BLAST vertical datums:
Overview, conventions and recommendations

Authors:

Strykowski G., O.B. Andersen, I. Einarsson and R. Forsberg
DTU Space, Denmark

L. Doorst; T. Ligteringen,
Hydrographic Service of the Royal Netherlands Navy, The Netherlands

Authors

Name	Organisation
Strykowski, Gabriel	DTU, Space (NSI)
Andersen, Ole Baltazar	DTU Space (NSI)
Forsberg, Rene	DTU Space (NSI)
Einarsson, Indridi	DTU Space (NSI)
Doorst, Leendert	Hydrographic Service of the Royal Netherlands Navy, The Netherlands
Ligteringen, T.	Hydrographic Service of the Royal Netherlands Navy, The Netherlands

Reviewers

Name	Organisation

Approval of report

Name	Organisation	Signature	Date

Document history

Revision	Date	Organisation	Initials	Revised pages	Short description of changes
First Draft	10-06-2010	NSI	GS		
Draft 2	04-10-2010	NSI	OBA+GS		
Draft 3	25-10-2010	NSI+HS RDN	OBA+GS +RF+IE+ LD+TL		
Draft 3.2					
Draft 3.3					
Draft 3.4					

Table of Contents

1 Introduction

WP 3.5 of the INTERREG IV North Sea Region Program project BLAST deals with developing practical tools for transforming between various relevant vertical datums (VD). The main focus point is the development of a transformation tool in the near coastal areas between the land height datums (e.g. the national VD, the global VD or the regional VD) and the marine VD also called Chart Datum (CD).

One such CD might be the Lowest Astronomical Tide (LAT). Such transformation yields a tie between the marine VD, which are used for the purposes of marine navigation, with the control points on land (e.g. in the harbors) and which are tied either to the land VD or both the land and the marine VD (e.g. through connections using tide gauges).

Another main focus point of WP 3.5 is the transformation between the various national marine and land VD and the way this can be implemented will also be outlined in the following.

It is very great acknowledgement that the joint work of the North Sea Hydrodynamic Committee (NSHC) Tidal Working Group is used for this report. This work is an important contribution to the BLAST project and it has been carried out on behalf of the NSHC Tidal Working Group, which aims to cooperate with BLAST WP3. The overview of existing Chart Datums used within the North Sea was presented in the Annex to the Report of the 17th meeting of the NSHC-TWG to the 29th NSHC Conference (NSHC Tidal Working Group, 2010) and will be the fundament of Chapter 4 of this report.

The NSHC tasked its Tidal Working Group (TWG) to coordinate the introduction of LAT in its member states, which led to an action item to create a common seamless LAT-level for the North Sea. This is work in progress and the work of the BLAST WP3 project could benefit this work through being a practical demonstrator project to the NSHC on one practical implemented of common reference surfaces and transformations between these.

2 Recommendations in WP 3.5 concerning the gridded realization of the VD

There are, in principle, two ways of linking the VD. One way is a parametric linking, i.e. any two VD, when defined for the same sub-area of the BLAST area (see below), could be linked mathematically by the defining functions and/or by the data behind the two datums. In practice, and relating to the practical work of WP 3.5, such parametric linking requires implicitly a very thorough understanding of the definitions behind each of the involved VD.

The other alternative is the empirical linking, i.e. for a given area a link through a co-located realization of the two VD. For example, the realization of the two VD could be provided on a (partly) co-located grid. A transformation between the two datums for an arbitrary location for which both datums are defined could be obtained from the gridded realizations of both datums by interpolation. One advantage of this approach is that the responsibility for the construction of a correct realization of each VD could be transferred to the relevant national agencies, i.e. the agencies who often also define the datums. In this way, the possible errors and

misunderstandings in datum definitions will be avoided. Consequently, in WP 3.5 in order to create a transformation between two VD's we need a dense enough grid (or equivalent, see below) with an official realization of each VD.

In WP 3.5 of the BLAST project it is recommended that the transformations will be based on such empirical linking.

3 The vertical land datums in the BLAST project

WP 3.5 of the BLAST project aims at providing a transformation between various marine and land VD. For the land VD, there exist two main and partly independent modelling techniques; one is the levelling enhanced with GPS (GPS/levelling) and the other is the surface integration of the gravity data yielding the geoid/quasi-geoid model surfaces.

In GPS/levelling, the relative height differences between the levelling benchmarks are measured using a number of the intermediate setups where the levelling instrument is, for each setup, aligned perpendicular to the local direction of the plumb line. The measured height differences for all setups can subsequently be added to yield a height difference between the levelling benchmarks. The levelling data are connected to the mean sea level at one (or more) fundamental tide gauges. In general, the local "mean sea level" derived from the tide gauge data is biased with respect to the true "global mean sea level". The bias can be as high as several centimetres (and even up to few decimetres).

In the processing of the levelling data the gravity information is used, either directly or through models. In any case, the levelling theory requires at some stage a transformation of the measured geometrical height differences to the gravity potential differences (the geopotential numbers). In practice, the measured height differences can either be adjusted first followed by a correction (i.e. a correction from the height differences to the geopotential numbers) or, alternatively, the formal transformation of the measured height differences to the geopotential numbers is done prior to the adjustment.

The levelling network does not require any formal modelling of the zero level surface (ZLS). The VD (e.g. the national height system) can be defined solely through one point; e.g. a mean-sea-level point at the fundamental tide-gauge or, equivalently, a stable point in land with a fixed (i.e. defined) height. The densification of the levelling network does not require a ZLS either. A height is transferred by levelling as a difference in heights between a known benchmark of the primary network and the new station. The stations of the densification network, although higher in numbers and with a considerably better aerial coverage than the stations of the primary network, have often an inferior quality (i.e. lower accuracies) on heights. Although ZLS for levelling is not explicitly modelled the depth of ZLS below each benchmark of the levelling network are given through the station heights H. ZLS is simply at a depth H below the levelling benchmark.

