Relating Data to a Seamless Vertical Reference Surface

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Key words: Vertical reference surfaces, seamless data, Chart Datum, vertical separation model

SUMMARY

Traditionally, bathymetric and topographic measurements have been collected independently to serve different purposes. As well, depth and height data were referred to different vertical datums, which created inconsistency across the land-sea interface. With the growing number of coastal applications, such as coastal zone management and marine boundary delimitation, it is necessary that a seamless vertical reference surface be established. Unfortunately establishing the relationships between the various vertical datums, and consequently the seamless vertical reference surface, is not an easy task.

To tackle this subject, the FIG Working Group 4.2 (WG 4.2), Vertical Reference Frame, was established. This paper summarizes the activities and findings of the Working Group and discusses routes by which a vertical datum separation model could be developed. It also provides some examples of countries that have already developed one. This is by no means a complete survey of all modelling techniques used world wide and readers are invited to contribute with additional examples/input to enable WG 4.2 to develop this subject further.

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1. BACKGROUND

In the past, bathymetric and topographic measurements have been collected independently to serve different purposes. Also, depth and height data were referred to different vertical datums, which created inconsistency across the land-sea interface. With the growing number of coastal applications, such as coastal zone management and marine boundary delimitation, it is necessary that a seamless vertical reference surface be established. A seamless reference surface, as the name indicates, means a continuous and time-invariant surface.

The creation of seamless data (i.e., data referred to a seamless reference surface) is, understandably, far more than just joining more than one digital dataset together. Issues such as datum types, projection, temporal changes, and error budgets (including accuracy, scale and generalisation) must be considered. Ignoring these technical concerns will cause geospatial datasets to end up as meaningless and unreliable.

Various IAG and FIG working groups have been established since the mid 80s to tackle the problem of establishing a seamless vertical datum (Wells et al., 1996). More recently a new FIG Working Group 4.2 (WG 4.2), Vertical Reference Frame, was established at the XXII FIG International Congress, which was held in Washington, D.C., USA. The working group will address a number of issues, including:

- Developing and promoting the understanding and realisation of a vertical reference frame;
- Examining the demand for a seamless vertical reference frame for use in hydrography, marine navigation, and coastal resource management;
- Developing an inventory of vertical reference surfaces used in various countries of the international community;
- Making some recommendations towards the establishment of a global seamless vertical datum.

Readers are strongly recommended to read the initial papers from this Working Group as background to this paper (Adams 2003, El-Rabbany 2003).

2. WHAT IS A SEAMLESS DATUM?

The fact that the topographic surface of the earth is highly irregular makes it difficult for geodetic calculations to be performed. The surface of the earth can be approximated by the *geoid*, which is the equipotential surface of the Earth's gravity field which best fits global mean sea level, however it is not a suitable surface to which to measure. To overcome this problem, geodesists adopt a smooth mathematical reference surface to approximate the

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irregular shape of the earth's surface. This is the biaxial ellipsoid (Vanicek and Krakiwsky, 1986) or simply the *reference ellipsoid*. The geoid surface is described by geoid heights that refer to a suitable *reference ellipsoid*. Figure 1 illustrates these surfaces.

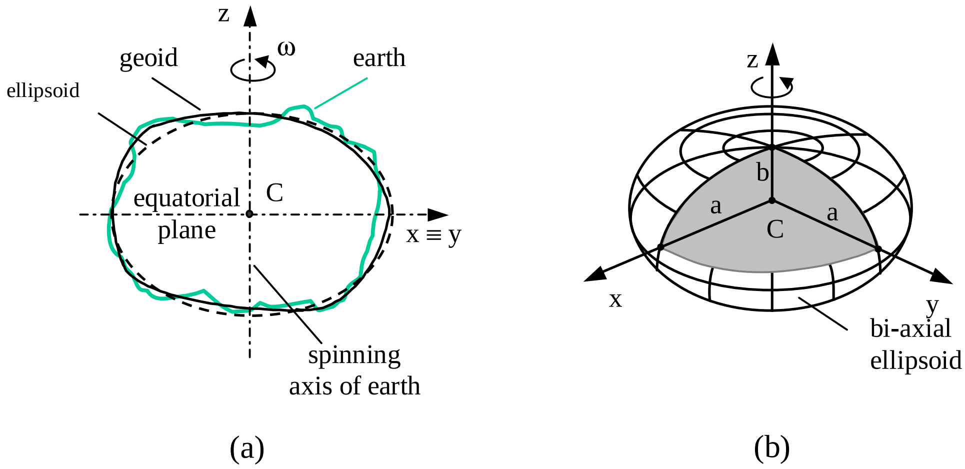

Figure 1: (a) Relationship between the physical surface of the earth, the geoid and the ellipsoid. (b) Ellipsoidal parameters.

