FUNDAMENTAL LEVELLING NETWORKS AND HEIGHT DATUMS AT THE TERRITORY OF THE REPUBLIC OF CROATIA

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In the Republic of Croatia there is a long tradition going on in carrying out systematic levelling works. These works have resulted, in the period of about 120 years, with the establishment of three fundamental levelling networks of geometric levelling. These are precise levelling network of the Austro-Hungarian Monarchy, I. levelling network of high accuracy and II. levelling network of high accuracy of former Yugoslavia. These networks are the basis of height system of the Republic of Croatia, and accompanied by adequate definitions of height datums they are used even today for solving fundamental and applied geodetic tasks and scientific researches.

Key words: levelling network; height datum, height system; geometric levelling

1. Introduction

In the Republic of Croatia there is a long tradition going on in carrying out systematic levelling works. These works, that have been carried out ever since the second half of the 19th century till today, have resulted in the establishment and usage of three fundamental levelling networks of geometric levelling of the highest order of accuracy. These networks have served in the period of about 120 years as the basis of height systems at the territory of the Republic of Croatia and have made it possible to solve a series of fundamental and applied geodetic tasks and scientific researches. These networks and height datums were established in the period as the Republic of Croatia was not independent and sovereign state, but an integral part of today former states: Austro-Hungarian Monarchy and Yugoslavia in all its forms from Kingdom up to Socialist Federative Republic. This fact is important because the comprehension and establishment of fundamental height networks were conditioned not only by geodetic scientific and professional criteria, but also by political, economic and other circumstances that characterised these states. It is therefore indispensable with respect to levelling network and height datums to consider, along with the territory of the Republic of Croatia, the territory of the neighbouring countries, independent today as well, i.e. the territory of the Republic Slovenia and the Republic Bosnia and Herzegovina.

The first systematically carried levelling network at the territory of the Republic of Croatia was the precise levelling network of the Austro-Hungarian Monarchy established in the period between 1874 and 1916. The second and the third levelling networks were carried out in the time of former Yugoslavia in the period after the Second World War. These are the I. levelling network of high accuracy made in the period from 1946 till 1963 and the II. levelling network of high accuracy made in the period from 1970 till 1973. These networks are still used today at the territory of the Republic of Croatia.

2. Precise levelling network of the Austro-Hungarian Monarchy

In the Republic of Croatia, the precise levelling of the Austro-Hungarian Monarchy is much more known under the title Austrian Precise Levelling - APL. It was made in the period from 1874 till 1916, and it encompassed the entire southern and southeastern part of the former

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Monarchy, i.e. the territory of the present independent states: the Republic of Croatia, the Republic Slovenia and the Republic Bosnia and Herzegovina. It was made at the end of the 19th century within the frame of extensive and systematic fundamental geodetic works, in accordance with the references of international geodetic organisations (conferences). Thus, in accordance with the references of the II. General conference of Government commissioners from 1867, the APL network was made with the purpose of establishing the height system. The works were carried out by the experts from the Military and Geographic Institute from Vienna in accordance with the precise defined scientific, professional and technical criteria. The network encompassed: projecting of geometric configuration, definition of levelling lines traces, benchmarks stabilisation, definition of geodetic height datum, performance of measurements, measuring data processing, accuracy determination and analysis, elimination some of the most important systematic influences, adjustment and determination of benchmarks heights, and publication of relevant data and results for practical usage in special publication of Military and Geographic Institute. The works on the network were carried out systematically and continuously, but in a long period of time of about 40 years.

Geometric configuration of APL network were not adjusted to the shape and size of the present day territory of the Republic of Croatia. On its territory, APL network does not have firm and suitable configuration, and the organisation and establishment of the network were not adjusted and brought into accordance with the national interests of Croatia, but was subjected to the interests of the Monarchy in its entire south and southeast part. The presentation of the geometric configuration of the APL network, including the original numbers of levelling lines, the numbers of levelling figures and the numbers of nodal benchmarks are given on Fig. 1.

