Status and Development of the European Height Systems

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Abstract. After a break of ten years, the work on the United European Levelling Network (UELN) resumed in 1994 under the name UELN-95. The objectives of the UELN-95 project are to establish an unified vertical datum for Europe at the one decimeter level with the simultaneous enlargement of UELN as far as possible to include Central and Eastern European countries. More than 3000 nodal points were adjusted linked to the reference point of UELN-73 (gauge Amsterdam). The new heights in the system UELN-95/98 are available for more than 20 participating countries.

The European Vertical Reference Network (EUVN) is designed to contribute to the UELN project along with the connection of European tide gauge benchmarks as contribution to monitoring absolute sea level variations, the establishment of fiducial points for the European geoid determination. The EUVN includes 196 points all over Europe. At every EUVN point, three-dimensional coordinates in ETRS89 and levelling heights primarily in the system of the UELN-95 have to be derived. The GPS computations are finalised, some levelling connections still have to be realised. At the tide gauge stations of EUVN additional sea level observations have to be included.

The height systems will be developed as a combination of GPS permanent observations, levelling, and geoid information under consideration of well known vertical movements towards an European kinematic height reference system.

1 Introduction

The IAG Subcommission for Europe (EUREF) started in 1994 with its activities for development and establishment of European height systems.

Since 1994 the work at the UELN has been continued after a break of 10 years under the name of UELN-95. In accordance with the Resolution No. 3 of the EUREF Symposium 1994 in Warsaw, the objective of the UELN project is to establish an unified vertical datum for Europe at the one-decimeter level with simultaneous enlargement of UELN as far as possible to the Eastern European countries. The results of the adjustment with status of end 1998 were handed over to each participating country under the name UELN-95/98.

The European Vertical Reference Network (EUVN) was prepared in parallel to the UELN. It is an integrated network of GPS, levelling and tide gauge observations.

In May 1997 the EUVN GPS campaign with more than 200 stations was realized. Most of the countries were able to support EUVN in their national area with own receivers, with own staff and at their own cost.

The final results of the successful EUVN GPS campaign as a set of coordinates in ITRF96 (Epoch 1997.4) and ETRS89 (ETRF96, Epoch 1997.4) for all sites are available. It was the result of the excellent cooperation of the observing agencies, of the preprocessing and analysis centres. The EUVN activity will be successfully finished if levelling heights in the system of UELN-95/98 (as result of levelling connections to the UELN or to the national height system) for all sites and sea level in tide gauges in the system of UELN-95/98, Epoch 1997.4 are available. The next step to an European kinematic height network (EVS 2000) is in preparation.

2 United European Levelling Network (UELN)

Starting point of UELN-95 project were the data of UELN-73 with which in a first step the adjustment 1986 was repeated. The weights were derived from a variance component estimation of the observation material which was actually introduced into the adjustment and where each national network was regarded as one group.

