Simulation of an Alternative Realisation of the Croatian Height Reference System

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Simulation of an Alternative Realisation of the Croatian Height Reference System

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Abstract. The current Croatian height reference system (HVRS71) has been established using the so-called Second High Accuracy Levelling Network (IINVT) of the former Yugoslavia. This network survey was realised from 1970 to 1973. Today almost 50 years later, it is quite clear that a renewal of the Croatian height reference system is necessary. The survey and design of a new fundamental levelling network for the Republic of Croatia is an expected step. In Croatian particular case there is a significantly limiting key factor for the levelling network design. That limiting factor derives from the fact that the size and the specific shape of the Croatian territory in comparison with the standards of realization of levelling networks have a negative correlation. Considering the aforementioned facts, a careful and comprehensive analysis was conducted. As a basis for the analysis of this issue, a simulation of the new Croatian height reference system realisation was performed. The simulation is based on the grounds of IINVT network observations which had originally been used to create the current official height reference system of the Republic of Croatia, but with a modification of its geometrical configuration. In accordance with the need for continuous monitoring of height displacements of the same benchmarks that had been observed previously (the recent crustal movements issue), the principle of preserving as big as possible segment of the IINVT network configuration on the Croatian territory had been retained. One of the fundamental elements of the height reference system quality certainly is the quality of the absolute benchmark height positioning. In this paper it is shown how radical change of network configuration due to the adjustments to the specific shape of the Croatian territory affects the accuracy of the absolute benchmark height positioning.

1. Introduction
The fundamental infrastructure for height positioning on the territory of the Republic of Croatia is the Croatian height reference system – epoch 1971.5 (HVRS71). That system had been established using the so-called Second High Accuracy Levelling Network (IINVT) of the former Yugoslavia. At the time the network survey was realised (from 1970 to 1973) the Republic of Croatia was an integral part of Yugoslavia. The IINVT network measurement data is quite dated and no longer in agreement with the crustal height displacements caused by the geodynamic forces during the last half of the century [1]. The originally calculated height positions of benchmarks included in the Croatian height reference system are not in compliance with reality (their current heights). Generally, this issue can be easily solved with an update of the height reference system. For such a solution, a re-survey of the IINVT levelling network is needed.
The survey and design of a new fundamental levelling network for the Republic of Croatia has a significantly limiting key factor. The re-survey of the entire IINVT network is not a realistic option, given the fact that Yugoslavia has been dissolved and that the IINVT network lies now on the territory of several different independent states. Considering that the existing IINVT network configuration does not comply with the size and the very irregular shape of the Croatian territory, there are some difficulties with the network design.

The new fundamental levelling network should have a coherent and appropriately firm geometrical configuration with the retention of the part of the IINVT network that is located on the Croatian territory exclusively. It would be very useful to perform a simulation of an alternative realisation of the new height reference system based on the IINVT network observations which was used to create the current official height reference system of the Republic of Croatia (HVRS71), but with a modification of its geometrical configuration. The analysis should determine to what extent an alternative realisation with a radical change of geometrical configuration affects the accuracy of a benchmark’s height positioning.

2. Height positioning accuracy in the current Croatian height reference system HVRS71

The relevant part of the IINVT levelling network for the Croatian height reference system is shown in figure 1. It spreads across the territory of Croatia, Slovenia, Bosnia and Herzegovina and partly across the Montenegro and Vojvodina in Serbia (the western parts of the former Yugoslavia).

![Geometrical configuration of the IINVT network and Croatian territory](image)

**Figure 1.** Geometrical configuration of the IINVT network and Croatian territory

The above-mentioned part of IINVT network consists of 63 levelling lines brought together in 16 closed levelling figures (including the lines that connect the network with the reference benchmarks...
near tide gauges). In addition to the closed figures, the INVT network is in the north connected with the fundamental levelling network of Hungary with three levelling lines. The reference benchmarks (5486, BP82, BV, PN167 and A496) of the Croatian height reference system HVRS71 were defined at the locations of five tide gauges stationed along the east coast of the Adriatic Sea (Koper in Slovenia and Rovinj, Bakar, Split and Dubrovnik in Croatia). The HVRS71 system realisation was matched with the mean epoch of the network survey (time epoch 1.7.1971. or 1971.5). The reference height surface was established with the equipotential surface of Earth gravity field whose height position is defined at the locations of five tide gauges determined by the mean Adriatic Sea level for the time epoch 1971.5. The mean sea level was calculated from the results of continuous sea level observations over the period of 18.6 years.