An appropriately positioned reference ellipsoid is known as the geodetic (or horizontal) datum (Vanicek and Krakiwsky, 1986). Further details can be found in the paper by El-Rabbany (2003).

In the past, horizontal datums were non-geocentric and were selected to best fit the geoid in certain regions of the world. These datums were commonly called local datums. Over 150 local datums are used by different countries of the world (El-Rabbany, 2002). With the advent of space geodetic positioning systems such as SLR (Satellite Laser Ranging), VLBI (Very Long Baseline Interferometry) and GPS, it is now possible to determine global three-dimensional geocentric datums. Generally, local datums are shifted, rotated and have scale differences with respect to geocentric datums. Therefore, unless proper datum shifts are considered when fusing various datasets, serious navigation hazards should be expected.

Figure 2 shows an example of a horizontal datum shift in the River Thames, United Kingdom. The portion of chart on the left is referred to the OSGB36 National Datum whereas the one on the right is ETRF89 world geocentric Datum (compatible with WGS84 Datum). The figure shows the difference in position with respect to the Thames Barrier for two vessels that have identical coordinates. If the ship on the left went through the lowest barrier and passed their position to the ship on the right without qualifying which horizontal datum they were using there could easily be a vessel collision or grounding.

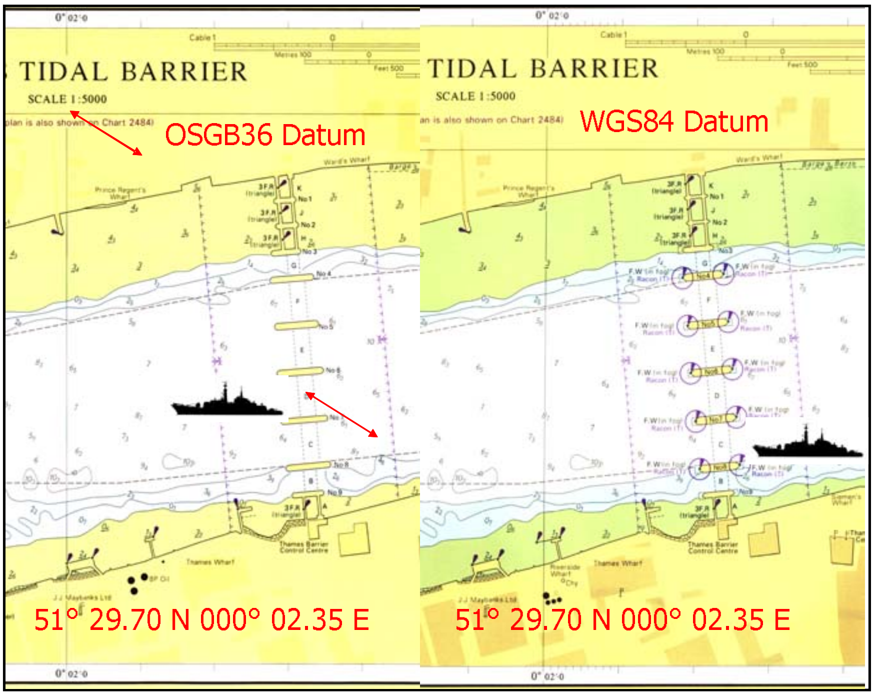

Figure 2: Portions of BA 3337 (previous and current edition).

3. WHAT IS A SEAMLESS VERTICAL DATUM?

In addition to the geodetic datum, the vertical datum is also used in practice as a reference surface to which the heights (or depths) of points are referred. The vertical datum is often selected to be the geoid for topographic (land survey) applications, whilst Chart Datum is selected as the vertical datum for hydrographic applications. Figure 3 shows the number of vertical datums in use by the UK Hydrographic Office.