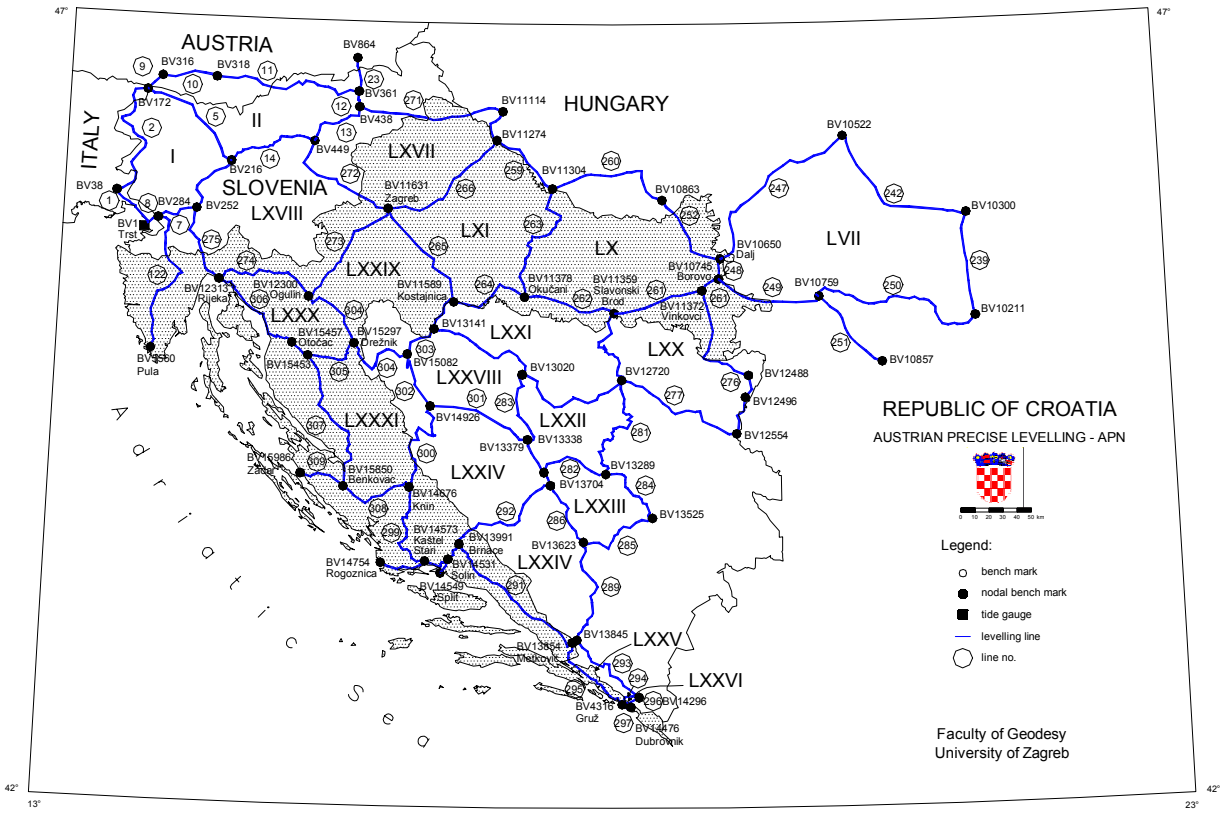

Fig. 1. Levelling network of Austrian Precise Levelling at the territory of the Republic of Croatia

During the survey of APL network there were no gravimetric i.e. gravity acceleration measurements made along the levelling lines. Hence, the system of normal (spheroid) orthometric heights was selected as a height system.

Height datum was defined by adopting the equipotential surface of the Earth's gravity field determined by means of the mean sea level of the Adriatic Sea at the tide gauge in Trieste

in Molo Sartorio (Militär-geographisches Institut 1884). This equipotential surface was adopted as reference surface, i.e. as the height datum, for determining benchmark heights in normal orthometric height system. Its determination is connected with the time epoch of the year 1875, and it is determined by computing the mean sea level of the Adriatic Sea on the basis of one-year recording period. The determination was made by Prof. Farolfi with the accuracy of 1 cm. In relation to the height system defined in such a way, there was also the height of the starting benchmark determined for the APL network. This was the benchmark HM 1, HM – HOEHENMARKE, in the levelling line No. 1 the height of which is 3.3520 m above the mean sea level, and it was stabilised in the vicinity of the tide gauge on the building of the financial blockhouse at that time.

