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To appear in: Technical Sciences

Received 3 March 2013;

Accepted 26 April 2014;

Available on line 4 May 2014.

European Vertical Reference Frame EVRF2007

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Abstract:

In Poland at the end of 2013 was completed implementation of the *European Vertical Refrence Frame* EVRF2007 in the country. This frame is the result of twenty years of works of the Subcommittee EUREF IAG. The paper in a condensed way describes the successive stages of development of the EVRF2007 frame in order to allow the readers to understand its essence.

In the first part of the work are given definitions and how the EVRF2000 frame has been implemented and then is described how the system has been improved. Then the EVRF2007 is characterized with particular attention paid to the vertical movements of the earth crust and tidal corrections.

Key words: Vertical reference system and frame, levelling networks, tide corrections.

Introduction

Height reference system is defined by the reference surface (geoid) and height. If the reference surface and height depend on the Earth's gravity field, such system is called a physical height system. If it is not related to the gravity, it is the geometrical height system. Normal and orthometric heights, obtained from the levelling and gravity measurements, are typical physical height systems.

The level surface (geoid) in respect to which the heights are defined, in practice is defined by the mean sea level, which is estimated at one or more tide gauge stations. The tide gauge stations of the national European height systems are located at various seas: the Baltic Sea, the North Sea, the Mediterranean Sea, the Black Sea and the Atlantic Ocean. Differences in mean sea levels of these seas come to several decimeters, what causes that heights in different countries related to different surfaces differ amongst themselves.

First definition of the European Vertical Reference System (EVRS)

In order to unify the local vertical systems in Europe, in 2000 the *European Vertical Reference System, EVRS* was defined (Ihde and Augath, 2000) as follows:

- ✓ The vertical datum in this system is the equipotential surface for which the Earth gravity field potential W_0 is equal to the normal potential of the mean Earth ellipsoid U_0

$$W_0 = U_0 = const \tag{1}$$

- ✓ The height component is the difference ΔW_P between the potential W_P of the Earth gravity field in the considered points P and the potential W_0 of the EVRS zero level. The potential difference $-\Delta W_P$ is also called a geopotential number C_P and its equivalent is the normal height,
- ✓ The EVRS is a zero tidal system accordingly to the IAG Resolution.

Practical realization of the EVRF2000

The practical realization of any height system is a vertical frame (datum). The first practical realization of the EVRS was result of the adjustment of the UELN-95/98 network.

The starting point of the UELN-95 project was levelling data from Western Europe so called the UELN-73 network, which was adjusted once more in 1986. Afterward the new data were included to the UELN-73 network from the precise levelling campaigns from the Czech Republic, Hungary, Slovenia, Poland and Slovakia also eastern part of Germany (former GDR). The UELN-95 network was then adjusted, step by step, as a nodal network of the geopotencial heights referred to the Normaal Amsterdams Peil NAP at Amsterdam (tide) gauge (Lang and Sacher, 1995), (Sacher at al., 1999). A consequence of this the geopotential number of NAP is zero:

$$C_{NAP} = 0 \tag{2}$$

and in practice the EVRF2000 datum is fixed through the geopotential number and the equivalent normal height of the reference point of the UELN No. 000A2530/13600 located near to the gauge in Amsterdam (Table 1)

Table 1 Characteristic of EVRF2000 reference point (Ihde and Augath, 2000)

Station name	UELN number	Position in ETRS89	Height in UELN 95/98	gravity in IGSN71

		ellipsoidal latitude and longitude	geopotential number in m^2s^{-2}	normal height in m	in ms^{-2}
reference point 000A2530 Netherlands	13600	52° 22’ 53” 4° 54’ 34”	7.0259	0.71599	9.81277935

In January 1999 the results of the adjustment of the network have been passed on to the participating countries in the project under the name the UELN-95/98 (Fig. 1). In addition to the results of the adjustment also report prepared by the UELN Data Centre was handed over. It describes the adjustment method and the manner of calculating normal heights. A year later, after the EUREF symposium in Tromsø in 2000, the realization of the UELN-95/98 solution as the *European Vertical Reference Frame* (EVRF2000) was accepted.

