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Time-Invariant Bathymetry: A New Concept to Define and Survey it using GPS**

(Submitted by the United States of America)

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TIME-INVARIANT BATHYMETRY
A NEW CONCEPT TO DEFINE AND SURVEY IT

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Currently, there are hundreds of vertical datums, both for land and ocean areas, in use all over the world. As we live on land, the land datums always got the priority attention. Thus, to update them either datums, viz., the North American Datum (NAD) 1983, European Datum (ED) 1979, and EUREF 1989 have already been established or efforts to establish new datums, viz., SIRGAS for South America and KRF 1994 for Korea have been started.

Another important point is that no rigorous horizontal datum has ever been defined over ocean areas; the practice has been to always extrapolate the land datums to map the charts over oceans.
For nautical chart vertical datums, the situation is still more complicated by the lack of agreement on the definition(s) by different countries which in turn jeopardizes the safety of international navigation.

Further, the tidal surfaces used in the vertical datums to define elevations and bathymetry are time-variant and do not have a common zero. This generates slopes between and along the coasts and prevents creation of consistent data sets for global usage.

This paper deals with the chart vertical datum problem and presents a new concept for defining/surveying a time-invariant bathymetry using a high accuracy geoid as the new zero reference surface. Details have also been included on how to realize this zero surface and use the same in real-time navigation. It would also be necessary to avoid use of different regional or global geoids to maintain consistency in the zero reference.

1. INTRODUCTION

In the complex mapping, charting, and geodetic world, 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, information is not available that can be used to determine an accurate height 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 usages, 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 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., and then due to our efforts to use such tidal surfaces in relating them to land and nautical chart datums in depicting heights or ocean depths.

The above approach can and has varied from one country to another country and is dependent on the adopted definitions and tide models, surveying techniques, and durations (for computing "means"), 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 critical. Thus, in this complex and difficult to measure time-dependent scenario, it is quite obvious why internationally it would be difficult to agree to a common datum for nautical charts and ocean depths.

However, we now have the capability to compute a geoid of very high accuracy over ocean areas and thus define an accurate nautical chart vertical datum without using time-dependent tidal surfaces. Also, the availability of the Global Positioning System (GPS) makes it easy to establish this vertical datum for chart by surveying time-invariant depths in the field and then depicting them on charts. Then, reversing the survey mode, these charted depths can be realized in real-time during navigation to check depth clearances to avoid ship grounding.

This paper presents a new concept to define a nautical chart vertical datum completely independent of time, to establish the same through GPS surveys, and also to realize the seafloor depths during navigation. The approach thus eliminates the necessity for the time-dependent sea level and other tidal data as the primary source of information for navigation.

2. CURRENT TIDAL LEVELS

Figure 1 shows an illustrative depiction to define various tidal levels and charted data as this information is currently in use by some countries (NOAA, 1990), if not by all. For example, use of the Lowest Astronomical Tide (LAT) as the vertical datum in charts is increasing. There are some interesting conflicts and deviations between various definitions in Figure 1. Mariners using the data based on these definitions would have a hard time understanding and correctly interpreting them, especially when hard pressed for time and faced with little margin of error. A few typical examples of such cases are:

(1) Use of MLLW as chart datum (CD) to depict charted depths versus use of chart LW (drying) line to depict drying heights.

(2) Use of Charted HW (coastal) line as land survey datum to depict charted heights. Here, MSL is shown separately, even though all the land vertical datums worldwide are defined with respect to it.

(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, at least in **Figure 1**.

In **Figure 1**, the "height of tide" is defined with respect to MLLW (CD), while Tide and Current Glossary (NOAA, 1989) does not define this important item. Further, this glossary includes Half-Tide Level, also called Mean Tide Level, to define a tidal datum which is midway between MHW and MLW; but the same is not included in **Figure 1**.

Table 1 (NOAA, 1990) shows a typical example of a tide table where tidal levels are related to "Datum of Soundings". Here, a user will then have to solve or interpret a newer set of terms like MHWS, MHWN, MLHW, and MHLW. To make the usage of available information more complex and thus more difficult to interpret correctly, the note in Table 1 indicates that the order of the included tidal levels, as referred to all the sounding datums, may be different in national tables. If this statement is taken to correct, the involved definitions of these terms may also be different (IHO, 1993).

Another important aspect in all of the above complexity of terminology and definitions is that all this information may also be time-dependent.

