EVRF2019 as new realization of EVRS

Martina Sacher[1], Gunter Liebsch[1]

1. Introduction

Since the 1950s, two separate projects for the unification of height networks had existed in Europe, one in Eastern and one in Western Europe. At the beginning of the1990s, the political conditions made it possible to combine the separated leveling networks into a unified European height system. At the same time the development of computer techniques enabled us to process the incurring data volume. The work on the United European Leveling Network (UELN) started in 1994 and has continued ever since. So far, two solutions with height data have been distributed to the European countries.

The first solution was provided in December 1998 under the name UELN-95/98. In 2000, the first definition of the European Vertical Reference System (EVRS) was given and the extended UELN-95/98 was used as basis for its first realization EVRF2000 (Augath and Ihde 2002). About ten years later, EVRF2007 was adopted at the EUREF symposium in Brussels (Sacher et al 2009). Together with the data of EVRF2007, the EVRS Conventions were published (Ihde et al 2009), which contain a revised EVRS definition as well as the principles and strategy for the realization. The realization EVRF2007 as well as the transformation parameters to the national height reference systems are nowadays of major importance for the European geodetic infrastructure, since INSPIRE has adopted the EVRS for European applications.

After 11 years, a lot of new leveling data are available. In the meantime, most of the national leveling data, which were contained in the network of 1994, have been replaced at least once. The added national leveling networks extended the UELN far to the East. Already in 2015, the EUREF resolution No. 4 was adopted, which considered the need for a new realization and noted the role of the quasigeoid for future height system realization. According to this resolution, the new realization EVRF2019 is submitted.

2. Data

Since the publishing of EVRF2007 (Sacher et al 2008) in December 2008, a lot of new data have been delivered to the UELN data center.

The following countries provided their leveling data for the first time:

- Russia, European part of the network (2012)
- Belarus (2017)
- Ukraine (2018)
- North Macedonia (2019)

These 11 countries sent an update of their leveling networks:

- Latvia (2011/2012)
- Spain (2012)
- Germany (2015)
- Switzerland (2015)
- France (2015), addition of zero order network NIREF
- Estonia (2016)
- Belgium (2018)
- Czech Republic (2018), partly

[1]Federal Agency for Cartography and Geodesy, Karl-Rothe-Straße 10-14, D-04105 Leipzig, Germany

- Slovenia (2018)
- Italy (2018), partly
- Bulgaria (2019), partly

Furthermore, some supplements or corrections were delivered by the following countries:

- Netherlands (2016)
- Norway (2018)
- Slovakia (2018)
- Austria (2019)

Figure 1 shows the status of the data in the UELN. More than half of the data have been changed after 2008.