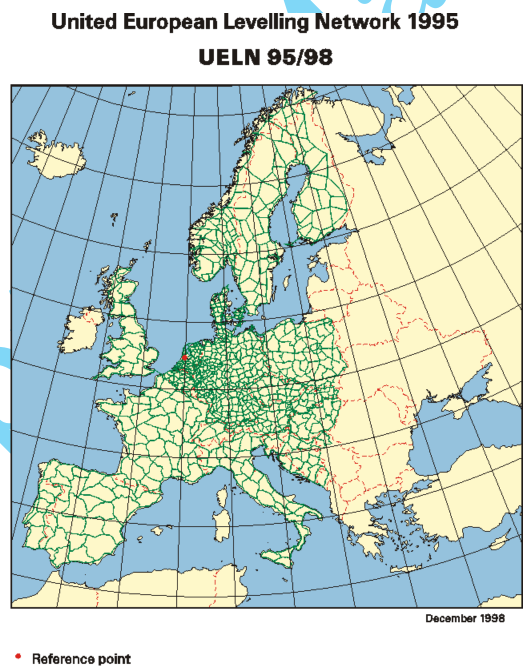

Fig. 1 UELN-95 network, December 1998 (Adam et al., 2000)

New definition of the European Vertical Reference System

Realization of the *European Vertical Reference Frame* EVRF2000 has provided heights in Europe with the accuracy of a few decimeters. This accuracy is satisfying only for the GIS users. In order to improvement the EVRS system a revision of the EVRS2000 realization, conventions and parameters was made (Ihde and Augat, 2000).

As a result of the work carried out in 2008 a new definition of the *European Vertical System* named EVRS2007 was given (Ihde et al., 2008). According to this definition EVRS is a geopotential reference system related to the Earth gravity field and rotates with the Earth. In this system positions of points are defined by geopotential values in relation to the reference potential and by corresponding coordinates (*X, Y, Z*) defined in a *Terrestrial Reference System* (TRS).

On the contrary the *European Vertical Reference Frame* (EVRF) is a collection of physical points with precisely determined differences of geopotential in respect to a reference potential W_0 at a defined epoch. Positions of the points are defined by the coordinates (*X, Y, Z*) in a specific spatial coordinate system attached to a *Terrestrial Reference System*. Therefore the EVRF is the realization of the EVRS at a defined epoch. Accordingly to this definition the *European Vertical Reference System* is a kinematic height system.

Definition of this system fulfils the following conventions (Ihde at al., 2008):

- ✓ The vertical datum is equipotential surface for which the gravity potential W_0 is constant, (formula (1)), and which is a potential in the level of the Normaal Amsterdams Peil.
- ✓ The unit of length of the EVRS is the meter (SI) and the unit of time is second (SI). This scale is consistent with the TCG time coordinate for a local geocentric frame, in agreement to IAU and IUGG (1991) resolutions. The TCG time is obtained by appropriate relativistic modeling.
- ✓ The height components are the differences ΔW_P between the potential W_P of the Earth gravity field through the considered point *P*, and the potential W_0 of the EVRS conventional zero level. The potential difference $-\Delta W_P$ also is designated as the geopotential number C_P. Normal heights are equivalent with geopotential numbers, provided that the reference gravity field is specified.
- ✓ The EVRS is a zero tidal system, in agreement with the IAG Resolutions No. 9 and 16 adopted in Hamburg in 1983.

Practical realization of the EVRF2007

Since the adjustment of the UELN 95/98 network in January 1999 and adoption of this solution as the EVRF2000 a significant number of new data have been delivered to the UELN Data Centre (Sacher et al., 2008). Between others fourteen counties carried out new campaigns of part or entire precise levelling networks (Fig. 2).

