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REVIEW OF THE LATEST TECHNOLOGY IN CARTOGRAPHIC DATA ACQUISITION, MANIPULATION, STORAGE AND PRESENTATION, WITH SPECIAL EMPHASIS ON POTENTIAL APPLICATIONS IN DEVELOPING COUNTRIES: SURVEYING AND MAPPING, GEODESY, MAP UPDATING AND GENERALIZATION

Global vertical datum to survey accurate orthometric heights and depths

Paper submitted by the United States of America**

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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, 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.

Then, due to our age old practices and usage, we still have not initiated any serious efforts to look for alternatives which are offered by 3-dimensional satellite survey techniques and our new capability in determination of geoid with high absolute accuracy. We still continue to use MSL and various tidal surfaces in relating them to land and nautical chart datums in depicting elevations or ocean depths.

The old approach has varied from one country to another and is dependent on the adopted MSL definition and tide models, surveying techniques, and durations 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 is quite obvious why it would be difficult for all the countries 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 vertical datum, which would be the same both for land and nautical charts all over the globe. This global datum will not use time-dependent tidal surfaces. Also, the availability of the Global Positioning System (GPS) makes it easy to establish this vertical datum, to survey time-invariant land elevations and ocean depths in the field, to extend the control, and to depict them on charts.

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

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 seafloor 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

Figure 1 shows an illustrative depiction to define various tidal and sea levels and charted data as these surfaces are used by some countries (NOAA, 1990), if not by all. Here, there are some inherent and practical problems when any such surface is selected to define a land and/or chart datum.

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 MSL requires observations taken regularly and un-interrupted over a cycle of 18.67 years.

It is interesting to note here, that this condition may NOT have been met in many of the selections. In one case, only one observation of the sea surface was used as MSL.

(5) As TOSs are situated along the coast in shallow waters, the selected MSLs do not represent the true mean sea level.

(6) In many "older" datums, the MSLs at all the TOSs used to define and adjust the level net were constrained to zero and this produced "distorted" networks.

Now, in recent times, an easier way was selected by using ONLY one TOS to avoid "distorted" level networks. In such a case, it is not clear how a large extended network over thousands of kilometer can be kept accurate and all elevations can be assumed to be within "permissible" errors far away from the "fixed" TOS. Of course, use of only one constraint in any adjustment is the most easy solution.

(7) In "land-locked" countries, the MSL has been borrowed from the neighboring country or countries.

A very interesting case is of Paraguay. Here, on the west side, the MSL may have been borrowed either from Chile or Peru and then through Bolivia. The level lines used run over the Andes and they may also have been "differently" processed. On the east side, the two MSLs may have been used, one from Brazil and other from Argentina. A closer study has revealed many problems.

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 other cases, there are some interesting conflicts and deviations between various definitions in Figure 1. 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:

(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 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, at least in Figure 1.

(5) It is not clear how anyone can be sure that once established LAT zero surface 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.

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. All this will make the use of available information more complex and thus 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 other national tables. If this statement is taken to be correct, the involved definitions of all 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 and 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 limitations to compute and establish the geoid with the desired accuracy, the MSL was and still is used to approximate the geoid.

In the new approach, it is proposed to utilize the geoid as the zero surface for the global vertical datum for use over land and in nautical charts and also to 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 either from adjustment of old observations with geoid as the new zero or transformation of local vertical datums. All new data surveyed and reduced under the new definition would be straight forward.

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).

DEFINING TIME-INVARIANT ZERO REFERENCE SURFACE

Using the latest theoretical corrections/research and globally extensive gravity, altimeter, and satellite data sets, a new geoid model has now been computed by National Imagery and Mapping Agency (NIMA) and National Aeronautics and Space Administration (NASA). It is now available with estimated absolute accuracy of about ±25 cm over the oceans and between ±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.From a practical stand point, it is also obvious that the lower accuracy levels should not be critical over all these areas.

GEOID COMPUTATIONAL CONSTRAINTS

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. More so, the global solution to improve absolute accuracy is also not easily derived and the "significant" improvement in the data required for attempting the next global solution is NOT that simple.

To eliminate conflicts between too many zero surfaces, the use of regional geoids will have to be avoided and to ensure globally consistent absolute accuracy, proliferation of too many "local" solutions must be avoided. To achieve these goals, international institutions/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 in coordination and adoption of one accurate global geoidal solution by all users.

However, countries can try to develop high resolution relative local or regional geoids with a fit to the global geoid.

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".

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

$$H_P \approx h_P - N_P \qquad (2)$$

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

$$D_P = S_P - H_P \qquad (3)$$

While the surveyed h_P and S_P and computed H_P would be time variant with the moving sea surface, the geoidal height (N_P) and computed depth (D_P) would be time-independent. Further, as the heights h_P and N_P would be established in the globally consistent World Geodetic System (WGS) 1984 used by GPS, the computed depth D_P 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 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.

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 ploted for height cleraace, the height (H_p), using the GPS surveys and the computed geoidal height (N_P), the height (H_P) 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.