The INVT network survey was carried out in accordance with the technical criteria of high accuracy levelling. The original observations of height differences were corrected using orthometric corrections computed by means of normal gravity acceleration values and with the levelling rods scale corrections. The INVT network was adjusted in its integral extent (figure 1) by indirect measurements adjustment and least square method [2]. Weights of height differences were introduced in reciprocity with the lengths of the levelling lines (expressed in km). Approximately 7300 benchmarks were included in the network adjustment. Detailed information on the Croatian height reference system, the realization of the INVT network, and the assessment of the “a priori” measurement accuracy are given under [2], [3] and [4].

As a basic indicator of the relative positional accuracy of the height differences, the reference standard deviation of measurement was calculated. Based on the adjustment, the reference standard deviation of height differences is 1.19 mm/km. For all 7300 benchmarks encompassed by the INVT network, regardless whether they were situated within or outside the Croatian territory, the accuracy of benchmark heights was calculated. Standard deviations (s_H) of the benchmark heights range from a minimum of 0.26 mm (benchmark MCCCIX in the levelling line No. 6, near the reference benchmark 5486 in Koper) to a maximum of 17.65 mm (benchmark 186K in the levelling line No. 53, the furthest north-eastern part of the INVT network in Vojvodina). Observing only benchmarks which are located in the Croatian territory, the standard deviations (s_H) range from a minimum of 0.37 mm (benchmark 2 in the levelling line No. 22, near the reference benchmark BP82 in Rovinj) to a maximum of 15.08 mm (benchmark 0037005-1 in the levelling line No. 82 in the furthest north-east of Croatia). Table 1 gives an overview of the achieved accuracy of the benchmark height positions for the node benchmarks which are located in the territory of Croatia.

| Benchmark          | s_H [mm] | Benchmark          | s_H [mm] | Benchmark          | s_H [mm] |
|--------------------|----------|--------------------|----------|--------------------|----------|
| 0037005-1          | 15.08    | CP131              | 12.17    | EP2                | 8.63     |
| 0035001-1          | 14.20    | C143               | 12.14    | MCCI/306           | 8.53     |
| O362               | 13.96    | BV11530            | 12.13    | C346               | 8.16     |
| NP400              | 13.95    | FR3063             | 11.70    | BP93               | 7.81     |
| FR1061             | 13.60    | 62/272             | 11.68    | C46                | 7.47     |
| FR3052             | 13.43    | BB                 | 11.30    | BV14296            | 4.88     |
| 0036001-1          | 13.34    | C650               | 10.98    | C620               | 4.36     |
| C62                | 13.20    | A437               | 10.84    | FR1029             | 3.85     |
| K274               | 12.90    | FR3020             | 10.72    | BV14530            | 3.16     |
| 7036b/322          | 12.80    | CP695              | 10.51    | FR1098             | 2.72     |
| CP317              | 12.53    | O472               | 10.29    | MCCI/306           | 1.37     |
| DCCLLV/259         | 12.40    | FR1039             | 10.22    | MCCC/298           | 0.49     |
| DCCLIII/259        | 12.38    | C162               | 8.97     |                    |          |
| FR3053             | 12.31    | BP589              | 8.75     |                    |          |
A more detailed insight into the achieved accuracy of the benchmark height positions is shown in Figure 2 where the distribution of the benchmark height accuracy is presented by means of corresponding contour lines (lines having the same value of standard deviations) within the entire scope of the IINVT network.

Figure 2 clearly shows how geometrical configuration of the levelling network and the height datum realisation affects the benchmark height accuracy distribution. There is a clear pattern of concentric and quite rapid decrease of the benchmark height accuracy from the locations of the reference benchmarks (benchmarks near tide gauges at the coastal line) towards the interior of the network (land part). Away from the zones influenced by the reference benchmarks, that have fixed height positions, the decrease of the height accuracy becomes more moderate. There is an obvious trend of decrease of the height accuracy from the south-west towards the north and north-east. This trend is correlated with the geometrical configuration of the IINVT network and with the geographical characteristics of the observed territory. It is quite clear that the lowest level of height accuracy in the IINVT network has been achieved in the furthest north-eastern part of the network. Taking into account exclusively the territory of Croatia, the lowest level of height accuracy has been achieved near the town Udvar in the border zone with the neighbouring Hungary. When analysing the benchmark height accuracy, in addition to the influence of the height datum realisation (number and the distribution of reference benchmarks) and the geometrical configuration of the network (size and shape of the network), one has also keep in mind the influence of the measurements accuracy (including the achieved level of systematic errors elimination).
3. Redesign of the levelling network