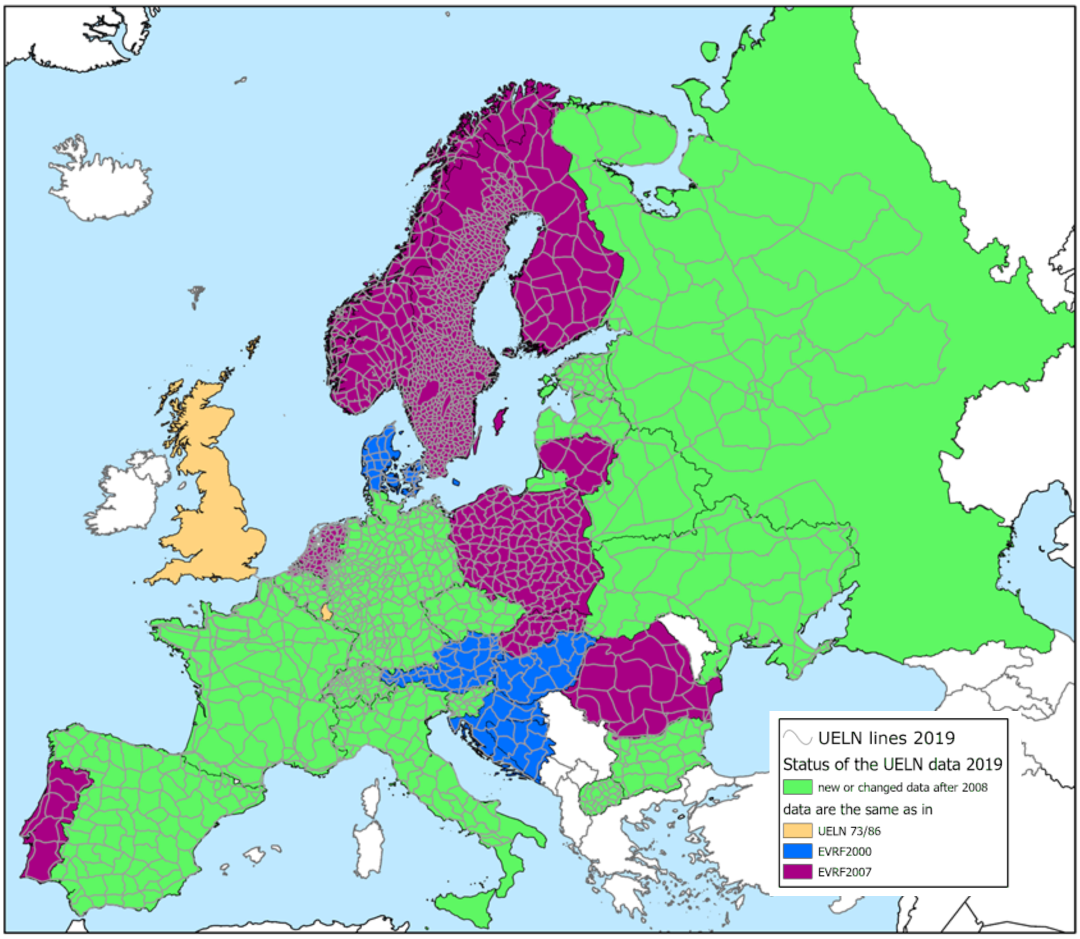

Figure 1: Status of the UELN data 2019

3. Special treatment of some national data sets

a. Belgium

The first order leveling lines of Belgium in the EVRF2007 had been measured in the 1970s. In the meantime, new measurements have been carried out in Belgium. These observations were concentrated on areas with vertical movements, regardless of the order of the lines. Subsequently, all 35891 measurements of the 1st to 3rd order were adjusted together. The new observations delivered by Belgium in 2018 are results of this adjustment. So, these observations are not independent. Nevertheless, they have been used in the computation of EVRF2019 in order to use the most current data of Belgium. A completely new observation of the 1st order lines in Belgium is not intended for the next years.

b. France

Already since 1971, a tilt of 23cm in North-South direction has been suspected in the French leveling network IGN69, deduced from comparison with tide gauge observations. In the meantime, a zero-order leveling network named NIREF ("nivellement de référence") is being developed, which is more accurate and not affected by such a systematic.

In 2015, France delivered a new data set to the UELN data center, consisting of NIREF data, measured between 1983 and 2014, and some new measured lines of IGN69 in the northern part of France. The NIREF network is connected to the measurement through the Channel tunnel and enables the use of this connection between France and Great Britain in the European network. Furthermore, NIREF contains new border connections to Spain, Italy, Germany, Switzerland and Belgium.

On the other hand, the density of NIREF is too low to replace IGN69 as national leveling network or in the UELN. So, a suitable combination of NIREF and IGN69 in the adjustment was necessary. Since only the nodal points of IGN69 are contained in the UELN data base, only 37 identical points could be used for the combination with NIREF. A common adjustment of both French networks using a variance component estimation presumes the existence of only random errors. In this way, the systematic error of IGN69 would still influence the other networks. In order to eliminate the influence of the tilt of IGN69, the observations of this network were supplied with very low weights: The original variances were multiplied with factor 100.

c. Great Britain

Up to now, the British part of UELN is beset by two problems:

In EVRF2007 and in former computations of European heights, the only connection between France and Great Britain was derived from hydro-dynamic leveling. There is no document available, which describes the details of the determination and the used hydro-dynamic model. In 1994, two measurements were carried out through the Channel Tunnel: Great Britain observed the height difference by trigonometric leveling, France by geometric leveling. The size of the difference of the results was in conflict with the estimated accuracy of both techniques, but the reason for the difference could not be found by the involved countries. After more than 10 years, both countries agreed to adopt the mean value as result. Not until the provision of the NIREF data, we have been able to replace the old connection by the height difference observed in 1994.

In the past, it was conspicuous that EVRS heights in Great Britain were not consistent with the national ODN (Ordnance Datum Newlyn) heights. There was a tilt between both reference frames, which could not be caused by a single connection between France and Great Britain. The reason was found after the study of publications of (Edge 1959) and (Christie 1994). There is described, that ODN heights were computed by an adjustment of the 3rd leveling epoch (1951-1956), where the results of the 2nd epoch (1912-1952) were held fix because of systematic errors in the 3rd levelling epoch. Only the observations of the 3rd epoch are available at the UELN data center.

In order to make the results of EVRF2019 consistent with national heights and with the gravimetric quasi-geoid the following approach was chosen: The EVRF2019 height of the British tunnel end point and 3 points in the vicinity were determined from the measurement through the channel tunnel. So, an offset between EVRF2019 and ODN of -0.16387 m for these southern points in Great Britain was computed. But ODN is in contrast to the EVRS in the mean-tide system, so that this value cannot be used as a constant difference for the whole country. Instead, the EVRF2019 height of every British point was computed by subtraction of a constant mean-tide difference and addition of a correction to convert the height to zero-tide. The steps for the conversion from ODN to EVRF2019 are in detail:

1) Determination of the height difference -0.17012 m between ODN and EVRF2019 in mean-tide
2) conversion of the difference to zero-tide according to formula 5-5 in (Ihde et al 2009)
3) Addition of a correction of 0.08593m to keep the data in the level of NAP. This correction corresponds to the geopotential value +0.08432kgal·m in formula 4 of chapter 4 in this document.

