained by 138 GPS-levelling points which was significant effort due to HRG98. Internal accuracy of HRG2000 is from ±*1-2 cm* for the most of Croatian territory to ±*5 cm* at edge border areas (Bašić, 2001).

In period from June to December 2000 within the GEOF UNIZG project for CSGA "The study and suggestion of new gravity network of Republic of Croatia" (Bašić et al., 2001) revision of 1st order gravity network of former Yugoslavia which covers the territory of Croatia was made. From 84 so called major gravimetric points of former Republic, 35 were found while 45 were destroyed. Developed proposal of new Croatian gravimetric network included: "Zero-order gravity network of Republic of Croatia" - consists of 6 UNIGRACE absolute gravity stations (AGT) which together with "1st order gravity network of Republic of Croatia" (25 stations from former 1st order gravity network of Yugoslavia + 11 new stations) forms "Basic gravimetric network of Republic of Croatia" (Figure 7). Also, besides proposal of new Croatian gravimetric network, "Gravimetric calibration base of Republic of Croatia" was proposed as well. It consists of 8 stations: absolute gravity station-AGT03 (*Zagreb-Puntijarka*), GT117, GT118, GT125, GT127, GT130, GT132 (1st order gravimetric network stations-GTs) and absolute gravity station-AGT05/AGT05E (*Makarska/Malakološki muzej*).

In 2001, a significant role in the area of basic surveying work played the results of the project "Development of service programs for usage of Croatian official geoid data and coordinate transformation between HDKS and ETRS89" (Bašić et al., 2002b). Within the mentioned project computer programs IHRG2000 and DAT_ABMO were developed. IHRG2000 (cro. *Interpolacija Hrvatski geoid 2000*) is computer program with purpose of interpolation (bilinear or spline) of HRG2000 geoid surface for an arbitrary point in area of model calculation DAT_ABMO (cro. *Datumska transformacija Altamimi Boucher model*) is computer program for coordinate transformation between HDKS and ETRS89.

2.1 DAT_ABMO - coordinate transformation program

DAT_ABMO is coordinate transformation program which included the usage of several sets of transformation parameters (Helmert's 7-parameters) for transformation between inherited horizontal reference system of Croatia (HDKS) and global reference system based on GRS80 (mostly ETRS89), that is its realization previously transformed from ITRFyy (datum of actual precise GPS ephemeris) for current epoch of measurements and moved to epoch 1989.0 using NNR-NUVEL-1A global velocity model of Eurasian tectonic plate. Sets of transformation parameters included in DAT_ABMO are (Bašić et al., 2002b; Šljivarić, 2010): set of unique parameters for the whole territory of Croatia with and without geoid model (Bašić et al., 2000; Bašić and Bačić, 2000), parameters for 7 blocks (2^{nd}, 5^{th}, 6^{th}, 14^{th}, 22^{nd}, 23^{rd}, and 25^{th}) of Austrian-Hungarian 1^{st} order trigonometric network, transformation parameters for Croatian counties according to territorial-administrative structure from the end of 20^{th} century, parameters at city levels for homogeneous GPS fields of cities and official EUREF transformation parameters from ITRF94, ITRF96, ITRF97 and ITRF2000 to ETRS89. Complete practical transformation from ETRS89 to HDKS was ensured using two computer programs: DAT_ABMO and IHRG2000. Most of surveyors used DAT_ABMO for transformation of GPS measurements in HDKS that is in former official cadastral documentation. As HDKS is compound coordinate reference system with height component determined in HVRS1875, ellipsoidal height obtained from GPS measurements had to be reduced for geoid undulation (GPS levelling) interpolated from HRG2000 (based on HVRS1875 and implemented in IHRG2000) so that accurate transformation procedure to HDKS could be performed.

The results in article Marjanović and Bačić (2001) would mark all future basic geodetic works in Croatia with use of GPS technology. In mentioned article combined solution of CROSLO'94, CROREF'95 and CROREF'96 GPS measuring campaigns for 78 points of 1^{st} order trigonometric network that later would be a basis for realization of new Croatian terrestrial reference system ("Basic GPS network of Republic of Croatia" or "1^{st} order GPS network of Republic of Croatia") is given. During November and December 2001 CSGA continued the project of "10-km GPS network" with measurements in 3 separate blocks: Task A - covered the eastern part of Croatia (*Podunavlje*), Task B - covered the area of *Primorje* and *Northern Dalmatia* and Task C - covered the area of *Southern Dalmatia*, with 417 new established points (Figure 9), 123 existing trigonometric points and 26 reference points with coordinates in ITRF96 (e1995.55) (Bašić et al., 2002a). In June 2001 GEOF UNIZG delivered to CSGA expert studies on geodetic and cartographic datums, reviewed by foreign experts: *E. Brockmann* (Swisstopo, Switzerland), *B.-G. Harsson* (Kartverket, Norway) and *J. Ihde* (BKG, Germany). Also in June 2001 Croatia was included in CEGRN'2001 GPS measuring campaign with CERGOP-2 stations *Brusnik* and *Hvar Observatory*, IGS stations *Dubrovnik* and *Osijek* and permanent GPS stations *Zagreb-GZAOP* and *Pula* (Solarić M., 2004).