GPS measurements on selected levelling benchmarks, i.e. the measurements of the ellipsoidal height h of the benchmark above a global ellipsoid, provide a link to the global system. Denoting a height of ZLS above the ellipsoid as N_{ZLS} the following simple relation exists:

$$h = H + N_{ZLS} \qquad\qquad (1)$$

Eq. (1) is general yielding a coupling through h between the station heights of any VD and the corresponding height of ZLS, N_{ZLS}. For the levelled heights $H^{(GPS/levelling)}$ and the corresponding $N_{ZLS} = N_{GPS/levelling}$ eq. (1) yield the following relation:

$$h = H^{(GPS/levelling)} + N_{GPS/levelling} \qquad (2a)$$

If ZLS is the gravimetric geoid (see below) the heights are called the orthometric heights H and the ZLS heights are the geoidal heights or the geoidal undulations $N_{ZLS} = N$:

$$h = H + N \qquad (2b)$$

For the so-called quasi-geoid, the heights are called the normal heights H^* and the ZLS heights are called the height anomalies ζ yielding

$$h = H^* + \zeta \qquad (2c)$$

A particular VD on land, e.g. a national height system, is in general associated with one of the above two main classes of height systems (orthometric heights/normal heights). In general, the difference lies in the methods used in the processing of the levelling data; especially, whether the corrections were made using the real gravity data or the model gravity data (a normal gravity model). It is important to emphasize that the classification of a particular height system into orthometric heights or normal heights is not always "clear-cut". The correction procedures for constructing a height system in a given country are sometimes complicated (and sometimes not very well documented), and each country often makes use of different modifications to the standard methods. In Norway the additional complication is the presence of significant land uplift (so that the heights vary with time) and the levelling was done in patches and continuously over many years.

By comparing eqs. (2b) and (2c), and using a power series expansion of the difference of the correction terms, linearized transformation formulas between the orthometric and the normal heights exist

$$H^* - H = N - \zeta \approx \frac{\Delta g_B}{\gamma} \qquad (3)$$

where γ is the normal gravity and Δg_B are the so-called Bouguer gravity anomalies.

However, the use of such formulas for transformation between various VD on land is not adequate. Instead, the obvious other possibility is to transform via ZLS models. Given two VD (index 1 and 2) and using eq. (1) we get:

$$h = H^{(1)} + N_{ZLS,1} = H^{(2)} + N_{ZLS,2} \qquad (4a)$$

Next we define the ZLS difference as

$$\varepsilon_{1,2} \equiv N_{ZLS,2} - N_{ZLS,1} \qquad (4b)$$

Finally, from eq. (4a) we can transform from one VD to the other using the ZLS difference model

$$H^{(1)} = H^{(2)} + (N_{ZLS,2} - N_{ZLS,1}) = H^{(2)} + \varepsilon_{1,2} \qquad (4c)$$

One could add that the ellipsoidal heights h also fit into the scheme of eq. (1) and eqs. (4a)-(4c) with $H = h$ and $N_{ZLS} = 0$.

The construction of the gravimetric geoid is a different technique to levelling. Firstly, the measured gravity data on- and above the Earth's surface (land- and sea) are reduced. Subsequently, a surface integration is performed. The theory behind the geoid modelling states (in all standard methods) that the reduced gravity anomalies are mathematically linked to the vertical partial derivative of the (anomalous) gravity potential. Conversely, the surface integration aims on obtaining a model of the gravity equipotential surface from the measurements of the derivatives of the gravity potential. The modelled surface (the geoid or the quasi-geoid) is regarded a ZLS for heights, see eqs. (2b-c). The surface integration requires in principle that the gravity data cover the whole Earth. In practice, the construction of a detailed geoid/quasi-geoid is done from gravity data in the limited geographical area. In order to account for the contribution from "the rest of the world" the standard techniques of the regional geoid modelling use the global geoid models as a reference. Conversely, the method of the regional geoid modelling uses gravity data in a local area to improve the global model regionally. One important detail related to WP 3.5 of the BLAST project is that the gravimetric geoid/quasi-geoid is well-defined both for marine- and land areas. Thus, unlike the ZLS for the levelling data (which is limited to the land areas) the geoid/quasi-geoid covers both the marine and the land areas.

Returning to the problem of the transformation between land VD and marine VD in connection with WP 3.5 of the BLAST project, the use of a difference in ZLS, $\varepsilon_{1,2}$, see eq. (4c), seems to be a suitable method. The main reason is that each the ZLS is smooth (much smoother than the associated VD, i.e. H) and, thus, more suitable for the interpolation/extrapolation without introducing the big (interpolation/extrapolation) errors. Furthermore, both the theory behind the geoid/quasi-geoid modelling and behind processing of the levelling data defines ZLS as a "mean sea level surface" (or similar) below the topography. Thus, ZLS of different VD look similar. Conversely, the first approximation to the ZLS difference, $\varepsilon_{1,2}$, is a constant function. This is exactly why the GPS\levelling data are often used to assess the quality of the gravimetric geoid models. As discussed above, the mean sea level at the location of the fundamental tide gauge which is used for defining the levelling VD can differ from the global mean sea level; the vertical datum off-set. In assessing the quality of a geoid/quasi-geoid model the main quantity to study is the standard deviation of the ZLS difference (which is independent of the datum bias).

The EVRF2007 project (web1) is a large pan-European project with the purpose of creating a common European VD for levelling data and this VD is a possible candidate for the joint surface for transformation.

The EVRF2007 project was conducted under the auspices of the International Association of Geodesy, IAG. The main advantage of this project is that the transformation to most important national height systems (VD) is explicitly established as a bias offset to EVRF2007. Table 1 shows the bias (in cm) as stated by (web2).