Formula (1) summarizes steps 1) - 3):

$$H_{EVRF2019} = H_{ODN} - 0.17012 - 0.29541 \cdot sin^2\phi - 0.00042 \cdot sin^4\phi + 0.0994 + 0.08593 \text{ [m]} \quad (1)$$

φ is the Latitude in ETRS89.

After summation of the constants we obtain

$$H_{EVRF2019} = H_{ODN} + 0.01521 - 0.29541 \cdot sin^2\phi - 0.00042 \cdot sin^4\phi \text{ [m]} \quad (2)$$

4. Realization of the datum

The datum of EVRF2019 is in the level of NAP, according to the definition of EVRS (Ihde et al 2009).

For the realization of the height datum we have to specify:

- the datum points
- the heights or geopotential numbers of these datum points
- the velocity of the datum points

The height datum realization is generally arbitrary (e.g. the selection of datum points) and need assumptions or definitions (e.g. the height and velocity of the datum points), since the height datum cannot be determined by the leveling itself and there is currently no other additional source of information.

In the EVRF2007, the datum was realized by 13 datum points with their heights in EVRF2000, converted to zero-tide. It was assumed that the velocities of these points were zero, although two of the points in Denmark were in the area of influence of the postglacial rebound (see figure 2).

It would be possible to realize the datum of EVRF2019 in the same way. All former datum points are still part of the network. The question was, whether these points and their height of EVRF2000 are still the best candidates to guarantee the same zero level of the European levelling network or if there are certain criteria to choose a different set of datum points. It should be emphasized that in principle every point of EVRF2007 is a representative of the datum NAP. Even using the same datum points as in EVRF2007 cannot ensure that the level will not be changed.

For the EVRF2019 the following criteria, requirements and assumptions were adopted:

- The datum should be realized using multiple datum points in order to avoid possible undetected height changes of an individual benchmark. The datum realization has to be unconstrained.
- The datum points should be widely distributed across the European levelling network in order to avoid a systematic influence in a certain part of the network. This explicitly includes also these countries, which were not part of the EVRF2000.
- There should be only one datum point per country
- The datum points have to be outside of areas with known vertical land movements. This also includes regions like Scandinavia and the Alps, where models about the

vertical velocities are available. This is to avoid the influence of possible uncertainties of these models on the datum realization of the EVRF2019.

- The datum points should not be effected by known systematic errors in the levelling networks, especially in EVRF2007. The differences between the heights in EVRF2019 and EVRF2007 has to be reasonable small, that is, in the magnitude caused by the random error of the levelling network. This excludes datum points in Great Britain as well as the western part of the levelling network (France, Spain and Portugal, southern Italy).

Not all datum points of the EVRF2007 fulfilled the criteria mentioned above. Finally, after different computations and investigations the new set of the 12 datum points listed in table 1 was used for height datum realization of the EVRF2019. Points that were datum points in EVRF2007 too are highlighted in blue. The additional selected points are fundamental points in the relevant countries or were proposed by the countries themselves. The heights of the datum points were obtained from the EVRF2007 adjustment and it was assumed that these heights have not changed (velocity 0 mm/a). According to the condition equation in the adjustment the sum of the height changes of all datum points is zero. The maximum differences between the heights in EVRF2007 and EVRF2019 are in the magnitude of +/- 1.5cm There is no noticeable un-normal distribution of the residuals. This result suggests that the chosen approach is in good agreement with the requirements for the datum realization mentioned above. An adjustment with the same datum points as in EVRF2007 would cause a constant height difference in all points of 5.7kgal·mm in contrast to the solution with the new datum points.

Table 1: Datum points in EVRF2019

Point No.	point No.	Country	Latitude	Longitude	geop. number EVRF2007	geop. number EVRF2019	difference EVRF2019-EVRF2007
(UELN)	(national)		degree (ETRS89)		kgal·m		kgal·mm
102105	937856	AT	48.664867	15.674783	300.7504	300.7630	12.6
200038	GIKMN	BE	50.799167	4.359400	96.0073	96.0130	5.6
401658	3549901400	DE	52.480537	13.983619	53.6139	53.6160	2.0
800432	N035#_###_####	IT	43.777458	11.259787	48.8335	48.8406	7.1
913011	000A1112	NL	52.141733	5.360567	41.0251	41.0225	-2.6
1103000	Nadap II	HU	47.255750	18.620017	173.0090	173.0101	1.1
1204377	ZNB I.	CZ	49.006910	14.584842	554.0825	554.0791	-3.3
1706115	26330081	PL	52.230100	20.948383	110.7007	110.7134	12.7
1802199	N1-V-FR_1049	SI	46.531944	15.470404	289.5289	289.5223	-6.6
1905325	EH-V.	SK	48.587200	18.947334	267.5709	267.5789	8.0
2007125	A496	HR	42.658883	18.061117	3.3031	3.2862	-16.9
2501420	BHP 28	BG	43.230000	27.833333	64.3113	64.2915	-19.7
							0.0

Figure 2 shows the distribution of the old and the new datum points.