In July 2002 GEOF UNIZG and CSGA signed a contract on project "Unique adjustment of 10-km GPS network of Republic of Croatia" (Bašić et al., 2002a). Within this project the adjustment of all 6 blocks of network established in 1997 and 2001 using 63 reference stations (with coordinates in ITRF96, e1999.6) was performed. Selected reference points (63) were part of combined solution from Marjanović and Bačić (2001). Unified GPS network counted 1054 stations ("2nd order GPS network"): 798 new points of homogeneous field (HP), 193 trigonometric points of homogeneous field (TP) and 63 stations of reference field (RP) (Figure 9).

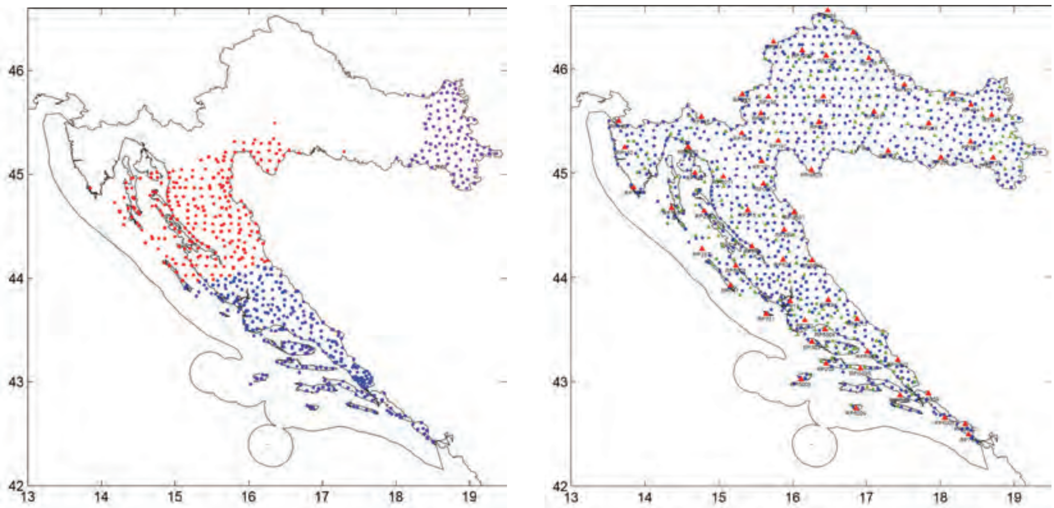

Figure 9: Part of "10-km GPS network" established in 2001 (left) and complete "10-km GPS network" (1054 points) (right) (Bašić et al., 2002a).

The analysis of obtained 3D accuracy after the unique adjustment of "10-km GPS network" showed that: 945 points (93.01%) had standard deviation less than 3 cm, 44 points (4.33%) had standard deviation larger than 3 cm but less than 4 cm, 17 points (1.67%) had standard deviation larger than 4 cm but less than 5 cm and 10 points (1.00%) had standard deviation larger than 5 cm, that is total of 71 points had standard deviation larger than 3 cm (Bašić et al., 2002a). Since HRG2000 geoid model was available, new unique set of transformation parameters for transformation between HDKS and ETRS89 using 241 identical points were computed. With 3D accuracy of ±*0.820 m* this solution was an improvement to one from Bašić et al. (2000), Bašić and Bačić (2000).

In period from June to August 2003 within the project "Basic gravimetric network of Republic of Croatia" (Bašić et al., 2004a) zero-series of relative gravimetric measurements on "Basic gravimetric network of Republic of Croatia" (defined by former project from 2001 "The study and suggestion of new gravimetric network of Republic of Croatia") were performed. Measurements were performed using *Scintrex CG-5 AUTOGRAV* and with two *Scintex CG-3M* relative gravimeters at 42 locations. For gravimetric datum definition (due to IGSN71) absolute gravity values at 4 absolute gravity stations

(AGT) were taken into consideration (AGT01-*Osijek*, AGT03-*Zagreb-Puntijarska*, AGT04-*Pula* and AGT06-*Dubrovnik*). During gravity measurements it was found that absolute gravimetric station in *Makarska* (AGT05) was destroyed so the measurements were performed at it eccentric station AGT05E (*Malakološki muzej*) (Figure 7). Within the project total amount of 30 000 km were traveled via personal vehicle. Horizontal calibration base was also a part of this project. It was realized from AGT03 to AGT05E with $\Delta\varphi \approx 2.6°$ and $\Delta g = 104.57 \cdot 10^{-5}\ ms^{-2}$.

