VERTICAL DATUM ISSUES FOR DATA CONTINUITY FROM THE LAND TO THE SEAFLOOR

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ABSTRACT

NGA is working to develop a database approach for product generation called the Geospatial Knowledge Base (GKB). One element of this effort is long-term development of a database to include a continuous elevation surface between topography and bathymetry. This approach faces a number of major obstacles, principally related to bathymetry. This paper discusses the obstacles: local and regional datums, difficulties of tides in the 0-200 meter depth zone, inadequacies of data processing systems and possible approaches for hydrographers to build such a database over time and reasons for doing so.

BACKGROUND

It is known that measurement of water depth by lead line dates back at least to 2000 BC based on the clay model found in an Egyptian tomb of a boat with a leadsman on its bow. Certainly tides presented a navigation problem for early navigators, and it must have been apparent to them that tide had a relationship to the lunar cycle. The earliest discovered non-harmonic predictions for tide extend back to China in about 1000 AD[1].

Nearly a thousand years later, during the 1919 Hydrographic Conference that led to the formation in 1921 of the now International Hydrographic Organization (IHO), nations reported differing methods of providing tides for charts and it was concluded that no recommendations could be made at that Conference. It additionally was concluded that the various Hydrographic Departments should further study the matter.

The first meeting of the IHO Committee on Tides[2] was held during an I.H. Conference in November 1926. At this Conference, it was concluded that it was appropriate to include descriptions of tidal phenomena, such as tidal bores, in Sailing Directions but that tidal constituents should not be included in that this would radically increase the size of Sailing Directions. The United Kingdom led this argument by citing that inclusion would mean adding constituents for 10,000 ports, requiring addition of a comparable number of pages, which would be quite impossible. Since many Hydrographic Departments were already publishing separate works on tides, the nations were left complete freedom as to the means for publishing tides information and tide tables evolved as separate and unique publications.

The Committee on Tides then addressed the issue of how nations should compute tides information, i.e., harmonic or non-harmonic methods. England, the Netherlands and the IHO had been studying the use of harmonic methods. France was using harmonic methods in their overseas regions but had not yet applied them to home waters. Germany had published tide

[1] Parker, Dr. Bruce B., 2007, “Tidal Analysis and Prediction”, NOAA Special Publication NOS CO-OPS 3, pp. 7
[2] International Hydrographic Conference (I.H. Conference) Proceedings, Monaco, 1926

tables since 1920 but had no knowledge of the 1919 proposals and was unable to introduce the harmonic method. Italy reported that it had not yet used the harmonic method. Although the United States, (National Oceanic and Atmospheric Administration (NOAA), then Coast and Geodetic Survey) attended the 1926 Conference, the Conference was run with parallel sessions, and the United States only submitted documents for consideration without actually attending sessions of the Tidal Committee. However, at that time, the United States was using harmonic analysis, as Paul Schureman's "Manual of Harmonic Analysis and Prediction of Tides" had been published in 1924.

It was noted at this Conference that the Netherlands was the first nation for which seamen used harmonic constants. The Netherlands second edition publication on harmonic constants was issued in 1913. Following the 1919 Hydrographic Conference, the United Kingdom, University of Liverpool, Tidal Institute, had studied the use of harmonic constants and recommended their use at the Geodetic and Geophysics Union, which met in Rome in 1922. After a lengthy discussion, **the 1926 Conference unanimously recommended the "use of harmonic constants** by seamen for predicting the tides of ports which are not standard ports (ports with continuously operating tide gauges).[3]" This was followed by discussion of standardization of the constants such that a Dutch sailor who was used to the Netherlands method might find the same in a British Admiralty Table. The U.K. acquired the latest constituent data from Netherlands in 1924/25 and published its first harmonic tides in 1927.

Datums

During the 1926 I.H. Conference, there was discussion of use of an international low water datum for charts and tide tables. The Netherlands noted that this seemed impossible in that they had only a six-year basis of harmonic tide observations. Japan had proposed that the universal datum for reduction of soundings should be the Indian Spring Low Water. However, during the Conference there was a discussion of the problems of determining tidal constituents for shallow water bodies, and it was considered that it might require thousands of constituents to predict the residuals of shallow water tides. In fact, to date, nations such as Sweden on the Baltic Sea do not produce a tide table for the Baltic because the meteorological effects dominate over the tidal signal in this shallow water body.