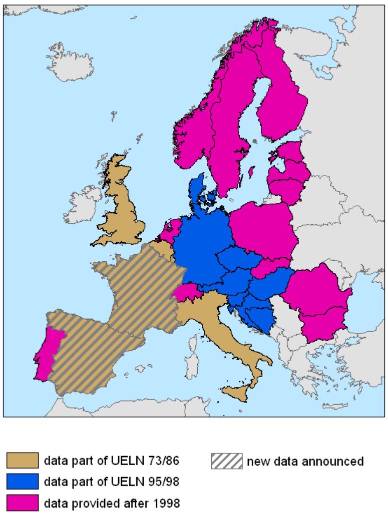

Fig. 2 Geographical range of the UELN network (Sacher et al., 2008)

Therefore Data Center had to realize a new variant of the *European Vertical System* as the EVRF2007. All countries participating in this project were asked to provide their current data. The results of measurements of precise levelling networks gathered in the UELN Data Centre come from very different epochs (Fig. 2). In order to refer all observations to one epoch, data from levelling were reduced due to the vertical movements of the Earth's crust. These corrections were introduced only to data of Finland, Norway, Sweden, Denmark, Germany (northern part), Poland, Lithuania, Latvia, and Estonia. The necessary corrections to the reduction were calculated from the land uplift model developed by (Ågren and Svenssonn, 2007)(Fig. 3).

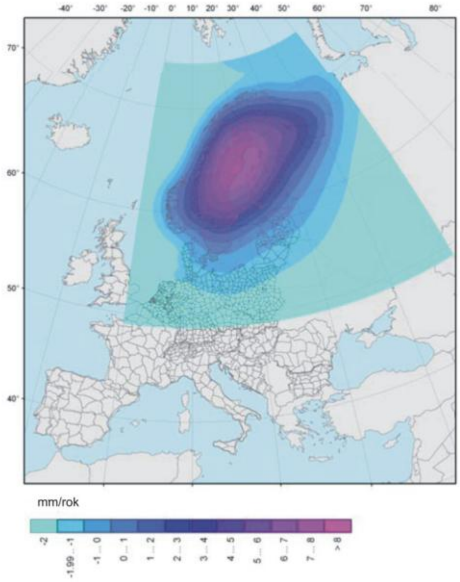

Fig. 3 The NKG2005LU model and UELN lines (Sacher et al., 2008)

The EVRF2000 vertical datum is determined by the geopotential number and the equivalent normal height of the reference point no 000A2530 (Table 1). Because this point is not included in the current levelling network of the Netherlands, therefore in new EVRF realization it could not be taken into account (no longer available) as a datum point. In order to keep in Europe the level of the EVRF2000 datum, the new UELN adjustment was fitted to the EVRF2000 solution by selecting several fixed points and introducing them in the new adjustment. This was realized by introducing the following condition:

$$\sum_{i=1}^{n}(C_{P_i,2007} - C_{P_i,2000}) = 0 \quad (3)$$

The chosen points should be on the stable part of the European plate. In December 2006, all the participating countries in the UELN project were asked for proposals for reference points in order to proper adjustment of the network. Fig. 4 presents the positions of proposed reference points.

