EUVN Densification Action

Final report

EUVN_DA Working Group:

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Abstract

The European Unified Vertical Network (EUVN), comprising of a set of high quality GPS/leveling benchmarks, was successfully completed in 2000 (Ihde et al, 2000). Due to the growing need for more detailed GPS/leveling information, the EUREF Technical Working Group (TWG) initiated the EUVN Densification Action (EUVN_DA) in 2003, targeting at the establishment of a dense, homogeneous continental GPS/leveling database. EUVN_DA relies on the experiences of EUVN; it also functions as a continental GPS/leveling reference network, but it was built up from separate national contributions, where the submitted data were homogenized and added to a uniform database.

EUVN_DA and the related database was primarily designed to support the European geoid determination, serving datum information and geoid control points, but the database is also relevant for

- understanding the differences between gravimetric and GPS/leveling geoids[1],
- identifying geoid, GPS or leveling errors,
- providing control points for height determination with GPS,
- supporting future realization(s) of the continental height reference surface.

The National Mapping Agencies generously supported the project; they provided existing, updated or new measurement data sets. As of December 2009, 25 countries participated, and the database contained more than 1400 GPS/leveling points. Although the project terminates with the publication of the present final report, the maintenance of the EUVN_DA database will be continued in the future within the framework of the EVRS activities, allowing further data updates and the solution of remaining data issues.

This report gives a general overview of the EUVN_DA status and summarizes the achievements obtained during the lifetime of the project.

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1 The European leveling network UELN and the related vertical reference system EVRS2007 are defined as a normal height system, which is referring to the non-equipotential quasigeoid surface. In that frame, the quasigeoid undulations are also called height anomalies. Throughout this report, where for the sake of simplicity the term geoid is used, the theoretically correct quasigeoid and height anomaly should be understood.

EUVN as a starting point

Following 6 years of activity, the EUVN project was completed successfully in 2000. The carefully established network consists of almost 200 GPS/leveling sites, including also tide gauges, which fairly well cover the European continent.
The high quality, but sparse EUVN network was designed to

- contribute to a unified European height datum and the unification of the different European height systems,
- connect European tide gauge benchmarks for monitoring absolute sea level variations,
- make preparations for a Kinematic European Vertical Network,
- establish fiducial points for the European geoid.

The station coordinates, expressed in ETRF96, epoch 1997.4, were derived from a coordinated 9-day GPS campaign. The GPS markers were connected to the nearest UELN benchmarks by 1st order leveling. Gravimetric measurements were also performed to derive geopotential numbers. Thanks to the careful preparation, standardization, data collection and the state-of-the-art processing techniques, the accuracy of both the derived ellipsoidal and leveled heights is considered as better than 1 cm. A detailed description of the project and the results can be found in (Ihde et al, 2000).

One of the most important products of the EUVN project was a set of high accuracy geoid values for all benchmarks. The so-called EUVN geoidal heights - computed as the difference of the GPS ellipsoidal and leveled (UELN) heights - were compared to the continental gravimetric geoid EGG97 (Denker and Torge, 1997) available at that time. The sparse, point-wise EUVN/UELN and EGG97 differences (plotted in Figure 1) exhibit medium to long wavelength structures as well as a few outliers. With this sparse network, only some obvious gross errors could be identified; with a denser station network it would have been easier to separate between outliers and long wavelength differences. Generally, the EGG97 and EUVN geoids agree within 2 dm and the variation of the differences may be considered as mostly ***random*** at this level. There are only a few regions (e.g., the Alps, SE-Europe, Atlantic coastline), where ***systematic, large scale trends and/or biases*** are clearly observable. In this context, the most significant feature can be seen in the Alps region, where the discrepancies reach up to –40 cm. Also the Anatolian part of Turkey shows significant variations of the differences, mainly due to lacking gravity data over Turkey in the EGG97 solution. There are also ***large outliers***, most likely caused by gross errors in the leveling information; the most obvious example can be found in Central Poland, where two nearby points show a difference of 69 cm. However, the residuals may also serve as an indicator for smaller outliers; an example is the Hungarian EUVN sub-network, where the PENC station exhibited a slightly higher difference (-16 cm) than the two adjacent sites (-11 cm). Following further indications, PENC was re-leveled in 2001 and a 4 cm leveling misalignment was identified. After applying the new height information, PENC fitted perfectly.

However, at the EUVN stage, a clear identification of large-scale biases was hardly possible and weaknesses were suspected in both the gravimetric geoid and the leveling; the main conclusion was that both datasets should be improved. In order to identify and eliminate inconsistencies in the EUVN database and refine the geoid modelling, a denser GPS/leveling network as well as an updated geoid solution were requested. In addition, the improvement of the leveling networks (re-measurements or re-adjustments using homogenized standards and reductions) at national and continental scales were also considered necessary.

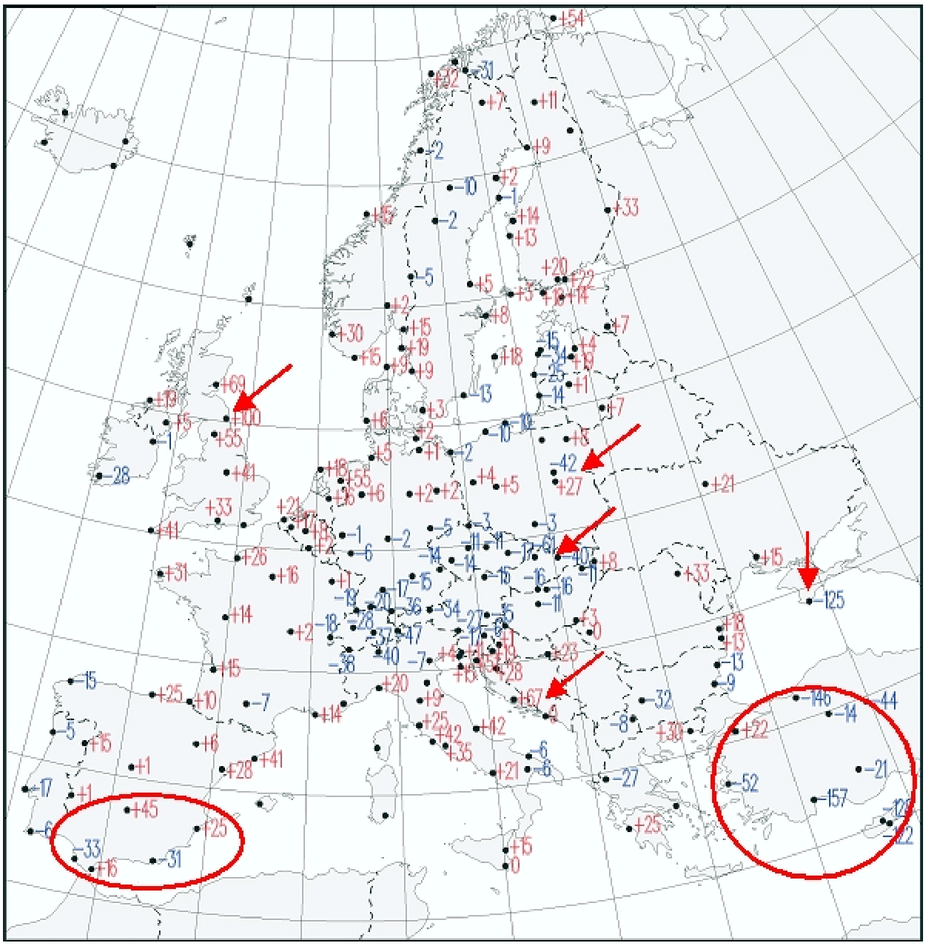

Figure.1 EGG97 and EUVN/UELN ($h^{EUVN} - H^{UELN}$) quasigeoid height differences [cm]. The original plot is taken from the EUVN final report, Ihde et al. (2000). The arrows and ellipses are indicating problematic points or areas.

