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Some remarks and proposals on the re-definition of the EVRS and EVRF

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Summary

With the increasing observational accuracy, the numerical discrepancy between the definition of the EVRS2000 as a World Height System (WHS) referred to the geoidal potential, and the EVRF2000 as its realization through the tide gauge datum NAP is becoming obvious. To resolve the discrepancy, either the system definition (S) or the realization (F) or both must be changed. I review some alternatives and their practical consequences. I argue that the best basis for continuous improvement of the European vertical reference frame is provided by genuine implementation of the WHS definition. If for some reason a regional system is preferred, then it should be defined through a numerical offset to the WHS, rather than through MSL at tide gauges or geopotentials conventionally assigned to physical artefacts (bench marks).

1. Background

For decades, the applications of the UELN (United European Levelling Network) results were predominantly scientific, and concerned only a relatively small group of geodesists and oceanographers. With the increasing need for unified European georeferencing, the situation is dramatically changing. In the latest development, the INSPIRE (Infrastructure for Spatial Information in Europe) initiative (http://www.ec-gis.org/inspire/) of the European Commission (EC) aims at creating a European GIS standard. Obviously, standardization of the geodetic reference frame, and in particular of the vertical reference frame is a necessary part of the work.

Whatever the initial scope for such a project, it is likely that the frame thus adopted will obtain a status and width of application that on the European scale correspond to the uses of the national height system(s) on the national scale(s). Indeed, many countries will, when the opportunity arises, e.g., when the national height systems are renewed anyway, seek to harmonize them with the European standard. And this quite independently of the design of the INSPIRE that only transformation formulas from national systems to the European frame are required, not the harmonization.

For European vertical geodesy, this “fixing of systems” comes at a somewhat awkward time. We are at the threshold of a technology jump that is likely to change completely the determination of potential values and potential differences (i.e., of gravity-related heights) on a continental and even on a country-wide scale. After the current (CHAMP, GRACE) and future (GOCE) gravity satellite missions, height differences across Europe can be determined from a combination of gravity data and 3-D positions with accuracy at least comparable to that of precise levelling. Moreover, even a medium-sized country will be able to access directly the WHS without, e.g., levelling ties to tide gauges (TGs) or even across borders. Finally, with the increased accuracy, heights cannot any more be considered time-invariable. And, unlike in the past, when precise repeated levelling was the prime source of information on vertical crustal motion, other methods like continuous GPS (CGPS) and repeated absolute gravity will dominate the monitoring of the reference frame, including gravity related heights in the European Combined Geodetic Network ECGN.

It is therefore important that the EVRS adopted for the INSPIRE should make it possible to wholly incorporate the progress that will take place, and to take advantage of the ever-increasing accuracy provided by the new technology. We should seek to emulate the success story of the ETRS89. Precisely because the ETRS89 only specified the principles, and did not specify any coordinates that Europe should consider fixed, the big progress in 3-D positioning has been wholly incorporated in successive realizations ETRF89…ETRF2000. At the same time the ETRS89 principles guarantee that the realizations are sufficiently consistent for a great number of purposes. It would be unfortunate if in the vertical the development would take a different course. The non-optimal scenario: in 2010 we might then have an "EC/INSPIRE vertical system" and "an EC/INSPIRE vertical frame", i.e., a definition and a set of fixed numbers reflecting the best that could be done in 200x, sub-standard in 2010 but used because of their administrational position in the European Union. At the same time a quite different, more modern system and frame would be used by geodesists and scientists, and even for high-level practical work. Such a situation is not untenable; on the national level it has existed and exists in many countries, both for 3-D and for heights. However, it is not desirable.