In 2003 CSGA requested three addition expert studies from GEOF UNIZG experts for the preparation of final documentation for the adoption of new geodetic datums and cartographic projections (Bašić, 2005b; Feil and Rožić, 2005; Lapaine, 2005).

3 NEW OFFICIAL GEODETIC DATUMS OF REPUBLIC OF CROATIA

Existing inhomogeneity of inherited horizontal datum (HDKS), state of preservation and the period of survey of 1st order gravimetric network of former Yugoslavia, unsatisfying accuracy criteria of precise levelling of high accuracy for APN and INVT, which are the basis for the definition of HVRS1875 and generally poor documentation of inherited reference systems as well as following the modern European trends were more than good reasons to introduce changes. On the proposal of the Working Group from University of Zagreb - Faculty of Geodesy (formed on request by CSGA), on 4th August 2008 the Government of Republic of Croatia brought "Decision on establishing new official geodetic datums and map projections of Republic of Croatia" (cro. *Odluka o utvrđivanju novih službenih geodetskih datuma i ravninskih kartografskih projekcija Republike Hrvatske*) (NN, 2004). According to Decision, Republic of Croatia has adopted a new horizontal reference system called "Croatian Terrestrial Reference System 1996" (cro. *Hrvatski terestrički referentni sustav 1996* - HTRS96), based on ETRS89 with GRS80 level-ellipsoid as a mathematical approximation of Earth's shape. The realization of HTRS96 (reference frame) represents the network of 78 permanently stabilized stations (Figure 10) with coordinates determined within combined solution of the GPS measuring campaigns: CROSLO'94 (ITRF96, e1994.4), CROREF'95 (ITRF96, e1995.7) and CROREF'96 (ITRF96, e1996.7) in mutual epoch of measurements 1995.55 (Marjanović and Bačić, 2001).

The new height datum of Republic of Croatia (based on same Decision) is realized with the network of 2nd High Accuracy Levelling (IINVT) which was stretched over the territory of former Yugoslavia (Figure 10). Levelling measurements on IINVT were performed in relatively short period from 1970 to 1973. Changes in IINVT network were related to extensions of INVT network along modern roads and railroads and inclusion of APN and INVT benchmarks at places of its overlapping (Rožić, 2001). Mean seal level was determined by measurements at 5 tide gauges at eastern shore of Adriatic Sea: *Koper* (Slovenija), *Rovinj*, *Bakar*, *Split* and *Dubrovnik* for period of 18.6 years and epoch defined on 1st July 1971 (e1971.5). MGI from Belgrade performed gravimetric measurements at only one part of IINVT network so the adapted height system was once again normal-orthometric. IINVT unlike APN and INVT matched the modern criteria of levelling oh high accuracy with reference probable error $u_0 = \pm 0.79\ mm\sqrt{km}$. The framework of IINVT are 5 regularly distributed so called "fundamental benchmarks": *Koprivnica*, *Kostajnica*, *Knin*, *Otočac* and *Strizivojna* (Klak et al., 1995). The height system with mean seal level determined by 5 tide gauges and realized by IINVT benchmarks in epoch 1971.5 is called "Croatian Reference Height System 1971" (cro. *Hrvatski visinski referentni sustav 1971* - HVRS71).

Republic of Croatia also adopted new gravimetric datum based on IGSN71 and GRS80 normal gravity field. New gravimetric reference system is realized by "Basic gravimetric network of Republic of Croatia" (6 absolute gravity stations from "Zero-order gravimetric network of Republic of Croatia" and 36 gravity points of 1st order gravimetric network of Republic of Croatia") (Figure 7) with measured gravity values in summer 2003. New gravimetric reference system of Croatia is called "Croatian Gravimetric Reference System 2003" (cro. *Hrvatski gravimetrijski referentni sustav 2003* - HGRS03).