As a result, Japan did not pursue discussion of its proposal for an international datum and the Conference concluded that nations should individually determine datum from direct observations. The Conference considered the wording of the 1919 Conference about use of a low water datum and with a slight modification adopted the wording in use by IHO today, i.e., "Nations should adopt a low water datum for which the values 'but seldom' would exceed those charted."

One must also consider that at this point in time nations did not know the distances between continents or far offshore islands and had no accurate method of positioning soundings beyond visual distances from shore. The horizontal error alone had a huge impact on the operational application of sounding data.

[3] I.H. Proceedings, 1926, Part III, E., Meetings of Committee on TIDES, pp. 484.

The end result of the decision to allow nations the freedom to adopt their individual vertical datum has been adoption of about 30 vertical datums of which low water datums in use by IHO Member States include[4]:

Mean Low Water Springs
Mean Lower Low Water Springs
Lowest Low Water
Mean Low Water
Lowest Low Water Springs
Approximate Mean Low Water Springs
Indian Spring Low Water
Low Water Springs
Approximate Lowest Astronomical Tide
Nearly Lowest Low Water
Mean Lower Low Water
Low Water
Approximate Mean Low Water
Approximate Mean Lower Low Water
Equinoctial Spring Low Water
Lowest Astronomical Tide
Local Datum
Lower Low Water Large Tide
Lowest Normal Tide

Other vertical datums in use by IHO:

Mean Sea Level
Mean High Water
Mean High Water Springs
High Water
Approximate Mean Sea Level
High Water Springs
Mean Higher High Water
Mean Water Level
International Great Lakes Datum 1985
Higher High Water Large Tide
Nearly Highest High Water

In general, this was acceptable when mariners only used paper charts for navigation. However, in the late 1980s after Canada and the United States (NOAA) had adopted cooperative charting, whereby one country conducted the surveys in boundary waters and the other then compiled the data, the of use of two different datums, LLWLT (or Lowest Normal Tide on some older charts) by Canada and MLLW by the United States, became an issue. At the border, on the east coast, there is a dredged channel crossing the border and it made no sense to have a "datum bump" in the middle of the channel forcing navigators to make a datum change in the middle of the channel. To resolve this problem, the United States adopted the Canadian datum for the channel, and both United States and Canadian mariners must apply Canadian tides. This data junction

[4] IHO Publication S-57, Appendix A, Chapter 2 – Attributes, Edition 3.0, Vertical Datum, Code 185.

problem exists in many areas in that tidal rivers are often the dividing line between nations, e.g., the United States-Canada boundary that is delineated between Maine and New Brunswick, where NOAA charts on MLLW junction to Canadian charts on LNT. Achieving continuity between land and two differing low water datums is a significant challenge.

Now that electronic charts are coming into wide use, mariners suddenly are using equipment that highlights the fact that regional datums are in use, i.e., depth contours between differing vertical datums are not continuous on the ECDIS (Electronic Chart Display and Information System) display. Even where nations may both be on the same low water datum, e.g., Mean Low Water, the fact that they have used different tidal epochs for the 19-year determination of their respective datum causes small differences that are now becoming of significance. The same is true for Mean Sea Level (MSL) used by nations as the vertical reference for topographic products. Again, use of differing tidal epochs causes small differences in MSL datum. These are all problems for achieving a globally continuous surface of seafloor and land topography.

Geodesists have proposed use of the geoid as the global reference surface. Satellite altimetry measured over past decades has made it possible to observe the tidal signal in the deep ocean and determine the shape of the marine geoid to better than a meter (+/- 0.25 meter) in the vertical. This immediately causes one to think that no one can know the Earth's shape more accurately than this and leads to the conclusion that the geoid should be the reference surface.