EUVN_DA initial steps

Following the success of EUVN, the EUREF TWG discussed the various scientific and practical arguments for extending this work, and agreed at the EUREF2001 symposium, held in Dubrovnik, to initiate the EUVN Densification Action (see the related Resolution #4 of the symposium in Attachment 1). However, EUVN_DA was not considered as a direct continuation of the EUVN project, as the tasks already treated successfully in EUVN (leveling network connections, height datum establishment, tide gauge investigations) were out of the scope of the new project. EUVN_DA was intended more practice-oriented; the primary target was the establishment of a dense continental GPS/leveling network, which then could be used for the realization of a European height reference surface (HRS) consistent with ETRS89 and EVRS2007.

The EUVN_DA project was started in close cooperation with the former IGGC (IAG's International Gravity and Geoid Commission, European Sub-Commission), now EGGP (European Gravity and Geoid Project). Both groups are benefitting from the cooperation as the standardized GPS/leveling database allows a better identification and elimination of medium to large-scale geoid discrepancies. Furthermore, a proper combination of the gravimetric geoid and the GPS/leveling data may lead to a more accurate (in an absolute and relative sense) height reference surface, which is badly needed for GPS heighting.

Following the detailed preparations, a “Call for Participation” was issued in March 2003.

EUVN_DA data requirements

The ideal case would have been a GPS/leveling network with evenly distributed sites, with the mean site separation defined by both scientific and practical constraints. From the scientific point of view, the spectral harmonization of the gravimetric geoid (its long wave component computed from a geopotential model) and the GPS/leveling network is the primary constraint. At the time of the project launch, geopotential models up to degree and order of 360 were available, corresponding to about 100 km (approximately 1 degree latitude/longitude difference) as the shortest wavelength information. To recover a similar spectral range, a network with 50 km mean site separation would have been desirable! However, such an enormously large network (several thousands of new points) was practically impossible to finance, measure and handle. Fortunately, the existing (GRACE, CHAMP), and at that time planned (GOCE) satellite gradiometric missions and the announced development of a new high resolution EGM model (Pavlis et al 2008) allowed to meet the scientific and practical constraints. In view of the expected significant improvements in the medium to long wavelength domains in the geopotential modeling, a mean site separation of not more than 100 km was proposed, corresponding to less than 2000 GPS/leveling benchmarks for the entire continent. A coordinated observation campaign for such a large number of stations was not feasible, and therefore each participating country was asked to provide a separate national contribution along pre-defined quality standards. Existing GPS/leveling data, corresponding to the standards, was also accepted.

Although the quoted resolution of the EUREF2001 symposium asked for a dm-accuracy height reference surface (see annex), the huge improvements in the geoid modeling during the last decade made feasible the realization of a combined height reference surface at the few cm level. Obviously, this requires homogeneous, 1 cm accurate ellipsoidal and leveled height information, which can only be achieved when the data conforms to certain quality standards for both the observations and the data analysis.

The predefined data requirements were the following:

(1) ellipsoidal heights

- n*24 hours GNSS measurement sessions ($n \geq 1$) are preferred,
- when existing campaign data with a shorter observation time span is provided, a denser network is expected,
- the 3D coordinates should refer to an ETRS89 realization (expressed at the observation epoch),
- the GNSS data should be processed with a scientific software package (e.g. Bernese) according to the EPN standards.

(2) leveled heights

- the EUVN_DA markers should be linked to the nearest UELN nodal point,
- when the link does not exist, the leveled heights in the EVRS realization must be determined with well established and verified transformation parameters,
- gravimetric measurements should also be performed to derive geopotential numbers.

The project partners were asked to submit the GPS and leveling data to the EUREF/UELN Data Centre (BKG Leipzig), where the leveling data were checked and analyzed in detail. In order to simplify the efforts for both the provider and analyst partners, an MS Excel worksheet (see Table 1.) was elaborated to facilitate the data collection/submission and most of the related data checks and transformations.

Left section of the worksheet:

Country: | **Status:** DD-MMM-YYYY

Data provider: | **Contact person:**

GPS data details:
Campaign date: | Elevation cutoff [deg] :
Session length: | Processing software :

Leveling information:
National height system: normal/orthometric
Related to tide gauge:

Station name	EUVN_DA identifier 5 char.	ETRFyy lat [deg]	ETRFyy lon [deg]	ETRFyy ell. height [m]	UELN nodal point parameters: UELN number	national identifier	year of leveling	coordinates lat [deg]	coordinates lon [deg]	gravity IGSN71 [mgal]	geopotential of the nodal point [GPU]

Right section of the worksheet:

EUVN_DA point levelling parameters

UELN-EUVN_DA distance [km]	EUVN_DA point gravity [mgal]	UELN-EUVN_DA geopotential diff. [GPU]	geopotential of the EUVN_DA-station [GPU]	normal height of EUVN_DA-station [m]	estimated accuracy [mm]	Neuvn = h-H [m]	Remarks

Table 1. The EUVN_DA worksheet used for data collection and analysis.

Database overview

The responsible national institutions and mapping agencies were asked to provide high quality GPS-derived coordinates and leveling data for selected benchmarks. The expected site separation was 100 km as a compromise between the spatial resolution of the global geopotential models and the data preparation costs. Some countries[2], where the GPS/leveling networks were established prior to the start of EUVN_DA, did not observe sessions of 24 hours, but submitted a denser database with a mean site separation close to 50 km.

The EUVN_DA database consists of more than 1400 GPS/leveling points (as of December 2009) contributed from 25 countries. The actual point locations are shown in Figure 3 and the data providers are listed in Table 2. The main data collection phase is finished now, but EUVN_DA will also be maintained in the future to integrate new and/or updated GPS/leveling data sets. The database covers fairly well continental Europe; white spots remain only in the south-eastern part of Europe, hopefully to be filled in the future.