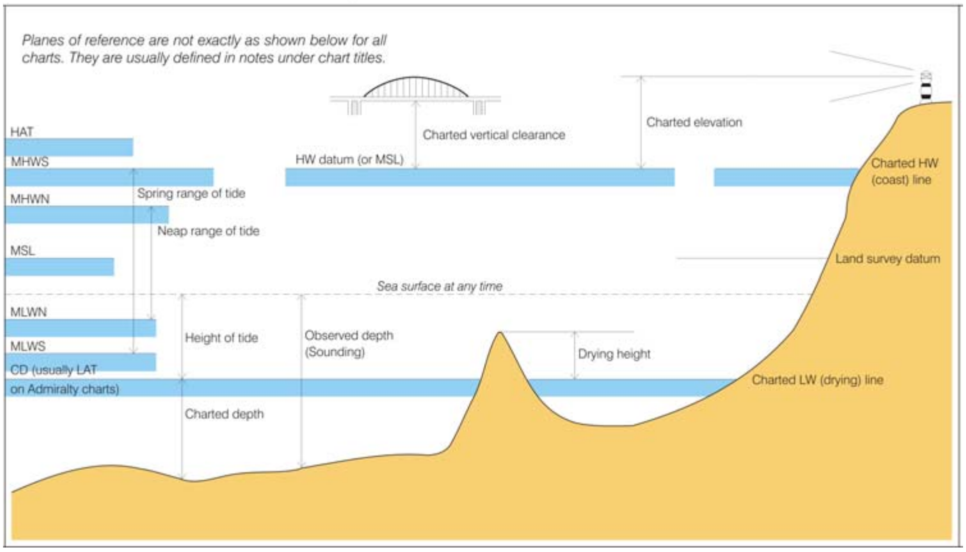

Figure 3: Different types of vertical datum (from UKHO publication 5011).

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Chart Datums are site-specific surfaces that vary from one location to another. They are established based on the water level measurements at discrete locations (Wells et al., 1996). Chart Datum is thus not a seamless reference surface. Chart Datums are defined differently among the various hydrographic offices, such as an approximation to LAT (Lowest Astronomical Tide) or MLLW (Mean Lowest Low Water). Depths may also be referred to other variable reference surfaces such as MSL (Mean Sea Level). The geoid, on the other hand, can be considered to be a seamless reference surface that could be used worldwide. However, the present geoidal accuracy varies from one location to another, with the worst accuracy in mountainous land areas and open oceans.

A seamless vertical datum is one that does not vary over time or location.

A stable reference surface which could be considered suitable for this is the WGS84 Datum and this paper will henceforth use WGS84 in place of the wording “stable reference surface”. However, it is recognised that many regions have realisations of WGS84 Datum, such as ETRF89 in Europe and GDA94 in Australia, that are compatible with WGS84 Datum due to their increased accuracy of definition. It should be noted that all defined reference surfaces will vary over time due to continental drift, Post Glacial Isostatic Rebound etc and it is important that all users are aware of this.

4. THE NEED FOR A SEAMLESS VERTICAL REFERENCE SURFACE

The development of a seamless vertical datum would benefit a number of applications such as;

- Coastal zone management – in the assimilation of land and marine datasets (O’Reilly et al, 2001) and for flood monitoring/surge modelling.
- Marine boundary delimitation – to achieve consistency in baseline definitions derived from low water features (El-Rabbany, 2003).
- Hydrographic surveying – to negate the need to measure tides and heave (O’Reilly et al, 1996).
- Defence capabilities – merging datasets on land, air and sea.
- ECDIS – for example in the provision of real-time and predicted depth under keel.

It would enable data to be held seamlessly with respect to WGS84 Datum but to be output on a vertical datum as selected by the user.

5. THE CHALLENGE

The challenge is not so much to develop a seamless vertical reference surface, but to develop a way of relating current and future datasets to it in a seamless manner.

Development of a separation model(s) is key to this. However, this is further complicated due to the availability, volume, coverage and quality of both bathymetric and topographic data. It

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is known that many regions of the world were either inadequately surveyed or have never been surveyed (see for example Barritt, 2001). Also auxiliary data, such as ellipsoidal heights at respective Chart Datum points or a geoid model, is needed so that the transformation function can be developed.

Several methods have been investigated to find the relationship between the Chart Datums and the seamless vertical surface at the regional level (see for example O'Reilly et al., 1996 in Canada; Hess at al., 2003 in USA; Solheim, 2003 in Norway; and Whitfield and Pepper, 2003 in UK). As would be expected, due mainly to the lack of data coverage, finding such a relationship on a global basis is not an easy task.

Digital data volume is another challenging problem which requires extensive study. As stated by Gesch and Wilson (2002), a 50-gigabyte dataset was used for the development of a seamless model covering the Tampa Bay region.

6. METHODS USED TO DEVELOP A VERTICAL DATUM SEPARATION MODEL

There is no single method to develop a vertical datum separation model.

In the ideal world all depth information would be resurveyed with respect to WGS84 Datum but this is obviously impractical.