This paper was prompted by the discussions at the workshop "Vertical Reference Systems for Europe", organized by the Joint Research Center (JRC) of the EC and EuroGeographics at the BKG in Frankfurt from April 5 to 7, 2004 (http://gi-gis.jrc.it/ws/evrs/). The debate centred on the question: should we change the EVRS definition, in order to retain the NAP datum (or some other continental European datum) in the EVRF? Or should we stay at the WHS definition of the EVRS, and genuinely implement it in the EVRF? And, in the former case—since just invoking the acronym NAP does not constitute a definition—how should the new system definition then be formulated? It needs to be precise, accessible, stable, and compatible with modern methods of measurement.

The reasons advanced for the NAP at the workshop were mostly those of continuity: NAP has been he datum of all UELN adjustments so far, including the EVRF2000. Some European countries (The Netherlands, Germany, Sweden, now Austria) have national systems referring to the NAP. Therefore I first examine these continuity arguments for NAP. Second, I try to establish a more general vantage point from which to consider definitions of geodetic reference systems and frames. I use the ITRS/ITRF and ETRS89 as analogies. I then discuss the practical advantages (independently of continuity) that a continental European datum at present might have over a WHS in Europe. Subsequently, assuming that NAP (in some sense) is the wanted outcome, I review different ways of getting there through EVRS and EVRF. And finally I make a proposal to adopt the WHS, or, if the NAP is judged imprescindible, to re-define it through the WHS.

In this paper I use the denomination World Height System (WHS) meaning the particular definition in EVRS2000. However, as the readers know there are other possibilities of defining a WHS. Further, I will not go into the technical details of a WHS. For instance, the current EVRS2000 invokes the normal potential U_0 of the mean earth ellipsoid (MEE). According to the classical definition of a MEE (Heiskanen and Moritz, 1967) using the Pizzetti theory this amounts to the geopotential at the geoid W_0. For the discussion here I therefore simply assume that the present WHS in EVRS2000 leads to the Gauss-Listing geoid as a reference.. However, other definitions of a MEE are possible (Burša et al., 1998, 2002b). Moreover, a definition over MEE would seem to require that the realization specify other aspects of the MEE, too, not only the potential that is needed. Further, is there really any need to couple the realization EVRF to the GRS80 for anything else than for the conversion from geopotential numbers to normal height? These questions will not be discussed here.

The various new acronyms (UELN05 etc.) in part reflect the schedule discussed at the Frankfurt workshop, consultable at http://gi-gis.jrc.it/ws/evrs/.

2. EVRS2000 and EVRF2000 definitions

First, for easier reference let us write down the current definitions EVRS2000 and EVRF2000 (Anonymous, 2001; Ihde and Augath, 2001).

2.1. Definition

The European Vertical Reference System (EVRS) is a gravity-related height reference system. It is defined by the following conventions:

a) The vertical datum is the zero level for which the Earth gravity field potential W_0 is equal to the normal potential of the mean Earth ellipsoid U_0:

$$W_0 = U_0.$$

b) The height components are the differences ΔW_P between the potential W_P of the Earth gravity field through the considered points P and the potential of the EVRS zero level W_0. The potential difference W_P is also designated as geopotential number c_P:

$$\Delta W_P = W_0 - W_P = c_P.$$

Normal heights are equivalent to geopotential numbers.

c) The EVRS is a zero tidal system, in agreement with the IAG Resolutions.

IIn a) and b) the potential of the Earth includes the potential of the permanent tidal deformation but excludes the permanent tidal potential itself.

2.2. The European Vertical Reference Frame 2000 (EVRF2000)

The EVRS is realized by the geopotential numbers and normal heights of nodal points of the United European Levelling Network 95/98 (UELN 95/98) extended for Estonia, Latvia, Lithuania and Romania in relation to the Normaal Amsterdams Peils (NAP). The geopotential numbers and normal heights of the nodal points are available for the participating countries under the name UELN 95/98 to which is now given the name EVRF2000.