In 1993, IHO issued a circular letter asking Member States their views on use of the geoid as the global reference surface. The responses favored use of the World Geodetic System (WGS 84) ellipsoid as the reference, but IHO deferred formal adoption of the ellipsoid as a reference and noted that to support marine navigation, nations would need to continue use of a low water datum. One of the major concerns of the Hydrographic Departments was that use of the geoid as a datum would lead to periodic revision of sounding values as geodesists refine the geoid, which would result in major recompilation work. NGA once developed algorithms based on the geoid model for use in predicting bathymetry, and it was found that the dynamic variation due to tides and currents resulted in errors too great to support the production of safety of navigation products and this capability was turned off. In responding to the proposed use of the geoid, while Hydrographic Departments agreed that a stable Vertical Reference Surface for Hydrography (VRSH) was needed and that an ellipsoid orientated and fixed at a particular epoch in terms of the International Terrestrial Reference Frame (ITRF)[5] would meet this need, the Member States also opposed use of the ellipsoid as a "datum." This can be understood when one considers that the difference between the local tidal datum of an individual chart and the ellipsoid is not known with sufficient accuracy to support marine navigation, i.e., not to 2 decimeters. Additionally, ocean surface elevation varies significantly, and when three-dimensional (3-D) Global Positioning System (GPS) measurements have been used for determination of ellipsoid values, some areas are negative by as much as 100 meters, e.g., offshore of Sri Lanka and Japan, making the ellipsoid undesirable as a "datum" and illustrating the value of satellite altimetry for determination of offshore Sea Surface Topography and the computation of an improved grid of geoid heights[6].

[5] FIG Publication No. 37, FIG Guide on the Development of a Vertical Reference Surface for Hydrography, 2006
[6] "Geospatial Information & Services Maritime Navigation Handbook", Willis, Zdenka S., Goodson, James C., & Danford, Edwin O., Version 1.0, 1997.

In 1998, the IHO published the 4th edition of "IHO Standards for Hydrographic Surveys[7]" stating that tidal observations, "…should be related to a low water datum (usually LAT) and also to a geocentric reference system, preferably the World Geodetic System 84 (WGS 84) ellipsoid." At the XVIth I.H. Conference of 2002, the United States submitted a proposal (Proposal 12) regarding revision of IHO Technical Resolution A 2.5 concerning ellipsoid height determination at tidal bench marks. This proposal was referred to the IHO Tidal Committee for consideration. At that Conference, the Tidal Committee stated its support for the need for bench marks to be connected to WGS 84. In 2005, the IHO Member States approved a revision to Technical Resolution A 2.5 for ellipsoidal heights to be measured at vertical reference marks and that such observations should relate to a geocentric reference system, preferably WGS 84. Finally, in 2005, IHO published the first "Manual on Hydrography[8]", which includes a section on high-accuracy GPS observations at tidal bench marks. IHO supports reference of tidal bench marks to an ellipsoid using high-accuracy GPS measurements. However, IHO has yet to formally specify the ellipsoid and coordinate system to be used to achieve the Vertical Reference for Hydrography as needed to provide for a seamless global representation of the seafloor and the eventual uniform depiction of seafloor and land topography.

A study conducted for the Canadian Hydrographic Service, "A Seamless Vertical-Reference Surface for Acquisition, Management and Display (ECDIS) of Hydrographic Data[9]", recommends use of the Geodetic Reference System 80 (GRS 80) reference ellipsoid, as do nearly all others who study this matter. The study notes that the North American Datum (NAD 83), WGS 84 and GRS 80 ellipsoids are practically identical and that heights obtained by using each of the three ellipsoids would differ from each other by less than one millimeter. However, the report goes on to state, "The NAD 83 and WGS 84 coordinate systems, which happen to use reference ellipsoids which are identical to better than a millimetre, do not provide coordinate values which are as closely related as are the reference ellipsoid sizes and shapes. Differences in the data and observing stations used to define each of these coordinate systems will lead to discrepancies between them at the meter, rather than the millimeter, level." In view of this, the IHO needs to formally specify GRS as the ellipsoid and end use of the WGS 84 coordinate system in order for the Electronic Navigational Chart (ENC) data to be consistent on a worldwide basis.

The problem unaccounted for by those that assume that the geoid would be the best reference surface is that hydrographers carefully measure the tide in the area of a hydrographic survey and apply hydrodynamic tidal models for corrections to meet the international standards for hydrographic surveys (Publication S-44 issued by the IHO), which require that the uncertainty component resulting from tide across the survey area in navigation critical waters typically not exceed 0.2 meters. Effectively, the hydrographer creates a very accurate local tidal datum for each survey area.