Reference epochs

The envisaged reference epoch of the ellipsoidal and leveled heights was 2000.0, but practically most the data refer to the epoch of the observations. The age of the leveling data is variable, ranging from 1 – 70(!) years, while the GPS campaigns have been performed during the last decade. The inhomogeneous reference epochs are a weak point of the current EUVN_DA database, because the validity of the collected height information relies on the assumption of the long term site stability. The oldest leveling data is from Spain and partially from Portugal; a re-leveling is in progress in Spain and in the near future a data upgrade will be performed.

The Nordic countries are exceptional, where due to the well modeled post-glacial rebound (PGR) the heights were transformed to the epoch 2000.0, using the latest PGR model NKG2005LU (Ågren and Svensson, 2006).

2 France, Great Britain, Spain, Portugal

Country	Contact	Institution	Area [1000 km2]	expected points	received points
Austria	N.Hoggerl	BEV	84	9 – 32	5+12
Belgium	P.Voet	NGI	31	4 – 12	4+5
Bulgaria	I. Georgiev	BAS	111	10 – 40	3+23
Croatia	Ilija Grgic	HGI	56	6 – 20	8+12
Czech R.	J.Reznicek	CUZK	79	8 – 32	3+14
Denmark	K.Engsager	SpaceCenter	43	5 – 16	4+37
Estonia	Karin Kollo	MAAMET	45	5 – 16	2+24
Finland	P.Hakli	FGI	338	30 – 120	50
France	F.Duquenne	IGN	544	55 – 220	164
Germany	G.Liebsch	BKG	357	36 – 140	10+75
Great Britain	Colin Fane	OS	244	25 – 100	181
Hungary	A.Kenyeres	FÖMI	93	10 – 30	4+18
Italy	R. Maseroli	IGM	301	30 – 120	75
Latvia	J.Kaminskis	VZD	65	7 – 20	4+15
Lithuania	E.Parseulinas	VTU	65	7 – 20	3+6
the Netherlands	A.J.Kosters	RWS	41	4 – 16	3+14
Norway	O.Vestol	Statens Kartverk	324	32 – 120	10+54
Poland	W.Graszka	GUGIK	313	32 – 120	8+ 52
Portugal	M.Vasconselos	IGEO	92	10 – 40	81
Romania	T.Rus	ANCPI	237	24 – 100	43
Slovakia	K.Leitmannova	GKU	49	5 – 20	3+22
Slovenia	K. Medved	SMA	20	5 – 10	3+10
Spain	R. Quiros Donate	IGN Spain	505	50 – 200	30/177
Sweden	M.Lilje	Lantmateriet	450	45 – 180	136
Switzerland	U.Marti	Swisstopo	41	5 – 20	8+12

Table 2. The list of contributing countries/institutions and the number of sites expected (according to a mean site separation of 100 and 50 km, respectively) and received (EUVN + EUVN_DA) points.

Reference frames

The submitted GPS and leveling data were transformed into the respective common reference frames. The GPS coordinates referred to the different realizations of ETRS89, while the leveling data were transformed to the actual realization of the European Vertical Reference System (EVRS). During the project's lifetime, the EVRS realization changed from EVRF2000 to EVRF2007 (Sacher et al, 2008). The introduction of the EVRS2007 standards in 2008 also changed the datum definition and the handling of the permanent tide. Formerly, the permanent tide was inconsistently handled in leveling (mean tide) and GPS analysis (tide free), disregarding the respective IAG recommendation to work in the zero tide[3] system (IAG, 1984). Due to the change from the mean to zero tide system in EVRS2007, the GPS-derived ellipsoidal heights were also transformed from the tide free to the zero tide system using the equation of Mäkinen (2008):

3 the tide generating potential is completely removed, but the permanent deformation of the Earth's figure is retained.

$$h^{zero} = h^{tidefree} - 0.179 \sin(phi)^2 - 0.0019 \sin(phi)^4 + 0.0603 \qquad [m] \qquad (1)$$

This transformation adds a ±5 cm N-S tilt to the tide-free ellipsoidal heights over the continent.

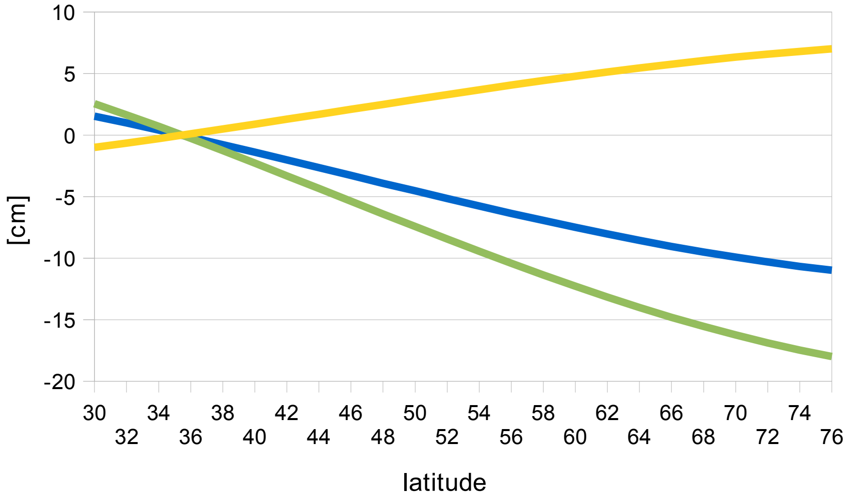

Fig.2 . Height changes over Europe caused by the application of different permanent tide concepts.
Blue : ellipsoidal height changes due to the conversion from tide free to zero crust;
Green : normal height changes due to the conversion from mean to zero tide system;
Yellow : quasigeoid geoid height changes due to the above ellipsoidal and normal height changes.

Leveling data

The leveling data validation and the sequential UELN adjustments were done at the UELN/EUVN Data Centre in Leipzig. To ensure the homogeneity of all leveling data, only those countries could be used, which are part of the UELN.

Depending on the submitted data, the leveling heights were derived by two different procedures:

a) Direct leveling connections between EUVN_DA benchmarks and corresponding UELN nodal points were recommended. In this case, the EUVN_DA benchmark could be integrated into the UELN and its subsequent adjustments. The computation of the normal heights based on the adjusted geopotential numbers was also foreseen in the EUVN_DA leveling form.

b) A few countries[4] provided EUVN_DA benchmarks without direct leveling connections to UELN nodal points, and therefore the benchmark heights/geopotentials were only known with respect to the corresponding national height systems. In those cases, the EVRF2007 normal heights were determined by a 3-parameter transformation using known transformation parameters between the national height system and EVRF2007 (see web_reference-1). However, this solution must be considered as less accurate than the direct leveling connection to UELN nodal points. The data validation/comparison indicated biases where only the height transformation solution (b) was available. These cases are briefly discussed later on. The precision of the transformation parameters of the various countries ranges from few millimeters to some centimeters, depending on the number of available identical control points as well as the epoch and quality of the national leveling network. For old leveling benchmarks, both possible marker displacements and site identification problems may cause transformation errors. In addition, the different definitions of the national height systems (orthometric versus normal heights) may downgrade the

4 Great Britain, Italy, Spain, Portugal

quality of the transformation, especially in mountainous regions. The situation may be improved if gravity data is available at both the identical transformation control points and the EUVN_DA benchmarks; then, knowing the gravity data and the orthometric correction formula applied in the national leveling network, the transformation can be done via the geopotential data, leading to more reliable transformed heights in EVRF2007. The latter solution was applied for Portugal and the approach proved to be favorable.

