Initial Considerations on Modernization of the Croatian Height Reference System

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Abstract. *Modernization of height reference systems has started in the past decade in the field of basic surveying work in the world. It was triggered mostly by intensive development and daily use of satellite positioning methods, as well as by increased accuracy of global and regional gravity models. The accomplishment of one-centimetre accurate geoid model in higher resolutions and implementation of the World Height System is expected in the next decade. The current height systems in the world, usually defined by means of tide gauge measurements and realized by means of levelling, do not meet the growing and diverse needs of geodetic engineering practice, especially in demanding infrastructure jobs. Therefore, the redefining of Croatian height system and reconstruction of its frame (Croatian Height Reference System 1971) will be an important task in the upcoming years. This paper analyses the current definition of Croatian height system and its framework, and considers the strategy for its modernization with the aim of finding the best long-term solution within the current world's experiences and guidelines.*

Keywords: *geoid, height reference system, HRG2009, modernization, II. NVT.*

1. Introduction

Heights are positional attributes of all geo-related data and are essential for a wide range of engineering and scientific activities such as mapping, surveying, agriculture, forestry, transportation, navigation, etc. Precise levelling used to be the main technique for height determination for a long time. However, the advancement of the GNSS (Global Navigation Satellite System) technology in the last two decades and its wide usage have replaced it with GNSS/levelling.

It is reasonable to expect that ellipsoidal heights will be determined in real-time with GNSS technology and CORS networks with absolute vertical accuracy of 1-2 cm during the next decade [Flury & Rummel 2005]. However, ellipsoidal heights have only geometrical meaning and cannot be used directly for the determination of physical heights because they do not have direct relation to the Earth's gravity field. The relation to the Earth´s gravity field is established with geoid models that would nowadays have to be determined with the same accuracy as GNSS ellipsoidal heights. Within this context, modernization of the height reference systems has lately received considerable attention worldwide and many countries are reviewing options.

2. Approaches and strategies to height reference systems definition and realization

Height (vertical) datum is a reference surface of zero elevation that geometrical or physical heights of points on the Earth are referred to. It can be defined by: observing the sea level, gravimetric geoid determination or the selection of reference ellipsoid (e.g. GRS80). Defined by observing the sea level and geoid datum relates to the reference surfaces for the gravity-related heights (geopotential, dynamic, orthometric, normal heights) whereas ellipsoid is the reference surface for the geometrical heights (ellipsoidal). A reference system consists from reference surface (height datum) and origin points with known height from which heights of all other points are calculated. Currently, there are more than one hundred different height reference systems worldwide that are non-consistent to each other. Generally, two different approaches of height datums and reference systems exist.

2.1. MSL/levelling based height reference system

Traditionally, tide-gauges have measured sea level over a longer period. These data are averaged in observation epoch to provide the value of the MSL as a zero reference surface (height datum origin). A levelling-based height reference system is realized by means of precise levelling at connected geodetic points (benchmarks) and the establishment of precise levelling networks over the territory. Until GNSS era, the MSL/levelling height reference system was the only possible option to use physical heights over some country or continent. Therefore, most of the height reference systems throughout the world are defined and realized in this way.

2.2. Geoid/GNSS based height reference system

The alternative approach in defining a height datum is my means of gravimetric geoid. The gravimetric geoid is an equipotential surface that is determined from the measurements of the Earth's gravity field and serves as a reference surface for the most physically meaningful orthometric heights (in terms of traditional geodetic glossary: *heights above sea level*). A geoid-based height datum would be defined solely by calculating the high-resolution gravimetric geoid model from satellite, airborne and terrestrial gravity data. If gravimetric geoid model should be adopted as height datum, its absolute vertical accuracy should be at the order of 1-2 centimetres. Height reference systems could be realised solely by GNSS surveying.

2.3. MSL/levelling vs geoid/GNSS height reference system

Each of the possible two approaches in definition and implementation of height datum and height reference system has its advantages and disadvantages. MSL/levelling approach offers an independency of geoid undulation in order to determine heights, and it is also more reliable especially in the areas without the GNSS signal. However, it lacks the consideration of the sea level rise and topography, it is exposed to systematic error accumulation, benchmarks are destructed over time, its maintenance is budget- and time-consuming, it exhibits 100 realizations worldwide that are non-consistent, etc.

The greatest advantages of geoid/GNSS approach are the replacement of costly and laborious levelling, possible achievement of real-time physical heights with 1-2 cm accuracy, and having globally consistent and exchangeable heights.

More advantages and disadvantages of two approaches are outlined in table 2.1, with *A* sign highlighting the *advantage*.