The computing data processing of the APL network measurement followed the course of its measurement. Hence, the APL network presented on Fig. 1 was never analysed during the time of the Austro-Hungarian Monarchy, nor processed and adjusted in the sense of a unique network. It was adjusted in a few parts, and the basic guiding line of the adjustment processing was the need for successive and the quickest possible determination of benchmarks heights for practical use. Thus, some parts of the network, western and northern, were adjusted within the frame of larger separate groups, and the part of the network, first of all the one at the territory of of Croatia and Bosnia and Herzegovina, was adjusted gradually for each levelling figure separately following the continuous survey. This refers especially to the levelling lines from No. 276 to No. 309. where the most simple way of adjustment was used based on separate including of levelling lines on two given heights of previously already adjusted benchmarks. Hence, the observation material was not homogeneously processed through adjustment, regardless of the systematically executed levelling works and field measurements. The results of measurement adjustment were namely influenced by the course, manner and method of adjustment which was reflected in the benchmark heights and their positional, i.e. height accuracy.

In order to understand the obtained measurement accuracies more adequately, modern analysis and data processing of the APL network data was made in the nineties (Feil et al. 1992a) that was encompassed by previously defined area, Fig. 1. In this sense, the accuracy estimate can be quoted that are expressed by the criteria of reference probable measuring error computed on the basis of misclosures in closing the levelling figures

$$u_F = \pm 3.20 mm/\sqrt{km}, \tag{1}$$

and of the reference probable error computed on the basis of network adjustment applying the least squares method.

$$u_o = \pm 3.27 mm/\sqrt{km}. \tag{2}$$

On the basis of network adjustment the positional (height) accuracy of nodal benchmarks in the network was determined in relation to the starting benchmark of the height system, i.e. the benchmark HM 1. The positional (height) accuracy of nodal benchmarks expressed by the mean errors criterion runs within the limits of ±2 to ±8 cm.

It should be pointed out that previously mentioned criteria of measuring and positional (height) accuracy of nodal benchmarks refer to the APL network considered and analysed as a unique network, and original data of adjustment, especially benchmarks heights and their positional accuracy refer to the manner and course of computing data processing that was originally made and published in previously already mentioned publications of the Military and Geographic Institute. In this respect, the true situation with regard to the positional accuracy of benchmarks in the APL network is also somewhat worse than the results obtained by the quoted modern analysis. The differences between original values of nodal benchmarks heights and their values obtained by previously quoted new adjustment illustrate very well for the territory of the Republic of Croatia the data from the table I. It can be seen from the heights differences, that the way of adjustment and the course of computing measuring data processing significantly influenced the values of benchmarks heights.

Table I. Differences of nodal benchmarks heights

Benchmark	Original height m	New height m	Difference mm
HM 5560	31,6185	31,6186	-0,1
HM 10745	91,4851	91,4189	66,2
HM 11274	132,2328	132,2200	12,8
HM 11304	108,5009	108,4742	26,7
HM 11359	94,9156	94,8550	60,6
HM 11372	93,3877	93,3210	66,7
HM 11378	119,9661	119,9180	48,1
HM 11589	112,5521	112,5037	48,4
HM 11631	123,6565	123,6492	7,3
HM 12300	324,3070	324,3387	-31,7
HM 12313	5,0378	5,0581	-20,3
HM 13845	9,2070	9,1578	49,2
HM 13991	323,3912	323,3446	46,6
HM 14316	3,5963	3,5478	48,5
HM 14476	3,7115	3,6628	48,7
HM 14531	7,7623	7,7174	44,9
HM 14549	4,5571	4,5122	44,9
HM 14573	92,3117	92,2657	46,0
HM 14676	224,1427	224,0773	65,4
HM 14754	1,4549	1,4089	46,0
HM 15297	424,0453	424,0458	-0,5
HM 15453	466,0216	466,0159	5,7
HM 15457	459,4107	459,4037	7,0
HM 15850	182,0887	182,0530	35,7
HM 15986	1,1797	1,1429	36,8

