

# Realizing A World Height System (WHS) Using Geoid As Zero Reference Surface

**MUNEENDRA KUMAR**

National Imagery and Mapping Agency  
Bethesda MD 20816-5003 (USA)

## ABSTRACT

There are hundreds of vertical datums, both for the land and ocean areas, used worldwide. For land, until now all the vertical datums have been defined with respect to Mean Sea Levels (MSLs), which can be locally or regionally defined. For ocean areas, the chart datums are based on various tidal surfaces, e.g., Mean Lower Low Water (MLLW), Mean Low Water (MLW), Lowest Astronomical Tide (LAT). These "zero" reference surfaces are time variant and differ from one place to another on earth's surface. In almost all cases, it will be practically impossible to determine or even estimate the absolute accuracy of elevations or depths in the local datum. There is a substantial need to improve the vertical positioning capability for geodetic, mapping, charting, and navigational applications.

Numerous theories have been developed and many approaches are being proposed. One such suggested model would require connections between all the local and regional vertical datums to establish a global vertical datum. This approach would have the basic problem of requiring height data in all the local and regional datums with accurate positioning of some specific Bench Marks (BMs), which in turn would have to be tied to each other with high accuracy survey through Global Positioning System (GPS). In addition, extremely dense gravity data around these selected leveling BMs would also be required. If we consider all the associated difficulties to obtain the required data for all the local and regional datums and the costly and time consuming effort in collection of "dense" gravity covering near the selected BMs for land datums alone world wide, this approach would be extremely difficult. If we include also the collection of accurate tidal data world wide for all the nautical chart datums, this method would be impossible.

As we know that the definition of "true" orthometric heights on land is implicitly linked to the geoid, an alternative proposal can be to define a new vertical datum with the geoid as zero reference surface. The bathymetric data sets over all the ocean areas can then be redefined, along with the land elevations, as orthometric depths to achieve global consistency. Such a datum can be then realized accurately with ease world wide by all users, both on land and ocean areas. In a recent comprehensive research effort it was shown that the geoid would be the most appropriate zero reference surface for a global vertical datum. Once the new definition is established, new orthometric elevations and depths can be computed afresh with respect to the new zero and/or can be directly established in the future with new surveys using GPS.

This new "zero" reference surface is equipotential and would be time invariant. It also has no "slope" and will not vary from place to place like the MSL and other tidal surfaces. The absolute accuracy of new elevations and depths will then be a statistically estimated quantity with global consistency.

This paper describes the concept and provides details how the new global vertical datum can be realized to establish accurate and globally consistent orthometric elevations and depths for use in the twenty first century.

## INTRODUCTION

In the complex mapping, charting and geodetic world, as it exists presently, there are hundreds of vertical datums in use. Some datums are properly defined, while in some cases there is hardly any validity in the definition. For many others, required information may not be readily available to determine an accurate height and its absolute accuracy, even in the local system.

In the above environment, the definitions of the nautical chart datums and the depiction of all other related information useful

for safe navigation to avoid underwater and/or overhead hazards vary from one chart to another, coast to coast, between charting agencies and also between countries. Furthermore, in the hydrographic usage, statements like, "Owing to the many varied tidal characteristics, a precise scientific definition for chart datum, which could be used universally, has not been agreed upon" (IHO, 1993), can still be found. This type of situation arises due to our age old practice of measuring various time-dependent mean ocean surfaces, such as Mean High Tide (MHT), Mean High Water (MHW), Mean Lower Low Water (MLLW), Mean Sea Level (MSL), Mean Higher High

Water (MHHW), Mean Low Water (MLW), Low Water (LW), High Water (HW), etc., with varying definitions, both nationally and internationally.

Then, following our "common" practice and usage, we still have not initiated any serious efforts to look for and shown any inclination to accept any alternative zero reference surface. The new three-dimensional satellite survey techniques and our recent capability in determination of geoid with high absolute accuracy now offer another option for an accurate vertical datum with global consistent.

The old approach has varied from one country to another and is dependent on the adopted MSL definition and tide models, surveying techniques, and duration for computing "mean" tidal surfaces and instrumentation. As the sea level changes can be excessive and are also time-dependent, the knowledge of accurate tide modeling, which is always complex, becomes very critical. Thus, in this complex and difficult to measure time-dependent scenario, it seems obvious why all the countries have so far not agreed to have a common datum for nautical charts and bathymetric data or ocean depths.