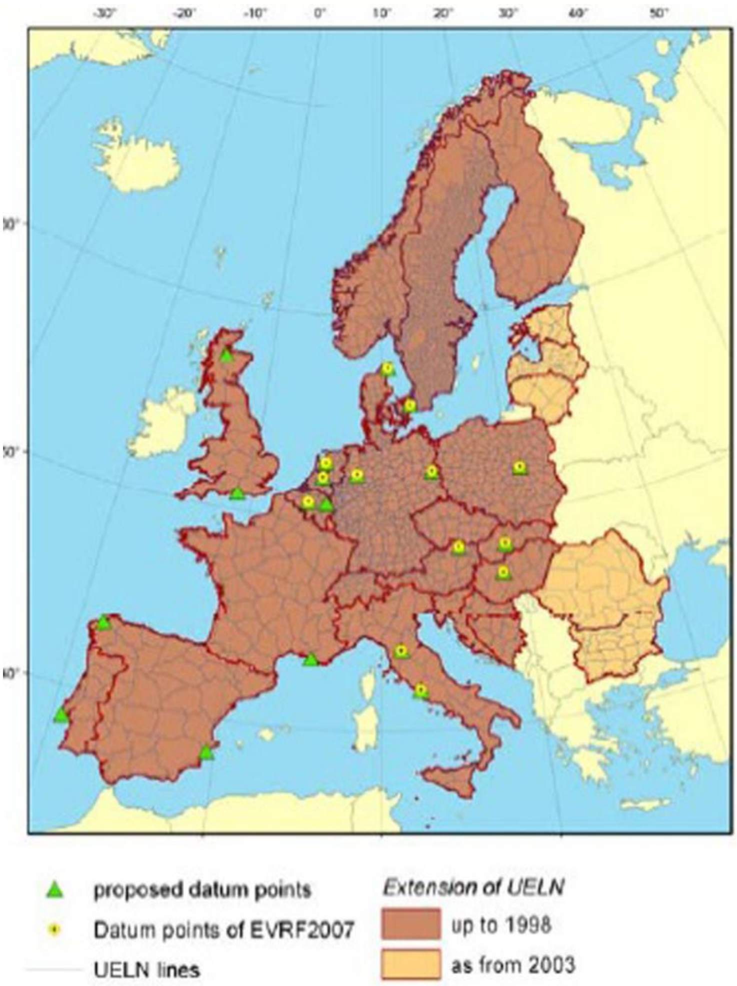

Fig. 4 Proposed and used reference points (Sacher et al., 2008)

Then several variants of adjustment of the network were performed with different selections of data sets of reference points. Change in heights caused by different reference points was from 1 to 5 mm. In the final adjustment were only used 13 of 20 proposed reference points. Seven points were rejected for a variety of reasons.

For example, the Netherlands had proposed three reference points from which one has changed height considerably in comparison to the EVRF2000 solution. United Kingdom proposed two reference points but finally they were not used in adjustment, because the country is located on the island and is connected to the continental network only by one uncertain levelling line. After a planned inclusion a levelling line through the tunnel, significant height variations in these reference points are to be expected. There was a similar problem with the reference points of France, Spain and Portugal. After including the new data from these countries, variations in the reference points could be large and therefore also these proposed reference points have been rejected.

Influence of tidal corrections on reference level

In the formula (3) which is the condition which should be included into the new adjustment of the levelling network a system of tidal corrections must be specified. In the new UELN adjustment consisting of geopotential differences it was assumed that the zero tidal system was used.

Despite the fact that the system EVRS2000 is also defined as a zero-tide system, mostly data that have been used in UELN-95/98 adjustment were not reduced for tidal effects, and therefore adjusted geopotential numbers $C_{95/98}$ referred approximately to mean tidal system. This means that the geopotential numbers of reference benchmarks, on which is based the adjustment of EVRF2007, are related to mean tidal system.

A separate problem is the tidal system of the NAP datum in EVRF2007. It could be concluded that since the NAP originally was determined from observations of the mean sea level (the mean high tide at Amsterdam in 1684), the reference level of the EVRF2007 defined by the NAP should relate to a mean-tide system. On the other hand EVRS2007 is defined as a zero tidal system which implies that its NAP datum should be in zero tide system. As the authors of the vertical system intend to keep the numerical values of the bench marks in EVRF2007 as close as possible to the EVRF2000, therefore adopted NAP datum should be in zero tide system. The condition for datum of the height reference frame can be written in the following form:

$$\sum_{i=1}^{n}\left[C_{P_i,2007}-\left(C_{P_i,95/98}+W_2\left(\varphi_{P_i}\right)-W_2\left(\varphi_{NAP}\right)\right)\right]=0 \quad (4)$$

where $C_{P_i,95/98}$ is the geopotential number of the EVRF2007 reference point P_i adopted for calculation of EVRF2007, $W_2\left(\varphi_{P_I}\right)$ is its correction from the mean tide system to the zero tide system, a $W_2\left(\varphi_{NAP}\right)$ is the same type correction but for reference point 000A2530 in EVRF2000.

Reference ellipsoid and normal gravity field

EVRS2007 system is defined by the gravity potential and geopotential numbers determined by results of levelling and measured gravity accelerations. None of these quantities depend on the size of the reference ellipsoid and the reference ellipsoid is not part of the definition of EVRS, as long as we are dealing with geopotential numbers.