From the present point of view, the APL network is the first systematically established levelling network at the territory of the Republic of Croatia that has been used in practice as the basis of the height system since the end of the 19th century. Although the works on that network were made in a serious and pedantic way speaking terms of the circumstances related to that time, that is, although numerous fundamental geodetic works lean on that network, it also has a few essential deficiencies. The most important deficiencies are very long time of surveying, inhomogeneous way of network adjustment, the measuring accuracy and the positional (height) accuracy of bench marks that do not meet the demands of up-to-date scientific and professional criteria, and the lack of systematic gravimetric measurements along levelling lines. One should not forget the height datum error that appeared due to the very short period of recording the sea level. The consequence of this error that has the amounts from 9 to 12 cm, according to various authors (Feil et al. 1992a), are to high benchmarks heights in the network. In spite of all these deficiencies, the APL network benchmarks are still in official use within the frame of geodetic height system in the Republic of Croatia, and due to the very good quality in stabilising benchmarks, HOHENMARKE, a considerable number of them has been preserved so far (Rožić 1999).

3. The I. levelling network of high accuracy

After the Second World War there was only APL network existing at the territory of the Republic of Croatia, being the heritage from former Austro-Hungarian Monarchy, because no significant levelling works were made in the period between the two World Wars. Since a longer period had passed since the network was measured, and due to the war destruction during the Second World War, as well as to the lack of insight into the preserved state of benchmarks, the Geodetic Administration of that time at the Government of the National Republic of Croatia - NRH organised the work on field revision of the APL network, i.e. the work on defining the level of benchmarks being preserved and on publishing the data for practical usage. This task was very quickly done, so that the revision was completed in the course of the year 1948, and all

relevant data published for practical usage in a special publication (Geodetic Administration at the Government of NRH 1948).

Taking the level of benchmarks destruction in the APL network into consideration, the works started on the new levelling network much more known under the title I. levelling of high accuracy - I.NVT. Geometric configuration of the new levelling network was mostly congruous with the configuration of the APL network, so the existing traces of APL lines were supplemented considerably by the stabilisation of new benchmarks. In the majority of cases the original number of levelling lines were retained, as well as the numbers of preserved benchmarks. The works on stabilisation and survey of I.NVT were carried out in moderate material, technical and other circumstances. The survey of the network lasted from 1946 to 1955, and with additional measurements of some levelling lines until 1963. The works were carried out by the Military and Geographic Institute in Belgrade, the Main Geodetic Administration of former Yugoslavia and Geodetic Administration of NRH. The geometric configuration of the I.NVT levelling network is presented on Fig. 2. Apart from some minor changes, it is practically identical to the configuration of the APL network.