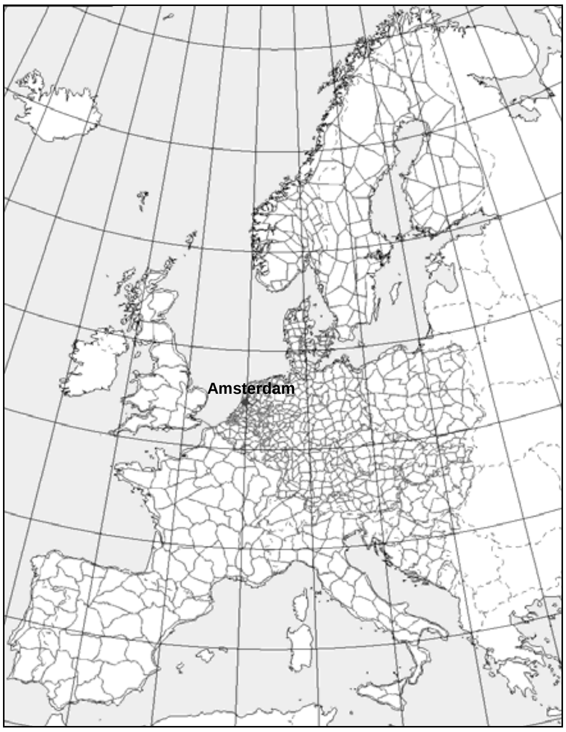

Figure 1 UELN with status of Dec. 1998

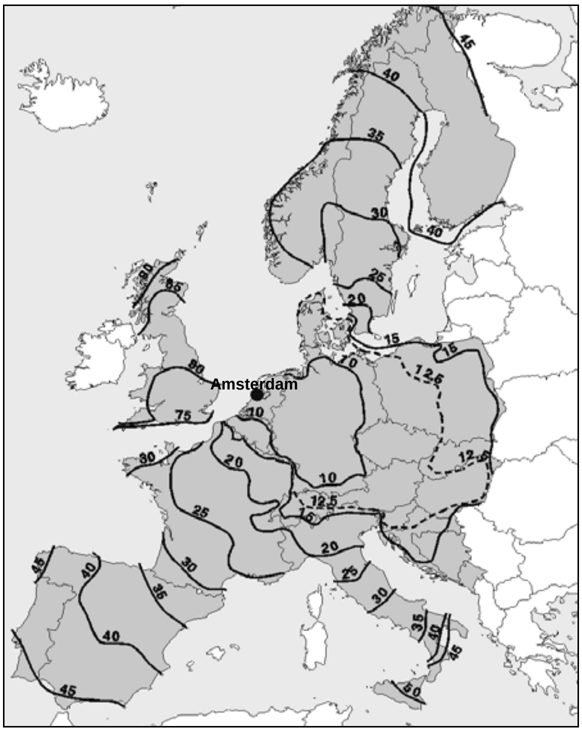

Figure 2 Error propagation of the UELN (in mm)

The enlargement to UELN-95 is performed in two qualitatively different steps:

- Substitution of data material of such network blocks which were already part of UELN-73 but show current new measurements with improved (mostly more dense) network configuration (intensive enlargement)
- Adding new national network blocks of Central and Eastern Europe which were not part of UELN-73 (extensive enlargement)

At the UELN data and computing centre at the Bundesamt für Kartographie und Geodäsie (BKG) in Leipzig the data handling and adjustment are carried out.

The adjustment in geopotential numbers is performed as constraint-free adjustment linked to the reference point of UELN-73 (gauge Amsterdam). For the UELN adjustment the program system HOENA developed at BKG is used.

The parameters of the last adjustment version. UELN-95 are the following:

– number of fixed points: 1
– number of unknowns: 3063
– number of measurements: 4263
– degrees of freedom: 1200
– average redundancy: 0.281
– a-posteriori standard deviation referred to the levelling distance of 1 km:1.10 kgal · mm.

Figure 2 shows the error propagation.

In January 1999 the last adjustment version of UELN-95 was handed over to the participating countries as the UELN-95/98 solution (Figure 1).

Looking at the current network configuration of the UELN-95/98 some problem areas are found and should be solved in the next steps:

- Some of the oldest data of the UELN are found in the parts of Western Europe which were already included in the UELN-73. Several countries are repeating the observation of their levelling networks or have established new networks with better configuration. The concerning network blocks in the UELN should be replaced in order to increase the precision of UELN. On the other hand the repetition of the observation of a levelling network presents the chance to take a first step on the way to a geokinematic height network. The data bank of UELN is prepared to store more than one epoch.
- A request in the Resolution No. 4 of the EUREF-Symposium 1998 is the extension of the UELN to the Black Sea.
- The closing of the network around the Baltic Sea would be an important step to improve the reliability of the Scandinavian part of the UELN. The next condition for that is the inclusion of the Baltic States into the UELN.

- Inclusion of a second height difference between France and Great Britain by using the EURO Tunnel measurement.

In 1999 representatives from Estonia and Latvia carried out the adjustment of their national levelling networks at the UELN data and computing center at the BKG. The results were delivered to the UELN database.

3 The European Vertical Reference Network (EUVN)

The initial practical objective of the EUVN project is to unify different European height datums within few centimeters. In addition this project is to prepare a geokinematic height reference system for Europe and to connect levelling heights with GPS heights.

At all EUVN points *P* three-dimensional coordinates in the ETRS89 $(X_p, Y_p, Z_p)_{ETRS}$ and geopotential numbers $c_p = W_{o\ UELN} - W_p$ will be derived. Finally the EUVN is representing a geometrical-physical reference frame. In addition to the geopotential numbers c_p normal heights $H_n = c_p / \bar{\gamma}$ will be provided ($\bar{\gamma}$ is the mean normal gravity value between the ellipsoid and the telluroid.).