- The obvious starting point is to look at the locations where Chart Datum is established. Are there known links to other vertical datums – for example to a local land datum? If not, can these be established or measured? Is the vertical datum to which the Chart Datum is linked WGS84 (or similar)? If not, how can it be defined? Are there suitable geoid separation models available that may help?

  For example, in the UK the relationship between Chart Datum and Ordnance Datum Newlyn (ODN) is accurately known at discrete locations. ODN is the national land levelling datum for the UK and its relationship to ETRF89 (an European realisation of IRTF) can be found via the OSGM02 geoid model (Forsberg et al, 2002). Hence the relationship between Chart Datum and ETRF89 (ie WGS84) can be found for these locations around the UK (Whitfield and Pepper, 2003). This approach would not be possible but for the recent and accurate definition of the geoid via OSGM02.

  However, in Canada, the Canadian Hydrographic Service chose to survey WGS84 heights at known tidal locations to directly establish the separation between Chart Datum and WGS84 (O'Reilly et al, 1996, Parsons and O'Reilly, 1998).

- Once the relationship between Chart Datum and the chosen vertical reference frame, such as WGS84, is known for individual points the challenge is then how to (a) densify this around the coast and (b) extrapolate it offshore.

The United States National Oceanic and Atmospheric Administration (NOAA) has developed a Chart Datum model in Tampa Bay and Delaware Bays using a hydrodynamic tidal model and a known relationship to NAD83 (Parker, 2002, Hess et al, 2003). NOAA is now using this methodology to extend it further round the coast of Continental U.S. (Parker et al, 2003).

The problem of extrapolation offshore is challenging. There is a paucity of tidal information out at sea and hence the nature of Chart Datum is less well known. In some areas co-tidal charts exist. These define the behaviour of Chart Datum offshore with respect to a tidal station onshore. However, in many cases, these are not now thought to be the most accurate models of Chart Datum at sea and other techniques should be used (Adams 2003).

A more modern method for defining Chart Datum offshore is with the use of satellite altimetry and tidal models (O'Reilly et al, 1996, Solheim, 2003).

The method employed to develop the vertical datum separation model can depend on many factors such as:

- Availability of recent data – what vertical datum is the existing data referred to? What is the reference surface that the data needs to be related to? Do measurements need to be conducted to establish the relationship or do existing geoid models (for example) already exist?
- For what purpose is the separation model? Is high accuracy needed, in which case resurveying may be the suitable option, or is the model for deep water where vertical accuracies are less critical? How accurate is the current depth data? For example, if the depths are only accurate to ±1m a model accuracy of sub centimetre is unnecessary.
- Does the model need to cover a large or small area extent?
- Is the aim to develop a separation model from WGS84 to the minimum sea surface, or to the current Chart Datum? In the UK, Chart Datum was defined many years ago and in some places does not match LAT (or the minimum sea surface) precisely. Should a model be developed using modern techniques which models the minimum sea surface as it now exists, or should a model be derived which shows the relationship between Chart Datum and WGS84? Figure 4 illustrates this. Or even, perhaps, should a minimum sea surface be developed but then warped to fit the Chart Datum separation values known on shore? By how much would this degrade the modern altimetry data?
- Bearing in mind that Chart Datum is unlikely to be exactly the same as the minimum sea surface, should a 'corrector surface' be developed to transform between Chart Datum and this minimum surface?
- What resources are available – time, money, people?
- Do other local, regional or national models already exist which can be linked to?
- How will the separation model be maintained? How often will Chart Datum and/or the minimum reference surface be redefined?

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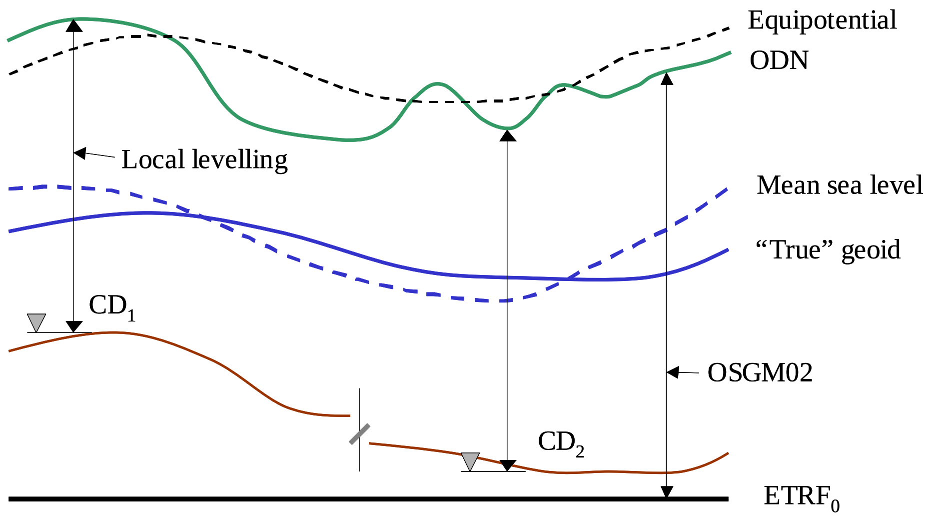