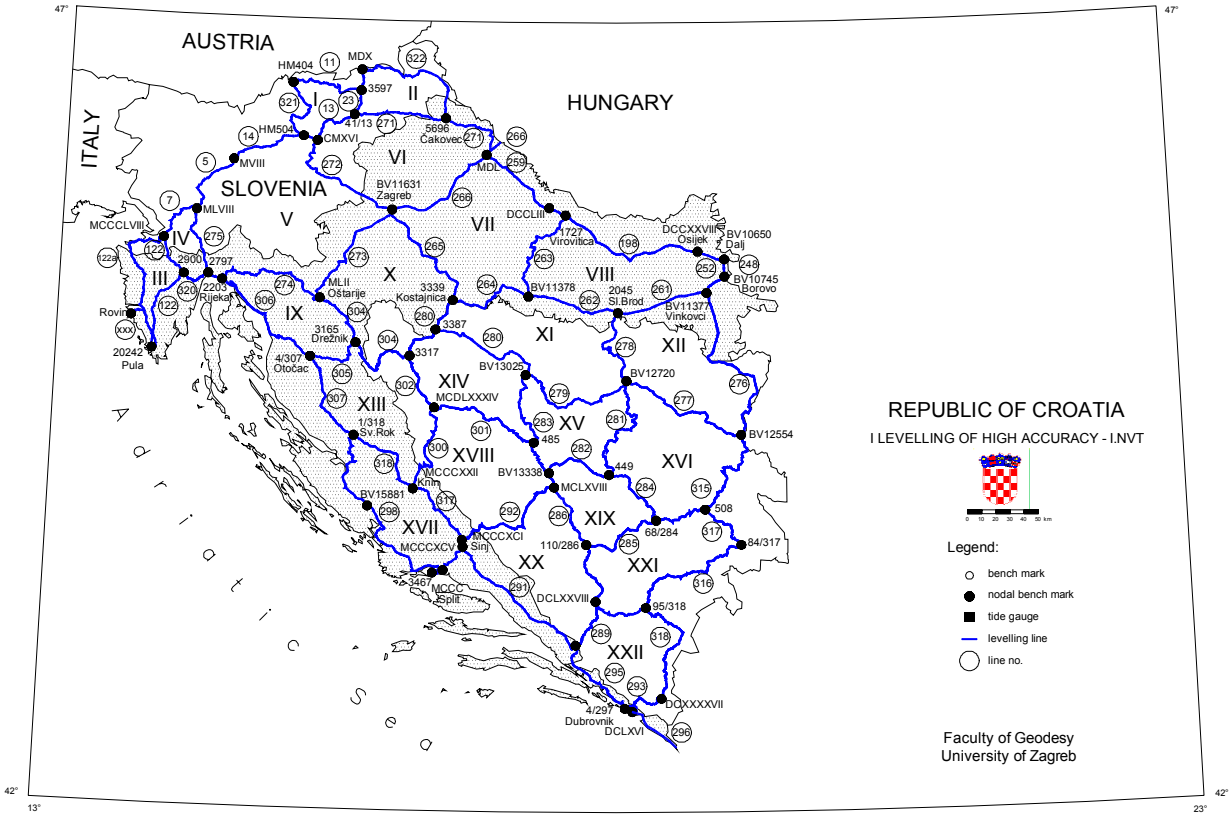

Fig. 2. Levelling network of the I. levelling of high accuracy at the territory of the Republic of Croatia

The measurement of I.NVT did not meet the requirements of professional and scientific criteria referring to the modern levelling of high accuracy. The reasons lie in the long period of surveying, the usage of different and non-unified instruments and accessories, lack of clear and precise technical criteria in the execution of works, moderate material and logistic conditions for the work of field teams and many others. The measurements resulted thus in inhomogeneous observation material in which on some parts of the network various measuring accuracy was obtained. The gravity acceleration measurements were not systematically made along levelling lines, so the system of normal orthometric heights was adopted for the height system like in the case of APL network. The measurements computing processing and adjustment of measuring data was also made in the simplest way. The measurements were adjusted in the majority of cases by direct including of I.NVT levelling lines into the preserved parts of the APL network, leaning on conveniently selected and preserved APL benchmarks. These benchmarks were

selected on the basis of analysing their stability. On other words, the levelling network based on the I.NVT measurements was not processed and adjusted as a unique network. The consequence of such data processing was reflected in accuracy, because more accurate I.NVT measurements were included into the less accurate height basis defined by the APL network. Apart from that it is obvious from the previously described procedure of computing processing that in the I.NVT network the definition of the same geodetic height datum was retained as well. In formal sense, the benchmark HM 1 at the tide gauge in Trieste was retained as the starting benchmark of the height system although it was already completely clear that that height datum was not correctly determined.

During the nineties, modern analysis was carried out as well on the accuracy of the I.NVT levelling network established for the first time as a unique network, Fig. 2. To be taken as usual accuracy estimate data (Bilajbegović et al. 1992), we can state the reference probable measuring error computed on the basis of misclosures in closing the levelling lines

$$u_F = \pm 1.67 mm / \sqrt{km}, \tag{3}$$

and the reference probable error on the basis of network adjustment applying the least squares method