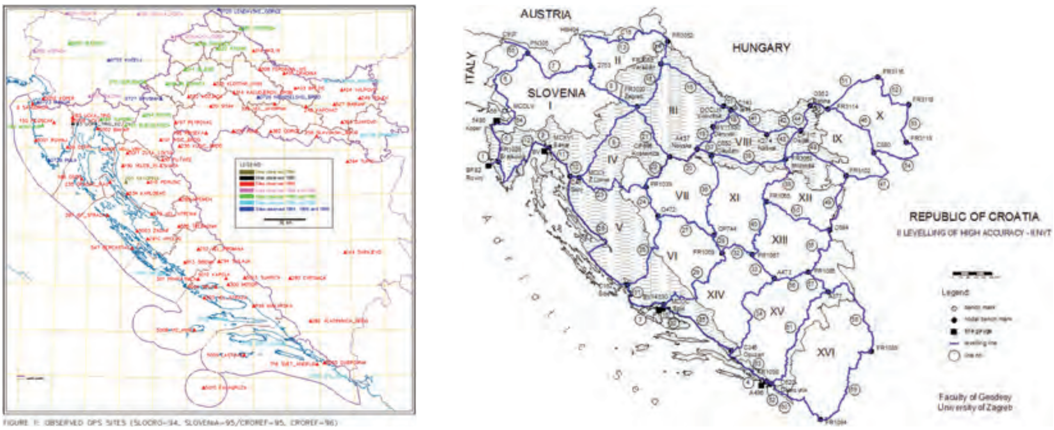

Figure 10: HTRS96 (left) (Marjanović and Bačić, 2001) and HVRS71 (right) (Rožić and Razumović, 2009).

According to mentioned Decision, Republic of Croatia has also adopted a new plane cartographic projection for cadaster and detail state topographic cartography - Transverse Mercator (TM). New cartographic projection is based on HTRS96 and unifies the territory of Republic of Croatia in one unique meridian projection zone with mean meridian defined at 16°30′ and mean meridian scale of 0.9999. According to ISO (2003) rectangular plane coordinates marks *y*, *x* (from inherited Gauss-Krüger projection) are changed to *E* (easting) and *N* (northing). False easting constant remains the same like within inherited projection (500 000 m). Reference mark of the new projection coordinate system is HR_ETRS89/TM, while an alias is coordinated with the new horizontal reference system - HTRS96/TM. Practical mathematical formulas for conversion from ellipsoidal to plane coordinates are the same as ones for inherited cartographic projection with some changes in notation (Lapaine and Tutić, 2007).

The final deadline for implementation and official usage of new Croatian geodetic datums was 1st January 2010.

4 CHRONOLOGY OF STATE SURVEY IN CROATIA FROM 2004 TO 2009

In July 2003 CSGA and GEOF UNIZG signed a contract on project "Project and stabilization of micro-gravimetric networks at five absolute gravity stations (Bašić et al., 2006b). The purpose of micro-gravimetric networks is preservation of absolute gravity stations. Project included stabilization of three eccentric points for each absolute gravity station of "Zero-order gravimetric network of Republic of Croatia" except for AGT02 (*Zagreb-Maksimir*) and AGT03 (*Zagreb-Puntijarka*). For those two stations total of three eccentric points were stabilized because it nearness. Eccentric points are distanced 0.5-5 km from AGTs. According to criteria, the differences between gravimetric measurements at two eccentric points should not be larger than $2 \cdot 10^{-4}\ ms^{-2}$ while locations should be geologically and hidrologically stable. Project also included the connection of eccentric points to "10-km GPS network" (for position determination) and to IINVT (for height component determination). Project was delivered in September 2004.

After the unique adjustment of "10-km GPS network" it was logical to fit "GPS network of City of Zagreb" into HDKS. Therefore in April 2004 Institute for Cadastre and Geodetic Affairs of City of Zagreb and GEOF UNIZG signed a contract on project "Geodetic-geodynamic study of area of City of Zagreb" with special subproject "The matching of GPS network of City of Zagreb into HDKS" (Bašić, 2006). Within this project readjustment of TM ZG in HTRS96 was made. Also the readjustment of eastern and western part of GPS homogeneous field of points of City of Zagreb was made as well. Comparison of new adjustment with previous one from 1998 indicated to large number of bad optimized vectors in adjustment from 1998. The new adjustment of TM ZG showed that due to time shift of adjustment fixed coordinates, the whole network suffered a few mm of position translation and height shift of ~2 cm. Transformation from HTRS96 (that is ETRS89) to HDKS was ensured by transformation parameters, which were calculated according to 90 identical points in both systems. Spatial (3D) accuracy of calculation of transformation parameters was ±*12.0 cm* and thanks to HRG2000 geoid model, height transformation accuracy was ±*1.0 cm*.