Table 2.1 MSL/levelling vs geoid/GNSS height datum – advantages and disadvantages

	MSL/levelling		**Geoid/GNSS**	
Height datum independent of *h*-*N* – it can be used as an independent surface for geoid model validation	yes	A	no	
Compatible with satellite positioning techniques	no		yes	A
High precision of heights in the areas with the no signal	yes	A	no	
Fixed to MSL, an unstable surface (globally rising at a rate of 1.8±0.3 mm/yr)	yes		no	A
Accumulates the systematic levelling errors over long distances	yes		no, independent	A
Requires an ongoing maintenance	yes		no	A
Sensitive to tectonic and seismic activity	no		yes	A
Vulnerable to changes in topographic slopes	yes		no	A
Laborious datum realization	yes		no	A
Expensive and unreliable benchmark revision	yes		no	A
Existence of network distortion	yes		no	A
Long-term sea level change considered	no		yes	A
Sea surface topography is not considered	no		yes	A
Requires continuous updating of terrestrial gravity database	no	A	yes	
High local relative precision	yes	A	no	
Compatibility with World Height system	yes		yes	

From user perspective, the necessity to modify traditional height reference system has not been sufficiently addressed yet. The existing height reference system is judged mainly from the aspect of usability being satisfactory for most of users as such, even though absolute vertical accuracy is completely wrong. Depending on the usage, the requirements related to the corresponding vertical accuracies are given in table 2.2.

Table 2.2 User requirements on absolute vertical accuracies

Absolute vertical accuracy	**Use**	**Users**
1-10 mm	land subsidence and uplift	scientists
<0.03 m	Cadastral survey	land surveyors
<0.1 m	Construction of the communal and buildings infrastructure, flood protection, irrigation schemes	local government agencies (city, district and regional councils)
<0.1 m	geospatial analysis, web-based applications	GIS users
0.15 m	topographic surveying and mapping	land surveyors
0.5-1 m	long-term environmental changes in large regional and national areas	scientists
1-5 m	other uses of GNSS technology	other users
depths less than 30 m accuracy: <0.25 m	nautical charting	sailors, marine workers

A significant number of field applications require high relative accuracy of the points in the local area. Their users use local networks and do not need connection to the official height reference system. For example, when researching land subsidence or deformations of the bridges. It is unlikely that any new definition of height datum will ever be able to support these millimetre accuracy requirements in absolute sense.

2.4. Change or no?

Although the scientific community has mostly agreed upon the necessity of the modernization and unification of local height datums, despite the problems that they bring along, there are still some different opinions on two available approaches.

In spite of all the benefits that a new height datum would provide, most users could find the transition to a new height datum reluctant and hesitate to implement it. Firstly, MSL/levelling height reference system has traditionally been used for many decades. Secondly, users are more focused on local and regional tasks and are not interested in the integration with the international height reference system. Thirdly, consistent transformation of existing geospatial data might be complicated and long-term. Finally, if benefits and improvements are not really necessary and significant, such obstacles discourage the users to perform changes.

3. Croatian Height Reference System

Croatian height datum was defined by MSL observed at five tide gauges during the period of 18.6 years, which resulted with the reference geoid surface of Croatia defined for the epoch 1971.5. Croatian Height Reference System (HVRS71) was realised by the levelling measurements conducted during 1970-1973 connecting the benchmarks distributed across the country by means of precise levelling. Because of the lack of gravity data that were not collected during the establishment of fundamental levelling network (II. NVT), the normal-orthometric heights were adopted for the height system [NN 110/2004]. Due to this approximation, HVRS71 fails to be rigorously and physically correct because normal-orthometric heights are related to the normal gravity field. The differences between *hybrid* normal-orthometric and *most desirable* orthometric heights are typically less than 2 cm but can be even 10 cm in the mountains.

HVRS71 is realized on about 3200 fundamental benchmarks of the highest order of accuracy. In 2000, around 30% were destroyed. Thus, today there are less then 2000 high-precision benchmarks in Croatia (~1 benchmark per 30 square kilometres).

Internal absolute accuracy of heights on benchmarks obtained from levelling network adjustment is 10 mm, reaching the extreme values from 0.4 mm to 14 mm [Tir *et al.* 2013]. Mainly because of two reasons these statistical measures are no longer valid and reliable. First, MSL value (height datum origin) has changed since the 1971.5 epoch because of the mean annual rise of the Adriatic Sea of 3 mm per year. This practically means all benchmark heights today increased for about 15 cm from 1971. Second, [Rožić *et al.* 2011] published the crustal velocities that have absolute values from 1 to 4 mm/yr over the Croatian territory. This implies that benchmarks have changed non-uniformly since 1971 between 5 cm to 20 cm. Apart from these two reasons, benchmarks have changed, distorted and destroyed because of tectonic and seismic activity and physical removal.