Country	VD	Offset (cm)
B	DNG (pure leveled heights)	-232
D	DHHN92 (normal heights)	1
F	NGF-IGN69 (normal heights)	-47
DK	DVR90 (orthometric heights)	0
N	NN1954 (orthometric heights	-1
NL	NL_AMST / UNCOR (pure leveled heights)	+2
UK	Newlyn (ODN) (orhometric heights)	+5

Table 1. *Offset to EVRF2007 of the national systems of countries in the BLAST (web2 and web3)*

Importantly, the UK VD (Newlyn) is connected to the pan-European datum EVRF2007 via levelling through the tunnel under the British Channel. Furthermore, EVRF2007 has an explicit and well established link to the tide system (zero-tide) and handles explicitly the land uplift in Scandinavia. The model has been delivered in 2008 to the mapping authorities in all involved countries. Norway is currently evaluating a new national height system where the correction of levelling data by the land uplift is improved (Lysaker et al. 2007). UK has also introduced a newer land VD, OSGM02 (Forsberg et al., 2003).

A relevant recommendation (in WP 3.5) is, that the mapping authorities in all involved countries can provide a set of point data from their countries for the relevant land VD with the following information: the GRS80-ellipsoid geographical latitude and longitude ϕ, λ , the ellipsoidal heights h , the EVRF2007 height $H^{(EVRF2007)}$, the station height H in one or more national VD. In fact, this information is already available by request (web 4). From this information the values of ZLS differences $\varepsilon_{1,2}$ of all national land datums to EVRF2007 can be established and extrapolated as a grid (sec. 1) both to the near-shore marine areas and slightly outside the national borders. Having a $\varepsilon_{1,2}$ grid for a land VD, which also extends to the near shore marine areas, Eq. (4c) can be used to transform from one land VD to any other land VD through EVRF2007 wherever both VD are defined.

The link between EVRF2007 and marine VD in marine areas can be done through global and European quasi-geoids which are defined both on land and off-shore. EVRF2007 was verified against EGG2008 pan-European quasi-geoid (Denker et al., 2008; web4). In WP 3.5 of the

BLAST project it would also be obvious to include EGM96 (Lemoine et al., 1998) and EGM2008 (Pavlis et al, 2008; web5).

4 Overview of existing CD in the North Sea

At sea several other reference levels can be identified besides LAT. Each reference surface can only be identified with respect to other reference surfaces. To enable water level reduction of bathymetric data using satellite navigation techniques, a relation between LAT and the relevant ellipsoid, i.e. GRS80, needs to be established. Such a connection cannot be made directly, but needs to be made using Mean Sea Level (MSL) or a geoid as an intermediate surface. Some contries define their Chart Datum as identical to the latest realization of LAT, others have a need to identify Chart Datum as a fifth reference level.

The current state of the realizations of those surfaces with respect to each other for each country are sketched in Figure 1. BE, NL, and UK have data available that fully cover their North Sea areas, DE and FR have data that partially cover their North Sea areas, and DK and NO only have data available at specific coastal locations.

All available data was collected as part of the work within the NSHC - TWG, and interpolated to a grid of 0.02° for both Easting and Northing. The grid spacing was chosen to equal the spacing of the sparsest data that is used. As the English Channel region is of great importance to the North Sea region, it was included in the grid. North of Scotland, the grid ends at the 4°W meridian. The grid uses ETRS89/WGS84 as its geodetic datum. Further, only data that could be connected to the ellipsoid level was used. The resulting grids represent the MSL levels of the North Sea, the LAT levels of the North Sea, and the CD levels of the North Sea, all in relation to the ellipsoid. The following Subsections will describe each surface.
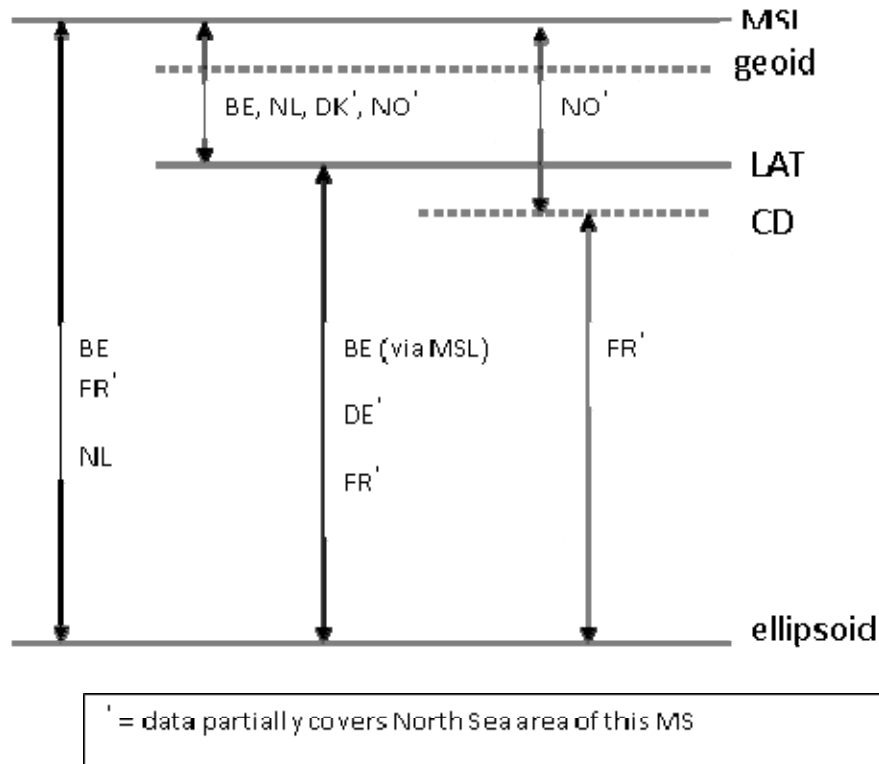
Figure 1: *sketch of available data.*

4.1 MSL in relation to the ellipsoid

The grid of the resulting MSL levels is shown in Figure 2. Note that the surface is not seamless, and covers the North Sea area only partially. The differences at the maritime boundaries are equal to or less than 0.6 m. Graphs of the differences are given in Appendix A.1 of the (NSHC Tidal Working Group, 2010)

Also, the BE and NL surfaces contain an inconsistency, which is due to the geographic limit of the available part of the GEONZ97 MSL surface. Where this surface is not available, the original EGM96 geoid model is used as a representation of MSL, as the GEONZ97 data are based on the EGM96 geoid. Maps of these differences are given in Appendix B.1 of the (NSHC Tidal Working Group, 2010).