In May 2005 CSGA, Institute for Cadastre and Geodetic Affairs of City of Zagreb and GEOF UNIZG signed a contract on project "Design and establishment of 2nd order gravimetric network of City of Zagreb and gravimetric survey of micro-gravimetric networks of absolute gravity stations" (Bašić et al., 2006c). Within the project 2nd order gravimetric network for the whole territory of Croatia was designed. Designed 2nd order gravimetric network of Croatia was planned to be connected to: "10-km GPS network" for position determination, IINVT benchmarks (HVRS71) for height determination and "Basic gravimetric network of Republic of Croatia" for relative gravity measurements. Within the part of project financed by Institute for Cadastre and Geodetic Affairs of City of Zagreb, 2nd order gravimetric network of City of Zagreb (which is based on TM ZG and nearby points of "10-km GPS network") relative gravimetric and levelling measurements were performed. Gravimetric measurements were performed on total of 34 locations (33 stations of TM ZG and 1 station of 1st order gravimetric network of former Yugoslavia) (Figure 11) with connection to "Zero-order gravimetric network of Republic of Croatia" at AGT02 and AGT03 for network datum definition (IGSN71). Precise levelling measurements were performed on total of 39 locations (34 + AGT02, AGT03 and their eccentric points) with connection to IINVT benchmarks: FR3020, R109, R2077, R19774 and R5968 with total length of all sides in levelling figures (20) of 794.9 km (Figure 11). Mean standard deviation of adjusted levelling measurements of 1.32 cm and for gravimetric measurements $2.45 \cdot 10^{-8}\ ms^{-2}$ indicate to high reliability of performed measurements.

In November 2005 and April 2006 relative gravimetric and precise levelling measurements were performed on 4 established micro-gravimetric networks (total of 12 points), defined within the project "Design and stabilization of micro-gravimetric networks at five absolute gravimetric stations-1st phase" (Bašić et al., 2006d).

In September 2005 CSGA, within joint collaboration of CSGA, Surveying and Mapping Authority of the Republic of Slovenia and Federal Geodetic Administration of Bosnia and Herzegovina measurements in CROREF'05 GPS measuring campaign were performed. Measurements were obtained in two 24h sessions at total of 40 locations: 28 in Croatia, 7 in Slovenia and 5 in Bosnia and Herzegovina. In adjustment procedure, 5 IGS stations were used (4 fixed and 5 control stations) (Marjanović et al., 2006). Accuracy (RMS), obtained from repeated daily solutions of ±*0.6 mm* (N), ±*0.7 mm* (E) and ±*2.8 mm* (U) indicate to high quality of performed measurements. Comparison with combined solution of CRO/94/95/96 from Marjanović and Bačić (2001) in ETRS89 (±*12.0 mm* for position and ±*9.3 mm* for height) indicated to possibility of bad stabilizations of observed stations and to differences between ITRF96 and ITRF2000 realizations (in which CRO/94/95/96 and CROREF'95 were adjusted) and between used velocity models NNR-NUVEL-1A and ITRF2000 as well.

After the adoption of new geodetic datums, established GPS homogeneous fields of following cities (in period from 1996 to 2001) were needed to be homogenized and fitted into new horizontal reference system: *Karlovac*, *Varaždin*, *Čakovec-Nedelišće*, *Prelog*, *Sisak*, *Velika Gorica*, *Samobor*, *Krapina*, *Zabok*, *Križevci*, *Koprovnica*, *Orahovica*, *Đakovo*, *Našice*, *Osijek-Ivanovac*, *Split*, *Plitvička jezera*, *Kanal Dunav-Sava* and *Babina Greda*. GPS homogeneous fields of following cities count total of 8330 stations (Bašić et al., 2006e). Homogenization is done by readjustment of GPS homogeneous fields of cities fixing the reference stations of combined solution for realization of HTRS96 from Marjanović and Bačić (2001) and by fixing points of "10-km GPS network". Coordinates of adjustment fixed stations were previously transformed to ITRF96 in mean epoch of measurements 2000.5 using DAT_ABMO transformation model.

During April 2005 Republic of Croatia was included in EUVN_DA project by widening of existing EUVN network (8 stations) from 1997 with 12 (Figure 11) additional stations (Grgić et al., 2006).

New established stations were connected to HVRS71, UELN and HGRS03. Station coordinates were determined due to ITRF2000 (e2005.34) with 4 IGS (GRAZ, MATE, ZIMM and WTZR) adjustment fixed stations and later transformed to ETRS89 using DAT_ABMO transformation model.