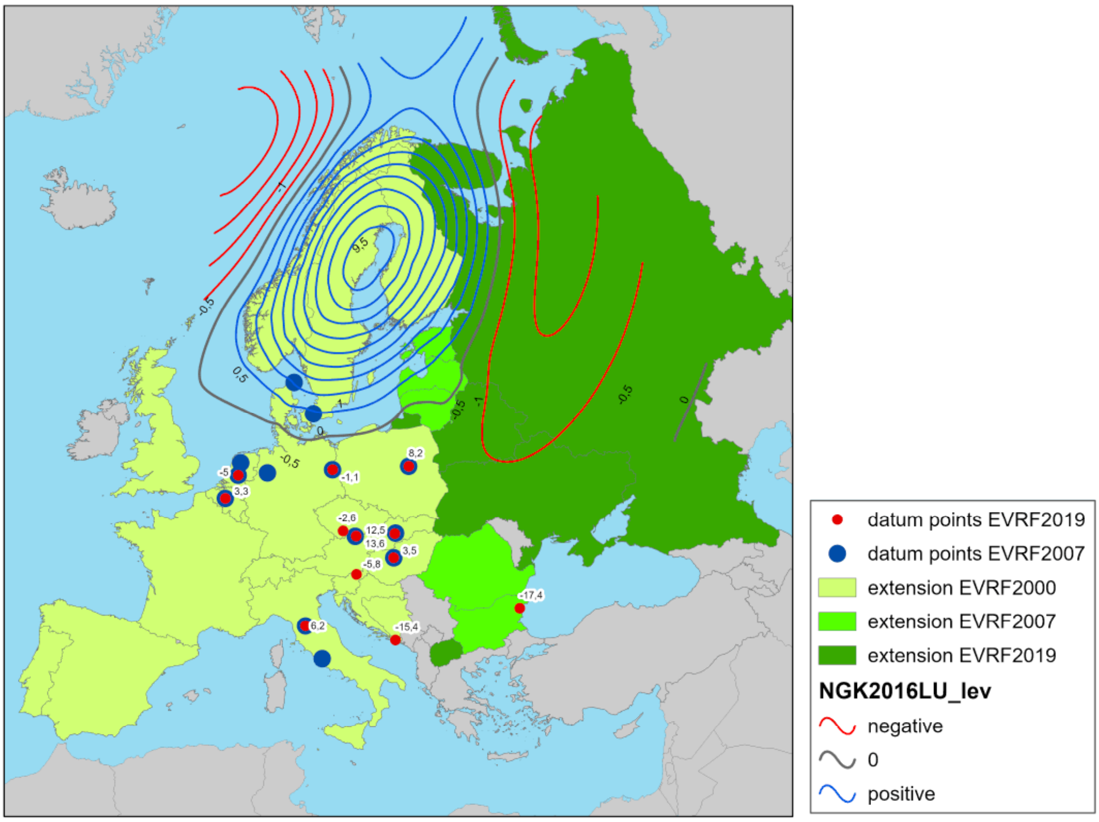

Figure 2: Distribution of the datum points

5. Tidal corrections

According to its definition, EVRS is a zero-tide system (Ihde et al 2009). So, both EVRF2007 and EVRF2019 are computed in the zero-tide system. This agrees with IAG resolution No.16 adopted in Hamburg 1983, which recommends zero-tide for gravity field and mean-tide (=zero-tide) for 3D-positioning (Mäkinen, Ihde 2009). However, this resolution was never applied strictly in the geodetic praxis.

In reality, zero-tide is used for gravity, the GNSS community uses conventional tide-free systems, and we find national height systems mostly in mean-tide, but there are also zero-tide and non-tide systems. Sometimes it will be necessary to transform coordinates into another tidal system to make them comparable with other products. An example is the computation of geoid or quasi-geoid values as differences from ellipsoidal and leveling heights.