The application of the GPS technique for practical levelling would dramatically extend if the geoid would be known precisely enough in relation to the concerned GPS reference system and the levelling reference system. To derive such a geoid, an European reference geoid is required in the reference system ETRS89 and the reference system of UELN. Up to now there is no precise geoid available for Europe with an accuracy of a few centimeters which fulfils the requirement for the practical applications. This proposal points out a possibility to derive a geoid tailored for the GPS-levelling methods by combining the existing reference network EUREF/ETRS89 with the UELN95.

The EUVN project contributes to the realization of an European vertical datum and to connect different sea levels of European oceans with respect to the work PSMSL (Permanent Service of Mean Sea Level) and of anticipated accelerated sea level rise due to global warming. The project provides a contribution to the determination of an absolute world height system.

Three kinds of observation groups are necessary:

- GPS measurements for the determination of the ellipsoidal heights of all defined EUVN points,

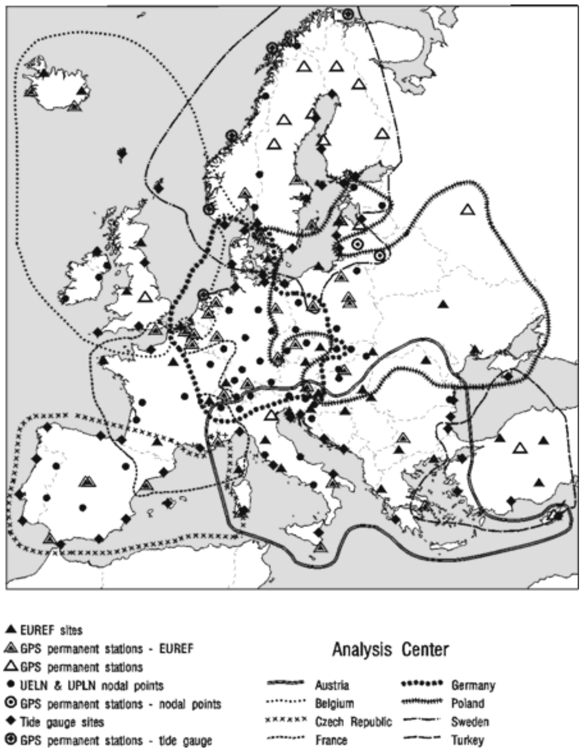

Figure 3 EUVN Distribution of EUVN points and analysis center areas

- levellings between the EUVN sites and the UELN nodal points for the determination of the physical height of all defined EUVN points,
- observations of sea level at tide gauge stations.

In total the EUVN consists of about 196 sites: 66 EUREF and 13 national permanent sites, 54 UELN and UPLN (United Precise Levelling Network of Central and Eastern Europe) stations and 63 tide gauges (Figure 3).

The GPS observations for the EUVN were carried out in the period from May 21 to May 29, 1997. Three types of receiver were used: 35 Turbo Rogue Receivers, 134 Trimble SSI or SSE and 51 Ashtech Z12. The time interval was set to 30 s, the elevation mask was 5°. The campaign was running very smoothly and everybody who participated in the campaign supported the action successfully.

The data preprocessing after the EUVN campaign performed by 9 EUVN Preprocessing Centers (PPC) was mainly a check concerning completeness and consistency of the data and the auxiliary information. The PPCs were requested to prepare complete access information and/or data flow guidelines for the observing agencies before the start of the campaign (Luthardt et al., 1998).

The task of the EUVN GPS Analysis Center (AC) was to process the data of a special subnetwork. A subdivision of the whole EUVN Network was done under the aspect of receiver type and regions.

10 European institutions were ready to contribute as Analysis Centers. On the Analysis Center Workshop in September 1997 in Leipzig the subdivision of EUVN was discussed and decided (see Figure 3) (Ineichen et al., 1999). The AC of Croatia was responsible for the analysis of the collocation points and the investigation of the biases introduced by using different antenna types within one GPS network. Simultaneously with the EUVN 97 Campaign the Baltic Sea Level (BSL) GPS campaign was performed. The BSL 97 GPS campaign was processed by the Finnish Geodetic Institute.

The Astronomical Institute of the University of Bern (AIUB) and the BKG were responsible for the computation of the final GPS solution of EUVN (Ineichen et al., 1998).

