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Contents

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Editorial

This edition comprises four articles and two notes. The first article from Greece discusses the merits of Satellite Derived Bathymetry (SDB) techniques and the use of this technology where traditional hydrographic surveying methods may not be cost effective or difficult to undertake.

Two articles have been submitted from the USA describing innovative open source software initiatives – ping-to-chart workflows and sound speed profiling capabilities. With so many software solutions and systems in use for hydrographic data collection and processing, it can be a challenge to maintain an open capability and not get too locked into proprietary solutions. At least with an open source code capability, users have the option to test data using their own parameters and use additional verification processes that provides a level of independence.

The final article from the UK and USA discusses the use of forward looking navigation sonar systems to improve safety of navigation and bathymetric data holdings through crowd sourcing. The article describes the technology and, provides good arguments for the adoption of this technology to be installed on various vessels, particularly those that are navigating in areas with significant white space on the navigation charts.

The Chilean Navy Hydrographic and Oceanographic Service (SHOA) has contributed a Note describing the survey and charting work required to complete the coverage of their Interior Water's Commercial Navigation Route – a significant task that will improve navigation safety and enable more vessels to use the waterway rather than navigate through open seas.

Finally, the IHO Secretariat has included a Note describing the revised IHO Convention that will operate as the IHO moves into its new structure.

I would also like to take the opportunity to congratulate Mr Juha Korhonen of Finland on his award of the Price Albert 1st Medal for Hydrography 2017 (IHO CL24/2017). Juha's achievements over many years are well known and he was pivotal in the production of the Baltic Sea Special Edition of the IHR in November 2014. A worthy recipient indeed.

On behalf of the Editorial Board, I hope that this edition is of interest to you and may inspire you to submit a future paper on the work that you have done or are currently engaged in.

Thank you to the authors for your contributions and to my colleagues who provided peer reviews for the Articles in this edition.

Ian W. Halls
Editor

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Article

SATELLITE DERIVED BATHYMETRY (SDB) AND SAFETY OF NAVIGATION.

By A. K. Mavraeidopoulos [abc] , A. Pallikaris [c] , E. Oikonomou [d]

Abstract

This paper reviews the use of Satellite Derived Bathymetry (SDB) technology to derive depths from remote sensed (RS) data and how this technology can be used to address crucial aspects of safety of navigation. The estimation of bathymetric depth using optical RS techniques has advantages and disadvantages. Using imagery techniques, depths can be determined quickly over large remote coastal areas. These areas can however consist of dangerous hazards, submerged objects and steep seabed morphology. SDB processing techniques introduces new perspectives to potentially improving safety of navigation charting. The feasibility of deriving bathymetry from remote sensed images, requires that the accuracy of such data should be evaluated and an assessed in terms of how this data can be used and depicted in nautical chart production. The parameters associated with SDB capabilities that contribute to cartographic production are further discussed and evaluated against current IHO Standards.

Keywords – Hydrography, Remote Sensing (RS), Satellite Derived Bathymetry (SDB), Cartography, ENCs, Charts, Algorithms for bathymetry extraction, IHO Standards.

Résumé

Cet article étudie l'utilisation de la technologie de la bathymétrie par satellite (SDB) afin de déduire des profondeurs à partir de données de télédétection (RS) ainsi que la manière dont cette technologie peut être utilisée pour traiter des aspects cruciaux de la sécurité de la navigation. L'estimation de la profondeur bathymétrique à l'aide de techniques de télédétection optique présente des avantages et des inconvénients. En utilisant des techniques d'imagerie, les profondeurs peuvent être déterminées rapidement sur de vastes zones côtières lointaines. Ces zones peuvent néanmoins contenir des risques dangereux, des objets immergés et comporter des fonds marins escarpés. Les techniques de traitement de la SDB introduisent de nouvelles perspectives pour une éventuelle amélioration de la cartographie pour les besoins de la sécurité de la navigation. La possibilité de dériver la bathymétrie à partir d'images de télédétection nécessite que la précision de ces données soit évaluée et analysée afin de savoir comment elles peuvent être utilisées et décrites dans la production de cartes marines. Les paramètres associés aux capacités de la SDB qui contribuent à la production cartographique font l'objet de discussions plus poussées et sont évalués par rapport aux normes de l'OHI en vigueur.

Mots clés – Hydrographie, télédétection (RS), bathymétrie par satellite (SDB), cartographie, ENC, cartes, algorithmes pour l'extraction de la bathymétrie, normes de l'OHI.