To meet the latest high accuracy with "global" consistency and be able to solve the complexity of local/regional variability, we must not restrict to the old type solution(s). What we need is a new solution (Balasubramania, 1994) which provides a product to work accurately in real time and does not have to depend on the local and regional data we do not control. In the present set up, we may also not have necessary and sufficient information and/or required data from local sources to make our navigation safe.

Considering the marine application, we compute a geoid of very high accuracy, define an accurate vertical datum, which would also be coincident with the land datum, establish time-independent orthometric depths (like orthometric elevations on land) consistent in definition and accuracy all over the globe, and then go back to sea to use these depths in real time for safer navigation. nautical charts all over the globe. In this scenario, the "high or low" tide data will be used as auxiliary information to help navigation in coastal areas and in harbours. This global datum, being not time dependent on variable tidal surfaces, will be realized with very high accuracy through surveys done with Global Positioning System (GPS). Further, this approach will establish a vertical datum to survey time-invariant consistent land elevations and ocean depths, to easily extend the control and to depict them both on land maps and nautical charts.

Then, reversing the survey mode, these charted ocean depths can be realized in real-time during navigation to check clearance from the sea bottom to avoid ship grounding. Similarly, elevation or height clearances can be determined for an isolated point or a station on land.

As we now have a new option, we can easily collect the depths with respect to the geoid and test them for real time usage. If it ensures safer navigation to all users world wide, we adopt the new approach otherwise we continue to use various tidal surfaces as before. We can now establish a new global zero reference and the GPS surveying technique to realize and then use the newly defined elevations and depths with better accuracy, even in real time, for safer navigation.

This paper presents in detail the problems with the old zero surface(s), the realization of an accurate geoid, a new concept to define a global vertical datum completely time-independent, and the method to establish the same through GPS surveys. It also describes how to realize the sea floor depths during navigation. The approach thus eliminates the necessity for the time-dependent sea level and other tidal data as the primary source to establish and use depths and elevations.

## **PROBLEMS WITH CURRENT TIDAL LEVELS**

### **A. For Land Areas -**

In case of vertical datums, at least, every country has used the same surface as zero reference, viz., MSL. However, the realized surface in such cases may NOT be the same and the selected zero may have many limitations.

- (1) MSL is NOT an equipotential surface. It has slope with respect to the geoid.
- (2) Practically, all Tidal Observation Stations (TOSs) are located inside the bays and not on the open ocean side along the coast.
- (3) Some TOSs still have old and obsolete instruments.
- (4) An accurate determination of MSL at any TOS would require observations taken regularly and without any interruption over a complete cycle of 18.67 years as a minimum.

It is very interesting to note here, that this 18.67 years cycle condition may NOT have been met in many of countries. In one case, it was discovered that a country used only one single observation of the sea surface as its MSL to

define the national vertical datum.

- (5) As most of the TOSs are located (at least so far) along the coast in shallow waters, the MSLs so determined at these locations do not represent the true mean sea level.
- (6) In many "older" vertical datums, the MSL at all the TOSs was used as "zero" to define and adjust the level net. This rigid constraint in turn distorted the resulting datum networks.  
  
Now, in recent times, an easier approach has been adopted to select the MSL of ONLY one TOS for datum definition to avoid "distortion" problems in the level networks. Here, it is not clear how a large extended network over thousands of kilometer can be kept within the desired absolute accuracy and then, all the elevations can be assumed to be within "permissible" errors for all the BMs far away from the "fixed" TOS. Of course, use of only one BM constraint in any adjustment may be the most easy solution, but it will definitely not going to provide high absolute accuracy over the entire network.
- (7) In "land-locked" countries, the used MSL definition has to be a borrowed one from the neighboring country or across many countries.

A very interesting case is of Paraguay. Here, on the west side, the MSL may have been borrowed either from Chile and/or Peru and then through Bolivia. The level lines so used to connect with the sea are over the Andes and it is also quite obvious that they must have been processed very differently by each of these countries. On the east side, the two MSLs may have been used, one from Brazil and other from Argentina. A recent study has revealed a large discrepancy with the satellite derived orthometric heights using geoid and many other problems in the old national datum and thus a redefined datum solution seems inevitable.