2.1 Realization of the datum

a) The vertical datum of the EVRS is realized by the zero level through the Normaal Amsterdams Peil (NAP). Following this, the geopotential number in the NAP is zero:

$$c_{NAP} = 0.$$

b) For related parameters and constants of the Geodetic Reference System 1980 (GRS80) is used. Following this the Earth gravity field potential through NAP W_{NAP} is set to be the normal potential of the GRS80

$$W_{NAP}^{REAL} = U_{0GRS80}.$$

c) The EVRF2000 datum is fixed by the geopotential number and the equivalent normal height of the reference point of the UELN No. 000A2530/13600.

Station name Country	UELN number	Position in ETRS89 ellipsoidal latitude ellipsoidal longitude in ° ′ ″	Height in UELN95/98 geopotential number in $m^2 \cdot s^{-2}$	 normal height in m	Gravity in IGSN71 in $m \cdot s^{-2}$
Reference point of EVRS 000A2530 The Netherlands	**13600**	52° 22′ 53″ 4° 54′ 34″	**7.0259**	**0.71599**	9.81277935

3. Implications of a datum redefinition for the changes in numeric heights from EVRF2000 to UELN05 to EVRF2010

Keeping numerical coordinates (heights) unchanged is often an important consideration in national systems, due to the large amount for changeover labour involved if the old heights have been extensively used in practical work. For the EVRF2000 this is not a major issue, as it has so far been applied mainly in scientific contexts. Even in the future, science will mostly use the best available realization regardless of continuity of the coordinates.

In any case, let us look at the changes in numeric heights expected from going from the EVRF2000 to new versions. First assume that the ***NAP*** (in some sense) ***be retained as the datum***. Even in this case, all heights (except perhaps for a datum point) will change already in the next version UELN05, and in the corresponding EVRF200x. This is because

(1) New levelling data will be introduced in many countries, not only in the Nordic area
(2) The treatment of the permanent tide will be harmonized to the zero model
(3) For referring the heights to a well-defined epoch, it may turn out necessary to correct them for vertical motion, at least for the by-now reasonably "well-modellable" Postglacial Rebound (PGR), even outside the Nordic area (where this has been done since UELN-55).

The change compared with EVRF2000 will be up to 0.1 m, except in the Nordic PGR area, where it is up to 0.5 m.

For the following realization (EVRF2010?), the heights will change once more, even if nothing new would happen for the items (1) and (2) or the datum. This is because by 2010

(i) Enough data (and modelling efforts) will have accumulated (from EPN and ECGN and other sources) to produce a high-quality velocity field all over Europe
(ii) The combination of 3-D positions from GNSS, and gravity field information including the satellite mission GOCE will be superior to precise levelling already over medium distances

The changes from UELN05 to EVRF2010 will be some centimetres.

Second, assume that instead, the ***WHS definition in the EVRS2000 is*** retained, and ***realized in the next EVRF***. This by itself would mean adding a shift of $(W_0\text{-}W_{NAP})/\gamma$ to all (normal) heights. The current best estimate of W_0 (Gauss-Listing geoid) is (not rounded here)

$$W_0 = (62\,636\,856.13 \pm 0.5)\ \mathrm{m^2s^{-2}}$$

(Burša et al. 2002b; 2003) while the estimate for the NAP datum is

$$W_{NAP} = (62\,636\,857.25 \pm 0.53)\ \mathrm{m^2s^{-2}}$$

(Burša et al., 2002a). This W_{NAP} value uses the whole EVRF2000 network without corrections for the inhomogeneous tidal systems or epochs. However, it is very close to values obtained by Burša et al. (2003) using smaller patches (Netherlands, Germany), which are close to the NAP physical reference BM and approximately at the same latitude (such that the tidal system does not matter). Thus at the present level of knowledge, (–11 ± 8) cm would be added to EVRF2000 normal heights. The error estimate is conservative and probably pessimistic.