On the other hand, also users from other scientific sectors may use EVRS heights, especially in the field of oceanography. These users may have large scale or even global applications and expect that gravity-related heights are conform to the real world, i.e. to the mean sea level. From a practical point of view, physical heights should describe as good as possible how the water flows. For this task users need heights in the more natural mean-tide system. Also the future International Height System will be provided in the mean-tide system according to the IAG resolution No. 1 adopted in Prague 2015. The end users are not necessarily familiar with the concept of the permanent tides, just as many geodesists. We should help them and provide a more user-friendly geodetic product.

That’s why the results of EVRF2019 will be additionally provided in the mean-tide system – together with the comment to use these heights for tasks of oceanography as well as for clock rates. Furthermore, mean-tide heights can be used in the future for comparison with heights in the International Height System.

How are the EVRF2019 heights transformed from the zero-tide to the mean-tide system? There are two possibilities: We can reduce the geopotential differences to mean-tide and compute a new adjustment with these values. For this, we use formula 3 from (Sacher et al 2009) with opposite sign:

[kgal·m] (3)

In this case we have to transform the geopotential values of the datum points to mean-tide too.

For the computation of EVRF2007, we transformed the geopotential numbers of the datum points in EVRF2000 from mean-tide to zero-tide. In this process, we added the constant of +0.08432 kgal·m, the size of the tidal correction of point 913600 (representing NAP in EVRF2000) with opposite sign, to the reduction. As a result, points in the latitude of Amsterdam had the same height in mean and zero-tide system.

Now we do the same with opposite sign and subtract the constant of 0.08432 kgal·m in the course of the transformation of the datum points from zero- to mean-tide:

[kgal·m] (4)

φ is the Latitude in ETRS89.

The other possibility is to transform each adjusted geopotential number from zero-tide to mean-tide by formula (4).

Both ways were tested and produced the identical result.

6. Epoch of the measurements

The measurements of EVRF2007 had been reduced to the epoch 2000 using the land uplift model NKG2005LU (Ågren and Svensson 2006). All leveling data, which were located in the area of the model, had been reduced.

Most of the data of EVRF2019 were observed before 2000 or shortly after. Therefore it makes sense to reduce these measurements also to epoch 2000 as in EVRF2007. A later reference epoch would increase the difference between the epochs of the measurements and the reference epoch, and this would increase the influence of velocity errors in the used models. Furthermore, the use of the same reference epoch as in EVRF2007 enhances the comparability of the results. To enable the user to compute an EVRF2019 height at a particular epoch, the velocities of the points will be published together with the heights.

At the UELN data center, velocity models are available only for two areas in Europe: for the area of the Scandinavian land uplift and for Switzerland. We haven't enough knowledge about vertical velocities in the other parts of Europe to reduce all other leveling data to a common epoch too.

In 2016, the Nordic Geodetic Commission published the new model NKG2016LU_lev (Vestøl et al 2016). The former model NKG2005LU ended at the contour line of -2mm/year. The new model contains data also outside this line. That means, in contrast to the former model the new one has also impact on the data of the Netherlands, parts of France, parts of Czech Republic and more southern parts of Germany and Poland. The question was whether it makes sense to reduce the data in all these areas. How reliable are the data at the edges of the model? The effect of the land uplift model is there probably smaller than other effects including leveling errors. The application of a realistic model should result in a higher accuracy of the adjustment of the reduced data. To investigate the influence of the model, a lot of test adjustments were computed. Single national networks were adjusted with and without reduced data as well as several versions of the full UELN. In the end it was decided to reduce only the data of Finland, Norway, Sweden, Denmark, Estonia, Latvia, Lithuania, Russia and Belarus (see figure 3). The reduction of the data in the remaining areas would result in a decreasing of the accuracy of the adjustment results.