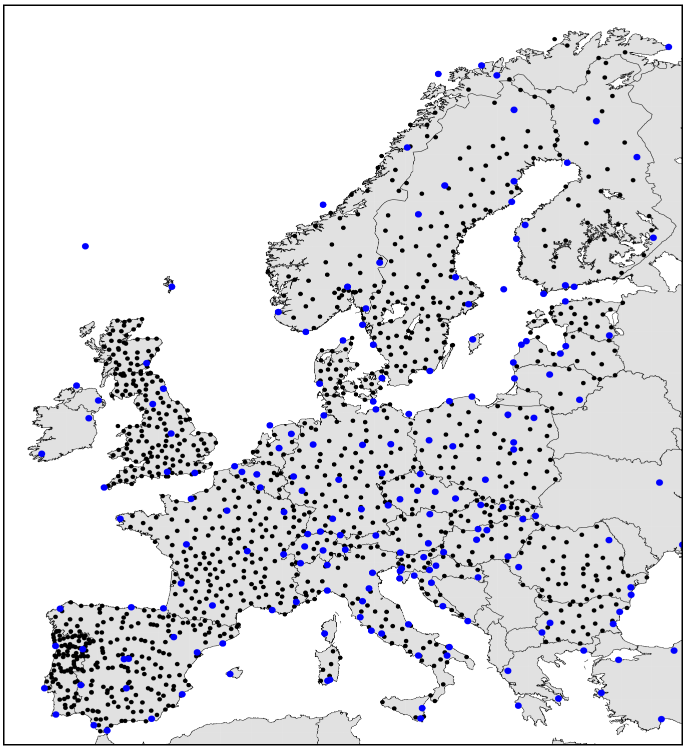

Figure 3. Distribution of the EUVN and EUVN_DA benchmarks (blue and black dots, respectively) as of December 2009.

Up to 2008, the EUVN_DA leveling data was available in the EVRF2000 realization of the EVRS2000 system (see the description in the reference EVRS, 2001). After the adoption of the new European height system EVRS2007 and its realization EVRF2007 (Sacher et al 2008), the normal heights were converted into EVRF2007. The UELN/EUVN_DA benchmarks received EVRF2007 heights directly in the new adjustment, while the EUVN_DA benchmarks, having only transformed heights, were converted to EVRF2007 heights by a new transformation; the new transformation parameter sets were estimated between the respective national height system realization and EVRF2007.

The height differences between EVRF2000 and EVRF2007 are usually at the cm-level and reach one decimeter only in the Fennoscandian region. The observed EVRF2000/2007 differences may be related to different causes:

- following the publication of EVRF2000, the leveling networks of 14 countries were re-observed and the new data was included in the EVRF2007 realization,
- instead of the former single datum point (NAP), the EVRS2007 datum level was realized by 13 points distributed over Europe (Sacher et al 2008),
- the observations in EVRF2007 over Fennoscandia, the Baltic States, Denmark, the northern part of Germany and Poland were reduced to the epoch 2000.0, using the new land uplift model NKG2005LU,
- the change of the tide system (the EVRF2007 heights are in the zero tide system; Mäkinen and Ihde, 2007).

Analysis of the GPS/leveling data

Beyond the separate internal consistency checks of the GPS and leveling data sets, the consecutive European geoid solutions (EGG97, EGG03 (Denker et al., 2005), EGG06 (Denker, 2006), EGG07 (Denker et al, 2007) and EGG08 (Denker et al., 2008)) were used to identify biases and gross errors in the combined EUVN_DA GPS and leveling data. All EGG geoid versions (European Gravimetric (Quasi)Geoid) were computed as a combination of a global geopotential model, land, marine and altimetric gravity data, as well as a high resolution digital terrain model. The geoid modeling was done by the remove-restore procedure and the spectral weighting technique (Denker et al 2005). Within the time frame of the above mentioned EGG solutions, the geoid modeling technique was refined, but the major progress is attributed to corresponding improvements of the terrestrial data and the global geopotential models. The latest EGG2008 computation is based on the EGM2008 global geopotential model (Pavlis et al, 2008) and certainly surpasses all previous solutions; therefore the earlier analysis results are considered as provisional and not discussed here.

At present, no location-dependent error estimates exist for the EGG2008 gravimetric quasigeoid model, but this is planned for the future. However, a rough error estimate was derived by the degree variance approach; based on an accuracy of 1 mgal for the terrestrial gravity data, a standard deviation of roughly 3 cm was obtained. The latter figure can be considered as realistic for areas with a good quality and coverage of the input gravity and terrain data (e.g., central western and northern Europe); for other areas the accuracy degrades accordingly. The EGG2008 model is based on the zero tide system and refers to the GRS80 ellipsoid. The absolute level (zero order undulation) was determined from an earlier version of the EUVN_DA data set (Version 2009; ETRS89, EVRS2007, zero tide system), excluding Great Britain and Italy (due to the slope observed between the geoid and GPS/leveling data sets). A similar approach was already used for the EGG97 model. As a result, the present EUVN_DA and EGG2008 data sets should fit without applying additional transformations.

The inter-comparison of the height anomalies from the ***regional*** GPS/leveling and the gravimetric quasigeoid models is a crucial step, as the database has been built up from separate, independent ***national*** contributions. As the general geoid modeling capabilities are not yet at the 1 cm accuracy level, moderate medium to long wavelength biases may be present in the current models. Hence, if a tilt is observed in the comparisons, it is difficult to clearly attribute it to one of the input data sets, without additional information (e.g., known leveling or gravimetric data problems, etc.). The series of geoid comparisons clearly demonstrate significant improvements in the European geoid modeling during the last decade. All statistical parameters show some 50% reduction of the discrepancies between the GPS/leveling and gravimetric height anomalies; the overall statistical parameters are reported in Table 3. A series of plots, showing the differences between the different EGG solutions and the EUVN_DA GPS/leveling geoid values were created. In this final report, only the EGG97 (Figure 4) and the EGG08 (Figure 5) comparisons are presented. The results with the intermediate EGG solutions, as EGG03 and EGG06, were discussed already in Kenyeres et al (2006). For each case, clear improvements were observed, although the intermediate test solutions had limitations as either the terrestrial database was not completely updated (EGG03) or the geoid solution itself had limited area coverage (EGG06).