Tides vary continuously along coasts due to **meteorology**, e.g., wind, barometric pressure, freezing, melting, etc.; **oceanographic effects**, e.g., currents, precipitation, heating, cooling,

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[7] "IHO Standards for Hydrographic Surveys", Publication S-44, Edition 4, April 1998.
[8] "IHO Manual on Hydrography", Publication M-13, 2005, Section 2.2.5.1.7 GPS Observations at Bench Marks, pp. 283.
[9] "A Seamless Vertical-Reference Surface for Acquisition, Management and Display (ECDIS) of Hydrographic Data", Wells, David; Kleusberg, Alfred; and Vanicek, Petr, Department of Geodesy and Geomatics Engineering, University of New Brunswick, Canada, 2004.

deflection of the Coriolis force; effect of **varying bathymetry**, e.g., 1 meter tide at New York vs. 10 meter tide in the Bay of Fundy; and **shape of the coastline**, e.g., 1-meter tide at Norfolk, Virginia and the Florida coast vs. 2 meters along the Georgia coast. While the astronomic components are predictable, it is these nearshore variations that make development of a continuous reference surface very difficult for areas where tides must be applied, i.e., in less than 200 meters water depth. It is this region where such variations cause satellite altimetry to be ineffective in determining the marine geoid.

In 1997, the IHO agreed[10] to a recommendation that Hydrographic Departments begin migration of their tide datums to Highest Astronomic Tide (HAT) and Lowest Astronomic Tide (LAT). This was a step toward more uniformity and a better junction between nations' sounding data. This still leaves certain small differences in that IHO did not recommend that nations use a common tidal epoch for computation, nor did IHO specify the method for computation of LAT. The steps agreed in 1997 by IHO improve the situation, by encouraging a common relationship through a common method of tidal computation, but do not lead to knowledge of the shape of the Earth and the development of a continuous surface of shore side topography with the seafloor. Each survey/chart is left with its own tidal reference resulting in what one NGA employee termed "lumpy data" because when one looks at a tide table and realizes that the thousands of reference stations all have differing times and heights to be applied to charts, one is faced with a myriad of hydrodynamic adjusted surfaces related to a point standard tide gauge or referenced short-term gauge. Measurement of 3-D GPS at the standard gauge sites provides the reference to the ellipsoid at that location, but to determine the relationship of the other reference sites would minimally take 3-D GPS observations at the temporary gauge sites used by the hydrographer when the survey was conducted. This approach would take decades and still result in lumpy surfaces!

Approach to Development of a Continuous Surface

When IHO developed Edition 4 of S-44, it recommended that 3-D GPS measurements be made at tidal benchmarks so as to create a common reference to the WGS 84 ellipsoid for worldwide tidal datums. This was an important first step. NOAA subsequently developed the VDatum transformation approach allowing one to transform between any datums, including all the historic datums, within a region. This approach utilizes 3-D GPS measurements at tide gauges, bathymetric data of varying datums, the local geoid, a high resolution digital elevation model, and most difficult of all, a hydrodynamic model, which could take six months to three years to develop. The resulting transformation formulae are only applicable to the local area and cannot be used in other areas. NOAA, to its credit, makes the VDatum transformations available gratis on the web for use by scientists and researchers. The United Kingdom has since begun development of VDatum transformations for the historic data sets throughout their home waters. This is a good approach where significant historic data exists along with the necessary input data. NOAA has more recently been developing means for VDatum transformation in areas where geoid information is lacking, e.g., Alaska. While transformation can be possible without the geoid input, the distance of application beyond the tide gauge site becomes limited. However, this is another important advancement for remote areas with limited gravity data.

[10] IHO Circular Letter 25/1997, Global Vertical Reference Frame, Adoption of Lowest and Highest Astronomical Tide, 13 June 1997 and revised "Resolutions of the International Hydrographic Organization", IHO Publication M-3, Resolution A 2.5, Datums and Bench Marks.