4.2 LAT in relation to the ellipsoid

The grid of the resulting LAT levels is shown in Figure 3. Note that the surface is not seamless, and covers the North Sea area only partially. The differences at the maritime boundaries are equal to or less than 0.6 m. Graphs of the differences are given in Appendix A.2 of the (NSHC Tidal Working Group, 2010).

Also, the BE and NL surfaces contain an inconsistency, which is due to the geographic limit of the available part of the GEONZ97 MSL surface. MSL is used as an intermediate surface between the ellipsoid and LAT.

4.3 CD in relation to the ellipsoid

The grid of the resulting CD levels is shown in Figure 4. Chart Datum equals the latest LAT realization for BE, DE, NL and DK, and these surfaces differ for FR, NO, and UK. Note that the surface is not seamless, and covers the North Sea area only partially. The differences at the maritime boundaries are equal to or less than 0.8 m. Graphs of the differences are given in Appendix A.2 of (NSHC Tidal Working Group, 2010).

Also, the BE, FR and NL surfaces contain an inconsistency, which is due to either the geographic limit of the available part of the GEONZ97 MSL surface (BE and NL), or a zoning in the CD definition (FR). MSL is used as an intermediate surface between the ellipsoid and CD. Maps of the zoning differences are given in Appendix B.2 of the (NSHC Tidal Working Group, 2010).
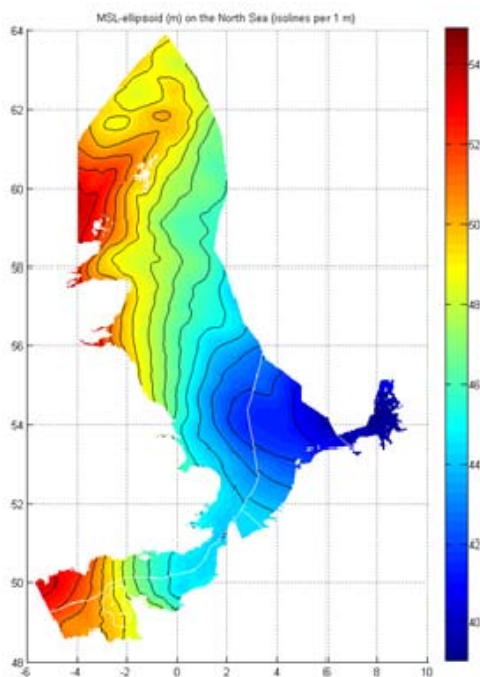

Figure 2: Created MSL surface in relation to the ellipsoid, shown in ETRS89/WGS84 in Plate Carrée projection, including one metre isolines in black and maritime boundaries in white As there is no established maritime boundary between the territorial seas of DE and NL, a new line was created for the purpose of DE/NL data comparison only.
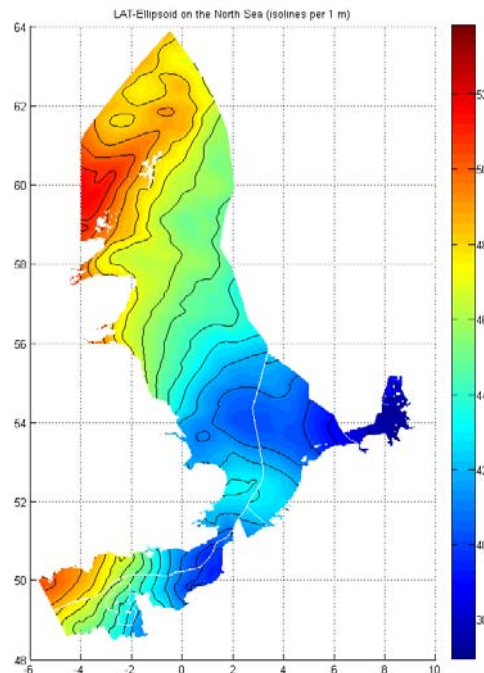
Figure 3: *created LAT surface in relation to the ellipsoid, shown in ETRS89/WGS84 in Plate Carrée projection, including one metre isolines in black and maritime boundaries in white. As there is no established maritime boundary between the territorial seas of DE and NL, a new line was created for the purpose of DE/NL data comparison only.*
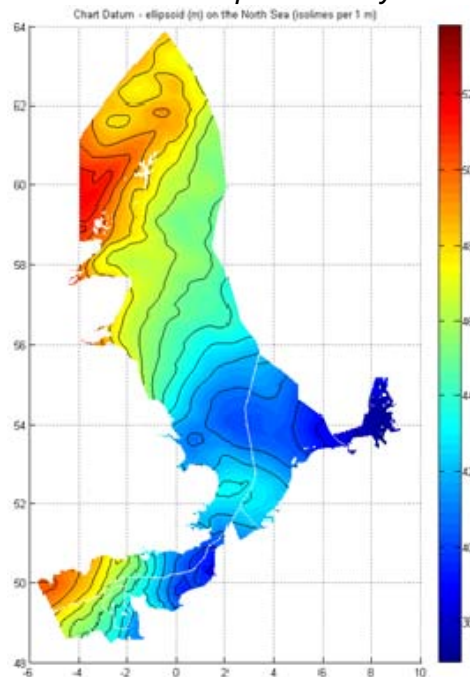

Figure 4: *created CD surface in relation to the ellipsoid, shown in ETRS89/WGS84 in Plate Carrée projection, including one metre isolines in black and maritime boundaries in white. As*

there is no established maritime boundary between the territorial seas of DE and NL, a new line was created for the purpose of DE/NL data comparison only

4.4. Choices made in the creation of the data

The choices made by each country in the creation of their surfaces were expressed during the 16th TWG meeting held in Copenhagen in May 2010. The countries give additional clarifications in Appendix C of the (NSHC Tidal Working Group, 2010).