Benchmark heights determined in the HVRS71 system refer to the surveying epoch of the IINVT network, i.e. the epoch 1971.5. Those heights are not identical with today’s height position of the benchmarks. This is mostly the consequence of the vertical crustal movements and sporadically of the vertical movements of a particular benchmark caused by the inadequate construction stabilisation at the local level. Detailed information about crustal movements on the territory of Croatia, Slovenia and Bosnia and Herzegovina, their direction and size of displacements, empirical patterns and characteristics are given in [1] and [5]. In the period of some 100 years’ height movements of the decimetre value were quantified with uniform height movements of up to several millimetres annually [1]. The observed area has a specific relief structure (the Alps, the Dinarids, the Pannonian basin) and strong seismic activity (zone of the Adriatic lithosphere micro-plate). Taking all of the above into consideration there is an obvious need for an update of the Croatian Height Reference System based on re-survey of the IINVT levelling network. It is very clear that a re-survey of the entire IINVT network, after the disintegration of Yugoslavia, is not a realistic or sustainable option. Therefore, there is a real need for designing a new fundamental levelling network that would be adjusted to the shape and size of the territory of the Republic of Croatia by its geometrical configuration (figure 1). It will not be easy to achieve a firm and compact geometrical configuration of a new network for the territory that has a specific shape like Croatia.

An analysis based on a simulation of an alternative realization of the Croatian height reference system can serve as a basis for solving the network design issue. An alternative realization of the Croatian height reference system is based on the observation data of the IINVT network but with a modification of its geometrical configuration. It is possible to create an alternative height reference system that is comparable to the existing HVRS71 system by using the principle of preserving as big as possible a segment of the IINVT network configuration in the Croatian territory. The use of that principle is also in accordance with the need for continuous monitoring of height displacements of the same benchmarks that had been observed previously (the recent crustal movements issue). In that case, the alternative height reference system would be comparable with the HVRS71 system in terms of height accuracy of the adjusted benchmark heights. The convenience of such a simulation is that the influence of the IINVT network measurements accuracy is practically eliminated, but the geometrical configuration of the revised IINVT network is fully expressed.

Adhering to the principle of preserving as big as possible a segment of the IINVT network configuration in the Croatian territory, two distinctive parts can be clearly identified (figure 1). The first characteristic part is formed by the levelling lines spreading along the coastline of the Adriatic Sea (levelling lines No. 5, 1, 12, 2, 11, 26, 31, 30, 3, 35, 63, 4, 62 and 60), from Koper in Slovenia to the bay of Boka Kotorska in Montenegro. Those levelling lines strongly rely on tide gauges (i.e. reference benchmarks of the height system with fixed heights) and they are encompassed by the so-called “tide-gauge” levelling figures. On the other hand, levelling lines spreading across the Croatian continental region are joined in the levelling figures (figures III, IV, V and VIII). Considering the specific shape of Croatia, a certain number of levelling lines is now completely outside the closed figures if compared with the original configuration of the IINVT network. These are the levelling lines No. 29, 34, 61 and 60 in a central and south Dalmatia and the levelling lines No. 8, 14, 36, 39, 44 and 48 in the continental part of Croatia. The geometrical configuration of the revised IINVT network is based on a chain of levelling figures III, IV, V and VIII. These levelling figures are almost completely located in the territory of Croatia with the exception of a small part of the figures IV and figure V that spreads across the territory of Bosnia and Herzegovina (levelling line No. 24 and some parts of levelling lines No. 22, 23 and 25). This fact is not a problem for the simulation of an alternative geometrical configuration, but in the case of an actual realisation of a network, new levelling lines could be established on the Croatian territory near the border with Bosnia and Herzegovina. An alternative geometrical configuration redefined in such a way clearly points out the significant level of
deficiency regarding the compactness of the geometrical configuration. There is also the risk connected with the reliability of the alternative height reference system realisation compared to the original HVRS71 system. Using only levelling lines that are located in Croatian territory and considering the previously mentioned explanations the simulation of an alternative realisation of the Croatian height reference system has been performed. Just like the original HVRS71 system the alternative system has also been realised as a system of normal-orthometric heights, using the indirect measurements adjustment and least square method with the same measurement weights determination procedure. During the realization of the alternative system, the same realization of the height datum as in the original HVRS71 system was retained [6]. The created alternative system is directly comparable with the original HVRS71 system.