Within the United States significant bathymetric databases are maintained by several organizations: the NOAA National Geospatial Data Center (also the IHO Data Center for Digital Bathymetry) maintains all the publicly available bathymetric data; the Naval Oceanographic Office maintains grids of bathymetric data, including significant classified data holdings; the NGA Source Operations and Management Directorate (geodesy) maintains a grid of all available bathymetric data used for gravity computation; and the NGA Analysis and Production Directorate-Maritime maintains bathymetric data as individual surveys (lumpy data) for use in compilation of the NGA Digital Nautical Chart ®. NGA geodesists and bathymetrists have held Technical Exchange Meetings (TEMs) and come to agreement that bathymetric data should be referenced to the WGS 84 ellipsoid and that the multitude of worldwide bathymetric and topographic datums, including those with relatively minor differences, are becoming a problem. The end goal of these meetings was to consider means for development of a single, integrated bathymetric database. However, this consideration has revealed numerous obstacles that need to be overcome.

NGA has been developing a concept called the Geospatial Knowledge Base (GKB), and within this is a GKB-Elevation component intended to develop a continuous surface for worldwide elevation data, both topographic and bathymetric. For the marine component, there is a GKB-Eb (GKB-E bathymetry) component, and NGA has engaged two contractors to study available systems and conduct operational prototypes to determine if existing commercial systems might be capable of supporting the compilation of such a database. The effort became limited in scope from the original concept to develop a centralized bathymetric database, as discussed during the NGA Geodesy-Maritime TEMs, and is taking the initial step of investigating means for transforming the NGA Maritime Safety of Navigation holdings into a global database to include metadata that references the applicable low water datums and the WGS 84 ellipsoid where possible.

The effort has progressed beyond NGA and its contractors to include other potential users of such a database, i.e., NOAA, the Canadian Hydrographic Service and the United Kingdom Hydrographic Office. Issues identified have included:

- The need for a system that can archive global data not as a product database but as a geodetic database;
- The need for a system that can handle tracklines across ocean areas and provide global capability for display of broad area data sets;
- The need for a global system for cataloging bathymetric data both area surveys and tracklines;
- A model that includes all necessary metadata for both low water representations and reference to the WGS 84 ellipsoid;
- Capability to handle “navigation surface” data sets; and
- Capability to include VDatum transformations.

Once a system is capable of supporting the needed database, the challenges are only beginning for development of the GKB-Eb. Topographic elevation models and deep water bathymetry deeper than 200 meters will be the first data related to the WGS 84 ellipsoid through application of satellite altimetry. There are issues related to deep ocean tides and the widely spaced altimetry tracks, which repeat every few days, but the uncertainty will generally be in the range of a meter or so and does not present a problem.

The difficult issue concerns hydrographers and tidal specialists who need to relate bathymetric data in the 0- to 200-meter depth range to the WGS 84 ellipsoid. Possibilities for doing so are improving. In addition to the VDatum transformation methods developed by NOAA and being applied by several nations to relate historical data sets, the U.S. Naval Oceanographic Office[11] has achieved 3-D GPS controlled hydrographic surveys that meet the IHO S-44 standard without need for installation of tide gauges. It is not advocated that hydrographers conduct surveys without installation of tide gauges, as it is important to observe tides whenever possible. Observation of tides is essential for establishment of the low water datum and permanent tide gauges and reference station data still are required in order to provide predicted tides information in support of safe navigation. However, the U.S. Naval Oceanographic Office development is a significant step forward for relating the seafloor to the ellipsoid in addition to relating hydrography to a low water datum. That is, through use of the 3-D GPS technique, the entire survey area relationship to the ellipsoid is observed rather than relying solely on the point value of the Vertical Reference Surface at a tide gauge where 3-D GPS observations have been made. In this way, it is possible to achieve a continuous surface for the seafloor that is referenced to the ellipsoid, yet also support safety of navigation. Modern surveying supported by high-accuracy Global Navigation Satellite Systems, particularly with the emerging Internet-based models supporting wide area systems and OTF (On-The-Fly) GPS techniques, open the possibility for increased application of the techniques developed by the Naval Oceanographic Office.

The development of the capability for hydrographic surveying without tides also creates a possibility for assessment of how well vertical data is being transformed. Where VDatum has been developed, the hydrographer, using the technique developed by the Naval Oceanographic Office, could run reconnaissance lines of hydrography through the area of applicability to provide an assessment of how well the transformation is working. This could define the area of VDatum applicability as well as define areas where it is not necessary to schedule resurveys to relate data for the continuous land-water interface.