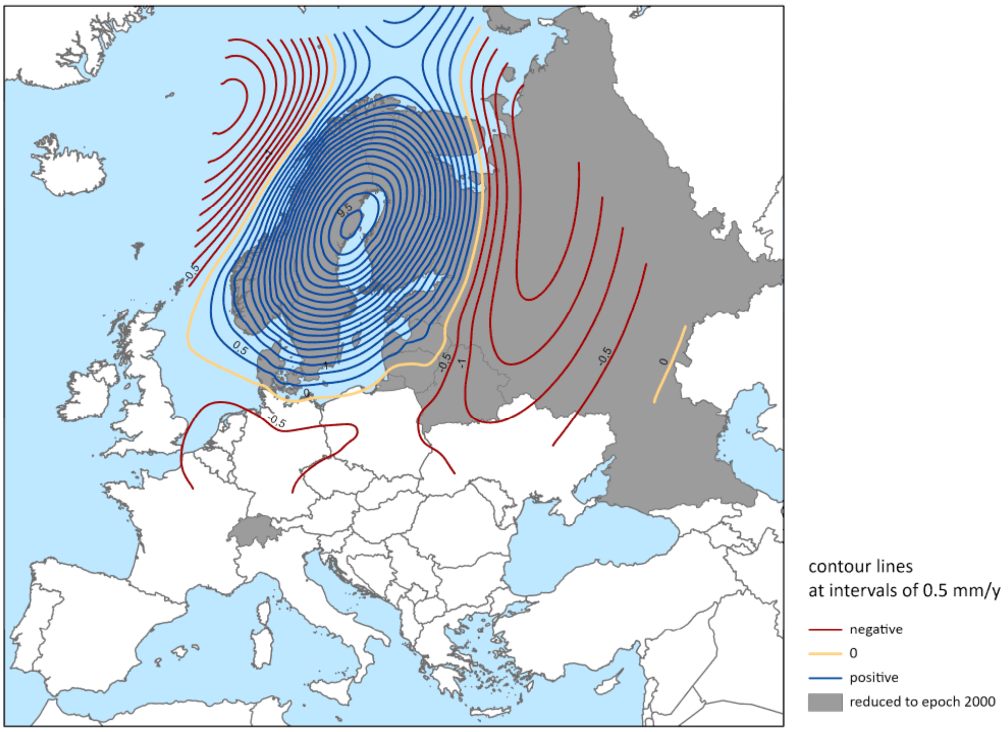

Figure 3: Land uplift model NKG2016LU_lev and countries with reduced data

For the first time, also the measurements of Switzerland had been reduced to a common epoch by a set of velocities, provided by A. Schlatter and U. Marti from swisstopo (see figure 4). The velocities of the points in the graphic are caused not only by large-scale tectonic reasons, but also by local instable areas. The consideration of the velocities leads to a significant improvement of the adjustment result for the Swiss network from 1.09 to 0.86 kgal·mm.

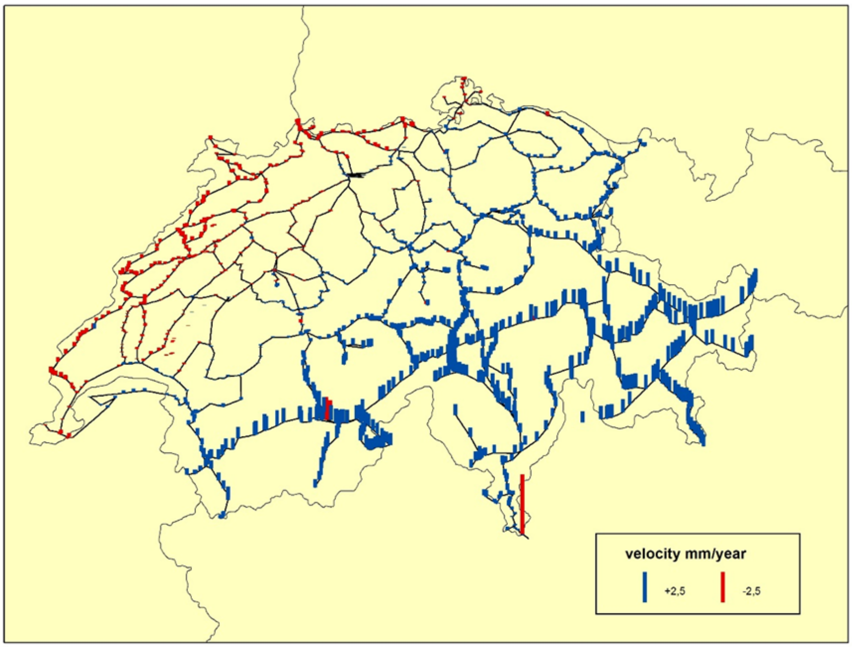

Figure 4: Velocities from: CHVRF15/UELN15. Bundesamt für Landestopografie swisstopo Bereich Vermessung. Andreas Schlatter / Urs Marti

7. Adjustment results

The heights in EVRF2019 differ from EVRF2007 between -439mm and +148mm (see figure 5). The largest differences are in the part of Western Europe, especially in Great Britain and France. In Great Britain, we have maximum differences of half a meter. In France we find differences between -135mm in the North and +65mm in the South. Main reasons are the including of the zero order network NIREF in France, which eliminates the tilt of the IGN69 network, and the modified computation of the heights for Great Britain. The largest positive height differences are in Italy, caused by the new Italian data.