RELATING THE TIDAL SURFACES

At any tidal station, the absolute zero of the tidal staff can be established by a GPS absolute point positioning survey at a nearby station and differential spirit leveling to the tidal 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 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.

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 MSLs and tidal surfaces based land and chart datums. Each of these datums, with its own definition, has valuable data and observational sets. Questions would arise over what to do and how to save all 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.

In case of land datums, a new solution using the old existing spirit leveling and new differential GPS data sets would be a good solution. It will then provide accurate and consistent elevations.

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 6).

The revision of all existing paper charts and maps to reflect a global vertical datum is not viewed as a feasible and economical alternative; however, development of accurate digital terrain model and bathymetric data base, and adjustment of digital nautical chart and geospatial land information to a globally consistent vertical datum should be a reasonable option.

ACCURACY ESTIMATION

In Figure 2, in offshore areas the ellipsoid height (h) can be surveyed using differential GPS with an accuracy of ± 1 meter 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 ± 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. 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 vertical 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.

CONCLUSION

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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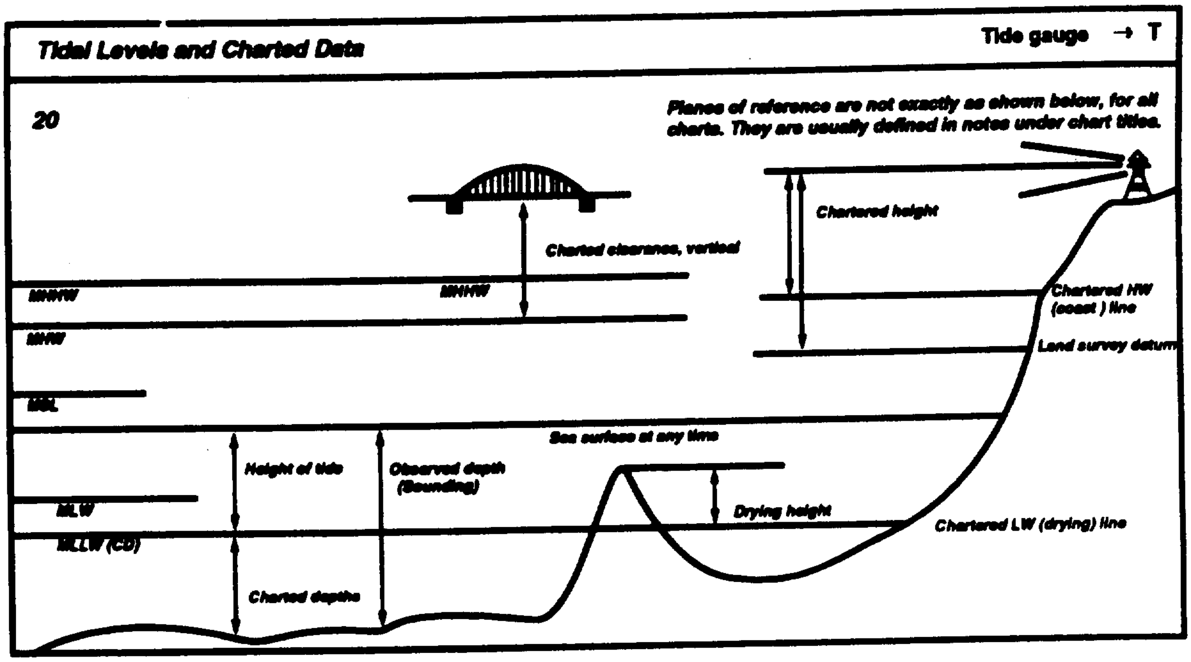
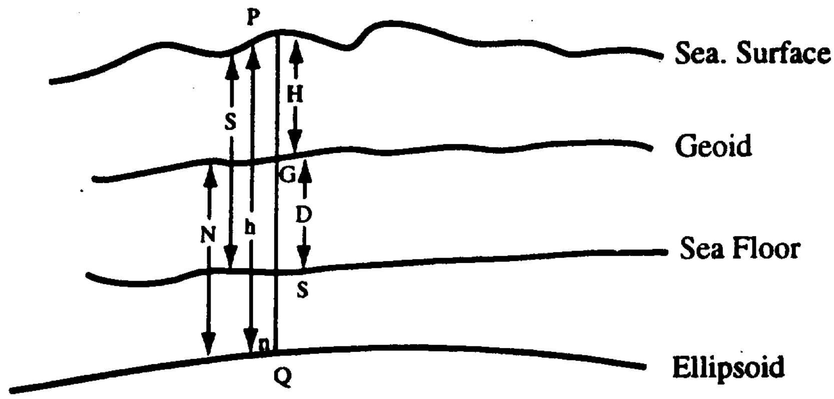


Figure 1. Tide Levels and Charted Data (NOAA, 1990)