A comparison of the preliminary EUVN_DA data set with the EGG97 quasigeoid model is already included in Kenyeres et al (2006). However, although the EUVN_DA database was completely updated since that time (e.g., transition from the mean/tide-free system to the zero tide system, inclusion of further updates), the main findings still hold and are shortly repeated here. It should be noted that in the previous comparisons the tidal system inconsistencies (GPS – tide free; geoid – zero tide; leveling – mean tide) were neglected. The correct tidal system handling eliminated some 10 cm north-south slope over the continent (see Figure 2), which also contributed to the improvement of the comparison statistics.

For all comparisons, the EUVN_DA height anomalies ζ were derived as differences between the zero-tide ellipsoidal heights h^{zero} (ETRS89 reference system, GRS80 ellipsoid) and the leveled heights in the EVRS2007 system $H^{EVRF2007}$ (normal heights, zero-tide system)

$$\zeta = h^{zero} - H^{EVRF2007} \quad .$$

These quantities were then compared with the height anomalies from the EGG97 and EGG08 gravimetric quasigeoid models (with all values related to the zero-tide system). It is emphasized here that no additional fitting was performed. The comparison results (just the raw differences) are shown in Figures 4 and 5, respectively. The statistics of the differences is provided in Tables 3 and 4.

	EGG97	EGG07	EGG08
R.M.S.	15	6	6
$\Delta\zeta$min	-64	-25	-18
$\Delta\zeta$max	56	22	19
$\Delta\zeta$range	120	47	37
$\Delta\zeta$average	-6	-6	0

Table 3. The general comparison statistics of the EUVN_DA and EGG height anomalies. UK was excluded from this comparison. The detailed statistics per country is shown in Table 4. All units are cm.

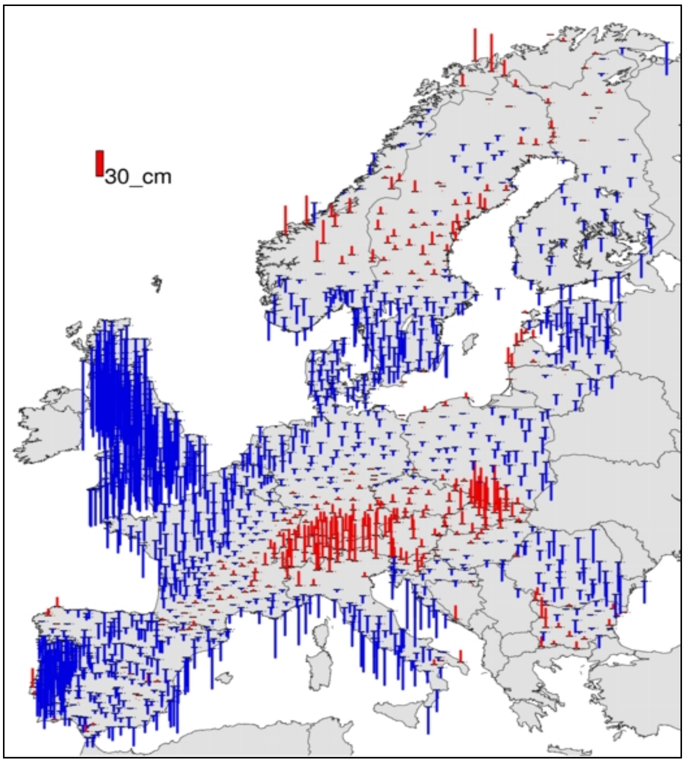

Figure 4. EUVN_DA and EGG97 height anomaly differences.

Regarding the EGG97 comparison (Fig. 4), the height anomaly differences (note the opposite sign definition compared to Fig. 1) clearly show continental-scale variations, indicating the limitations of the long wavelength geoid modeling capabilities and the underlying geopotential model at that time (EGM96; Lemoine et al 1998). The discrepancies over central Scandinavia are acceptable, but further south there is a belt extending from the Iberian peninsula over France to the Baltic states, showing higher negative differences (i.e., the EGG97 geoid estimates are higher than the corresponding values from GPS/leveling). Considering entire Europe, negative differences exist over large parts of the continent, while in the Alps and High Tatras significant positive differences are present, again reflecting the modeling deficiencies of EGG97/EGM96. The largest differences are found over the UK, which may be due to several reasons which will be discussed briefly in the section on country-specific results. Along the Mediterranean coastline, larger negative differences are observed as compared to the adjacent inland territories; this may indicate problems in the Mediterranean gravity data available at that time as well as problems for the land/sea transition. Such large-scale trends and detailed features could not be observed clearly with the sparser EUVN data.

In Fig. 5, the final EUVN_DA GPS/leveling database is compared for the first time with the recently published EGG08 quasigeoid model (Denker et al, 2008). The first general impression is that the improvements over large parts of the continent are tremendous with respect to the earlier solutions. The significant continental-scale long wavelength features (e.g., over the Alps, High Tatras, and the belt with negative differences from Iberia to the Baltic states) mostly disappeared. Also along the Mediterranean coast, the large negative differences have disappeared, which is due to the complete update of the corresponding land and sea gravity data sets. The remaining trends are in general much smaller as compared to EGG97, reflecting errors in the geoid, leveling as well as to some extent in the GPS data. For EGG08, the largest differences can be found over the UK and in the Mediterranean area; these will be discussed in the following section on country-specific results.

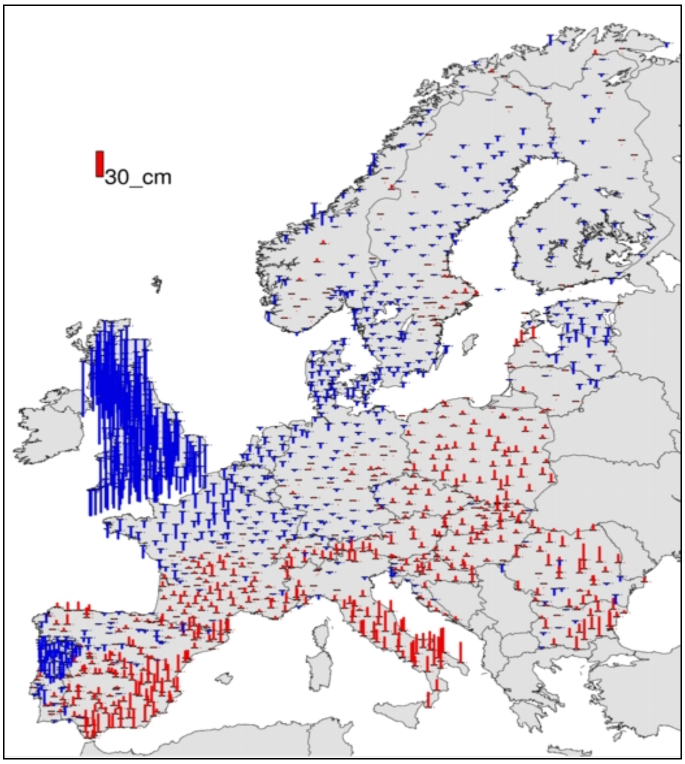

Figure 5. EUVN_DA and EGG08 height anomaly differences.