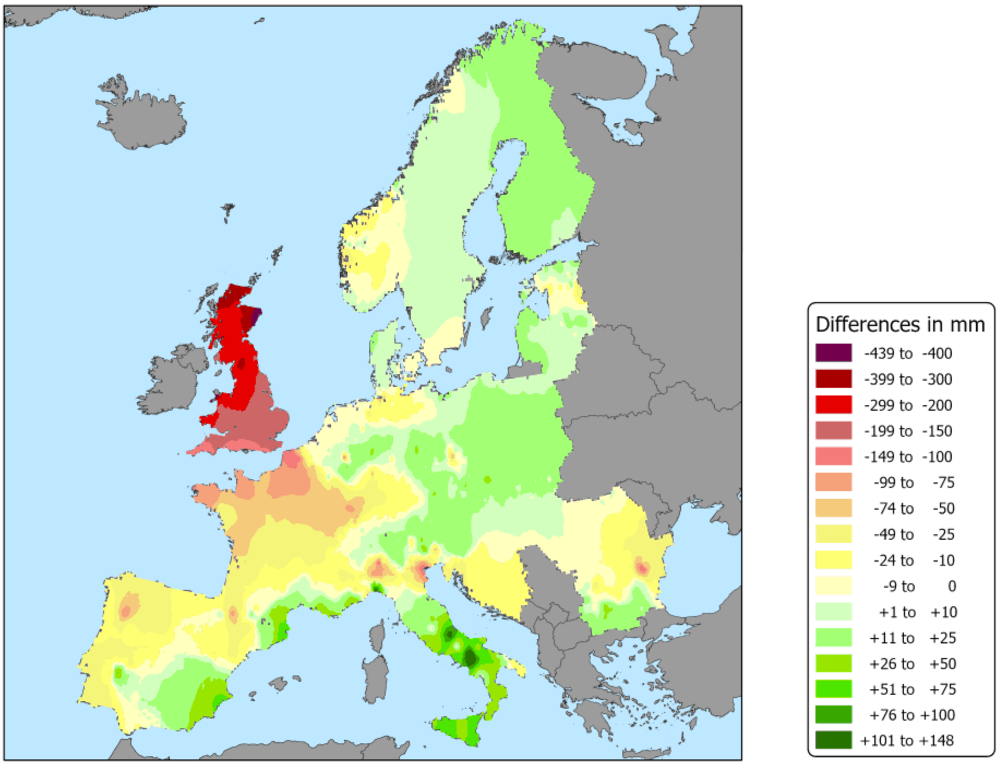

Figure 5: Differences EVRF2019-EVRF2007

Table 2 shows the parameters of the adjustment. The standard deviation for 1km leveling is in the magnitude of 1.1mm as in EVRF2007.

Table 2: Parameters of the adjustment

Parameter	EVRF2007	EVRF2019
Number of datum points:	13	12
Number of unknowns:	7942	10759
Number of measurements:	10354	13637
Number of condition equations:	1	1
Degrees of freedom:	2413	2879
A-posteriori standard deviation referred to 1 km levelling distance in kgal·mm:	1.11	1.10
Mean value of the standard deviation of the adjusted geopotential numbers (heights), in kgal·mm:	16.00	19.27
Average redundancy:	0.233	0.211

However, the precision of the data is inhomogeneous. That's why the adjustment was carried out using a variance component estimation. Table 3 contains the results. The values for Belgium and France have not been used as new variances in the adjustment because of the reasons described in chapter 3. For the data of Belgium, the same variance as in the EVRF2007 was assumed. The group of the old measurements of France was introduced with a variance factor of 100. Some groups in the table consist in principle of the same observations in both adjustments, but the number of observations or the precision differ in the new adjustment. In these cases, the reasons are new data in neighboring countries and new included border connections. Besides of the standard deviation of the weight unit, table 3 contains also the mean standard deviation of the adjusted heights of the countries. These values refer to the datum of the network; they are influenced not only by the precision of the measurements, but also by the distance to the datum points.

Table 3: Results of the variance component estimation

Group of measurements	EVRF2007			**EVRF2019 final solution**		
	number of observations	s_0 [kgal·mm] (1 km)	s_H [kgal·mm] (mean value)	number of observations	s_0 [kgal·mm] (1 km)	s_H [mm] (mean value)
Austria	167	0.82	7.7	**179**	**0.91**	**6.9**
Belgium	63	1.24	10.6	**113**	***0.59***	**7.7**
Switzerland	413	1.09	9.1	**719**	**0.91**	**7.5**
Germany	846	0.85	7.2	**1112**	**0.66**	**6.5**
Denmark	194	0.91	10.5	**196**	**0.85**	**10.9**
Spain	110	1.75	38.4	**227**	**2.38**	**41.8**
France	348	2.02	23.9	**344**	***3.08***	**29.7**
France (NIREF)				**1227**	**1.40**	
Italy	110	1.75	23.7	**202**	**1.47**	**14.4**
Netherlands	1424	0.75	7.0	**1373**	**0.76**	**6.7**
Portugal	30	2.09	44.1	**30**	**2.01**	**46.2**
Great Britain	60	1.72	81.2	**4**		**29.7**
Norway new	360	1.33	18.4	**489**	**1.34**	**18.4**
Norway old	341	1.57		**410**	**1.44**	
Finland	262	0.73	20.3	**272**	**0.74**	**18.3**
Sweden	4154	1.00	14.6	**4206**	**1.00**	**14.0**
Czech Republic new				**185**	**0.83**	**7.6**
Czech Republic old	100	1.16	8.8	**83**	**1.19**	
Hungary	82	0.47	8.4	**83**	**0.55**	**7.2**
Croa.,Bosn./Hc	112	0.90	12.3	**81**	**1.40**	**14.6**
Slovenia			10.6	**89**	**0.62**	**7.0**
Poland	456	0.88	8.8	**473**	**0.86**	**7.7**
Slovakia	214	1.55	11.4	**196**	**1.49**	**10.0**
Romania	90	1.75	22.7	**133**	**1.74**	**19.3**
Estonia	78	1.30	22.1	**418**	**0.23**	**13.6**
Latvia	159	1.72	16.4	**151**	**0.85**	**13.4**
Lithuania	72	0.87	12.7	**64**	**0.75**	**12.2**
Bulgaria	109	1.14	25.0	**97**	**1.64**	**23.0**
Russia				**176**	**2.21**	**28.9**
Belarus				**31**	**2.32**	**20.3**
Ukraine				**211**	**1.70**	**25.5**
North Macedonia				**66**	**0.95**	**25.5**
Total	10354	1.11	16.0	**13640**	**1.10**	**19.3**