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

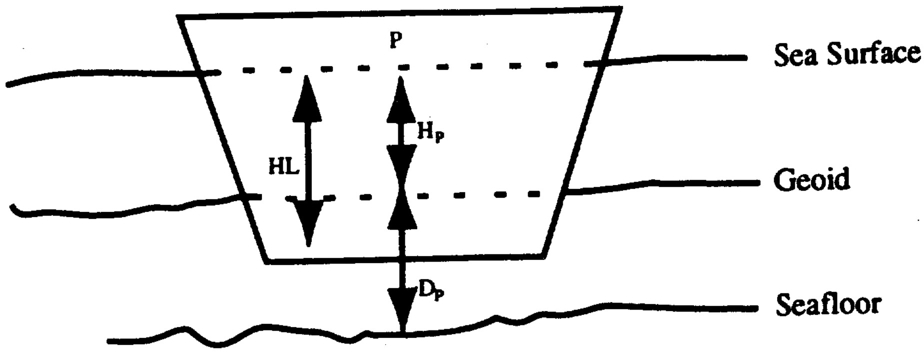


Figure 3. Surveying the Depth Clearance

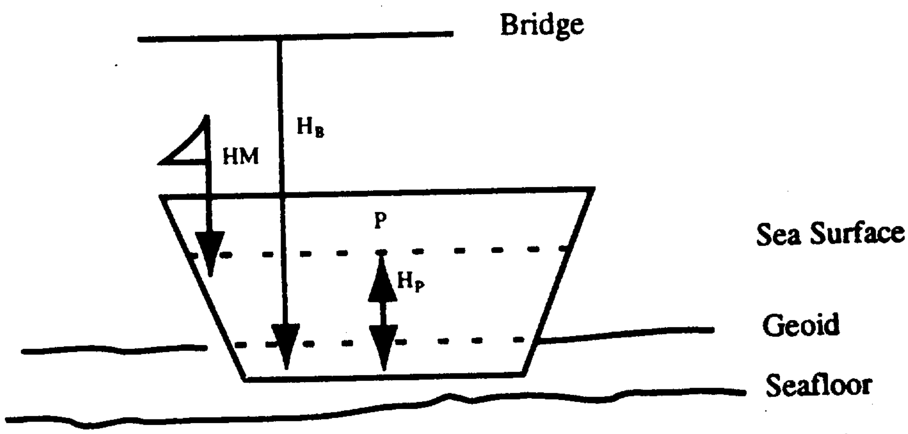


Figure 4. Surveying the Height Clearance

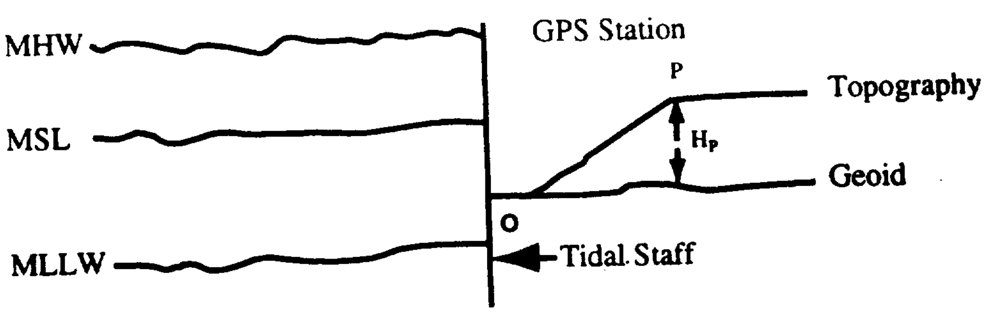


Figure 5. Surveying the Zero Height of the Tidal Staff

Table 1[1]

Tide Tables Referred to Datum of Soundings

<table>
<tr>
<td>30</td>
<td colspan="2">Tidal Levels referred to Datum of Soundings
<table>
<tr><td rowspan="2">Place</td><td>Lat</td><td>Long</td><td colspan="4">Heights in meters above datum</td></tr>
<tr><td>N</td><td>E</td><td>MHWS</td><td>MHWN</td><td>MLWN</td><td>MLWS</td></tr>
<tr><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td></td><td></td><td></td><td></td></tr>
<tr><td>MHHWO</td><td>MLHW</td><td>MHLW</td><td>MLLW</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
</table>
</td>
<td>Tabular statement of semi-diurnal or diurnal tides

Note:
The order of the columns of levels will be the same as that used in national tables of tidal predictions.</td>
</tr>
<tr>
<td>31</td>
<td></td>
<td>Tidal Stream table</td>
<td>Tidal streams referred to:
<table>
<tr><td colspan="2">Hours</td><td colspan="2">◇ Geographical Position</td></tr>
<tr><td>Before High Water</td><td>6
5
4
3
2
1</td><td rowspan="3">Directions of streams (degrees)</td><td rowspan="3">Rates at spring tides (knots)
Rates at neap tides (knots)</td></tr>
<tr><td colspan="2">High Water</td></tr>
<tr><td>After High Water</td><td>1
2
3
4
5
6</td></tr>
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</table>

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.