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Article

Resumen

Este artículo revisa el uso de la tecnología de Batimetría Satelital Derivada (SDB) para obtener profundidades a partir de datos obtenidos de sensores remotos (RS) y cómo esta tecnología puede utilizarse para abordar aspectos cruciales de la seguridad de la navegación. La estimación de la profundidad batimétrica utilizando técnicas ópticas RS tiene ventajas y desventajas. Usando técnicas de imágenes, las profundidades pueden determinarse rápidamente en extensas áreas costeras remotas. Sin embargo, estas áreas pueden contener amenazas peligrosas, objetos sumergidos y en una morfología escarpada del fondo marino. Las técnicas de procesado SDB introducen nuevas perspectivas para mejorar potencialmente la representación de la seguridad de la navegación. La viabilidad de la derivación de la batimetría a partir de imágenes obtenidas de sensores remotos requiere que la exactitud de tales datos sea evaluada y valorada en términos de cómo estos datos pueden utilizarse y representarse en la producción de cartas náuticas. Los parámetros asociados a las capacidades SDB que contribuyen a la producción cartográfica se discuten adicionalmente y se evalúan conforme a las normas actuales de la OHI.

Palabras clave - *Hidrografía, Teledetección (RS), Batimetría Satelital Derivada (SDB), Cartografía, ENCs, Cartas, Algoritmos para la extracción de batimetría, Normas de la OHI.*

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1. Introduction

The possibility to use satellite imagery data to generate bathymetric depths has been investigated since the 1970s. A study undertaken by the University of Michigan for the Spacecraft Project of U.S. Naval Oceanographic Office, demonstrated the successful remote determination of shallow water depth by measuring wave refraction changes and using the Fourier transform plane for wavelength measurements with data obtained at a Lake Michigan test site. This study showed that the technique is suitable, provided that water waves of suitable length occur in the region of interest (Polcyn *et al.* 1970).

In 1975, the NASA/Cousteau Ocean Bathymetry Experiment proved the usefulness of satellite bathymetry derived from LandSat MSS imagery. This joint venture proved the feasibility of detecting and mapping dangers to navigation in clear water to depths of 22m (10% rms accuracy). The processed depths were verified by the ground truth team onboard the Calypso Survey ship (Hammack, 1977). Since this study, advances in satellite technology, new techniques, sophisticated algorithms and software have all improved the potential for Hydrographic Offices (HOs) and scientists to improve the knowledge about the seafloor morphology and marine habitat conservation. Whilst SDB techniques can provide adequate data coverage, especially in remote areas and have capable object detection capability with good positional accuracy, it is not always considered that SDB methods have yet been developed sufficiently for safety of navigation purposes.

2. Conventional Hydrographic Surveys versus SDB

The International Hydrographic Organization's (IHO) definition of Hydrography (IHO, 2005) states:

"*That branch of applied sciences which deals with the measurement and description of the features of the seas and coastal are - as for the primary purpose of navigation and all other marine purposes and activities including - inter alia - offshore activities, research, protection of the environment, and prediction services.*"

The above definition does not limit scope of hydrography to the collection of bathymetric data from sea areas. It also covers delivery of reduced depths that are accurate for producing navigational products (charts, warnings, pilots, lights information, etc.) dedicated to the safety of life at sea.

The IHO's S-44 Standard (IHO, 2008) suggests that the "*minimum*" standards for conducting conventional hydrographic surveys are classified in four (4) categories, focusing in their interest to the navigation. These standards should be taken into account by agencies or surveyors when collecting data from sea areas, appropriate for safety of navigation purposes. Specifically, the suggested categories of hydrographic surveying are the *Special Order*, *Order 1a*, *Order 1b* and *Order 2* surveys (***Table 1***).

The agency responsible for acquiring surveys, should choose the most suitable order/category of survey to produce navigational products that will allow the "expected shipping" to navigate safely across the surveyed areas. However, what does the term "*expected shipping*" mean? What are the dimensions and the draft of ships which "expect" to navigate a particular sea area?