The relation with ellipsoidal GNSS heights and HVRS71 was established by adopting the HRG2009 quasi-geoid model. *HRG2009* was created gravimetrically and then mathematically adapted (fitted) to the benchmark heights of HVRS71, practically becoming *hybrid* quasi-geoid model. It currently serves as transformation surface between ellipsoidal and height reference system (HVRS71). According to [Bašić & Bjelotomić 2014], its accuracy is 3.5 cm throughout the country. Although *HRG2009* is the best national quasi-geoid solution at the moment, new gravity satellite missions with improved resolution and accuracy should yield data for the future improved geoid solution that the height reference system could be based on.

4. Future perspective of modernization

Basic requirements of a modern height reference system are: defined in the Earth´s gravity field; consistent, stable and reliable; compatible with GNSS without geoid model fitting; consistent with global and regional gravimetric geoid models; dynamic; suitable for scientific research; suitable for integration into global height datum; able to satisfy a large number of economic activities and applications (engineering, cartography, survey, mapping, scientific). The International Association of Geodesy (IAG) has adopted standards, conventions and guidelines for the definition of international height reference system (IHRS). According to these guidelines, we should adopt [Sanchez 2015]: 1) best-estimated value for the potential W_0 of a height reference surface (geoid), 2) parameters, observations, and data related to the mean tidal system/mean crust, 3) heights expressed in geopotential numbers, 4) positions of points in International Terrestrial Reference Frame (ITRF).

However, the main issues to be resolved prior to modernization of height reference system is choosing between two different approaches (MSL/levelling or geoid/GNSS). Several countries in North America, Europe and Asia have started to abandon the MSL/levelling height reference system and are adopting a geoid/GNSS based height reference system. The first such implementation has been adopted in New Zealand [Amos & Featherstone 2009]. In 2013, Canada replaced the old vertical datum dated from 1928 (CGVD1928) [Veronneau *et al.* 2006]. USA is planning to establish new height reference system by 2022 and are currently investing significant efforts in improving their data [Roman & Weston 2012]. Some other countries have recently discussed this issue, including Australia [Featherstone *et al.* 2012], Turkey [Ince *et al.* 2014] and South Africa [Wonnacott & Merry 2011].

5. Conclusion

The international experience shows that national and regional height datum definitions have limited life-span and should be replaced or upgraded every few decades. This is also the case with the traditional mean sea level (MSL) height datums that have significant limitations. These limitations could be successfully solved by defining a new height datum that could exploit all advantages of GNSS and precise gravimetric geoid models with addition to promising surveying techniques such as Terrestrial Laser Scanning (TLS), Mobile Laser Scanning (MLS), Airborne Laser Scanning (ALS) and Synthetic Aperture Radar (SAR).

Since the definition and the realization of the HVRS1971 nearly 50 years ago, immense changes in terms of technology, data and user requirements have occurred. Although HVRS71 will remain Croatian's official height reference system in the foreseeable future, a new height reference system is considered as an imperative for a long-term solution. Without significant time and financial investment HVRS71 does no longer satisfy the demands in terms of heights accuracy, cost and time efficiency. Redefinition of the height datum by determination of precise gravimetric geoid model is very promising despite the problems that might occur. The authors believe that its long-term benefits should trigger its implementation. Consequently, strategy development and planning should start as soon as possible.

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Razmatranje modernizacije Hrvatskoga visinskog referentnog sustava

Sažetak. *Proteklog desetljeća u području osnovnih geodetskih radova u svijetu aktualizirala se tema modernizacije visinskih referentnih sustava. Glavni uzroci tomu su intenzivni razvoj i svakodnevno korištenje satelitskih metoda pozicioniranja te povećanje točnosti globalnih i regionalnih modela geoida. U sljedećem desetljeću očekuje se ostvarenje točnosti modela geoida od jednog centimetra u većim rezolucijama te realizacija Svjetskog visinskog sustava. Sadašnji visinski sustavi u svijetu, najčešće definirani mareografskim mjerenjima i realizirani nivelmanom, ne udovoljavaju sve većim i raznovrsnijim potrebama geodetske inženjerske prakse, osobito ne u zahtjevnijim infrastrukturnim poslovima. Iz tih bi razloga Hrvatskoj u narednim godinama trebalo uslijediti redefiniranje visinskog sustava i obnova visinskog okvira (Hrvatskog visinskoga referentnog sustava 1971). U radu će se analizirati sadašnja definicija hrvatskog visinskog sustava i stanje okvira te razmotriti strategije i mogućnosti modernizacije, a s ciljem pronalaska najboljega dugoročnog rješenja.*

Ključne riječi: *geoid, HRG2009, modernizacija, visinski referentni sustav, II. NVT.*

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