A related question concerns the size of the corrections from national systems to the EVRF. In Fig. 1 they are given from the current national systems to the EVRF2000. In a UELN05 (NAP or global) these will change mostly of the order of 0.1 m, which does not seem problematic. Moreover, many countries that are about to select new national systems would be attracted by the new EVRS or EVRF whatever its definition, and get transformation parameters close to zero. So it does not seem to be possible to obtain much guidance from this argument.

However, there is a related practical question: Between the present, and the first possible realization of a true WHS in Europe in 200x, some countries will be forced to adopt new national height systems. The WHS will not yet be accessible at this time at the European level (though the countries could themselves get a reasonable tie using recent GRACE data) but the NAP is. For these countries, there is undoubtedly an advantage in continuing in the NAP beyond 200x.

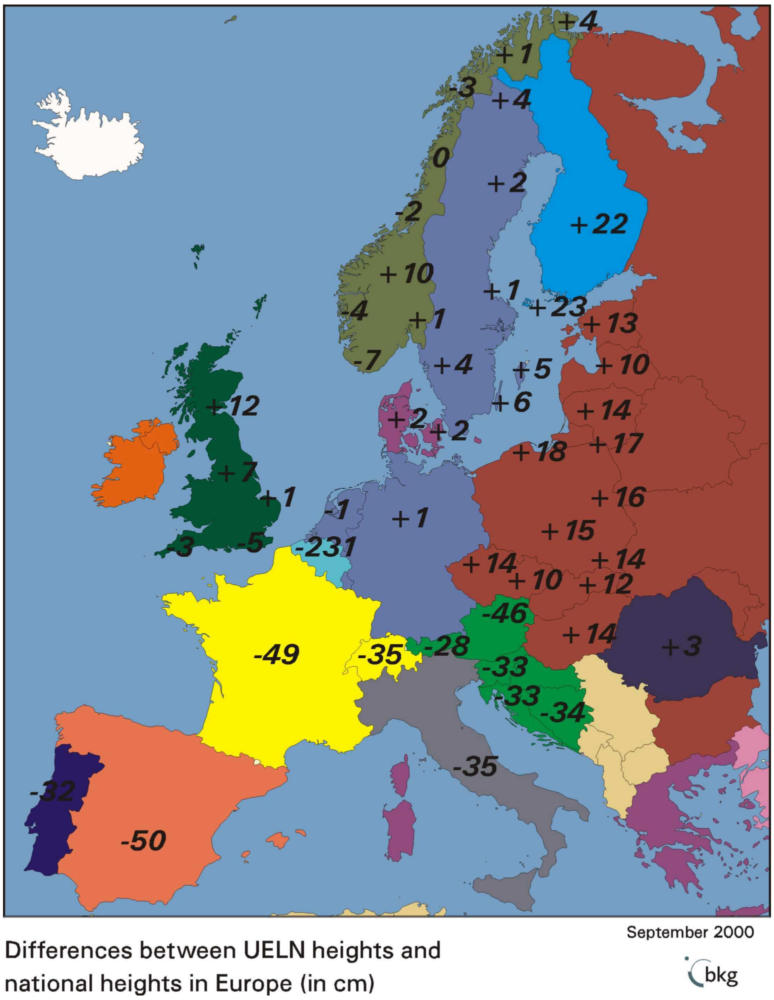

Fig.1. Taken from Sacher et al. (2002).

4. Reference systems and reference frames: physical and conventional definitions

The separation of geodetic referencing into the twin concepts, the *reference system* (S), and its realization, the *reference frame* (F) has proved very fruitful (Kovalevsky and Mueller, 1981). Roughly speaking, the system (S) definition contains the principles, and the frame (F) definition contains the numerical coordinates (in this case heights) of the concrete points.

A reference system can be constructed from physical or/and conventional definitions. It is useful to illustrate this using the ITRS and ETRS89, and ask whether analogous procedures could be found for the EVRS.

The origin of ITRS is the centre of mass of the Earth, a physical quantity. The direction of the z-axis in ITRS is related to the rotation axis, again a physical quantity.