The quality measure adopted for assessing the accuracy or even better the uncertainty of the collected data is the *Total Propagated Uncertainty (TPU)*. The *TPU* is a three dimensional quantity consisted of all measurement errors (systematic and random), derived from several sources (i.e. positional errors, settlement, dynamic draft uncertainty, depth errors, latency inaccuracy, etc.) (IHO, 2008). The *TPU* comprises two components. The horizontal component of *TPU* is defined as the *Total Horizontal Uncertainty (THU)*, which

Table 1. *IHO S-44 Classification of Surveys (IHO, 2008)*

Order	Special	1a	1b	2
Description of areas.	Areas where under-keel clearance is critical	Areas shallow-er than 100 metres where under-keel clearance is less critical but *features* of concern to surface ship-ping may exist.	Areas shallower than 100 metres where under-keel clearance is not considered to be an issue for the type of surface shipping expected to transit the area.	Areas generally deeper than 100 metres where a general description of the sea floor is considered adequate.
Maximum allowable THU 95% *Confidence level*	2 metres	5 metres + 5% of depth	5 metres + 5% of depth	20 metres + 10% of depth
Maximum allowable TVU 95% *Confidence level*	a = 0.25 me-tre b = 0.0075	a = 0.5 metre b = 0.013	a = 0.5 metre b = 0.013	a = 1.0 metre b = 0.023
Full Sea floor Search	Required	Required	Not required	Not required
Feature Detection	Cubic *features* > 1 metre	Cubic *features* > 2 metres, in depths up to 40 metres; 10% of depth beyond 40 metres	Not Applicable	Not Applicable
Recommended maxi-mum Line Spacing	Not defined as *full sea floor search* is re-quired	Not defined as *full sea floor search* is re-quired	3 x average depth or 25 me-tres, whichever is greater For bathymetric lidar a spot spacing of 5 x 5 metres	4 x average depth
Positioning of fixed aids to navigation and to-pography significant to navigation. (95% *Confi-dence level*)	2 metres	2 metres	2 metres	5 metres
Positioning of the Coastline and topogra-phy less significant to navigation (95% *Confi-dence level*)	10 metres	20 metres	20 metres	20 metres
Mean position of float-ing aids to navigation (95% *Confidence level*)	10 metres	10 metres	10 metres	20 metres

which concerns the positional accuracy, while the vertical component of *TPU* is called the *Total Vertical Uncertainty (TVU)*, which is calculated in vertical dimension and related to depths accuracy.

From ***Table 1***, the maximum allowable *THU*, at the 95% confidence level, is given in certain values, while the *TVU* is a function of the reduced depth (*d*) and two (2) other parameters (*a*) and (*b*) as follows:

$$TVU = \pm\sqrt{\alpha^2 + (b \times d)^2}$$

Where:

a represents the part of the uncertainty that does not vary with depth, usually related to the system noise,

b is a coefficient which represents the portion of the uncertainty that varies with depth, mostly associated with the physics of interaction of acoustic energy propagating in water,

d is the depth,

b x *d* represents that fraction of the uncertainty that varies with depth.

Translating the S-44 standards, the main concern of a hydrographic surveyor is related to shallow or relatively shallow waters areas to 40m depth. In these depths, there is increased risk in a marine casualty leading to a marine and coastal environment disaster, impacting the marine economy of all affected States. For this reason, the most demanding category of survey is defined as the *Special Order* surveys, and must be undertaken in coastal areas where under-keel clearance is crucial to the safety of navigation (***Table 1).***

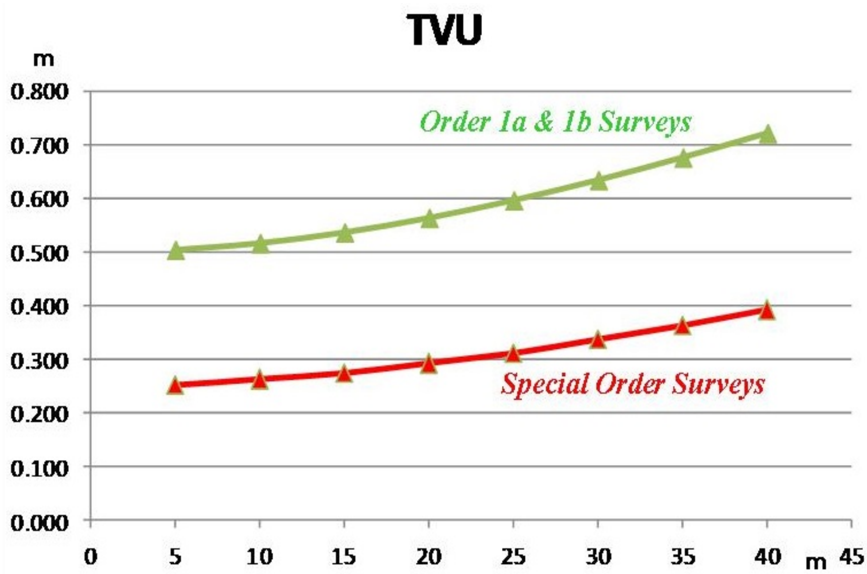

Figure 1. *Total Vertical Uncertainty (TVU) variation for Special Order, Order 1a and 1b surveys.*

Additionally, coastal areas which consist of areas shallower than 100m, often cover the majority of the waters depicted on large to medium scale charts and typically require *Order 1a* surveys. These areas are usually the approaches to ports, channels or adjacent water areas of significant importance to navigation. In these circumstances (*Special Order* and *Order 1a* surveys), total seafloor coverage of data is required.