However, to convert the geopotential numbers into normal heights, it is necessary a normal gravity field and geodetic latitude. For this reason normal gravity field of the GRS80 ellipsoid is adopted. Normal gravity at the ellipsoid GRS80 is computed from (Moritz, 1980):

$$\gamma_0 = 9.7803267715\begin{pmatrix}1+0.0052790414\sin^2\varphi+0.0000232718\sin^4\varphi \\ +0.0000001262\sin^6\varphi+0.0000000007\sin^8\varphi\end{pmatrix} \tag{5}$$

where φ is the geodetic latitude in ETRS89.

The normal height H_P^N is computed from:

$$H_P^N = \frac{C_P}{\bar{\gamma}} \tag{6}$$

where $\bar{\gamma}$ is the average value of normal acceleration along the line of the vertical between the GRS80 ellipsoid and the telluroid. The mean value of the normal gravity is calculated from the formula:

$$\bar{\gamma} = \gamma_0\left(1-\left(1+f+m-2f\sin^2\varphi\right)\frac{H}{a}+\frac{H^2}{a^2}\right) \tag{7}$$

where H is the approximate height the point P.

Tidal corrections

The EVRS involves both geopotential and geometric quantities (station position). Therefore their variations in time, caused by geodynamical phenomena such as tides of solid earth and ocean have significant impact on the EVRS. The IERS Convention (McCarthy and Péttit, 2003) defines exactly the size of both positions and geopotential and there is no need to duplicate it for the purpose of EVRS. One particular aspect has to be carefully considered, namely the treatment of the permanent tide.

The gravitational forces of the Moon and Sun cause tides not only seas and oceans but also the Earth's crust. The value of tide changes over time so there are diurnal, semi-diurnal or long period tides. It turns out that the average value of tides measured over a long period of time is not equals to zero. This average unchangeable in time value is called permanent tide. Because the permanent tide is larger at the Equator and smaller in the polar areas this causes additional slight flattening of the Earth.

Tides change the gravity acceleration of the Earth and affect the position of the geoid. Therefore, the definitions of geodetic coordinate systems, heights and gravity systems should take into account the tidal effects.

The existence of a permanent tide causes complications when defining how to take account tidal corrections in measured gravity acceleration in precise levelling and GNSS observations. There are known different ways of handling the permanent tide in these observations (Ekman, 1989) which leads to the *non- tidal, mean* and *zero tidal* corrections (Mäkinen, 2008).

In the *non-tidal* system, from gravity field the tidal potential variable in time and the permanent tidal potential are removed. The results that so improved gravity acceleration does not coincide to its mean value and geoid computed from such gravity data does not coincide with the mean sea level. Therefore Honkasalo proposed that the permanent tide should be restored to characteristics of the gravity field of the Earth. This approach has led to the concept of the *mean tidal* system and mean gravity and mean geoid.

Another approach is a *zero tidal system*. This system refers to the situation when characteristics of gravity field generating by the Sun and the Moon are eliminated and deformation of the earth crust caused by permanent tide is retained.

Resolution No 16 of the International Association of Geodesy recommends to use in the positioning systems, gravity and precise levelling *zero tidal system* to determine tidal corrections.

In the next chapter will be raised three issues. The first issue is about numerical values for the permanent tide, the second is about obtaining geopotential differences in zero-tide system from the mixed tidal systems of levelling in the UELN data and the last one is considering the fact that coordinates in the ETRS89 and ITRFxx gives the (conventional) tide-free position.

Numerical values for the permanent tide

The formula limited to the second degree of the development of the tidal potential in a series of spherical harmonics is

$$W_2 = B\left(\frac{r}{R}\right)^2 P_2(\sin\phi) = B\left(\frac{r}{R}\right)^2\left(\frac{3}{2}\sin^2\phi - \frac{1}{2}\right) = A\left(\frac{r}{a}\right)^2\left(\sin^2\phi - \frac{1}{3}\right) \tag{8}$$

where r ϕ are the geocentric radius and latitude, R is a scaling factor for distance, the coefficients A and B depend on the chose of R, and $P_2(\ )$ is the second-degree Legendre polynomial and a is a semi-major axis of ellipsoid GRS80.