But there is no way to obtain a physically preferred direction of the x-axis. Its definition is by necessity conventional. Historically, the International Reference Meridian was defined by an artefact, (the position of) the transit instrument in Greenwich. Subsequently, it has been defined by a multi-station adjustment of station coordinates and observations of earth orientation parameters applying certain continuity and stability principles. This has kept it near the original transit instrument but in fact the direction of the x-axis of the ITRS is now defined implicitly by the ITRF coordinates.

ETRS89 coincided with the ITRS in the epoch 1989.0 after which it “travels” with the stable part of the Eurasian Plate. The definition is obviously physical.

In the SC3 (“Fundamental Constants”) of the old IAG organization it was often pointed out that fundamental constants should be physically defined. It seems to me that in the same way, physical definitions in reference systems should be preferred, when they are possible. Moreover, the system definition should allow ever-improving realizations (coordinate systems), exploiting modern observation techniques.

5. Is there a need for a continental European height datum, apart from a world height system?

For the 3-D positioning we need a European system (the ETRS89) for a fundamental physical reason: the motion of the Eurasian plate in a global system like the ITRS. For the vertical, there is no similar problem. There is no uniform (or dominating) vertical motion of Europe that need to be eliminated by attaching the system to this motion. A physical argument for a specifically European datum could perhaps be constructed using the coastal levels of the surrounding seas. A world height system where MSLs on European costs would be, say, +1 m on the average, might be considered impractical by many. Or some might wish that the datum would be close to the average MSL on European coasts.

As things are, the NAP used in the EVRF2000 is close to the MSL on the coast of the North Sea. The Baltic is 0.1…0.2 m above the NAP, the Mediterranean about 0.3…0.4 m below, and the Black Sea perhaps 0.2 m (?) above. Using the current best estimate of W_0 in the realization of the EVRS2000 instead of NAP would modify these figures by 0.1 m. Clearly, this is no argument to prefer NAP over W_0 . (However, other alternative world height systems have been proposed in the past. For instance, the mean earth ellipsoid in the EVRS definition might be replaced by some reference ellipsoid, even by that of the GRS80, with a resulting big difference between the sea level and the reference geopotential.)

So, it would seem that the motivation for a continental European vertical datum is at the moment mostly technical and historical: the difficulty of measuring potential differences using global methods. This motivation is fast disappearing. Polemically, one could even claim that the “Europeanism” of a height datum NAP corresponds more to the Europe of the ED87 than to that of ETRS89.

There is a number of practical and scientific applications where a European vertical datum (as opposed to a WHS) is undoubtedly a drawback. Global hydrography, oceanography, and even aviation, to think of some.

6. Putting the NAP into the system (S) or into the frame (F)?

Let us assume that for some reason, the desired outcome is the NAP (in some sense) as a datum for the EVRF. We then have several possibilities:

(A) We introduce the NAP in the system definition, EVRS, either

(A1) On the basis of physical quantities

(A2) On the basis of a conventional definition

(B) EVRS datum is defined in a way that allows the NAP to come out as a reasonable realization in EVRF. Note that this is at present done in the EVRS2000 and EVRF2000, but with the increased observational accuracy the difference between NAP and the global datum of EVRS2000 has become evident.

A1. Physical definition of the NAP in the EVRS

This is straightforward to formulate, all tide gauge datums are physical. We would then use the original characterization of the NAP as the potential of the MHT at the Amsterdam TG in the year 1684. However, such a simple definition would put us into difficulties in the realization. We would need to pose the question: where is that equipotential surface now? The answer could well be that it is 0.1…0.2 m above what passes for NAP these days. The model of Glacial Isostatic Adjustment (GIA) by Milne et al. (2001) predicts a radial velocity of -2 mm/yr for the area in question. The model ICE-4G by Peltier (1998) gives –1.5 mm/yr (numerical predictions available at ftp://maia.usno.navy.mil/conventions/chapter7/pgr.model). In view of observations these rates appear large (Fig. 2), but even the velocity of –0.4 mm/yr predicted by Lambeck et al. (1998) and Kooi et al. (1998) from compaction and GIA would total -0.13 m during 1684–2000. In addition, it should be noted that the history of the NAP datum can with some accuracy only be traced back until 1928 (Anton Kosters, personal information May 17, 2004).