For reduced depths of 5-40m, the maximum allowable depth uncertainty *(TVU)* should be between 0.253m - 0.391m for *Special Order* and between 0.504m – 0.721m for *Order 1a* and *Order 1b* surveys (***Figure 1***), respectively. Also, it should be noted that the capability of the survey system should be approved for the mentioned *TVU* estimation.

Despite the guidance of the IHO towards the way that hydrographers should collect bathymetric data, paper nautical charts and Electronic Nautical Charts (ENCs), do not (always) depict the depths in line with the aforementioned standards. Both products (paper charts and ENCs), whilst dedicated to the safety of navigation, are compiled from data originating from multiple sources and different systems (sensors) using various procedures, especially in shallow or remote areas. This raises the question about how the HOs prove their capacity in producing marine products with "good coverage" with such limitations. How feasible is it to update their chart portfolios, especially within the current framework of reduced capacity building?

A crucial issue for *Special* and *Order 1a* surveys, is that the survey acquisition system should have the capability to achieve 100% total seafloor bathymetric coverage. Hence, the question - how often do surveys actually satisfy this particular specification in the real world, especially in areas with steep and very irregular topography of the seabed? S-44 requires that the survey system should detect cubic features with dimensions bigger than 1m in coastal areas of category *Special Order*. For *Order 1a* areas, the bathymetric system should detect submerged cubic objects larger than 2m. In reality, how many symmetric "cubic" submerged features exist in a real seabed?

To summarize, how safe are the navigational products since they depict to some extent, "not so safe" data? A nautical chart is not a "static" product and must be updated regularly. Nevertheless, the process of surveying and updating charts quickly and at regular intervals is costly and requires significant human and equipment resources. The fact is that modern acoustic systems can collect bathymetric data with better accuracies than other technologies such as satellite imagery, due to their physics-based techniques related to the propagation and beam-forming of sound in water.

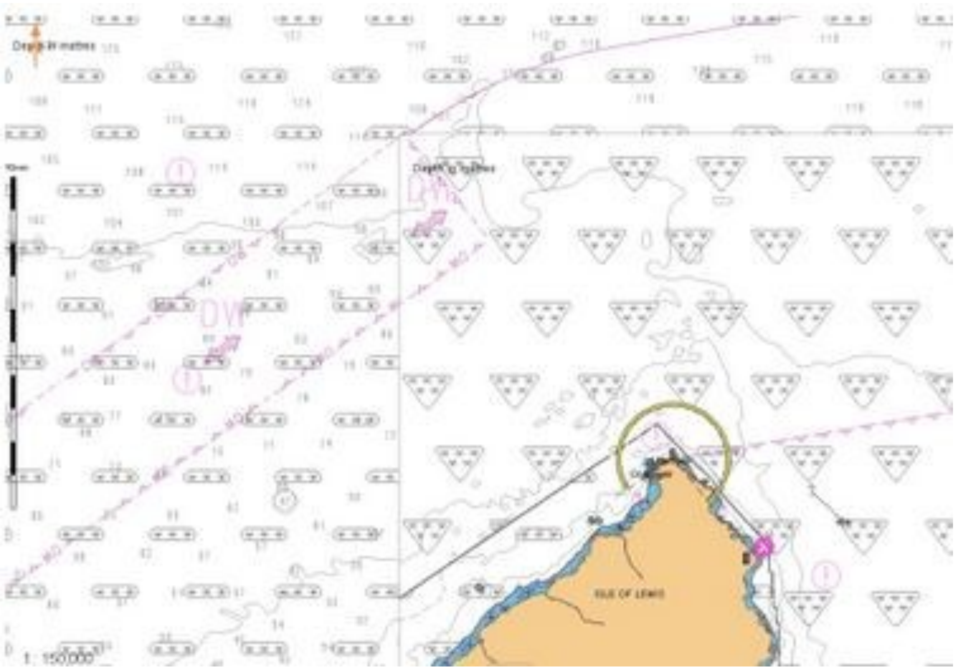

Figure 2. *ENC CATZOC portrayal in the ECDIS as a series of stars.*
(http://www.theartofdredging.com)