$$u_o = \pm 1.33 mm / \sqrt{km}. \tag{4}$$

Previous reference errors show that the accuracy in measuring the I.NVT is higher than in the APL network, but they also confirm the fact, that the I.NVT does not meet the accuracy criteria of modern levelling of high accuracy. One should also point out that regardless of measuirng the I.NVT the preserved part of the APL network and the height datum from the period of the Austro-Hungarian Monarchy remained the basis of the height system of the Republic of Croatia in the subsequent period. The accuracy of the I.NVT measurement that was, regardless of many deficiencies, higher than the accuracy of the APL measurement, had been disturbed by the way of data processing and adjustment. The same, wrong definition of the geodetic height datum was retained further on, and since no gravimetric measurements were made, the normal orthometric height system was also retained. Along with the above stated, numerous works on geometric general levelling of lower orders (precise levelling, city levelling, technical levelling of increased accuracy, technical levelling) that were carried out at the territory of the Republic of Croatia mostly in the period from 1945 to 1970, are connected with such height reference. The measuring data, computation processing and data for practical usage have not been published in special publications of competent geodetic institutions.

4. The II. levelling network of high accuracy

Since the levelling network I.NVT had not met modern scientific and professional criteria, the works on preparing the new levelling network started in former Yugoslavia during the sixties that was supposed to serve as the reference of a new height system. Serious preparations were encompassing the project of a new network, definition of a new height datum, selection of the place for fundamental benchmark stabilisation, defining measuring methods and procedures, analysis procedures and data processing, unifying instruments and accessories, defining clear technical criteria for the execution of field works, education of field teams, stabilisation of benchmarks and many others. This network was made at the western part of the territory of former Yugoslavia, Croatia, Slovenia, Bosnia and Herzegovina, in relatively short time, i.e. from 1970 till 1973 and it is more familiar under the title II. levelling of high accuracy - II. NVT.

Geometric configuration of the levelling network II.NVT is clearly presented on Fig. 3. In accordance with the project remarkable changes were made referring to the I. NVT network, i.e. a larger number of levelling lines is spreading over completely new traces following modern road and railway routes. On the parts where the II.NVT levelling lines traces are overlapping

with the I. NVT and APL traces, the preserved benchmarks of these preceding networks were also included into the new lines.