## **B. For Ocean Areas -**

The latest trend here is the use of the Lowest Astronomical Tide (LAT) as the vertical datum for nautical charts. In many cases, there are interesting conflicts and deviations between

various definitions. Many mariners using the data based on these definitions would be facing hard times to understand and interpret them correctly, especially when hard pressed for time and faced with little margin of error. A few typical examples of such cases are discussed below :

- (1) Use of MLLW as chart datum (CD) to depict charted depths versus use of chart LW (drying) line to depict "drying" heights  
  
It is obvious here that a common user would not know "what is the actual difference in the two cases.
- (2) Use of Charted HW (coastal) line as land datum to depict charted elevations. Here, MSL is shown separately, even though all the land vertical datums worldwide are defined with respect to MSL.
- (3) Both MHW and MHHW are shown differently from the charted HW (coastal) line.
- (4) While charted depths are defined with respect to MLLW, the charted vertical clearances are defined with respect to MHW, and not to MHHW. This definition may leave MHHW practically with no application.
- (5) The "height of tide" is defined with respect to MLLW (CD), while Tide and Current Glossary (NOAA, 1989) does not define this important item. Furthermore, this glossary includes Half-Tide Level, also called Mean Tide Level, to define a tidal datum which is midway between MHW and MLW.

It is not clear how anyone can be sure that once established as a zero surface, the LAT would remain as the "lowest" surface for all future times. Further, it also would NOT be representing the same zero in different parts of the world.

Table 1 (NOAA, 1990) shows a typical example of a tide table where the tidal levels are related to "Datum of Soundings". In typical cases Tidal levels can be related to "Datum of Soundings" where a user will have to solve or interpret a newer set of terms like MHWS, MHWN, MLHW and MHLW. All this will make the use of available information more complex and thus difficult to interpret correctly by a user in his or her daily routine. The note in this Table indicates that the order of the

included tidal levels, as referred to all the sounding datums, may be different in other national tables. If this statement is taken to be correct, the involved definitions of all these terms may also be different in other parts of the world (IHO, 1993).

Another important aspect in all the above complexity of terminology and definitions is that this information is time-dependent. It may also have vertical bias between different level surfaces used by different countries.

### **ALTERNATE SOLUTION**

On land, the orthometric heights or elevations are defined theoretically with respect to the geoid. However, in the past, due to our past limitations to compute and establish the geoid with the desired accuracy, the MSL was used to approximate the geoid.

In the new approach, it is proposed to utilize the geoid (and not the MSL as its approximation) as the zero surface for the global vertical datum for use over land and in nautical charts and also to reference all the bathymetric data to it. This referencing will then provide a time-independent and globally consistent definition and facilitate easy integration of all the bathymetric data sets which would originate either from adjustment of old observations with geoid as the new zero or transformation of local vertical datums. All the data sets surveyed and reduced under the new global definition would be directly available in the new system.

Paragraph 7 describes in detail how these orthometric depths could be used (by a user) in "real" time navigation without any ambiguity and with distinct advantage over the currently defined depth data based on time-dependent many level surfaces.

### **DEFINING TIME-INVARIANT ZERO REFERENCE SURFACE**

An important point here, which requires clarification under the proposed concept, is that the geoid (to be used) is defined basically as an equipotential-potential surface by the following equation:

$$W(X,Y,Z) = W_0 \quad (1)$$

where the "W" is the earth's total gravity potential and "W<sub>0</sub>" the geoid constant as specified by the International Association of Geodesy (Moritz, 1980). However, for usage at anytime, it will be the latest and most accurate model realized under this definition.

Using the latest theoretical corrections, algorithms, research methods, software and extensive global gravity, altimeter and satellite data sets, a new model, viz., WGS 84 (EGM96) geoid, has recently been computed by the National Imagery and Mapping Agency (NIMA) and National Aeronautics and Space Administration (NASA). Its estimated absolute accuracy is about  $\pm 25$  cm over the oceans and between  $\pm 50$  cm to 1 m over the land areas.

The lower accuracy values pertain to remote land areas and/or mountainous terrain where available gravity is not satisfactory in coverage, quality and density. For daily practical applications, it is also obvious that the lower accuracy levels should not be critical over such areas.

The new geoid is now available on the INTERNET (www) under the address

<http://164.214.2.59/geospatial/products/gandg/wgs-84/geos/html>

or as a CD ROM (from NIMA).

### **COMPUTATIONAL CONSTRAINTS**

The task of computing such a high absolute accuracy geoid solution using extensive satellite, altimeter and gravity data sets with coverage from all over the globe is a very time consuming and costly effort and takes years to complete the project. The next global solution to improve the absolute accuracy to a higher level will only be possible when "significant" improvement in the needed data sets would be available. It should also be clear here that the effort and funds required for attempting such a solution may also be extremely difficult to come. Further, another important issue will be the availability of the required "denser" data from all the countries for such an effort.