Briefly, this definition of the system (S) would get us stuck at quite irrelevant analyses of what happened between 1684 and the present. To shortcut them we would need to declare a conventional realization (F) of the NAP through some BM values independently of those analyses. Then why bother, we could take the conventional BM value as the system (S) definition directly (see next section). If we still want to define a contemporary NAP using sea level, it would be much easier to re-do it with modern TG data.

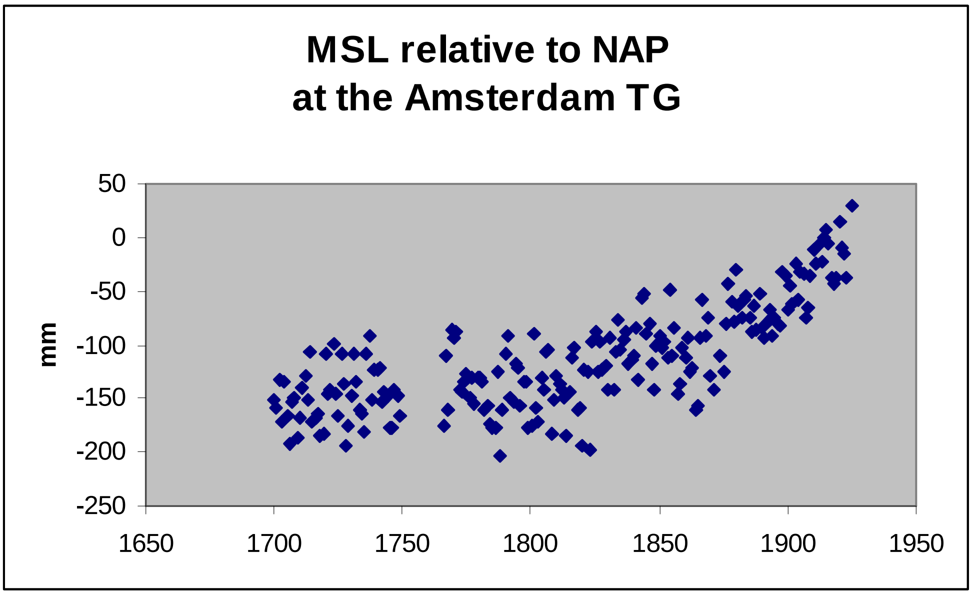

Fig.2. MSL relative to the NAP at the Amsterdam tide gauge. J.van Veen (1945), Spencer et al. (1988), http://www.pol.ac.uk/psmsl/pub/ancill.rep.

A2. Conventional definition of the NAP in EVRS

In its simplest form, this amounts to moving the current realization (the BM 13600 with geopotential number) to the system definition part. This is somewhat elementary and from the viewpoint of the system/realization concepts not very attractive. Even in national systems such “Fundamental Bench Marks” come usually in the implicit realization part: their heights are deduced from a tide gauge datum. In the analogy with longitudes, this would be the transit instrument, the single artefact. Note that the velocity of the reference BM needs dealt with in the definition, or otherwise we are going to have implicitly a moving datum. For the Dutch national height system based on NAP, a revision of the height of the BM 13600 by 2.0 cm (smaller) will take place in 2005 (Anton Kosters, personal information May 17, 2004). This is however due to local instability and not to the vertical motion discussed earlier in this section.