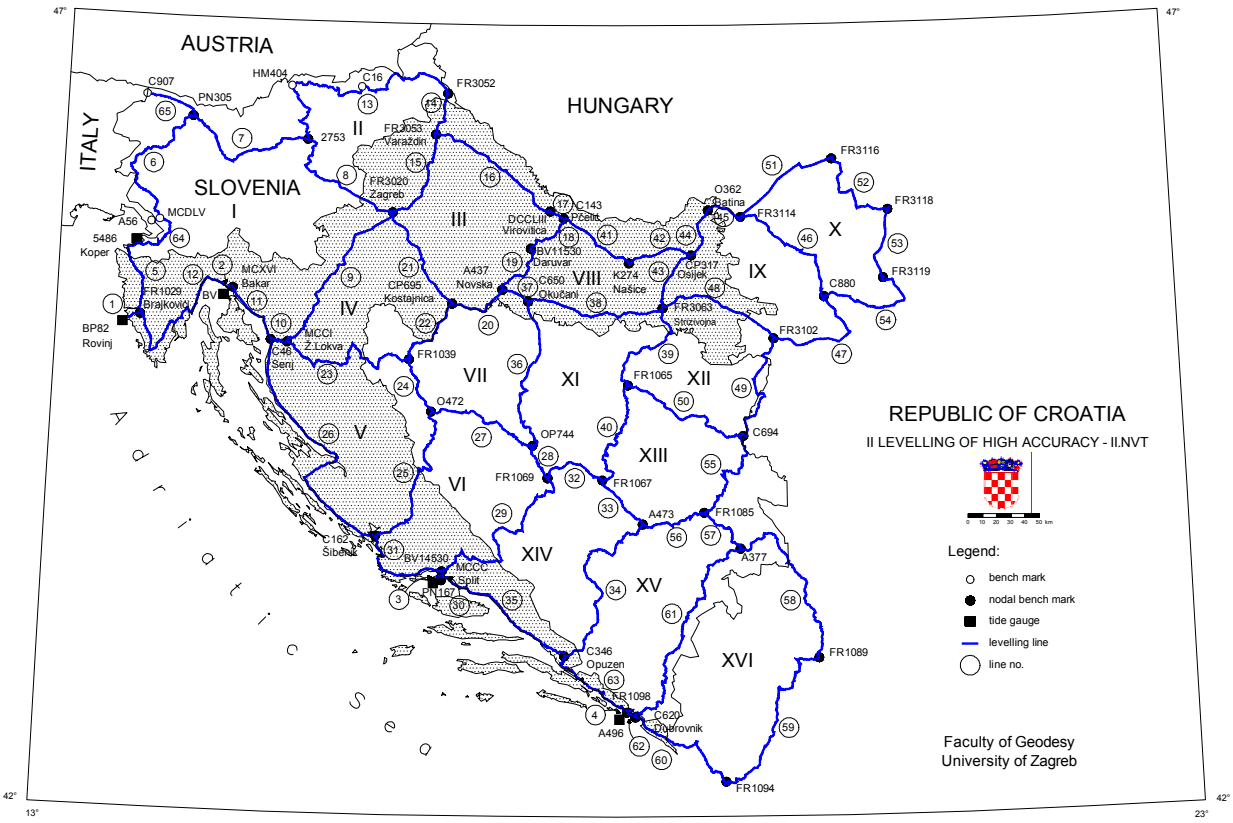

Fig. 3. Levelling network of the II. levelling of high accuracy at the territory of the Republic of Croatia.

The II.NVT network is connected by measurements with tide gauges at the eastern coast of the Adriatic Sea due to the determination of the new height system. The works were organised and conducted by the Federal Geodetic Administration of former Yugoslavia and the Geodetic Administration of Republics, and field works were made by a larger number of geodetic firms. The Military and Geographic Institute from Belgrade made gravimetric measurements in only one part of levelling lines, but there are no such systematically measured, computer processed, published and verified data for the entire levelling network. Therefore, the normal orthometric system was, already almost traditionally, adopted for the height system.

In the period from 1973 until today, the II.NVT network data are the subject of computer processing, modern analyses, fundamental and applied scientific researches and application in solving some practical tasks. The II.NVT network encompassing the territory of now independent and sovereign states: Croatia, Slovenia and Bosnia and Herzegovina, was entirely and unanimously computer processed and analysed at the Faculty of Geodesy, University of Zagreb led by Dr. Sc. Stjepan Klak, Professor Emeritus. On the basis of executed analyses the observation material of the II.NVT was estimated as homogeneous observation material of adequate accuracy, i.e. as the observation of highest quality that the Republic of Croatia has at its disposal at the moment. Systematically processed measuring data of the II.NVT have been originally published in a series of special publication of the Faculty of Geodesy, University of Zagreb (Bilajbegović et al. 1986, Feil et al. 1992).

Within the scope of the II.NVT the defining of a new height datum has also been made referring to the Adriatic Sea level measurements at the tide gauges in Kopar, Rovinj, Bakar, Split and Dubrovnik. The reference equipotential surface for the determination of heights has been adopted as a mean sea level on all tide gauges for the time epoch 1.7.1971. In the determination of the mean sea level, the measurements of sea level for the full period of 18.6 years were taken

into consideration. In relation to the mean sea level, the heights of five starting benchmarks were also determined for the II.NVT network, table II.

Table II. Heights of starting benchmarks

Tide gauge	Benchmark	Height m
Koper	5486	1.88260
Rovinj	BP82	4.83770
Bakar	BV	2.66010
Split	PN167	3.33220
Dubrovnik	A496	3.67706

The analysis and determination of accuracy criteria for the II.NVT network were also made in accordance to usual criteria (Rožić 1995). Just like in the case of APL and I.NVT networks, the reference probable measurement error were computed on the basis of misclosures in closing levelling figures

$$u_F = \pm 0.79 mm / \sqrt{km}, \quad (5)$$

and the reference probable measuring error on the basis of network adjustment applying the least squares method

$$u_o = \pm 0.79 mm / \sqrt{km}. \quad (6)$$

These criteria indicate adequate measuring accuracy, especially in relation to the previous levelling networks. In accordance with the international references for determination of accuracy (Braaten et al. 1950) and with regard to separation of influences of random and systematic errors, the reference probable random error

$$\eta = \pm 0.29 mm / \sqrt{km}, \quad (7)$$

the reference probable systematic error

$$\xi = \pm 0.86 mm / \sqrt{km}, \quad (8)$$

and reference probable total error of measuring height differences were determined

$$\tau = \pm 0.91 mm / \sqrt{km}. \quad (9)$$

On the basis of reference probable total error of measurement, the II.NVT meets the criteria of levelling of high accuracy with remark that the influences of systematic errors are larger than allowed. Positional, i.e. height accuracy of nodal benchmarks in the network is also satisfactory, because mean errors of all nodal benchmarks in the network are smaller than ± 10 mm. This accuracy corresponds practically with the accuracy of mean sea level determination at tide gauges.