Country-specific results

The statistics of the country-specific results are provided in Table 4, documenting the significant improvements in geoid modeling during the last decade and proving also the high quality of the EUVN_DA database. The gravimetric geoid models and the GPS/leveling data agree well over large parts of the continent. However, in areas where the gravimetric, terrain or GPS/leveling data sets remain weaker, some discrepancies still exist. Such regions are listed and briefly discussed below:

- Over the Iberian peninsula, a moderate improvement was obtained, but the comparison results are more noisy than in other areas. This may reflect the great age of the available Spanish leveling data (coming from the 1930s), included in UELN and EUVN_DA. With the completion of the new national leveling network in Spain in 2008, the situation should improve and it is hoped that this new data will be included in UELN and EUVN_DA in the future.
- Significant differences can also be observed over Portugal. Again, the leveling data is partly originating from the 1930s, and moreover the EVRF2007 heights were derived by transformation. The transformation solution, however, was confirmed by including all Portuguese UELN points, with the transformation residuals indicating a good agreement.
- The north-south trend over France is remarkable; IGN reported at the EUREF2007 symposium (Duquenne, 2007) that this trend is in agreement with the tilt they found in the French leveling network. IGN is continuing with further primary leveling lines to verify the tilt. The expected future re-adjustment of the French leveling network will also have significant consequences for the south-western part of the UELN network!
- The EUVN_DA/EGG comparisons over Bulgaria and Romania are noisier because the gravimetric geoid solution is based only on sparse and older gravimetric data.
- Regarding the British Isles, all comparisons (EGG97, EGG08, etc.) show negative differences (higher EGG values with an average of -59 cm) and a clear negative trend (50 cm) towards the north. As this level of inconsistency is well exceeding the current geoid modeling capabilities, the tilt is probably not resulting from the geoid model alone. The observed GPS/leveling and EGG inconsistencies may be caused by several factors:
  (a) a tilt in the UK leveling networks may exist and was already detected and discussed by Edge (1959) from a comparison of the 2^{nd} and 3^{rd} leveling epochs. It appears that the 3^{rd} leveling is more tilted than the 2^{nd} leveling, and it has to be noted that the national ODN heights mainly rely on the 2^{nd} leveling, while in UELN only data from the 3^{rd} leveling is included.
  (b) the current ***official*** connection of the UK and continental leveling is based on hydrodynamic leveling (done in 1963); the connection of the Ordnance Survey's leveling network (ODN) to UELN through the EuroTunnel is not yet finalized, and therefore an unknown datum offset may exist,
  (c) a (small) tilt in the EGG08 geoid solution may exist like in other regions.

  However, the internal consistency of the UK data set is quite good; if the tilt is removed by simple linear trend estimation, the RMS of the fit residuals decreases to only 2 cm!
- Over Italy, the comparisons of EUVN_DA with EGG97 and EGG08 show different features, which are due to the numerous gravity and terrain data updates in the region. For EGG08, the discrepancies are mainly positive and a clear trend from north to south is evident (Fig. 5). If this trend is removed, the RMS of the residuals decreases to 6 cm (Maseroli et al, 2009), which is basically in agreement with the EGG08 error estimates (see above). The source of the observed tilt could not be identified within the framework of the EUVN_DA project and further investigations should be performed to explain or eliminate that tilt.

country	*no. of points*	*LC**	*RMS [cm]*		*average difference [cm]*		*MAX-MIN range [cm]*	
			EGG97	*EGG08*	*EGG97*	*EGG08*	*EGG97*	*EGG08*
Austria	17	D	11	5	23	5	32	16
Belgium	9	D	7	3	-13	-5	19	7
Bulgaria	26	D	9	8	2	8	39	28
Croatia	20	D	20	4	-17	4	80	13
Czech Rep.	22	D	6	4	4	2	28	12
Denmark	41	D	3	2	-12	-6	17	9
Estonia	26	D	9	4	-22	-5	38	14
Finland	50	D	10	2	-9	-2	49	8
France	168	D	12	7	-9	-1	68	36
Germany	85	D	10	3	-1	-2	45	13
Great Britain	181	T	18	12	-59	-43	73	51
Hungary	22	D	9	3	1	6	39	10
Italy	75*	T	23	10	-11	12	90	46
Latvia	19	T	12	7	-2	-1	36	28
Lithuania	9	D&T	7	3	-7	2	17	9
the Netherlands	17	D	6	2	-20	-6	19	7
Norway	64	D	18	5	-5	-4	84	22
Poland	60	D	9	3	-6	6	48	15
Portugal	81	T	18	7	-33	-12	89	27
Romania	43	D	15	8	-17	6	83	30
Slovakia	25	D	18	3	22	4	71	9
Slovenia	13	D	12	3	4	3	39	11
Spain	30	D	12	7	-12	4	58	26
Spain	142	T	11	8	-11	7	80	36
Switzerland	20	D	10	5	27	3	32	19
Sweden	136	D	13	3	-8	-3	55	15

Table 4. Statistics of the comparison between EUVN_DA and the EGG97/08 solutions for all participating countries. The statistics refer to the raw differences; no bias and tilt estimation is applied.

* Italy submitted 75 points, but only 61 are used in this comparison, as 7/7 points are located on the islands Sicily/Sardinia.

LC: type of leveling connection: T: transformation between EVRF2007 and the national network
D: direct leveling connections to the UELN benchmarks

In summary, the RMS values presented in Table 4 indicate that the latest EGG08 solution has the potential to serve as an accurate continental height reference surface in areas with a good coverage and quality of the input data.

EUVN_DA web pages

In order to announce the EUVN_DA results and support both the data providers and future users with relevant information, EUVN_DA web pages were established and integrated into the EVRS web site of BKG (see *web_reference-2*). The pages include information on the history, general project description, data requirements, status and results of the analysis. A meta database was also created, showing general information of the submitted data on a country-by-country basis.

A separate map is available for each country, displaying the distribution of the EUVN_DA markers. Plots are also presented, showing the results of the EUVN_DA – EGG97/08 comparisons. The web pages also provide access to the GPS/leveling meta database.

Towards the modeling of the height reference surface

The primary target of the EUVN_DA project was to set up a consistent continental GPS/leveling database which can be used for controlling gravimetric geoid computations and (in a later phase) for realizing a combined continental height reference surface (HRS). The HRS concept is primarily introduced for practical reasons and it is understood as the surface resulting from the differences between available GPS ellipsoidal heights (ETRS89, GRS80 ellipsoid) and leveled heights (EVRS2007, normal heights). As the GPS/leveling points are usually too sparse to allow a high resolution modeling of the HRS, a (gravimetric) quasigeoid model has to be utilized as the third main input data set within this process. However, in this context it must be understood that such a HRS will incorporate systematic errors from ellipsoidal, leveling, and geoidal sources; hence it cannot be considered as a pure gravity field related surface as the geoid or quasigeoid, respectively.