The analysis centers produced different solution types in order to investigate the influence of the processing strategy on the results. Mainly the following three types of solutions were looked at:

– 15 degrees without weighting: The 'standard' solution with the highest priority. Data down to an elevation cut-off angle of 15 degrees were used for generating this solution type. All observations were introduced with the same weight. This solution type corresponds to the processing strategy used for the permanent EUREF network at the time of the EUVN campaign.
– 5 degrees with elevation-dependent weighting: Measurements down to an elevation cut-off angle of 5 degrees were used for this solution type. In addition, the observations were weighted with $w = \cos^2 (z)$, where z is the zenith angle of the observed satellite.
– Satellite-specific weighting: The IGS precise orbit files (in SP3 format) contain accuracy codes for each satellite. These accuracy codes can be used by the Bernese GPS Software to weight the corresponding observations. Not all analysis centers delivered solutions of this type, and therefore no combined solution was generated.

The question which solution to choose as the official EUVN97 solution (the unweighted 15-degree solution or the weighted 5-degree solution), was discussed during the Analysis Center Workshop at Wettzell (April 2-3, 1998): The unweighted 15-degree solution was selected as the official one. The following aspects had to be taken into account:

- The comparison of the height component of redundant points in both solution types showed a slightly better repeatability for the unweighted 15-degree solution.
- Not all sites within EUVN97 were tracking satellites below 15 degrees with the same quality and quantity. For some sites the number of observations is hardly increasing when changing to the lower cut-off angle, whereas for others the number of observations increased by up to 20 %. Therefore the site coordinates within the EUVN97 GPS network could be more inhomogeneous in the 5-degree solution.
- The elevation-dependent antenna phase center variations are not yet well known below 10 degrees. Introduction of poorly defined corrections could lead to additional systematic errors.
- We do not have enough experience yet with the performance of the tropospheric mapping functions at very low elevations.

The final solution was constrained to ITRF96 coordinates (epoch 1997.4) of 37 stations with an a-priori standard deviation of 0.01 mm for each coordinate component. As a consequence of these tight constraints the resulting coordinates of the reference points are virtually identical with the ITRF96 values.

A comparison for the combined solutions of BKG and AIUB showed that these two solutions were identical.

For many practical purposes it is useful to have the ETRS89 coordinates available. To get conformity with other projects, the general relations between ITRS and ETRS were used. The coordinate transform formula from ITRF96 to ETRF96 and the final coordinates are given in Ineichen et al 1999.

In order to reach the goal it is necessary to connect the EUVN stations by levellings with nodal points of relevant levelling networks. So it is possible to use levelling observations to update the gravity related EUVN heights in context with the new adjustment of UELN. At present for about 80% of the EUVN points levelling heights are available.

As the EUVN is a static height network it is necessary to know the value of the mean sea level in relation to the tide gauge bench mark at the epoch of EUVN GPS campaign 1997.5. However for future tasks it is useful to have available the monthly mean values over a period of some years.

The Permanent Service for Mean Sea Level (PSMSL), as member of the Federation of the Astronomical and Geophysical Data Analysis Service (FAGS), is in principle in charge of the data collection. The information which are sent to the PSMSL databank in general should also be made available for the EUVN project.

EUVN is a step to establish a fundamental network for a further geokinematic height reference system such as European Vertical System (EVS 2000) under the special consideration of the Fennoscandian uplift and the uplift in the Carpathian-Balkan region.

4 Transformation Relations between National European Height Systems and the UELN

In Europe three different kinds of heights (normal heights, orthometric heights and normal-orthometric heights) are used. Examples for the use of orthometric heights are Belgium, Denmark, Finland, Italy and Switzerland. Today normal heights are used in France, Germany, Sweden and in the most countries of Eastern Europe. In Norway, Austria and in the countries of the former Yugoslavia normal-orthometric heights are used.

The vertical datum is determined 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 in Europe are located at various oceans and inland seas: Baltic Sea, North Sea, Mediterranean Sea, Black Sea, Atlantic Ocean. The differences between these sea levels can come up to several decimeters. They are caused by the various separations between the ocean surface and the geoid.

Figure 4 shows the distribution of the mean transformation parameters between the national height systems and the UELN.

If the differences in one country are not sufficiently constant then parameters for a 3-parameter-transformation are determined. For more information see Sacher et al. (1999b).