BE: *For BE region CD equals LAT, in the past CD equalled MLLWS. The LAT is calculated from harmonic tide prediction over a period of 19 years.*

DE: *Since 2005 LAT is the official CD in Germany. The surveys, tide tables and most of the nautical charts of the North Sea are referred to LAT.*

DK: *In Danish waters the tides are small. Along the North Sea-coast the difference between MLWS and LAT increases southward and reaches 0.35 m at the German border. Future nautical charts for the Danish part of the North Sea will be published showing the difference between LAT and MLWS for the North Sea area, where differences between both levels are in the order of 0.2 to 0.3 m.*

FR: *FR currently uses a level of CD close to LAT. The coast is subdivided in 15 tidal zones, the maximum of difference reaches 50 cm in the river Gironde. LAT is always above CD, except in a zone where it's only 5 cm below CD. On charts, it is precised "soundings related approximately to LAT". For the same reasons as UK, we don't move CD exactly to LAT. We change CD only when the difference between CD and LAT becomes significant.*

NL: *NL has established CD precisely at LAT.*

NO: *Before 2000 our CD was "Equinoctial spring low water" where Z0 (vertical distance between MSL and CD) was defined as the sum of the amplitudes of the tidal constituents M2, S2, N2, K2, K1 and 0.5•Sa. As from 1987, an extra safety margin was added. During surveys they used a vertical datum that varied between 10 cm and 40 cm below CD, lowest along the southern coast where the astronomical tide is small compared to the meteorological surge. The CD that is used today is LAT, except for the southern part where CD is lower for safety reasons (30 cm in the inner Oslo-fjord and 20 cm from Stavanger to the Swedish border). The difference between the CD calculated in 2000 and the "old" datum used for surveys vas less than 10 cm, and the charts have not been changed.*

UK: *UK currently uses a level of Chart Datum as close to LAT as possible, in accordance with IHO Technical Resolution A2.5. Therefore the statement used on the relevant Admiralty Charts reads "approximately the level of Lowest Astronomical Tide". To have to establish Chart Datum precisely at LAT would present a significant financial problem to UK as all soundings on charts would have to be amended, and continue to be amended each time the level of LAT was updated. Any subsequent rises in Mean Sea Level (MSL) affecting the true depth of water can be accommodated by the data published in Admiralty Tide Tables (ATT). There would be no requirement to re-adjust the level of Chart Datum until the change in MSL becomes significant in terms of safety to navigation.*

5 Global altimetric surfaces for Mean Sea Level and LAT

During the last 20 years Satellite altimetry has revolutionized the determination of the mean sea surface and the determination of global ocean tide models. From satellite altimetry the mean sea surface in reference to ellipsoid model can be determined with an accuracy of between 5-10 cm in the open ocean (Andersen and Knudsen, 2009).

Satellite altimetry works conceptual by the satellite transmitting a short pulse of microwave radiation with known power towards the sea surface, where it interacts with the sea surface and part of the signal is returned to the altimeter where the travel time is measured accurately. Due to the width of the radar beam being 5-10 km some degradations will be seen close to the coast.

5.1 Altimetric determined MSL model

The DNSC08MSS mean Sea Level or Mean Sea Surface (MSS) model have been derived as the time-averaged physical height of the oceans surface derived from a combination of 12 years of satellite altimetry from a total of 8 different satellites covering the period 1993-2004 and the model is shown in Figure 5
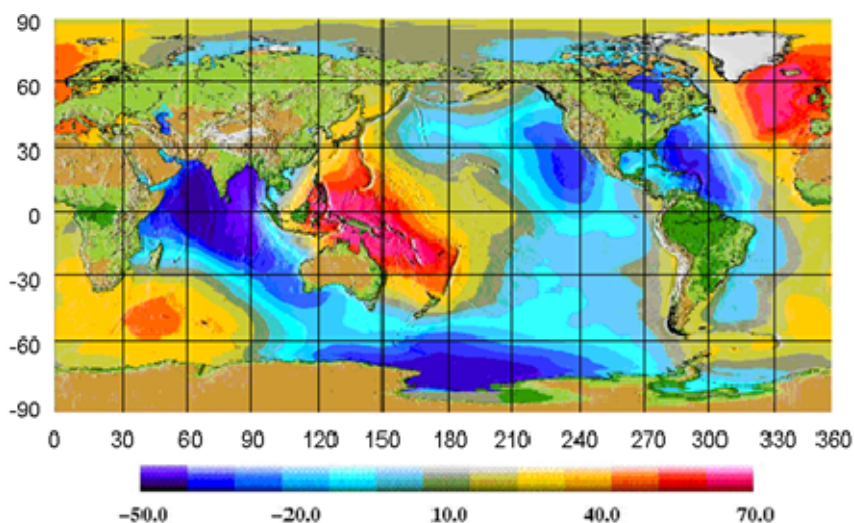

Figure 5. *The DNSC08MSS Mean Sea level or Mean Sea Surface model given relative to the TOPEX ellipsoid (See Table 2 in chapter 6).*

An independent validation of the vertical accuracy of the DNSC08MSS in the North Sea region was made for the British VORF project by J. Illiffe and M. Ziebart of the UCL. Here the DNSC08MSS-NIB (No inverse barometer corrected MSS) was compared with a large set of GPS leveled tide gauges around Britain. The NIB version of the DNC08MSS is chosen as the tide gauges measure the average of the physical sea surface in the presence of the atmosphere.

A total of 320 GPS leveled tide gauges with more than one year of data was compared with the height interpolated or extrapolated from DNSC08MSS. The mean height difference between tide gauges and DNSC08MSS is 1.24 cm with a standard deviation of 6.3 cm. The differences are

shown in Figure 6 as color coded dots. The largest height differences with GPS data are found in the Bristol Channel and in the Irish Sea where the differences range up to 80 cm. These differences can originate from both the tide gauges or from the DNSC08MSS. It is most likely that they originate from the DNSC08MSS, as several obvious reasons might explain these differences: Firstly, the accuracy of the global tide model applied to satellite altimetry (GOT 4.7 se section 5.2) will degrade close to the coast and un-modeled shallow water constituents might contribute up to several decimeter [Andersen, 1999]. Secondly, the altimetric observations close to the coast might be missing or heavily degraded and no altimetric data is generally available closer than roughly 5-10 km to the coast, which means that the comparison is generally based on extrapolated MSS values.