Despite the efforts of HOs, paper charts and ENCs do not always depict the reality as it would be desired. When the IHO developed the S-57 Standard (IHO, 2000) for the production of ENCs, a need was identified for ENCs to include quality indicator metadata called "Category of Zone of Confidence" (CATZOC). This indicator takes into consideration the horizontal *(THU)* and vertical uncertainty *(TVU)* of the hydrographic data, along with an estimation of the completeness (seafloor coverage) of the survey and combines these through an algorithm to classify bathymetry in one of five (5) categories (A1, A2, B, C, D), with a sixth category (U) for data which has not been assessed. (Geomares, 2012).

Each CATZOC can be displayed in the Electronic Chart and Display Information System (ECDIS) as a series of stars overlaid on the ENC. The greater the number of stars the better the survey (***Figure 2***). For instance four (4) stars represent a CATZOC B. However, the mariner's impression looking at the ECDIS with "stars" can be at odds when looking at the echosounder which may be indicating a different depth to that of the ENC depths. The CATZOC encoding cannot indicate and/or visualize the temporal degradation of the bathymetry. The problems discussed above will be addressed with new algorithms being implemented in the new S-101 data Model.

An alternative technique of collecting bathymetric data rapidly is by exploiting satellite imagery (Rocchio, 2016). Satellite Derived Bathymetry (SDB) is a technique based on the empirical, semi-analytical or analytical modeling of light transmission through the atmosphere and the water column. SDB offers great advantages to the planning and executing of hydrographic activities as follows (EOMAP, 2014):

- It is a cost-effective methodology, with 5-10 times reduced costs compared to the conventional hydrographic techniques.
- Provides fast bathymetry acquisition and production, in some cases the data collection and processing exceed the 1000 km^2 per month.
- High resolution up-to-date bathymetric data comes from recent imagery, with a spatial resolution of 0.5x0.5m.
- It is no more a problem to gather data from remote areas, or areas which cannot be physically accessible.
- Seabed classification maps can also be produced from coastal areas with optically sensed seafloors.
- SDB is a carbon neutral and non-destructive environmentally technique.

Although the acquisition of imagery data is not a problem today, the processing of imagery data is more complex than data collected from conventional surveys as SDB requires special treatment for processing subsurface irradiance reflectance signal ($R(0^-)$). Imagery data processing consists of atmospheric correction (i.e. 6SV, OPERA, etc.) (Vermote *et al.* 2006 and Sterckx *et al.* 2011); air-water interface corrections (Kay *et al.* 2009) and implementation of inverse optical models (i.e. HYDROLIGHT, SAMBUCA, etc.) (Mobley and Sundman, 2000 and Wettle and Brando, 2006).

The remaining signal contains the bathymetric information propagated from the seabed (***Figure 3***). Empirical or analytical-based inversion models should be applied for estimating corrections that must be used for estimating bathymetry. These models are sophisticated algorithms that retrieve the seafloor signal from the noise induced due to the interaction of radiation with atmosphere, water volume, sky and sea-surface reflected radiance. In general, water bodies reflect (as subsurface irradiance reflectance) in the range of 1% to 15% of downwelling irradiance ($E_d(\lambda)$). The majority of water bodies reflect between 2% and 6% of downwelling irradiance (Brando and Dekker, 2003). In every case, the maximum range of deriving depths depends on water clarity or in other words, the *color of the ocean* (IOPs, turbidity, etc.).