Approximately 3300 benchmarks in the Croatian territory were included in the network adjustment, including a negligible number of benchmarks in Slovenian territory (part of the levelling line No. 5 from the border to the reference benchmark 5486 near tide gauge Koper and of the levelling line No. 14 from the border to the benchmark FR3052). Based on the adjustment, the reference standard deviation of height differences is 0.86 mm/km. The accuracy of the benchmark height positions has also been determined for all 3300 benchmarks in Croatian territory. Standard deviations (s_H) of the benchmark heights range from a minimum of 0.27 mm (benchmark A510 in the levelling line No. 2, near the reference benchmark BV in Bakar) to a maximum of 15.36 mm (benchmark in the levelling line No. 48, the far-east end of the network near the border with Serbia). More detailed insight into the achieved accuracy of the benchmark height positions is shown in Figure 3 where the distribution of the benchmark’s height accuracy is presented by means of corresponding contour lines. An overview of the achieved accuracy of the benchmark’s height positions for the node benchmarks is given in table 2.

![Benchmarks height accuracy on Croatian territory](image.png)
Table 2. Standard deviations of the node benchmark heights (revised IINVT)

| Benchmark     | $S_H$ [mm] | Benchmark     | $S_H$ [mm] | Benchmark     | $S_H$ [mm] |
|---------------|------------|---------------|------------|---------------|------------|
| 0037005-1     | 15.28      | CP131         | 14.15      | EP2           | 7.16       |
| 0035001-1     | 13.17      | C143          | 12.31      | MCCI/306      | 6.94       |
| O362          | 14.71      | BV11530       | 12.20      | C346          | 6.54       |
| NP400         | 14.69      | FR3063        | 13.52      | BP93          | 5.93       |
| FR1061        | 13.60      | 62/272        | 11.31      | C46           | 5.87       |
| FR3052        | 13.03      | BB            | 12.43      | BV14296       | 3.66       |
| 0036001-1     | 12.89      | C650          | 12.02      | C620          | 3.26       |
| K274          | 13.23      | A437          | 11.43      | FR1029        | 2.82       |
| 7036b/322     | 12.37      | CP695         | 10.19      | FR1098        | 2.01       |
| CP317         | 13.57      | O472          | 9.51       | MCCI/306      | 1.01       |
| DCCLV/259     | 12.38      | FR1039        | 9.20       | MCCC/298      | 0.36       |
| DCCLIII/259   | 12.37      | C162          | 6.87       |               |            |
| FR3053        | 11.94      | BP589         | 7.15       |               |            |

4. Results and discussions

Figure 3 shows how the revised geometrical configuration of the IINVT network affects the benchmark height accuracy distribution. There is a clear pattern (very similar as in figure 2) of concentric and quite rapid decrease of the benchmark height accuracy from the locations of the reference benchmarks (coastal line) towards the interior of the network (land part). The direct comparison between the alternative height reference system and the original HVRS71 system is quantified by the differences of the adjusted benchmark heights ($\Delta H$) and the differences between the standard deviations of the benchmark heights ($\Delta S_H$). These differences for all of the node benchmarks in the network are given in the table 3.