5 The European Vertical System (EVS2000) - Outlook

The European Vertical System is planned as geokinematic height network as combination of the European GPS permanent station network, the UELN with repeated levellings, the European gravimetric geoid and tide gauge measurements along European coast lines as well as repeated gravity measurements. In May 1999 a special working group was formed to determine the direction of future work. At the first working group meeting three first tasks were established:

– analysis of available repeated levelling measurements and store the data base in the UELN data
– development of software as base for test computation
– testing of the principles in a test area (Netherlands, Denmark, northern part of Germany).

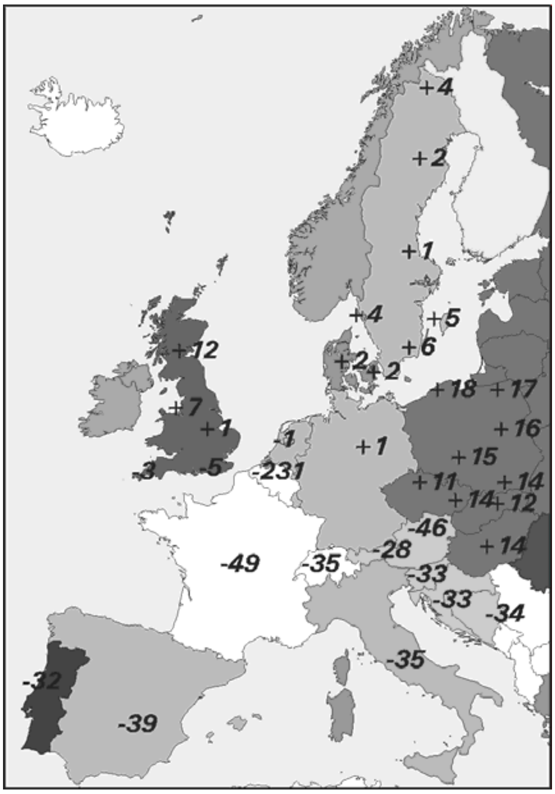

Figure 4 Preliminary Transformation Parameters from National Height Systems to UELN

The GPS observations of about 80 European permanent stations are available. The analysis of 10 European GPS permanent stations shows daily repeatabilities between 7 to 9 mm in the height component. This is in good agreement with the special GPS height campaigns in Germany for deriving GPS levelling geoidal heights ($m_h = \pm 7$ mm).

Furthermore the linear height regression analysis gives for a three year period an accuracy of a GPS height difference of about

$$m_{V_h} = m_h \sqrt{2} / \sqrt{365} \text{ / year} = \pm 0.5 \text{ mm/year},$$

that means from a statistical point of view that a vertical movement of V_h = 1.0 mm/year can be significantly determined after a three years GPS observation period (m_{V_h} = ± 0.3 mm/year).

Repeated precise levellings (1 mm · km$^{-1/2}$) with an epoch difference of 20 years give velocities for height differences with an accuracy of about ± 0.07 mm · km$^{-1/2}$ / year.

From this follows, that GPS permanent stations in a distance of about 300 km can significantly support repeated levellings with above mentioned suppositions. This combination of GPS and levelling is promising for a stable kinematic height reference system (Ihde, 1999).

The observation equation for levelling observations $\Delta h_{ij,k}$ between points i and j at the epoch k is:

$$\Delta h_{ij,k} = H_j - H_i + V_j(t_k - t_0) - V_i(t_k - t_0)\,. \quad (1)$$

Two unknowns per point are to be determined: the levelling height H (gravity related height) at the reference epoch t_0 and the velocity V.

For datum fixing of the network a height for one point at a determined epoch and a velocity for this or another point shall be given.

The relation between levelling heights H and GPS heights h is given by the geoid height N

$$h = H + N. \quad (2)$$

Since the accuracy of the geoid heights resp. geoid height differences is not in the same order like the levelling observations, GPS heights cannot be used as observations. But under the condition of no significant geoid height changes, velocities v derived from GPS permanent station observations can be used as additional observation type in levelling points i

$$v_i = V_i. \quad (3)$$

The unknown velocities V are to be determined in combination with the repeated levellings. It is necessary, that the variance-covariance matrix of the observed GPS velocities is given.

The EVS project will start in late 1999 with a circular letter of the IAG Subcommission for Europe to all European countries with a call for participation.

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