3. DEFINING TIME-INVARIANT ZERO REFERENCE SURFACE

On land, the orthometric heights or elevations are defined theoretically with respect to the geoid. However, in the past, due to our limitations to compute and establish the geoid with the desired accuracy, the Mean Sea Level (MSL) was and still is used to approximate the geoid, though the MSL does not coincide with an equipotential surface. Another complication in using MSL to define a vertical datum is that it deviates from coast to coast, both in east-west and north-south directions. There are cases when the MSL has been very poorly "meaned" in defining zero surface for the vertical datums and related elevations. In ocean areas, the bathymetric data, as available currently, is related to a zero reference surface which may be even more poorly defined than MSL for the land areas.

In view of our present capability with the newer technology and availability of accurate observed data sets, the geoid over ocean areas can now be computed easily with <u>absolute</u> accuracy of about ± 25-30 cm. All indications reflect that this accuracy may be even better in the near future.

It is thus proposed to utilize the geoid as the zero surface for the nautical chart datum and reference all bathymetric data to it. This referencing will then provide a time-independent and globally consistent definition and facilitate easy integration of different data sets which would originate from newly surveyed projects under this definition.

Another important point, which requires clarification under the proposed concept, is that the geoid (to be used) is defined by the following equation:

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

where the "W" is the earth's total gravity potential and "W_0" the geoid constant as specified by the International Association of Geodesy (Moritz, 1980). The computational task of such a high absolute accuracy geoidal solution using extensive data sets with coverage from all over the globe would be a very costly and time consuming effort. To eliminate conflicts between too many zero surfaces arising from the use of regional geoidal solutions will have to be avoided. In addition, to ensure consistent accuracy, worldwide proliferation of too many solutions must be checked. To achieve these two desirable goals, international institutions like the International Hydrographic Organization, International Maritime Organization, International Commission on Geoid, and

International Federation of Surveyors would play an important role in coordination and adoption of an accurate global geoidal solution by all.

4. SURVEYING CONSISTENT BATHYMETRY

Figure 2 illustrates a typical survey scenario using GPS. In open and deep ocean areas, where accuracy of 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 accuracies 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:

$$Hp \approx hp - Np \qquad (2)$$

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

$$Dp = Sp - Hp \qquad (3)$$

While the surveyed hp and Sp 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 WGS 84 geoid, the information can be utilized to contour the 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.

5. RECOVERING DEPTH AND HEIGHT CLEARANCES DURING NAVIGATION

a. Depth Clearance :

While navigating in an area with its nautical chart plotted and contoured for depths (Section 3.), the height (H_P), using the GPS surveys and the computed geoidal height (N_P), depth (D_P) and the ship's hulk (HL) are configured in **Figure 3.**

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

$$HL < H_P + D_P \qquad (4)$$

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

b. Height Clearance :

While navigating in an area with its nautical chart plotted for height clearance, the height (H_P), using the GPS surveys and the computed geoidal height (N_P), the height (H_B) of a bridge and length of the ship's mast (HM) are configured in **Figure 4**.

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 :

$$HM < H_B - H_P \qquad (5)$$

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.

6. RELATING THE TIDAL SURFACES

At any tidal station, the absolute zero of the tidal staff can be established with the GPS absolute point positioning survey at a nearby station and then performing differential leveling to the staff (**Figure 5**). Its orthometric height H ($\approx$ h - N) set to the geoidal zero 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 zero of the tidal staff or to the geoid and used with consistent definition worldwide as auxiliary information with the time-invariant bathymetry.

Though the tidal surfaces will be tied to the same zero as the elevations and depths determined with the GPS surveys and a global geoid, it is emphasized that the tidal measurements and/or reductions would not be required when navigating with GPS fixings and using depths which are referenced to the geoid. In this mode, the ship navigator can 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.

7. EVALUATING 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 the numerous 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 tidal datums, each with its own definition and how to save this valuable information.

One solution for the integration of the existing data sets is datum transformations but this method would not improve the quality and accuracy of the data based on the numerous tidal and chart datums. However, it 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 definition.

It is also noted that the proposed method to determine the depths with respect to the geoid also involves the sounding data and the accuracy of final results would require accurate acoustic modeling. As the issue concerning the accuracy of the soundings is not a new one, the improvement in the acoustic modeling should be considered as an area for future research (Section 5.).

8. ACCURACY ESTIMATION

In **Figure 2**, in offshore areas the ellipsoid height (h) can be surveyed using differential GPS with an accuracy of ± 1 meter in routine field surveys. Also, the achievable accuracy of the geoid over ocean areas would be within the desired range of about 25 cm in the near future, even though some doubts may still exist about the accuracies of the current geoidal model(s).