The height comparison between the MSS and the GPS leveled tide gauges had to be adjusted for the difference in the tidal system used to derive the two MSS height quantities. GPS data are processed in the tide-free system whereas the DNSC08MSS is given in the mean tide system. The adjustment is given as closed formulas [Lemoine et al., 1998] and it ranges up to several decimeters from Pole to Pole and is described in more detail in Section 6 below.
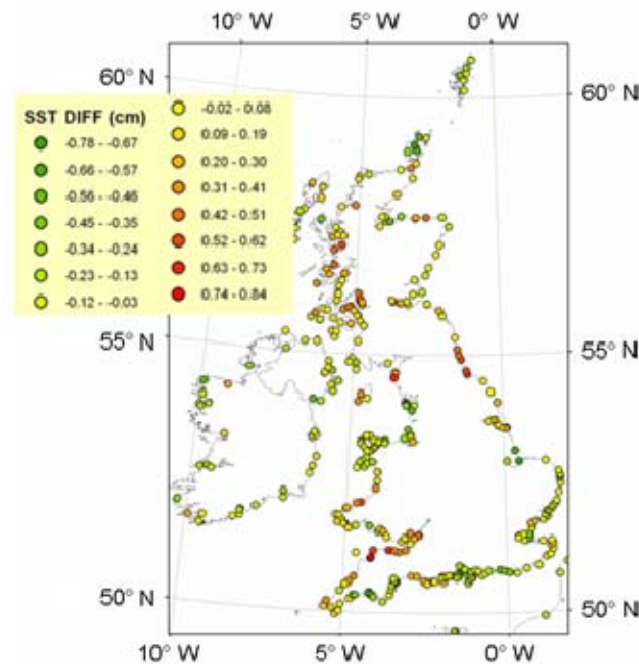

Figure 6. *Sea surface height (called SST) difference between the DNSC08MSS and 320 GPS leveled tide gauges around Britain. The color scale is indicated in the figure and ranges from -80 cm to 80 cm. The figure is courtesy of M. Ziebart and J. Illiffe, UCL London.*

5.2 Global LAT model

One of the most widely used global ocean tide model derived from satellite altimetry is the global ocean tide model called GOT4.7. This model is from 2006 and is the latest in a sequence of empirical ocean tide models derived from satellite altimetry (Ray, 2002). The model corrects for the major eight diurnal and semi-diurnal constituents (K1, O1, P1, Q1, M2, S2, K2, N2) along with a 19 smaller constituents deduced by admittance interpolation (Andersen, 1994). Furthermore the quarter diurnal constituent M4 and the long period constituents (mM, mF, Sa, Ssa) were included. The model was interpolated onto a 1/8° degree resolution corresponding to roughly 13 km resolution. The Lowest Astronomical Tide was calculated by time stepping the GOT4.7 model for the 18 year period 01-01-1997 until 01-01-2015 using 30 minute timesteps and taking the lowest obtained range as the LAT value.
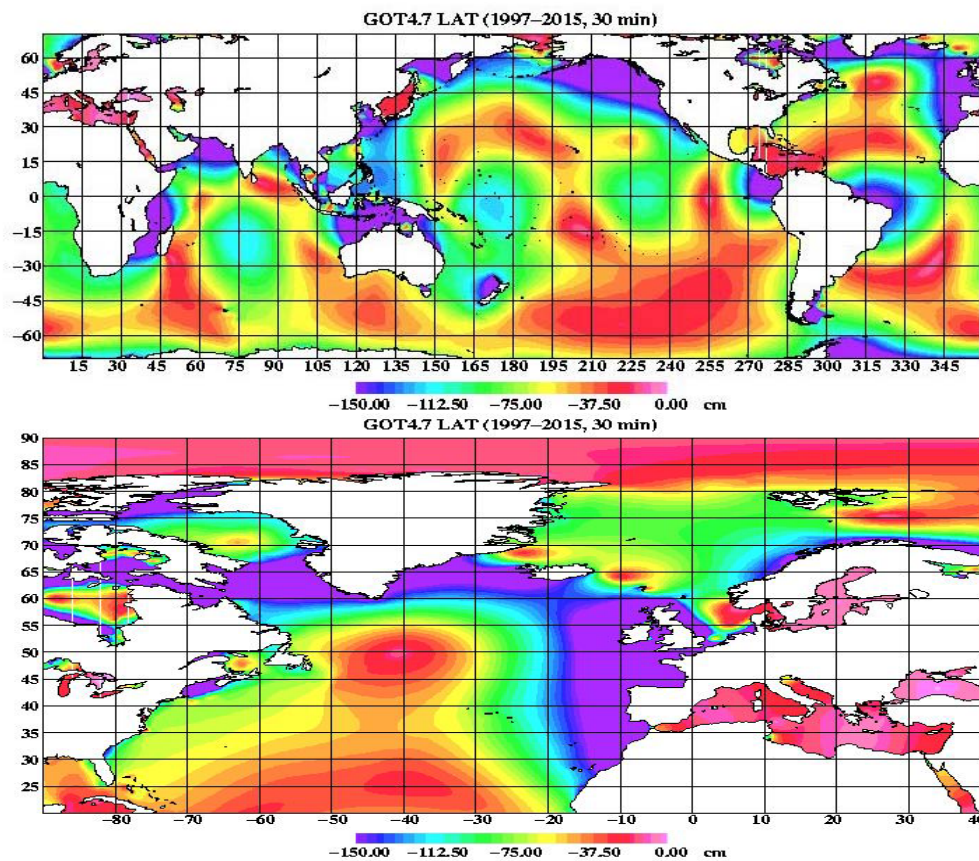

Figure 7. The minimum range obtained for the 19-year period (1997-2015) obtained from timestepping the global GOT4.7 ocean tide model. Global, North Atlantic and North Sea is shown in the three panels.