IERS convention of 2003 (McCarthy and Pétit, 2003, section 7.1.3) says that the amplitude of W_2 Cartwright-Tayler-Edden normalization is 0.31460m (as the symbol H_0). Transforming it into the formula above and using the parameters given in the Section 6.5 of paper (McCarthy and Pétit, 2003) we have:

$$W_2 = A\left(\frac{r}{a}\right)^2\left(\sin^2\phi - \frac{1}{3}\right) \quad (9)$$

which gives A = -2.9166 m^2s^{-2}.

The value H_0 = 0.31460 given in the IERS Conventions and used to determine the coefficient A refers to the epoch 2000.0. The Conventions does not provide any change of this magnitude over time. Recently obtained a high-accuracy tidal expansion (Kudryatsev, 2004) gives the coefficient A in the epoch 2000.0 slightly different than in the Convention. The difference is less than 0.0001m^2s^{-2} and the change this ratio is -0.0009 m^2s^{-2} /century.

For the GRS80 ellipsoid there is a practical formula for W_2 as a function of geodetic latitude φ and height above ellipsoid h:

$$W_2(\varphi,h) = \left(1 + 0.31\cdot 10^{-6} m^{-1}h\right)\left(0.9722 - 2{,}8841\sin^2\varphi - 0.0195\sin^4\varphi\right) \quad [m^2s^{-2}] \quad (10)$$

where h is the height above the ellipsoid. In order to make practical use of the equation (10) in the EVRS we can neglect the impact of topography expressed by h and then this formula has the form:

$$W_2(\varphi) = 0.9722 - 2.8841\sin^2\varphi - 0.0195\sin^4\varphi \quad [m^2s^{-2}] \quad (11)$$

Error due to negligence of height h is less than 0.001 m^2s^{-2}. Equation (11) determines the permanent tide-generating potential. Because geopotential numbers have the opposite sign than potential differences, thus equation (11) is the value that should be added to the geopotential numbers in the mean tidal system to obtain geopotential numbers in the zero tidal system.

In the case of normal height $W_2(\varphi)/\gamma_0(\varphi)$ should be calculated where $\gamma_0(\varphi)$ is normal gravity on the ellipsoid GRS80.

$$H_2(\varphi) = W_2(\varphi)/\gamma_0(\varphi) = +99.40 - 295.41\sin^2\varphi - 0.42\sin^4\varphi \quad [mm] \quad (12)$$

Equation (12) gives the values that should be added to normal heights in the mean tidal system in order to obtain normal heights in zero tidal system. In this case, this should not be a normal acceleration on ellipsoid but the mean normal acceleration along the plumb line (7).

In the case of point P at 5 km elevation, using directly the formula (12) instead converting the geopotential numbers from one system to the other and then converting these numbers to normal heights, gives the error no greater than 0.15 mm (Ihde et al., 2008).

The permanent tide in 3-D coordinates calculated using IERS Conventions

Typically the 3-D position of a bench mark computed from GSNN observations is in a tide-free system. It serves to compute potential values from geopotential models. Contrary the potential values from spirit levelling and gravity measurements are in zero-tide system. In order to obtain both potential values in the same tidal system the 3-D coordinates have to be transform into zero-tide system. For this reason, a suitable correction must be added to these coordinates to change them in the mean-tide system. The correction which has to be added to these coordinates in non-tidal system depends on how they were entered in the past. There are minor differences in the tidal correction proposed by the IERS various Conventions published in 1992, 1996 and 2003.

Corrections due to the mean tide (IERS, 2003, Convention) are given to the nearest 0.1mm. Authors (Ihde et al., 2008) have recalculated these corrections with higher accuracy and have received the following formula:

$$\Delta\hat{r} = \{[-120.61 + 0.12 P_2(\sin\phi)] P_2(\sin\phi)\}\hat{r} + \{[-25.21 - 0.06 P_2(\sin\varphi)]\sin 2\phi\}\hat{n} \qquad (13)$$

where $\hat{r}$ is the unit vector from the geocenter to the point on the surface of the Earth, $\hat{n}$ is the unit vector, ϕ is the geocentric latitude, a $P_2(.)$ is the second-degree Legendre polynomial.