To eliminate conflicts between too many zero surfaces and to achieve globally consistent absolute accuracy, the use of other geoids will have to be avoided; proliferation of too many local, regional, or global solutions should NOT be allowed. Significant improvement in absolute accuracy have to be a globally coordinated effort rather than a set of individual efforts. To achieve these goals, international institutions and/or organizations like the International Hydrographic Organization, International Maritime Organization, International Commission on Geoid, International Geoid Service and International Federation of Surveyors, must play an important role to

coordinate the adoption of one accurate global geoidal solution by all users at any given time.

However, countries can develop High Resolution (HR) relative local or regional geoids with a fit to the global geoid for maintaining consistent absolute accuracy. This resolution will, of course depend on the available gravity density.

### **SURVEYING CONSISTENT BATHYMETRY**

In a typical survey scenario using GPS in open and deep ocean areas, where accuracy of the measured depths will be less critical, the ellipsoidal height (h) of the ship can be determined with GPS in navigation or single point positioning mode. As the survey scenario would approach the coast with shallower water depths, high accuracy requirements would also become more critical. In such cases, the ship's ellipsoidal height (h) would be established or surveyed with differential GPS technique where the survey can be designed to achieve desired higher accuracy in "h".

The surveyed ellipsoidal heights (h) of the ship can provide the hp of the sea surface, which when combined with the computed geoidal height (NP), would give the orthometric height (HP) as:

$$HP = hp - NP \quad (2)$$

Then, at the same epoch, the ship measures through sounding the distance SP. Combining the SP with the sea surface orthometric height HP (using equation 2), the depth DP can be computed as:

$$DP = SP - HP \quad (3)$$

While the surveyed hp and PS and computed HP would be time variant with the moving sea surface, the geoidal height (NP) and computed depth (DP) would be time-independent. Further, as the heights hp and NP would be established in the globally consistent World Geodetic System (WGS) 1984 used by GPS, the computed depth DP through ship's soundings would also be defined with respect to the WGS 84 geoid (DMA, 1991).

Once an area is surveyed with all the depths referenced to the new WGS 84 geoid, the information can be utilized to contour nautical charts. The data can also be stored as individual depths in a digital data base and will also be available for use with digital charts.

### **REAL TIME NAVIGATION**

#### **Recovering Depth Clearance :**

A measure of depth clearance (or the safe distance between the ship's bottom and the sea floor) will then be given as :

$$HL < HP + DP \quad (4)$$

Where HL is ship's hulk, HP is height and DP is depth.

A new measurement of sounding (SP) at the sailing time will then provide a check on the plotted depth DP on the chart.

#### **Recovering Height Clearance :**

A measure of height clearance (or the separation between the highest point of the ship's mast and the bridge bottom) will then be given as :

$$HM < HB - HP \quad (5)$$

Where HM is ship's mast, HB is height of bridge and HP is height.

It is important to point out that the distance from the sea surface to the GPS antenna would be a measured correction in all of the above relationships.

### **RELATING THE TIDAL SURFACES**

At any tidal station, the absolute zero of the tidal staff can be established by a GPS single point positioning survey at a nearby station and differential spirit level line to the tidal staff. Its orthometric height H (h - N) can be used to set the tidal staff zero to the geoidal zero and this method will be consistent all over the globe.

Then, all the tidal surfaces, e.g., MLLW, MLW, MSL, MHW, can be surveyed with respect to the absolute zero (the geoid) of the tidal staff and used with consistent definition worldwide as auxiliary information with the time-invariant bathymetry.

Though the tidal surfaces be tied to the same zero surface as the depths, it is emphasized that the tidal measurements and/or any reductions with respect to them would not be required for depth determination during navigating with GPS. In this mode, the ship navigator would use the high tide information as auxiliary data to compute the "safe" time when the high tide would improve ship's clearance to entering the shallower areas.

### **USING THE NEW CONCEPT**

The proposed use of the geoid as the zero reference for a global vertical datum will enable us to integrate and analyze

the depth and elevation data over the sea and land interface. It will also eliminate all the existing local tidal datums which are in use around the world.

However, the adoption of a new vertical datum would raise an immediate issue of what to do with the existing data sets based on the numerous MSLs and tidal surfaces. Each of these datums, with its own definition, has very valuable data and observational data sets. Questions would arise over what to do and how to save all this valuable information.

The solution will of course differ for the land and ocean areas.