The Altimetric surfaces can subsequently be used to derive a altimetric model for the ellipsoidal Chart datum defined as the MSL – LAT surface using the DNSC08MSS – GOT4.7 LAT model.
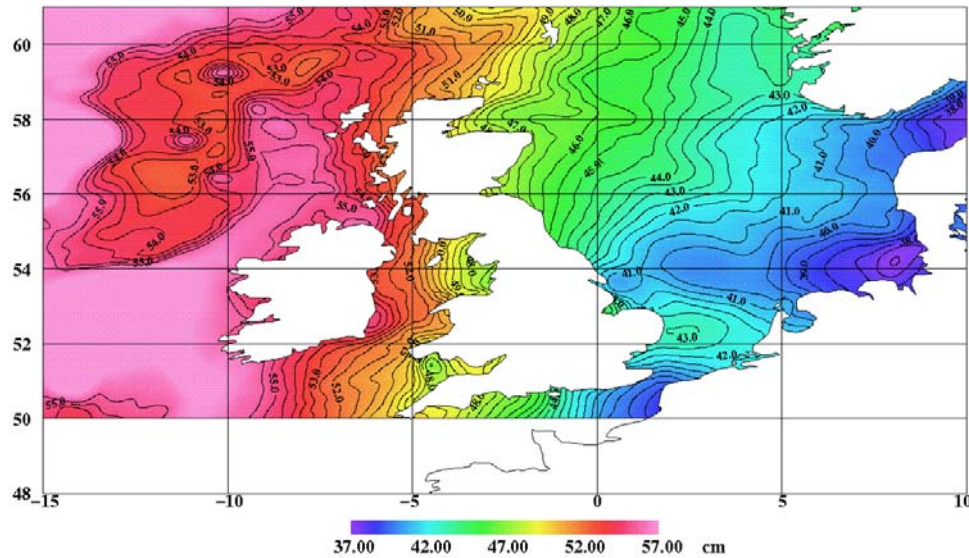

Figure 8. *The DNSC08MSS model – GOT 4.7 LAT derived surface shown for the North Sea Region. (units in meters). The height is shown relative to the GRS80 Ellipsoid.*

6 Global reference ellipsoids

Both altimetric mean sea surface heights and geoid heights are given relative to a reference ellipsoid, which corresponds to a theoretical shape of the Earth. The characteristics of different, currently used, reference ellipsoids are given in Table 2.

Ellipsoid name	a (m)	1/f	GM (×10^9 m^3/s)
GRIM	6378136.46	298.25765	398600.4369
TOPEX	6378136.3	298.257	398600.4415
GRS80	6378137.	298.257222101	398600.5
WGS84	6378137.	298.257223563	398600.5
WGS84 rev 1	6378137.	298.257223563	398600.4418

Table 2: *Different reference ellipsoids (a: semimajor axis, f: flattening; G: gravitational constant; M: Earth's mass)*

Altimetric Mean Sea Level are most commonly computed relative to the TOPEX ellipsoid.

7 Global tide systems

For the comparison between GPS derived height of the sea surface and altimetric or geoid surfaces it is important to notice that GPS is observed in the TIDE FREE tide system.

Geoid heights (and mean sea surface heights) also differ depending on what tidal system is implemented to deal with the permanent tide effects. In the MEAN TIDE system, the effects of the permanent tides are included in the definition of the geoid. In the ZERO TIDE system, the effects of the permanent tides are removed from the gravity field definition. In the TIDE FREE or NON-TIDAL system, not only the effects of the permanent tides are removed but the response of the Earth to that absence is also taken into account. Altimetric mean sea surfaces are usually expressed in the MEAN TIDE system. Figure 8 shows the difference between the TIDE FREE and the MEAN TIDE reference systems.
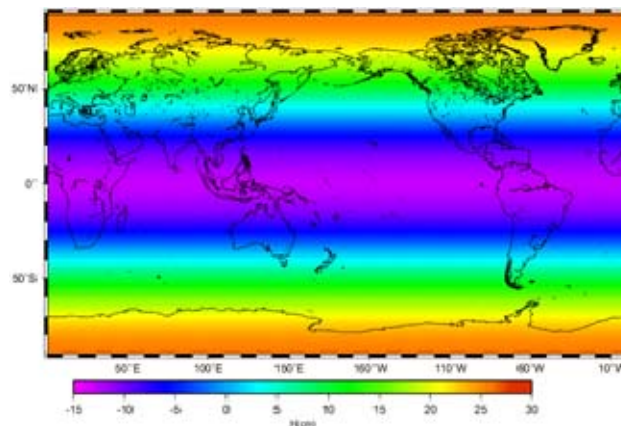

Figure 8: *Height difference between the TIDE FREE and the MEAN TIDE reference systems*

References

Andersen, O. B., and R. Scharroo (2009), Range and geophysical corrections in coastal regions, book chapter in eds. (Chippolini et al), Satellite altimetry in coastal regions, in press, 52 pp.

Andersen O. B, Knudsen P (2009) The DNSC08 mean sea surface and mean dynamic topography. J. Geophys. Res., 114, C11, doi:10.1029/2008JC005179, 2009

Andersen OB (1995) Global Ocean tides from ERS 1 and TOPEX/POSEIDON altimetry. J Geophys Res 100(C12):25,249 25,260.

Andersen, O. B., Egbert, G. D, Erofeeva, SY., and Ray R. (2006) Mapping nonlinear shallow water tides: a look at the past and future, Ocean Dynamics 56, 5-6

Denker H, Barriot JP, Barzaghi R, Fairhead D, Forsberg R, Ihde J, Kenyeres A, Marti U, Sarrailh M, Tziavos IN (2008): A new European Gravimetric Quasigeoid EGG2008. Poster, IAG International Symposium on 'Gravity, Geoid and Earth Observation 2008', 23-27 June 2008, Chania, Crete, Greece.

Forsberg, R., G. Strykowski, J.C. Illife, M. Ziebart, P.A.Cross, C.C. Tscherning , P. Cruddace, K. Stewart, C. Bray and O. Finch: OSGM02: A new geoid model of the British Isles. Proc. 3rd meeting of the International Gravity and Geoid Comission, GG2002, Aug. 26 - 30, 2002, Thessaloniki, I. Tziavos (ed.), Editions Ziti, pp. 132-137, 2003.