For further calculations we need the projection of the vector Δr in equation (13) onto the ellipsoidal normal. Near the surface of the ellipsoid GRS80 we

$$h_T(\phi) = 60.34 - 179.01\sin^2\phi - 1.82\sin^4 \qquad (14)$$

Definition of the EVRS2000 system which says that the EVRS is a zero tidal system, in agreement with the IAG resolutions, this part of the definition was not completely realized until now. To the data computed by the UELN center there were not applied reductions because of the permanent tides. The countries participating in the project provided data in different tidal systems, therefore it was assumed that the EVRS2000 is a mixed system. It is now known that it is mostly mean-tide system.

In 2004, within the framework of the project of the Geodetic Information and Service System CRS (Sacher et al., 2005) to all European countries, was sent a questionnaire on national height systems. There was also a question about the tidal system of these national heights. Most of the countries responded that their height systems are in the mean tidal system. Some countries that have used other national systems provided data in required by UELN tidal system (the Netherlands and Scandinavia). Poland and Denmark delivered a new data in the non-tidal system to the UELN data center. There is, however, no information about the tidal system from Italy. It can be assumed that the data of Czech Republic and Latvia are in the mean tidal system because these countries have participated, in the late seventies, in the common adjustment of the East European countries in that system. It can be also expected that the data from Bosnia-Herzegovina, Croatia are in the same tidal system, since they come from a common network of the former Yugoslavia.

In order to realize the EVRS definition concerning the tidal system, in the measuring table of the UELN data base, there was created an additional column which shows the geopotential difference in the zero tidal system. To solve the problem of the reduction of the reference points, in a first step their geopotential numbers were corrected by following correction to move them from the mean-tide system to the zero-tide system (Mäkinen, 2008):

$$\Delta = -0{,}28841 \sin^2\varphi - 0{,}00195 \sin^4\varphi + 0{,}09722 \quad kgal\ m \tag{15}$$

The result of the applied treatment were a value ranged between –0.030 (Italy) and –0.108 kgal·m (Denmark). In order to minimize the differences to the EVRF2000 solution also was added the constant value +0.08432 kgal·m which is the value of the tidal correction of point 13600 (000A2530) with opposite sign.

This is equivalent to the assumption that the level of reference of the NAP is EVRF2000 zero tidal system in accordance with the definition of EVRS2000 (Ihde et al. 2008). Fig. 6 shows the differences in the adjusted geopotential numbers in EVRF2007 and in the EVRF2000.

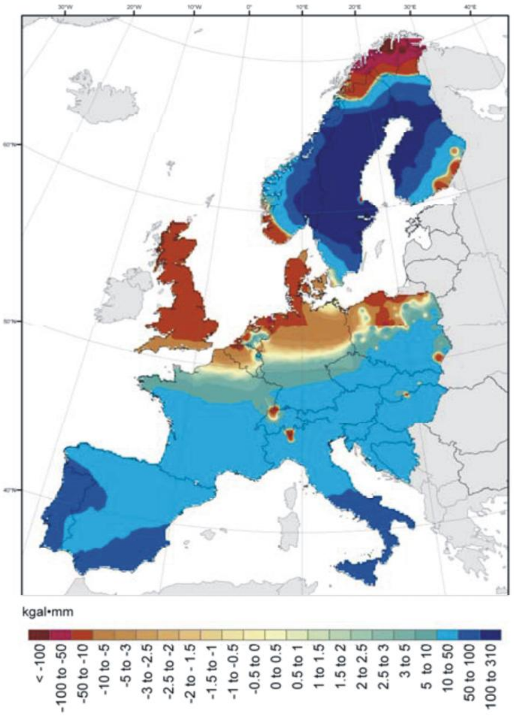

Fig. 5 Differences between EVRF2007 and EVRF2000 (Sacher et al., 2008)

Characteristics of adjusted parameters

The vertical datum of EVRF2007 is realized on the basis of 13 reference points and their location is presented in Fig. 4. The geopotential numbers of these points from the EVRF2000 and reduced to the zero tidal system adjustment by following formula (Ekman, 1989), (Mäkinen, 2008):

$$C_{2007} = C_{95/98} - 0{,}28841\sin^2\varphi - \\ - 0{,}00195\sin^4\varphi + 0{,}09722 + 0{,}08432 \quad [kgal\, m] \tag{16}$$

served for independent adjustment.