As the realization of a HRS is out of the scope of the EUVN_DA project, the intention here is mainly to demonstrate the future capabilities for realizing a continental-scale HRS by combining the EUVN_DA GPS/leveling data with a gravimetric geoid model. This combination can be done either at the observation level, integrating all gravity field related measurement types, e.g., by using the least squares collocation approach (e.g. Jiang, Duquenne 1996; Kotsakis, Sideris 1999), or by using the so-called corrector surface approach, where the point-wise differences between GPS/leveling and a gravimetric geoid model are modeled by a smooth surface (e.g., Featherstone 2000).

For the short demonstration case provided here, the corrector surface approach was adopted. Numerous well known interpolation methods (e.g., minimum curvature, kriging, polynomial fitting[5]) were tested. The main aim was to select a simple, but robust solution which models only large-scale difference signals and suppresses data blunders. For this reason, the ***Local Polynomial*** approach was finally selected for this first test. In this procedure, a local polynomial surface is computed for each point from the neighboring scattered input points (here a circle with a 6 degree search radius was used). Different local polynomial surfaces were implemented and tested, but finally a simple local plane approximation was selected as the most stable and smoothest corrector surface. The extended data search radius of 6 degree improved the robustness, so that single outliers could not degrade the results very much. The differences between the EUVN_DA GPS/leveling data and the EGG97 and EGG08 gravimetric quasigeoid models, modeled by the local polynomial approach, are displayed in Fig. 6 and 7, respectively. Both plots show the corrector surfaces as contour maps and the residuals as vertical bars.

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5 All methods are, e.g., provided by the SURFER v9 software package (Golden Software).

Comparing the EGG97 and EGG08 related solutions, both the smoothness of the corrector surfaces and the statistics of the fit residuals clearly indicates the superiority of EGG08. While the EGG97 corrector surface is more structured and the fit residuals are higher, the corresponding EGG08 surface is quite smooth and the residuals are well below ± 7 cm over most parts of Europe; residuals above this level can be observed only for regions discussed above (Iberian and Balkan Peninsula), where either the gravimetric geoid may be less accurate or the GPS/leveling data may not strictly conform to all quality standards. Histograms of the EUVN_DA/EGGyy differences are shown in Figure 8a-b, while the post-fit residuals are presented in Figure 8c-d. From Fig. 8 the following can be concluded:

- the EGG97 solution contains significant long wavelength errors due to the underlying EGM96 geopotential model and the incomplete gravity and terrain databases,
- the EGG08 solution agrees much better with the EUVN_DA GPS/leveling data,
- the simple local polynomial fit models the biases in both cases quite well, but as expected, the distribution and magnitude of the residuals are superior for EGG08.

These results clearly demonstrate the feasibility of realizing a high accuracy HRS based on the EUVN_DA and EGG08 data. In the future, further analysis is planned in cooperation with the EGGP, but this is out of the scope of EUVN_DA.

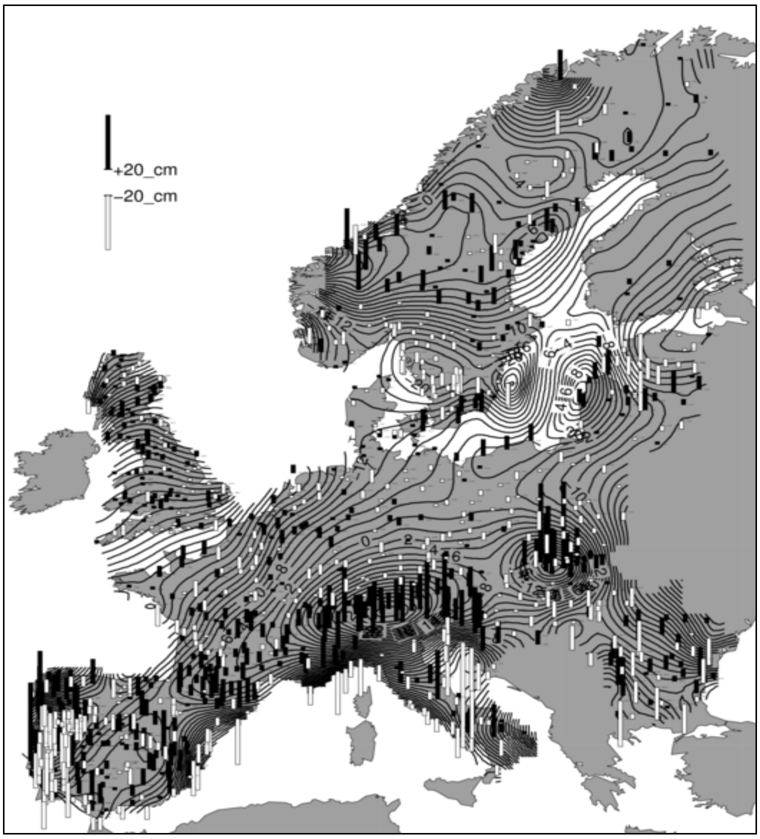


Figure 6. Modeling of the EUVN_DA minus EGG97 height anomaly differences (contour interval: 2 cm). The contours represent the corrector surface and the black vertical bars show the positive and negative post-fit residuals, respectively.