Forsberg R. and C.C. Tscherning: An overview manual for GRAVSOFT Geodetic Gravity Field Modelling Programs. 2ed, DTU Space, 2008

Lemoine, F. S., S. C. Kenyon, J. K. Factor, R.G. Trimmer, N. K. Pavlis, D. S. Chinn, C. M. Cox, S. M. Klosko, S. B. Luthcke, M. H. Torrence, Y. M. Wang, R. G. Williamson, E. C. Pavlis, R. H. Rapp and T. R. Olson: The Development of the Joint NASA, GSFC and NIMA geopotential model EGM96. NASA Goddard Space Flight Center, Greenbelt, Maryland, 20771 USA, July 1998.

Lysaker, D; Omang, O.; Pettersen, B.; Solheim, D.: Quasigeoid evaluation with improved levelled height data for Norway. Journal of Geodesy, Volume 81, Number 9, September 2007, pp. 617-627(11)

NSHC Tidal Working Group, 2010, Merging and comparison of reference surfaces for the North Sea area, Annex D to the report of the 17th meeting of the NSHC-TWG to the 29th NSHC Conference, published by the Hydrographic Service of the Royal Netherlands Navy.

Pavlis, N. K., S. A. Holmes, S. C. Kenyon andJ.K. Factor: An Earth Gravitational Model to Degree 2160: EGM2008. Presented EGU General Assembly, Vienna, Austria, 2008.

Rio MH, Andersen O (2009) GOCE User Toolbox - Standards and recommended models. ESA publication, online: http//earth,esa.int/gut/, 70pp

Web1: http://www.bkg.bund.de/geodIS/EVRS/EN/Home (The official web-page of EVRF on the web site of Bundesamt für Kartographie und Geodäsie, Germany)

Web2: http://www.bkg.bund.de/nn_164776/geodIS/EVRS/EN/Projects/03HeightDatumRel

(The official web-page of EVRF on the web site of Bundesamt für Kartographie und Geodäsie, Germany)

Web3: http://www.crs-geo.eu/nn_124226/crseu/EN/CRS__Description

Web4: http://www.bkg.bund.de/nn_166736/geodIS/EVRS/EN/Projects/02EUVN-DA/04Product

Web5: http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/index.html

Appendix 1 Grid conventions

For the realization of each VD of WP 3.5 we recommend to use the GRAVSOFT grid format (Forsberg and Tscherning, 2008) where the grid area is bounded to the South and to the North by two parallels (φ_S and φ_N) and to the West and to the East by two meridians (λ_W and λ_E). Furthermore, the grid spacing in latitude and longitude ($\Delta\varphi$ and $\Delta\lambda$) must be defined. A grid header for the BLAST area could look like this:

52.00 62.00 -4.00 12.00 0.01 0.01

(a negative longitude of -4 means)

Given the grid header (i.e. the above six numbers φ_S φ_N λ_W λ_E $\Delta\varphi$ $\Delta\lambda$: all in degrees), the location of each grid node is given. The number of grid nodes from North to South NN is $NN = \dfrac{(\varphi_N - \varphi_s)}{\Delta\varphi} + 1 = 1001$. In the same way, the number of grid nodes from West to East NE is $NE = \dfrac{(\lambda_N - \lambda_s)}{\Delta\lambda} + 1 = 1601$. The grid values follow the header in order from West to East along the parallels starting from the NW corner of the area (the first grid value) and ending in the SE data corner (the last value).

Concerning the grid spacing for each VD realization, it is required that it is sufficiently dense so that the interpolation error to an arbitrary location covered by the grid is negligible. Implicitly, if the grid spacing is much denser than the spatial resolution of a given vertical datum, the interpolation error can justifiable be neglected. In WP 3.5 we have recommend to choose <u>the coarsest fundamental spacing of a grid</u> (in geographical coordinates with respect to the GRS80 ellipsoid) of $\Delta\varphi \times \Delta\lambda = 0.01° \times 0.01°$, corresponding to some 1.1 km x 0.6 km at the center latitude for the BLAST area ($\varphi = 57°N$). The chosen coarsest resolution is sufficiently dense for realizations of the global and the regional VD. In case a gridded realization of a given VD requires a higher resolution, a grid spacing of one or more orders of magnitude can be used. For example $\Delta\varphi \times \Delta\lambda = 0.001° \times 0.001°$, $\Delta\varphi \times \Delta\lambda = 0.0001° \times 0.0001°$ .... etc. Also, the bounding parallels and meridians should be $\varphi_N \equiv 52°N + n \cdot \Delta\varphi$ and $\lambda_E \equiv -4°W + m \cdot \Delta\varphi$ where n and m are whole numbers. In this way, whenever possible, the grid nodes of several VD will coincide providing co-located realizations of two or more VD at highest possible level of accuracy.

Another issue that needs to be addressed is the strategy for defining the aerial validity of a given VD, i.e. whether for a given horizontal location (φ, λ) the datum exists. This issue can be easily handled by the header, i.e. whether a station (φ, λ) lies within the area defined by a header. A simple rule-of-thumb is only to allow interpolation, but not extrapolation.

VD realization of more complex aerial geometry (e.g. following the national borders) can be carried out by associating the VD with several grids (i.e. patches) so that there exist at least one

grid for each location within the area where VD is valid. The interpolation software scans the headers first and chooses the grid where a given point (φ, λ) is within the validity area.

Norwegian Hydrographic Service • Aalborg University, Denmark • Agency for Maritime and Coastal Services, Belgium • Danish Coastal Authority • Federal Maritime & Hydrographic Agency, Germany • Hjørring Municipality, Denmark • Jeppesen GmbH, Germany • Local Government, Denmark • Mälardalen University, Sweden • National Space Institute, Denmark • National Survey and Cadastre, Denmark • Natural Environment Research Council, United Kingdom • Norwegian Coastal Administration • Seazone Solutions Limited, United Kingdom •T-Kartor AB, Sweden • TU Delft, the Netherlands • UK Hydrographic Office