Differences of geopotential numbers were reduced to zero-tide system using the formula:

$$\Delta C_Z = \Delta C_M - 0{,}28841(\sin^2\varphi_2 - \sin^2\varphi_1) - \\ - 0{,}00195(\sin^4\varphi_2 - \sin^4\varphi_1) \quad [kgal\, m] \tag{17}$$

and referred to the epoch 2000 through the use of the land uplift model NKG2005LU. This was data from Poland, Finland, Norway, Sweden, Denmark, Germany, Lithuania, Latvia and Estonia.

Table 1 shows the comparison of the parameters obtained from the EVRF2000 and EVRF2007 adjustment while

Table 1Characteristics of parameters of the adjustment (Sacher et al., 2008)

Parameter	EVRF2000	EVRF2007
Number of reference points:	1	13
Number of unknowns:	3063	8133
Number of measurements:	4263	10568
Number of condition equations:	0	1
Degrees of freedom:	1200	2436
A-posteriori standard deviation referred to 1 km levelling distance in [kgal·mm]:	1,10	1,12
Mean value of the standard deviation of the adjusted geopotential numbers (=ˆ heights), [kgal mm]:	19,6	16,2
Average redundancy:	0,281	0,231

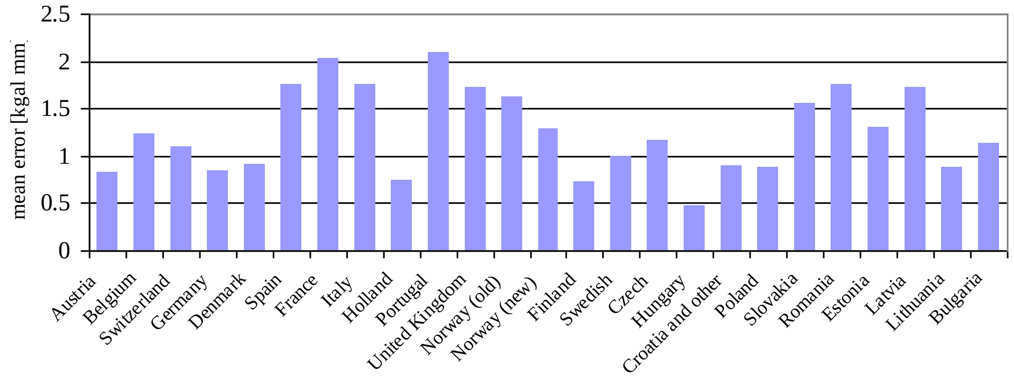

Fig. 6 Standard deviations for EVRF2007derived for each country on the basis of the separate groups of observations in kgal·mm

From Fig. 6 it follows that the accuracy of precise levelling network measured in Poland between 1999 – 2001 is high and is characterized by mean error 0.88 kgal·mm (~ 0.88 mm) and in terms of accuracy is as good as accuracy of networks from the Netherlands, Denmark, Germany and Lithuania.

The results of evaluation of EVRS

Just before the EUREF Symposium in Brussels in 2008 preliminary results of the network adjustment with the report were passed on to the countries participating in the project. Since then there was no an agreement on the exchange of data between the countries, therefore, each of the countries received only his own part of adjustment of levelling network. Representatives most of the countries taking part in the UELN during this symposium agreed to exchange the full results with each other.

Each country received two files saved in Excel spreadsheet. The first one contained data with reference points i.e. number of internal identification in the country, adjusted geopotential numbers and normal heights and their standard deviation. The second file contained survey data at the beginning and end point of the measured line, weight, correction, standardized correction, redundancy number, adjusted geopotential differences and their standard deviations. The files also contain the end points of border connections with neighboring country.

Finally, at the EUREF Symposium June 2008, the EVRF2007 was adopted as new realization of the EVRS. Resolution No. 3 suggested to the European Commission adoption of EVRF2007 as a vertical reference for pan-European geoinformation systems.

After the presentation of the preliminary results of the adjustment, some minor updated data from Norway as well as some additional measurements related to the EUVN_DA project were included. The final results of the EVRF2007 were delivered to all participating countries in UELN project in autumn 2008.

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