Also in April 2005, CSGA and GEOF UNIZG signed a contract on project "Development of unique transformation model-HTRS96/HDKS" (Bašić et al., 2006a). Main goal of this project was to develop a unique transformation model between inherited (HDKS) and new adopted horizontal reference system (HTRS96) with accuracy better than 15 cm in all components and to implement it in a proper software solution.

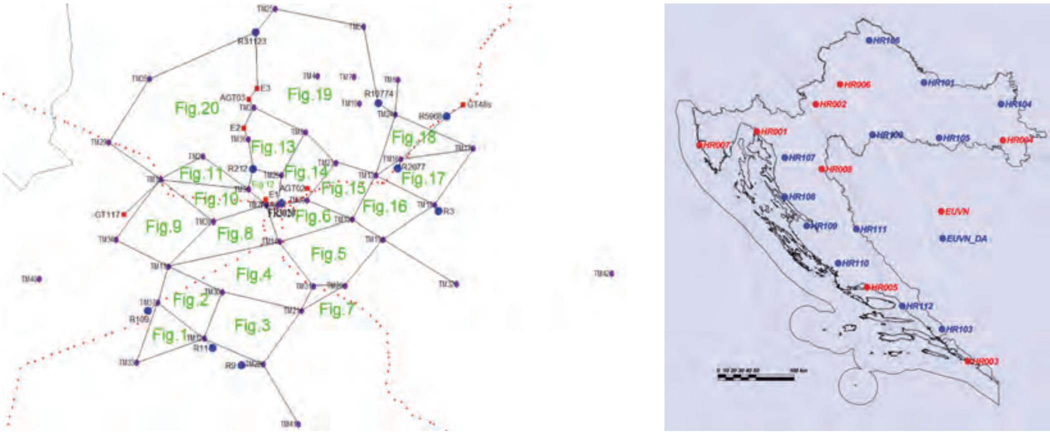

Figure 11: "2nd order gravimetric network of City of Zagreb" (left) (Bašić et al., 2006c) and EUVN'97 & EUVN_DA stations in Croatia (right) (Grgić et al., 2006).

4.1 T7D2006 transformation model

The project "Development of unique transformation model-HTRS96/HDKS" (Bašić et al., 2006a) resulted with first grid transformation model in Croatia called "T7D" (T-transformation, 7-parameter, D-distortion). This model was a result of detail analysis of series of transformation model of European and worldwide countries. T7D consists of unique (Helmert's) 7-parameter 3D transformation HDKS ⇔ HTRS96 for the whole territory of Croatia and distortion model calculated on the basis of 1780 identical points in both systems (Figure 12). Distortion model was calculated in 60″×90″ grid by LSC method with usage of empiric covariance function for every coordinate component - plane projection coordinates in N-S and E-W direction and for height component in HVRS1875 with usage of HRG2000 geoid model. Unique transformation parameters for the whole territory of Croatia ensure horizontal (2D) transformation accuracy of *±71 cm* that is spatial (3D) of *±74 cm*. Horizontal transformation accuracy of T7 transformation once again pointed out to existing inhomogeneity of 1st order triangulation network of Austrian-Hungarian Monarchy (Figure 12).

After the prediction of distortion component in HDKS and inclusion of height discrepancy between HVRS1875 and HVRS71 (calculates on the basis of 5000 identical benchmarks in both systems), created unique transformation model T7D2006 ensured horizontal (2D) transformation accuracy of *±5 cm*, that is spatial (3D) of *±7 cm*. T7D2006 transformation model was integrated in official Croatian coordinate transformation software "T7D".

Significant work in field of state survey were performed by former Croatian Geodetic Institute (CGI) in period from 2007 to 2008. From the end of February to the end of April 2007 GNSS measurements were performed on "Basic gravimetric network of Republic of Croatia" with purpose of coordinate and height determination. GNSS measurements were adjusted in ITRF2005 realization (e2005.24). Height determination was performed by precise levelling measurements to existing benchmarks of IINVT. Coordinate transformation to HDKS and ETRS89 was performed using "T7D" transformation software (Grgić et al., 2007).