#### **(a) For Land Areas**

One solution for the integration of the existing data sets can be datum transformations. This method would not improve the quality and accuracy but would definitely help in utilizing the existing information until the new and more accurate data sets are surveyed and integrated under consistent, time-invariant, and accurate geoidal definition.

A practical solution would be to integrate the old existing spirit and new differential GPS leveling data sets to the geoidal zero reference. It will provide an accurate height system with a globally consistent definition.

#### **(a) For Ocean Areas**

For bathymetric data, the only plausible solution would be to approximate a "common" zero and accept lesser accuracy. The "improvement" thus would start with the new data.

It is also to be noted that the proposed method to determine the orthometric depths with respect to the geoid also involves the sounding measurements. Thus, the accuracy of new depth data would require accurate acoustic modeling and the improvement in acoustic modeling should be considered as an area of high priority research topic (Section 6).

The immediate revision of all existing paper charts and maps to reflect a global vertical datum is not viewed as a feasible economical alternative; however, development of accurate digital terrain and bathymetric data base and integration of all such data into digital nautical charts and geospatial land information system within a globally consistent vertical datum should be a reasonable option for the coming years.

### **ACCURACY ESTIMATION**

In offshore areas the ellipsoid height (h) can be surveyed by differential GPS with an accuracy of  $\pm 1$  m with respect to land control points in routine field surveys. Also, the current

achievable accuracy of the geoid over ocean areas would be within the desired range of about  $\pm 25$  cm.

The above two estimates shift the emphasis to the sounding measurements and their surveyed accuracy which would impact the final accuracy of the bathymetric data. One such very important document, which specifies international standards and classification criteria for hydrographic surveys and soundings, is the IHO Special Publication No. 44 (IHO, 1987).

Though the above table or the IHO publication specifies the desired accuracy requirements, standards and classifications for soundings and related hydrographic surveys, the users would still be concerned about the accuracy actually achieved and/or obtained during any marine field survey over an area, especially when one would consider all the rapidly varying environmental conditions and use of different definitions. Thus, under the newly modified and more accurate survey scenarios with GPS techniques, the new concept of using a global geoid as zero vertical reference would be very timely. Further, the measuring of ship's soundings with modern instrumentation, a complete revision of achievable accuracy requirements and specifications for the GPS and marine surveys and soundings, and setting of new international standards would also become an immediate necessity.

### **SUMMARY**

The practical complexity and difficulties arising from the use of different vertical datums and time-dependent tidal surfaces with inconsistent definitions are impeding the correct integration of valuable information. This also affects safe navigation over international waters.

The new concept of the geoid as the zero reference surface for the time-invariant bathymetry and elevations is practical and also realizable with sufficient accuracy using current technology and available data sets. The computation of a modern global geoid with an absolute accuracy of  $\pm 25$  cm is a costly project, but to achieve the same at this time would be very timely. Problems arising from use of various relative and regional models and also of different global geoids with lower accuracy would have to be avoided. Use of local geodetic datums for differential GPS surveys would be another dangerous and critical problem. If the new survey data is not properly coordinated and collected under "strict" standardized specifications, the present complexity may crop up in a different form.

## REFERENCES

- Balasubramania, N., 1994. "Definition and Realization of a Global Vertical Datum". Department of Geodetic Science and Surveying, Report No. 247, The Ohio State University, Columbus, OH 43210-1247 (USA).
- DMA, 1991. "Department of Defense World Geodetic System 1984, Its Definition and Relationship with Local Geodetic Datums", DMA TR 8350.2, Second Edition, Defense Mapping Agency, Fairfax, VA.
- IHO, 1987. "IHO Standards for Hydrographic Surveys Classification Criteria for Deep Sea Soundings and Procedures for Elimination of Doubtful Data", Spec. Publ. No. 44, International Hydrographic Organization, Monaco.
- IHO, 1993. "A Manual on Technical Aspects of the United Nations Convention on the Law of the Sea - 1982", Special Publication 51, International Hydrographic Organization, Monaco.
- Moritz, H., 1980. "Fundamental Geodetic Constants", Report of the Special Study Group 5.39, International Association of Geodesy, Paris, France.
- NOAA, 1978. "Hydrographic Field Handbook", National Oceanic and Atmospheric Administration, Silver Spring, MD.
- NOAA, 1989. "Tide and Current Glossary", National Oceanic and Atmospheric Administration, Silver Spring, MD.
- NOAA, 1990. "Nautical Chart Symbols Abbreviations and Terms", USA Chart No. 1, National Oceanic and Atmospheric Administration, Silver Spring, MD.