new data after 2008:
small update after 2008:

8. Delivery of the results

In the past, there was no agreement on the exchange of leveling data in Europe. Only the national parts of the results of EVRF2000 were handed over to the respective countries.

At the EUREF symposium 2008 in Brussels, the exchange of the results of EVRF2007 was discussed. Finally all UELN participating countries apart from Bosnia and Herzegovina agreed to make available the adjusted geopotential numbers, normal heights and coordinates of the UELN nodal points of their countries to all other participating countries.

This approach was considered as the lowest common denominator for the handling of the results of EVRF2019. The EUREF Symposium 2018 in Amsterdam adopted resolution No. 2, which "*encourages National Mapping Authorities, universities and research institutes to release their gravity and height data where this is legally possible."* On the other hand, height and gravity were especially confidential data in the past, and we want to allow all European countries to participate in the project. That's why a questionnaire had been distributed where the countries could choose the desired handling of their national EVRF2019 results. All countries except Belarus, Russia and Ukraine agreed to publish EVRF2019 heights in the Internet. The EVRF2019 heights of Belarus, Russia and Ukraine will be exchanged only with countries that are part of the United European Leveling Network (UELN). The results of all other countries will be published on the EVRS website
https://evrs.bkg.bund.de/Subsites/EVRS/EN/Home/home.html

Two excel files with adjustment results are handed over with this report. The file "EVRF2019_final.xlsx" contains point-related data (table 4) and the file "measurements_**.xlsx" contains measurement-related data (table 5). The files contain also the end points of border connections in the neighboring country.

Table 4: Contents of the point file

	Column header	**contents**
	Point UELN	UELN point identifier
	Country	country code
	Point No. 1	national point identifier (1)
	Point No. 2	national point identifier (2), remarks
	No. in a neighb. country	point identifier in a neighboring country
	neighb. Country	country code of the neighboring country
ETRS89	Lat	latitude in degree
	Lon	longitude in degree
EVRF2019 (zero tide)	geop. number	adjusted geopotential number in kgal·m (zero-tide)
	normal height	adjusted normal height in m (zero-tide)
	sH	standard deviation of the adjusted height in mm
	v	velocity in mm/year, provided by country and used in the adjustment
EVRF2019 converted to mean-tide	geop. number	adjusted geopotential number in kgal·m (mean-tide)
	normal height	adjusted normal height in m (mean-tide)

Table 5: Contents of the measurement file

Column header	contents
start point	start point of the line
	country code of the start point
end point	end point of the line
	country code of the end point
weight	weight of the measurement
residual	residual in kgal·mm
residual (stand.)	standardized residual
redundancy	redundancy
adjusted geop. diff.	adjusted geopotential difference in kgal·m (zero-tide)
standard dev.	standard deviation of the adjusted geopotential difference in kgal·mm

9. Outlook

Currently we are able to provide heights in the EVRS only on the territory of the UELN, which is more or less limited to mainland Europe. For the determination of EVRS heights on islands, the use of GNSS and a European quasi-geoid is the appropriate method. This requires a correction surface to the gravimetric European geoid model, which can be computed using an updated version of EUVN_DA. The current EUVN_DA data set (Kenyeres et al 2010) contains GNSS/leveling points with the status of 2009 or earlier. The leveling data are in EVRF2007 and can be replaced altogether, but also for a large part of the ellipsoidal heights new GNSS measurements will be available. So, the next step will be an update of the EUVN_DA data set. Furthermore, the use of EVRF2019 heights requires the determination of transformations between national height reference systems and EVRF2019. For these tasks, we count on the support of all UELN participating countries.

10. References

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