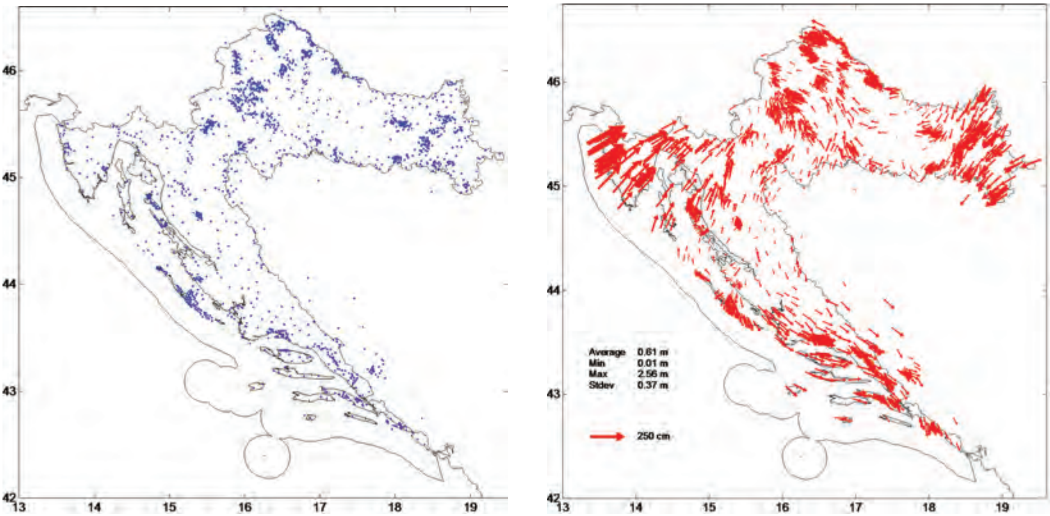

Figure 12: Distribution of 1780 identical points in HDKS and HTRS96 for creation of T7D2006 (left) and existing inhomogeneity of 1st order triangulation network of former A-U Monarchy after T7 transformation in 1780 points (right) (Bašić et al., 2006a).

In article Barišić et al. (2007) the project plan of "2nd order gravimetric network of Republic of Croatia" with 206 new stations and average density of 30 km was presented. Project also included re-observation of "Basic gravimetric network of Republic of Croatia" and densification of "1st order gravimetric network of Republic of Croatia" to land and islands. In September and October 2007 "Basic gravimetric network of Republic of Croatia" was extended to north Adriatic islands with total of 16 stations: 7 old and 9 new (Repanić et al., 2008). The extension of "Basic gravimetric network of Republic of Croatia" to islands withdrew the need for realization of HVRS71 at islands as well. For that purposes in November 2007 trigonometric levelling to island Rab was performed (Grgić et al., 2008a) as well as to islands Cres, Krk and Pag (Grgić et al., 2008b). In April 2008 first series of gravimetric measurements on "2nd order gravimetric network of Republic of Croatia" within "Pilot project Istra" at 15 new stabilized locations were performed (Barišić et al., 2008). CGI performed the extension of "Basic gravimetric network of Republic of Croatia" to middle south Adriatic islands. In September 2008 "Basic gravimetric network of Republic of Croatia" was extended with 5 new stations (2 at island Dugi otok, 1 at island Pašman, 1 at island Žirje and one at land in place Pakoštane) (Repanić et al., 2009) while in September 2009 "Basic gravimetric network of Republic of Croatia" was also extended with 9 new gravimetric stations: 2 at island Hvar, 1 at island Brač, 1 at island Vis, 1 at island Korčula, 1 at island Lastovo and 1 at island Mljet (Repanić et al., 2010).

The period of 18 years from 1991 to 2008 resulted with many projects and expert studies in the field of basic geodetic works of Republic of Croatia. All results of pass projects and expertise brought the idea for one of the most important projects in the field of basic geodetic works of Republic of Croatia - "New geoid model of Republic of Croatia and improvement of T7D transformation model" (Bašić, 2009). The main reason for this project was the fact that T7D2006 transformation model was developed on the basis of relatively small amount of irregularly distributed points and that HRG2000 model was compliant with inherited height system HVRS1875. This project was started with the establishment of 500 GNSS-levelling points with geoid undulations determined in relation to HVRS71 by connecting GNSS-levelling points to the nearest benchmarks of IINVT with known heights in HVRS1875 and in HVRS71 while coordinates were determined using CROPOS real-time high-precise positioning service. From 500 GPS-levelling points, 495 were selected for the absolute orientation of the new geoid model HRG2009. GNSS-levelling points had a double purpose: the absolute orientation of the new geoid surface and determination of outer accuracy of old geoid model HRG2000. Standard deviation of *9.3 cm* in 495 GNSS-levelling points pointed out to high accuracy of HRG2000 geoid model despite that fact that it was calculated with the relatively small amount of data. In addition to the need for the new geoid model was also the fact that new combined geopotential solution EGM2008 has maximal order and degree of 2160 (2190) which correspondents to wavelength of 9 km, while old geoid model was computed using EGM96 (with order and degree of 360 and wavelength of 55 km). Standard deviation of differences between geoid undulation of 495 selected GNSS-levelling points and geoid undulations from EGM2008 was 4.8 cm. Topographic influences were obtained from Croatian SRTM 3″×3″ DTM (Bašić and Buble, 2007). The calculation of HRG2009 geoid model (Figure 13) was performed on the basis of 30 000 carefully selected free air anomalies at GRS80. Calculation limits were the same like for HRG2000 but with denser grid 30″×45″ which correspondents to spatial resolution of ~1×1 km. Inner accuracy at 495 GNSS-levelling points of *2.7 cm* indicates to very high accuracy and calculation reliability. Independent outer accuracy was calculated in 59 equally distributes GNSS-levelling points which weren't included in model calculation. The standard deviation of differences between geoid undulations in those points and geoid undulation interpolated from HRG2009 of *3.5 cm* indicates to very high absolute reliability of the new geoid model.