Table 3. Node benchmarks height differences and height accuracy.

| Benchmark     | $\Delta H$ [mm] | $\Delta S_H$ [mm] | Benchmark     | $\Delta H$ [mm] | $\Delta S_H$ [mm] |
|---------------|-----------------|-------------------|---------------|-----------------|-------------------|
| 0037005-1     | 34.11           | -0.20             | C650          | 27.56           | -1.04             |
| 0035001-1     | 25.13           | 1.03              | A437          | 26.72           | -0.59             |
| O362          | 34.14           | -0.75             | FR3020        | 23.31           | 0.38              |
| NP400         | 34.11           | -0.74             | CP695         | 24.08           | 0.32              |
| FR1061        | 30.34           | 0.00              | O472          | 22.54           | 0.78              |
| FR3052        | 25.11           | 0.40              | FR1039        | 21.33           | 1.02              |
| 0036001-1     | 27.79           | 0.45              | C162          | 7.86            | 2.10              |
| C62           | 33.48           | -2.16             | BP589         | -4.42           | 1.60              |
| K274          | 30.34           | -0.33             | EP2           | -7.32           | 1.47              |
| 7036b/322     | 25.13           | 0.43              | MCCI/306      | 11.56           | 1.59              |
| CP317         | 32.28           | -1.04             | C346          | -3.70           | 1.62              |
| DCCLV/259     | 27.79           | 0.02              | BP93          | -3.39           | 1.88              |
| DCCLIII/259   | 27.81           | 0.01              | C46           | 8.19            | 1.60              |
| FR3053        | 25.14           | 0.37              | BV14296       | -0.03           | 1.22              |
| CP131         | 32.42           | -1.98             | C620          | -0.34           | 1.10              |
| C143          | 28.09           | -0.17             | FR1029        | 0.02            | 1.03              |
| BV11530       | 27.48           | -0.07             | BV14530       | -0.18           | 0.82              |
| FR3063        | 32.05           | -1.82             | FR1098        | -0.26           | 0.71              |
| 62/272        | 24.61           | 0.37              | MCCI/306      | 0.19            | 0.36              |
| BB            | 27.51           | -1.13             | MCCC/298      | -0.01           | 0.13              |
The distributions of the differences between the benchmark heights (ΔH) and between the benchmark’s height accuracy (ΔsH) are presented by means of corresponding contour lines in figure 4 (ΔH) and in figure 5 (ΔsH).

![Figure 4. The differences between benchmarks heights ΔH](image)

The data in table 3 and in figures 4 and 5 indicates the level of influence of the revised geometrical configuration of the IINVT network on the amounts of benchmark heights and their accuracy. The results show that the benchmark heights in the alternative realisation of the height reference system are generally lower than the original HVRS71 values. It can also be noted that there are no significant changes in terms of benchmark height accuracy.

There is a clear pattern of a systematic and continuous increase of the benchmark height differences (ΔH) from the coastal line towards the north-east part of the Croatian territory (figure 4). The biggest benchmark height difference in the amount of 34.11 mm was determined in the furthest north-east part of the network on the benchmark 0037005-1 in the levelling line No. 82. Benchmark height changes between the alternative height reference system and the original HVRS71 system are noticeably less significant than the influence of recent crustal movements. It can also be assumed that the benchmark height changes are less significant or at least at the same level as any possible changes that may occur as a consequence of a new and more updated height datum realisation (the assumption about the trend of increase of the mean sea level).
As far as height positioning accuracy is concerned (figure 5), the alternative realisation of the height system leads to formally somewhat more favourable height accuracy than in the original HVRS71 system, but not in the significant level. This formal improvement of accuracy is primarily a consequence of the radically changed configuration of the IINVT network and of the fact that the measurement reference standard deviation is somewhat lower in the alternative realisation of the height system (0.86 mm/km), compared to the value obtained in the original realisation of the HVRS71 system (1.19 mm/km).

Figure 5. The differences between benchmarks height accuracy $\Delta s_H$

5. Conclusions
Based on the displayed data it can be concluded that the simulated realisation of the Croatian height reference system is a sustainable solution. Despite the radical change of the IINVT network configuration due to the adjustments to the specific shape of the Croatian territory retaining only the part of the network that is located exclusively in the Croatian territory, it is possible to achieve a usable and reliable height reference system. That alternative height reference system has a similar or practically identical quality of benchmark height positioning like the one in the original HVRS71 system (although relatively moderate differences between absolute benchmark heights exist).

The solution for the geometrical configuration of the levelling network is not an ideal one. To what extent the modification of the network configuration affects the heights and their quality is visible from the direct comparison of the simulated and original realisation of the height reference system. It is quite clear that in order to update the HVRS71 system, regardless of the need for the
The implementation of the geopotential height system and the normal height system derived from it (abandoning the normal-orthometric height system), the impact caused by the change of the geometrical configuration of the levelling network would be replicated and would influence the quality of the new height system in a similar manner.

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