The longitude analogy of the ITRS gives us however a clue how to get a more sophisticated convention: through a multi-station realization, which implicitly defines the system. In this analogy, the current EVRF2000 would somewhat correspond to the BIH Terrestrial System of 1984 which gave the initial orientation of ITRS (see Boucher and Altamimi, 1985, and the references therein). We would introduce for the EVRS200x the "average datum", defined by the totality (or some subset) of the heights in the EVRF2000, their errors included. New improved reference frames would (in some sense) be translated to maintain this datum, which then would be technically detached from the NAP and carried by the ensemble of the BMs used.

B. Find a system definition (S) that allows a near-NAP to emerge as a realization

B1. Mixtures of TG datums

Given the MSLs on European coasts, it should not be too difficult to come out with a linear combination of TG datums (or more generally, of averaged MSLs) close to the NAP. While the rules of the mixture (epochs, TGs) could be permanent, the combination (or spatial averaging) would take place through the ties offered by the EVRF20xx being constructed.

B2. EVRS defined by the World Height System plus an offset

The offset would be a number close to the estimated difference (W_{NAP}- W_0). To be credible, the number should be fixed once and for all at the creation of the EVRF200x, and not changed by a new EVRS definition every time new data allows a better estimate of the difference. If we want the NAP (or any other continental datum), this appears to me by far the most attractive alternative. For one, it allows to use the full capabilities of new geodetic methods to connect to the EVRS thus defined, namely of geopotential models and 3-D positions. Note that whatever the datum definition, these will be the methods actually used to connect to it at large distance. Fixing a conventional offset eliminates any vagueness due to the definition of the NAP (or of other continental datum). The only problem with this definition is that it immediately begs the question: why do we need the NAP and the offset?

7. Conclusions and recommendations

1) With the technology now available a continental datum of the NAP type serves no practical purpose and within 5 years it will be an impediment to progress. Now is the time to get rid of it.

2) The following practical steps are foreseen:

3) Keep the EVRS2000 and EVRF2000 as-such for the time being

4) Introducing a time-tag for the W_0 and with it an updated EVRS200x might be needed later e.g. due to thermal expansion of the oceans. Otherwise it seems to me that the EVRS2000 definition can stand and accommodate all the progress outlined below for the EVRF.

5) The next EVRF200x will be a genuine realization of the WHS using:
a) UELN0x with all levellings brought to the zero tidal system and including
b) model corrections for postglacial rebound (to the epoch 2000.0)

c) A time-tag for the heights but not necessarily associated velocities
d) The post-GRACE global geopotential model
e) EUVN_DA
f) The beta-version of the European Gravimetric Geoid EGG200x

6) The EVRF20xx will be a cm-order genuine realization of the WHS using, in addition to the above:
a) UELN0x including
b) corrections using an highly accurate European velocity field from EPN and ECGN and other sources
c) A time-tag for the heights, and possibly associated velocities for all of them
d) The post-GOCE global geopotential model
e) A big number of EPN and other CGPS stations joined to the UELN0x
f) The final version of the EGG200x
If, alternatively the NAP is re-introduced as a WHS plus fixed offset, the only difference is that the offset is determined and fixed at 5) and put again to use at 6).

8. Objections to my recommendations, and responses

I can think plenty of both but must for the moment release this version. To take a few (forgive the polemical tone):

O: The use of the NAP is widespread and continuity must be maintained
R: It is in fact limited to a relatively small circle of professionals. Second, allowing for that, the use of ED50 was widespread, too.

O: There is no single datum point where the height will survive unchanged from EVRF2000 to EVRF200x to EVRF20xx.
R: There are none in ETRF89 to ETRFxx to ETRF2000 either

O: It will be difficult to explain a vertical datum without a local sea level or other “concrete” reference.
R: On the contrary, nothing could be intuitively more acceptable than “the global sea level”.

O: Some key nations in geodesy, both historically and contemporarily, like Germany and the Netherlands, have national height systems with datum close to NAP
R: For a widespread acceptance of the new system it might in fact be advantageous if it is neutral in this respect.

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