4.2 T7D2009 transformation model

Within the project "New geoid model of Republic of Croatia and improvement of T7D transformation model" (Bašić, 2009) the task was also to improve the old T7D2006 (Bašić et al., 2006a) transformation model. During 2009 CSGA together with its cadastral offices organized densification of transformation points to 5029 with coordinates in HTRS96 and HDKS (Figure 13).

Later the number of 5029 transformation was supplemented with additional 171 points. Total of 5200 identical points in HDKS and HTRS96 were used to calculate unique transformation parameters (T7 transformation) with horizontal (2D) transformation accuracy of ±*79.3* cm that is spatial (3D) of ±*80.4 cm* and height transformation accuracy of ±*12.9 cm* thanks to HRG2009 geoid model. Distortion modeling was performed using LSC technique like within T7D2006 model in 60″×90″ regular grid over the whole territory of Croatia. Discrepancies between HVRS1875 and HVRS71 are taken from Croatian height transformation model - HTMV08 v.1 (Rožić, 2009) and together with T7D2009 model implemented in new version of T7D computer software solution. After the distortion modelling (T7 + distortion), horizontal (2D) and spatial (3D) inner transformation accuracy in 5200 identical points were ±*5.8 cm* and thanks to new HRG2009 geoid solution, height transformation accuracy was just few millimeters. The comparison of T7D heights with the 59 independent GNSS-levelling control points with standard deviation of differences of *3.5 cm* for both height systems (HVRS1875 and HVRS71) indicate to equal level of confidentiality of T7D heights and HRG2009 heights.

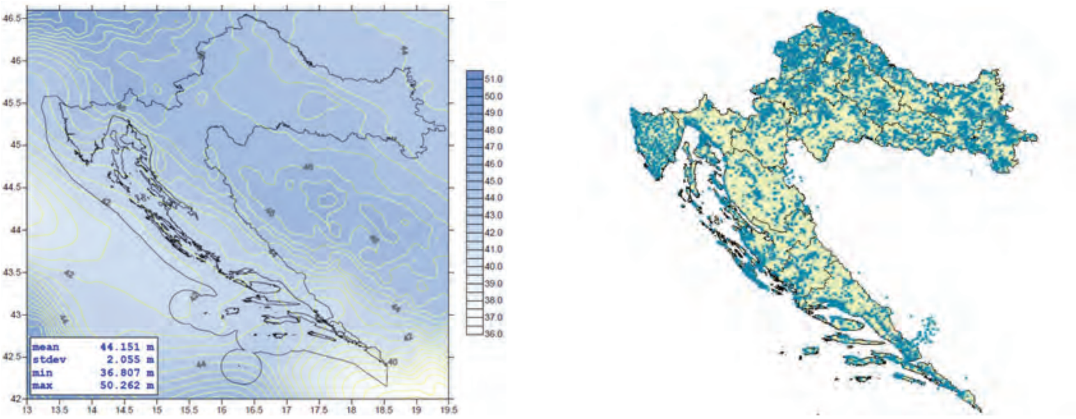

Figure 13: HRG2009 geoid model in meters (left) and 5029 HDKS/HTRS96 transformation points for T7D2009 transformation model (right) (Bašić, 2009).

5 CONCLUSION

The period of 18 years from 1991 to 2009 resulted with many projects in the field of basic geodetic works in Republic of Croatia. Most of them were the result of collaboration of CSGA and GEOF UNIZG. Thanks to these projects we can be sure that Republic of Croatia always had an intention to follow modern European trends in geodetic aspect. After the establishment of national positioning system of Republic of Croatia - CROPOS in 2008 and built T7D2009 transformation model within it, all future geodetic projects in Croatia will and are surely relied on CROPOS as unavoidable part of today's everyday geodetic practice.

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