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. **Table 2**, extracted from a National Oceanic and Atmospheric Administration publication (NOAA, 1978), is one such example which specifies the accuracy standards for measurement of soundings during field surveys. Another 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 reference would be very timely. Further, the measuring of ship's soundings with modern instrumentation, a complete revision of achievable accuracies and specifications for the GPS and marine surveys and soundings, and setting of new international standards would also become an immediate necessity.

9. SUMMARY

The practical complexity and difficulties arising from the use of numerous vertical datums and various 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 ± 25 cm is a costly project, but to accomplish the same at this time would be very timely. Problems arising from use of various relative and regional solutions and also of different global geoids with lower accuracies 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 standardized specifications, the present complexity may crop up in a different form.

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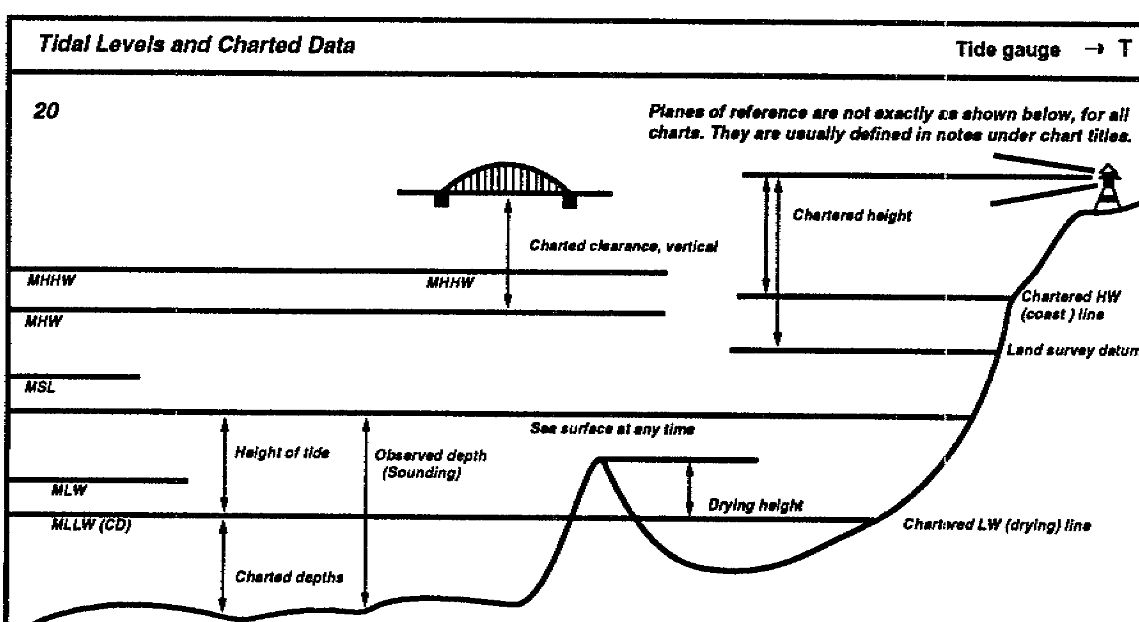
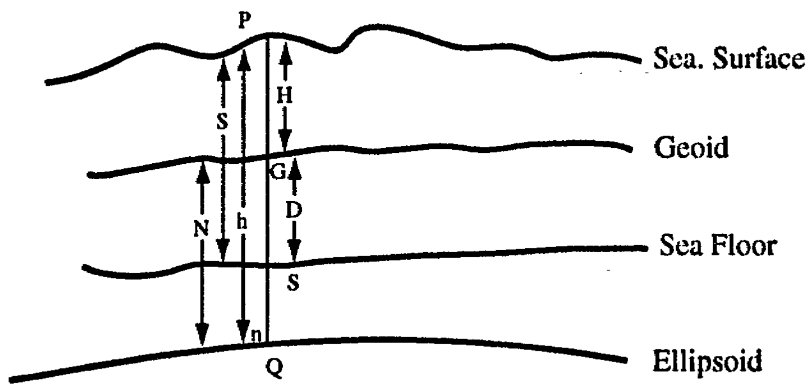


Figure 1. Tide Levels and Charted Data (NOAA, 1990)



PQ = Ellipsoidal height (h) of the survey ship surveyed with GPS

GQ = Geoidal height (N) computed with the Earth Gravity Model (EGM)