Figure 4: Relationship between Chart Datum (CD), WGS84 Datum (equiv to ETRF), local land datum (Ordnance Datum Newlyn) and the geoid UK (from Illife and Ziebart, 2003)

7. CONCLUSION

The development of a vertical datum separation model is worthy of consideration where datasets need to be combined which contain data referred to different vertical datums. It is shown that the development of a seamless vertical reference surface would benefit a number of applications, such as coastal zone management, marine boundary delimitation and hydrographic surveying. The availability of such a reference surface is also necessary for the development of the next generation ECDIS, which is expected to have significant economic and safety impacts.

The challenge is not so much to develop a seamless vertical reference surface, but to develop a way of relating current and future datasets together in a seamless manner. Vertical datum separation models are crucial to the future definition and modelling of Chart Datum.

This paper discusses routes by which a vertical datum separation model could be developed and provides examples of countries that have done this. It discusses the challenges associated with this such as perhaps a paucity of ellipsoidal height information, the limiting accuracy of existing geoid models and extrapolation of tidal datum offshore. This is by no means a comprehensive survey encompassing all modelling techniques used around the world. Readers are invited to contribute with additional examples/input to enable WG 4.2 to develop this subject further.

GLOSSARY

Chart Datum – Is selected as a surface that is so low that the tide will not frequently fall below it, not so low as to be unrealistic and only gradually varying between adjacent datums.

Technical Resolution A2.5 of the IHO (International Hydrographic Organisation) resolves that LAT (Lowest Astronomical Tide) shall be adopted as Chart Datum where tides have an appreciable effect on the water level.

ECDIS – Electronic Chart Display and Information System is an ECS, Electronic Chart System, that has been type-approved by an IHO appointed type-approval authority and is displaying ENCs (Electronic Navigational Charts) or a combination of ENCs and official raster charts such as ARCS.

ETRF89 – European Terrestrial Reference Frame 1989 – a realisation of WGS84 Datum in Europe.

GDA94 – Geocentric Datum of Australia 1994 – a realisation of WGS84 Datum in Australia.

IAG – International Association of Geodesy

LAT – Lowest Astronomical Tide

OSGM02 – Ordnance Survey Geoid Model – derived in 2002.

Satellite Altimetry – The use of data from satellites such as TOPEX/POSEIDON to determine the mean sea surface at a particular point with respect to the ITRF/GRS80 ellipsoid.

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BIOGRAPHICAL NOTES

Dr. Ahmed El-Rabbany obtained his Ph.D. degree in GPS from the Department of Geodesy and Geomatics Engineering, University of New Brunswick, Canada. He is currently working as an associate professor at Ryerson University in Toronto, Canada. He also holds an Honorary Research Associate position at the Department of Geodesy and Geomatics Engineering, University of New Brunswick, and an Adjunct Professor position at York University. His areas of expertise include: Satellite positioning and navigation, Integrated navigation systems, Geodesy and Hydrographic surveying. Dr. El-Rabbany has recently

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published an easy-to-read GPS book, which received a 5-star rating on the Amazon website and listed as a bestselling GPS book. He also published numerous refereed journal and conference papers. Dr. El-Rabbany holds a number of national and international leading professional positions, including, *Councillor* (Geodesy) to the Canadian Institute of Geomatics, and *Chair*, International Federation of Surveyors (FIG) WG-4.2: Vertical Reference Frame. Dr. El-Rabbany has received a number of awards in recognition of his academic achievements.

Ruth Adams works for the UK Hydrographic Office based in Taunton heading up the Geodesy, Photogrammetry and Remote Sensing sections. During her career she has worked closely with the Royal Navy hydrographic surveyors and has had periods of detached duty at sea. Her geodetic and imagery expertise are particular strengths. Other career postings have included Project Management and charting for the Fleet Air Arm.

She has a degree in Surveying Sciences from the University of Newcastle upon Tyne and is a chartered surveyor with the RICS. She is the RICS UK delegate for FIG Commission 4, Hydrography. She has presented at various conferences and frequently contributes to surveying and hydrographic journals.

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