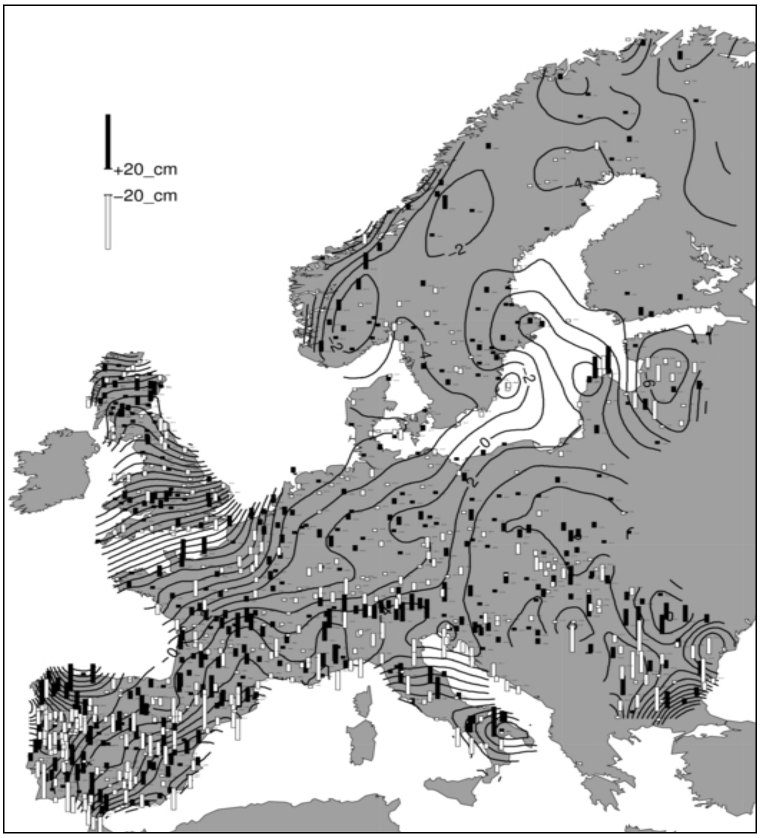
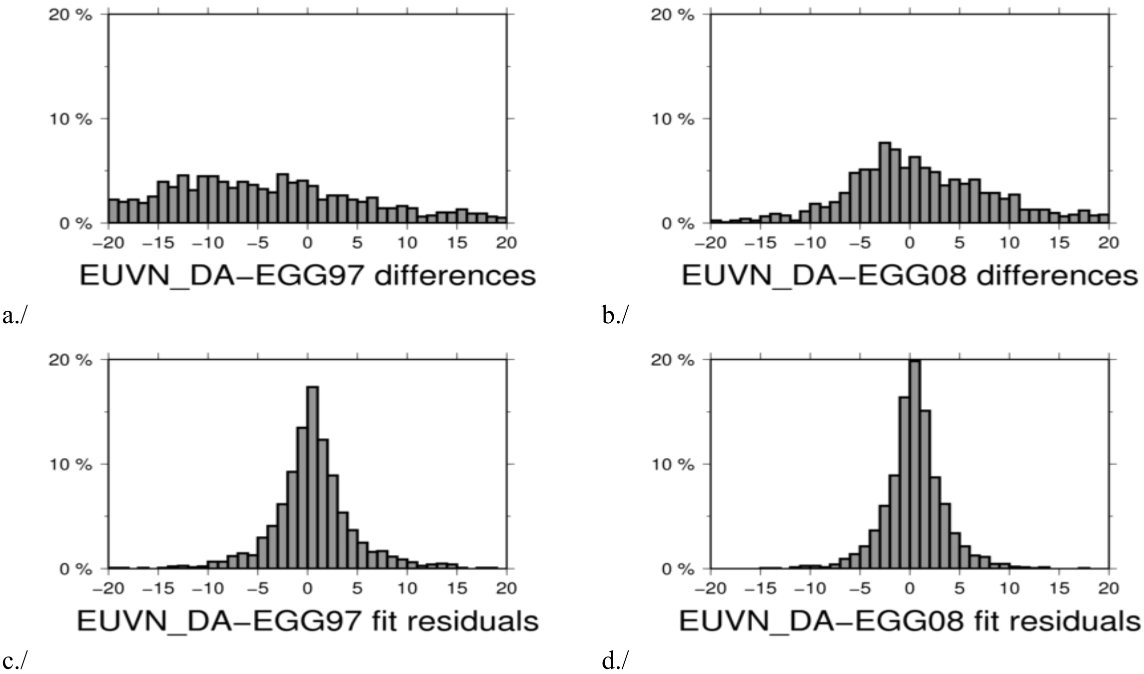


Figure 7. Modeling of the EUVN_DA minus EGG08 height anomaly differences (contour interval: 2 cm). The contours represent the corrector surface and the black vertical bars show the positive and negative post-fit residuals, respectively.



a./ b./ c./ d./

Figure 8a-b-c-d. Histograms of the EUVN_DA minus EGG97/08 differences in cm before (a-b) and after (c-d) removal of the estimated corrector surfaces. The data from the UK has been excluded from this comparison.

Summary and outlook

A regional GPS/leveling database has been created with the support of the European mapping agencies and in cooperation with EUREF and the EGGP. The database includes more than 1400 GPS/leveling points, where existing and new data, fulfilling predetermined quality requirements was collected. The submitted data was carefully checked and transformed into common reference frames (ETRS89/GRS80 for the GPS and EVRS2007/UELN for the leveling data). A milestone of the project was the transformation into the zero-tide system, conforming to the standards of IAG and EVRS2007; with this step, the existing systematic differences due to the inconsistent handling of the permanent tide were eliminated.

Each EUVN_DA data submission is stored in a uniform Excel worksheet, which comprises all relevant data, including the comparisons with the continental EGG gravimetric geoid solutions. The uniform and homogeneous database has great value for practical GPS/leveling applications and for the validation and analysis of geoid solutions, both at regional and local scales. The database has been provided to the contributing agencies; the data itself my be made available to interested groups by the project partners listed in Table 2.

The analysis of the EUVN_DA data revealed several problems and inconsistencies. Most of them were solved during the project operation, but some remained open. The connection of the Ordnance Survey's leveling network to EVRF2007/UELN should be solved in the near future and more investigations are needed to understand the nature of the tilt found in the UK GPS/leveling comparisons. A similar situation was revealed in the French leveling network; a clarification and future data update may lead to further effects over the southern parts of UELN. The expected upgrade of the Spanish leveling network will also improve the Iberian part of EUVN_DA. The observed tilt in the Italian and Portuguese EUVN_DA data also needs further attention.

Although the EUVN_DA project is declared as closed, the revealed open issues require further activities to improve the European Vertical Reference System.

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ANNEX: Related EUREF Resolutions

(1) Resolution No. 3
of the EUREF Symposium in Tromsø 22 –24 June 2000

The IAG Sub-commission for Europe (EUREF)
noting Resolution No.3 of the EUREF Symposium 1998 in Bad Neuenahr-Ahrweiler,
recognizing the completion of the EUVN height solution, which includes GPS/leveling geoid heights,
thanks the National Mapping Agencies for their support in supplying data,
recommends that the GPS/leveling heights of the EUVN solution should be used as fiducial control for the future European geoid determinations,
asks the relevant authorities

- to provide the necessary information for tide gauge connections,
- to densify the network of EUVN GPS/leveling geoid heights,

to complete and extend the EUVN project.

(2) Resolution No. 4
of the EUREF Symposium in Dubrovnik, 16-18 May 2001

The IAG Subcommission for Europe (EUREF)

recognizing

- the European Vertical GPS Reference Network (EUVN) with its GPS-derived ellipsoidal heights and leveled connections to UELN,
- the definition of the European Vertical Reference System EVRS with its first realization UELN 95/98, called EVRF2000,

considering

- this implicit point-wise realization of a European geoid consistent with both ETRS89 and EVRS,
- the existence of a large number of regional and local geoids in Europe,
- the urgent need by the navigation community for a height reference surface,

asks its Technical Working Group and the European Sub-commission of the IAG IGGC (International Gravity and Geoid Commission) to take all necessary steps to generate a European geoid model of decimetre accuracy consistent with ETRS89 and EVRS.

(3) Resolution No. 4
of the EUREF Symposium in Florence, 16-18 May 2009

The IAG Reference Frame Sub-commission for Europe (EUREF)

recognizing
the advantage of combining gravity field parameters with geometric observations to stabilize geodetic reference systems
and considering
the availability of the new realisation of the European Vertical Reference System EVRF2007 and the advanced status of the EUVN-DA project
and the continuation of the EUREF project "European Combined Geodetic Network" (ECGN)
asks the TWG to contact the European Geoid Project in order to develop a combined European geoid to link ETRS89 and the EVRS.