PS = Sounding (S) measured acoustically from the survey ship

GS = Depth of sea floor (D) from the geoid

Figure 2. Surveying the Time-Invariant Bathymetry

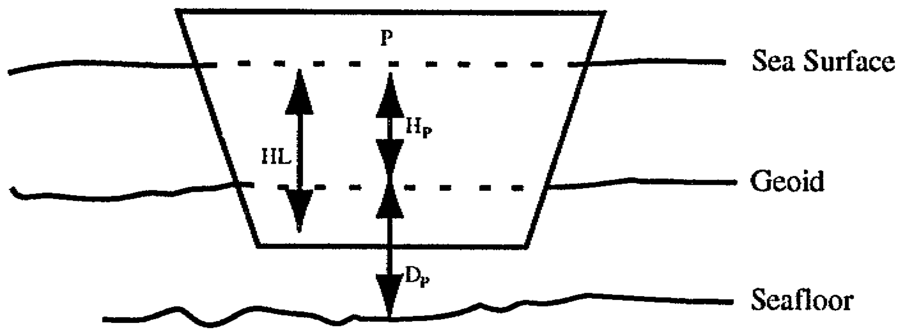


Figure 3. Surveying the Depth Clearance

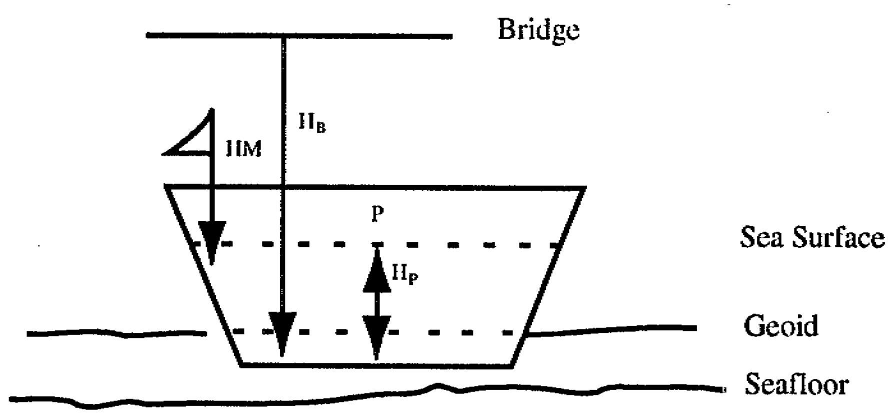


Figure 4. Surveying the Height Clearance

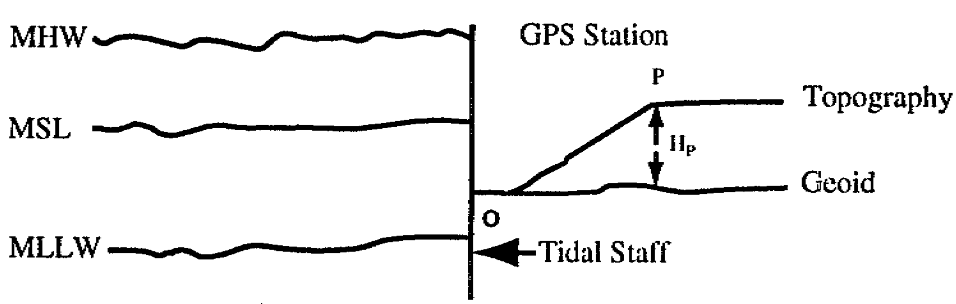


Figure 5. Surveying the Zero Height of the Tidal Staff

Table 1[1]

Tide Tables Referred to Datum of Soundings

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Tidal Levels referred to Datum of Soundings

Place	Lat N	Long E	Heights in meters above datum			
			MHWS	MHWN	MLWN	MLWS
			MHHW0	MLHW	MHLW	MLLW

Tabular statement of semi-diurnal or diurnal tides

Note:
The order of the columns off levels will be the same as that used in national tables of tidal predictions.

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Tidal Stream table

Tidal streams referred to:

Hours		◇ Geographical Position		
		Directions of streams (degrees)	Rates at spring tides (knots)	Rates at neap tides (knots)
Before High Water	6			
	5			
	4			
	3			
	2			
	1			
High Water				
After High Water	1			
	2			
	3			
	4			
	5			
	6			

1 NOAA, 1990.

Table 2[1]

Accuracy Standards for Soundings

Water Depth	Allowable Errors
0 - 20 meter	0.3 meter
20 - 100 meter	1 meter
> 100 meter	1% depth

1 Extracted from NOAA, 1978.