Usefulness of a Continuous Land-Water Interface

While the hydrographer and the ship navigator have not needed this in the past because their needs were satisfied by local datums for hardcopy navigational charts, there are numerous uses emerging that now need this continuity:

- Merging of adjacent electronic charts to achieve continuous contours
- Tsunami and Storm Surge inundation modeling/prediction
- Tide and current modeling
- Coastal Zone management/integrated Coastal Zone monitoring
- Improved Maritime Limits and Boundary delineation
- Amphibious operations of all types
- Improved gravity modeling

[11] Van Norden, M.F., E.N. Arroyo-Suarez, A.S. Najjar (2005), "Hydrographic Surveys to IHO Standards without Shore Stations using the Real-time Gipsy (RTG) Global Positioning System (GPS), Proceedings of the U.S. Hydro2005, March 29-31, 2005, San Diego, California, U.S.

Issues for the Future

- IHO Member States need to agree to a minor technical change to Technical Resolution A 2.5 and Publications S-44 and M-13 to specify GRS 80 as the Vertical Reference Surface for Hydrography; IHO also needs to specify use of the WGS 84 coordinate system;
- Hydrographic Offices need to place increased effort on relating the seafloor to the ellipsoid to better support seamless display for future Electronic Navigational Chart (ENC) compilations, modeling and predictions using marine/littoral data;
- In the future, time-variable predicted tides or real-time water levels should have defined areas of application, i.e., tidal experts need to provide defined polygons of the areas for tidal application;
- Marine data systems need to be enhanced to provide for better archival, display and cataloging, as outlined above;
- 3-D vertical measurements at tide gauge sites need to be incorporated into each hydrographic survey as is specified by IHO Publication S-44;
- 3-D GPS observations need to be as accurate as possible through ties to the IGS (International GPS Service for Geodynamics) stations or to regional stations that have ties to the IGS stations, and;
- Hydrographers need to change their way of thinking, i.e., chart the surface of the seafloor in addition to depth of the water in relation to a low water datum.

One of the future issues being worked on within NGA has been the use of imagery in relation to tides. There are many remote coastal areas of the world where predicted tides are not available. NOAA has been reworking its TCARI (Tidal Constituents and Residuals Interpolation) software, which provides for interpolation between tide gauges where tide gauges surround an area. NGA is working with NOAA to eventually implement this capability. This provides one of the means of improving predicted tides information between tide gauges. Use of a GPS Tidal buoy is another possibility.

Additionally, the InnoVision Directorate, the research and development component of NGA, has been studying possibilities for determination of tidal constituents or alternatively time and height differences from long-term imagery observations. This work is being conducted by the Naval Research Laboratory and to date has shown that this is a very difficult problem due to the random nature of the sampling. To date the models suggest that an image must be taken about daily over at least a year and preferably two years to resolve certain constituents like S2 and K2. Such investigations are important in that, as Canadians well know, installation of traditional tides gauges is difficult and often impractical for many remote areas.

Conclusion

Only about 5 percent of the world's oceans have been surveyed to GPS accuracy. While it will take decades for the Hydrographic Offices to create the data necessary for a seamless depiction of the seafloor, the time to start building such data bases is now. IHO Member States are seeking wider application of hydrographic data. "Lumpy data" is unlikely to satisfy this need and it is important for hydrographers to change their thinking and begin defining a seamless seafloor representation.

Biography

Rear Admiral CHRIS ANDREASEN is the Chief Hydrographer in the NGA Office of Global Navigation. He is a Civil Engineer and retired NOAA Commissioned Officer. He spent nearly 30-years with NOAA serving: in Geodesy; aboard several hydrographic survey ships; as Chief of Nautical Charting for the U.S.; and as Deputy for ships and aircraft operations within NOAA. From 1992 to 1997, he was the President of the Directing Committee of the International Hydrographic Organization. He joined NGA at the end of 1997, working in the Advanced R&D component for 5 years and has since been working in the Analysis and Production Directorate, Office of Global Navigation on maritime activities. He holds the Silver and Bronze medals of the Department of Commerce, the IHO Commodore Cooper medal, the Presidential Rank Award for Distinguished Service as a Senior Executive, the DoD Distinguished Civilian Service medal and the DoD Joint Meritorious Unit Award. He was a Department of Commerce Science and Technology Fellow, an American Congress on Surveying and Mapping Fellow and is certified by ACSM/THSOA as both Inshore and Offshore Hydrographic Surveyor. He is married, has two children and one grandchild.