At this moment the II.NVT levelling network as the basis of height system has under the circumstances not yet been introduced into the official usage at the territory of the Republic of Croatia although it has been used for a longer time unofficially, first of all in the sense of various scientific and applied researches. However, during the nineties, and regardless of difficult condition caused by the Homeland War, all preliminary works for it introduction into official usage have been made, and there is official and for that matter legally foreseen procedure going on right now in this respect (Feil, Rožić, 2000). The detailed data about the II.NVT levelling network as the height system basis of the Republic of Croatia can be found in (Feil et al. 1993), as well as in national reports of the Republic of Croatia that were presented at EUREF Symposia in Bad Neuenahr-Ahrweiler in 1998 and in Prague in 1999 (Feil et al. 1999, Feil et al. 1999a).

During the nineties the adequate national geopotential height system was also established on the basis of measuring data of the II.NVT and on the basis of testing the possibility to define an adequate gravimetric model (Bašić 1997, Klak et al. 1997), because the values of gravity acceleration along levelling lines have not been measured. This geopotential height system has been successfully integrated into the United European Levelling Network - UELN (Sacher et all. 1999).

Hence, and on the basis of all previously mentioned data, the II.NVT network is so far the levelling network of the highest accuracy systematically established at the territory of the Republic of Croatia, and its introduction into the official usage is just going on. Rather inconvenient is the fact that a longer period of time has passed since its surveying and to the moment of its being introduced into official usage. This is the period of about 30 years being the consequence of objective circumstances. Namely, systematic II.NVT measuring data processing was made only during the eighties at the Faculty of Geodesy, University of Zagreb, and during the nineties extensive works were made on the revision of all levelling networks and their leaning on the II.NVT basis through the collaboration of the State Geodetic Administration of the Republic of Croatia and the Faculty of Geodesy. Apart from the long time that has passed since the II.NVT survey, there is also the lack of measured gravity acceleration values being a considerably inconvenient factor.

5. Conclusion

On the basis of all previously mentioned data, the most important information about basic levelling networks and height datums at the territory of the Republic of Croatia can be summarised and presented in the table III.

Table III. Data about basic levelling network and height datums of the Republic of Croatia

Network title	Period of survey	Type of geometr. levell.	Measuring of gravity accelerat.	Height system	Height datum			Measur. accuracy	Measur. accuracy
					Tide gauge	Epoch	Benchm.	u_F	u_o
APL	1874.-1913.	PN	none	normal orthometr.	Trst	1875.	HM 1	±3.20mm/km	±3.27mm/km
I.NVT	1945.-1963.	NVT	none	normal orthometr.	Trst	1875.	HM 1	±1.67mm/km	±1.33mm/km
II.NVT	1970.-1973.	NVT	-partly yes -modelled	-normal orthometr. –geopotent.	Koper Rovinj Bakar Split Dubrovnik	1971.5	5486 BP82 BV PN167 A496	±0.79mm/km	±0.79mm/km

PL – precise levelling
NVT – levelling of high accuracy
u_F – reference probable error from closing the levelling figures
u_o – reference probable error from network adjustment

It can be seen that in the time continuity in executing these networks there is a clearly expressed trend in increasing accuracy and expressively shortened time of surveying. All three networks were carried out in the period when Croatia was not independent state, and make, together with all their disadvantages and advantages its geodetic heritage from former states. The II.NVT network is by all means the one with the highest accuracy that entered legally prescribed procedure for being introduced into official usage thirty years after its survey. This network is a levelling network of highest accuracy that the Republic of Croatia has at its disposal. Apart from defining the national heights system, it has also made it possible to include the height system of the Republic of Croatia into UELN.

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