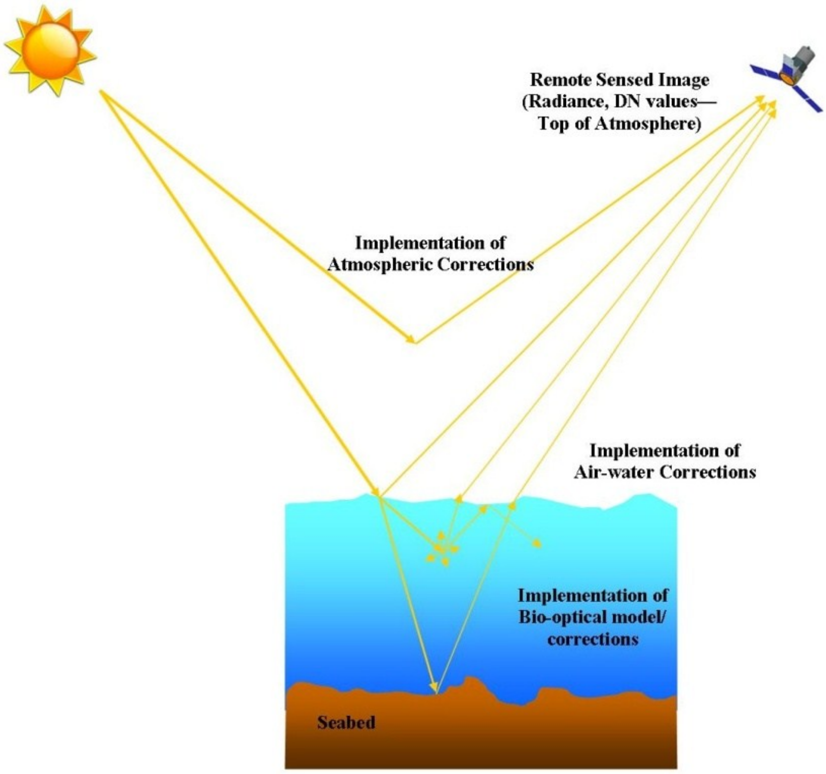

Figure 3. *Radiative Transfer Process*

Typically, depths down to 35m – 40m can be derived in clear waters such as found in the Mediterranean Sea and in particular, Greek coastal waters. Typically, the use of analytical or semi-analytical models results in more accurate depths and deeper penetration ranges. The issue that arises is, how can this data be exploited for safety of navigation products?

As the horizontal accuracy of SDB is a function of the spatial resolution of the satellite sensor used, the uncertainty contained in bathymetric data is usually of the order of 1 pixel size. For instance, if the satellite sensor has a spatial resolution of 5m, then for a 5m resolution product, the horizontal accuracy is $\leq$ 5m. Recent developments resulted in sub-meter horizontal resolution, specifically in this case 70cm spatial resolution of produced bathymetric data (Muhlbauer, 2014).

The critical issue of SDB is the achieved vertical accuracy. According to EOMAP (2014) the vertical accuracy is a function of an offset parameter equal to 0.5m and a depth-dependent factor of 10%-20%. Hence, for 10m water depths, the accuracy is between ±1.5m and ±2.5m. The depth-dependent factor depends on the Inherent Optical Properties (IOPs) of the water column and seabed texture, which means that areas with turbidity, large chlorophyll-*a* concentrations or dark colored sediments would provide larger uncertainties. Furthermore, some firms producing bathymetric data from imagery, provide pixel-based quality information on the reliability of their deliverables. When using SDB, a full seafloor search is feasible since the final product includes a continuous bathymetric model of the sea area imaged. Tests reported by Dekker et al. (2012) based on ALOS-AVNIR 10m pixel data, confirmed the calculation of a *TVU* value within IHO *1a* and *1b Order surveys* standards.

The S-44 standards do not include any particular quality procedure with respect to the bathymetric data derived from satellites. However, recently the IHO and the Intergovernmental Oceanographic Commission (IOC) provided a method (IHO-IOC, 2016) for processing and analyzing bathymetric data using imagery (Landsat) that is free and publicly available.

3. SDB Applications in Marine Cartography

Given the potential advantages of SDB, this technology is of interest to the hydrographic community and several markets including leisure crafts owners, mariners, large infrastructure construction (harbors works), marine science and technology consultancy, seismic surveying companies, and the oil & gas sector (Flemmings and Sartori, 2017). Although, the S-44 standards are intended mainly for safety of navigation purposes, chart products are widely used across a multidisciplinary market.

Several studies have been undertaken in Haiti coastal areas using Landsat and Worldview 2 imagery with encouraging results (Snyder and Maarten, 2013). Trials along the Queensland coast, Australia, using ALOS and Quickbird data, confirmed the adequacy of SDB data for use in cartographic production (Dekker *et al.* 2012). In October 2015, the UKHO published its first nautical chart - BA 2066 (Southern Antigua) (***Figure 4***) incorporating data derived from satellite sensors and in collaboration with the private sector. Likewise, the French HO (SHOM) has used satellite imagery data over the past 20 years for producing and updating their nautical charts (*Satellite Derived Charts-SDCs*). NOAA's Marine Chart Division has made SDB a prominent tool in their charting procedure, especially the Landsat 8 imagery with its new deep blue band, which uses a new and improved signal-to-noise ratio and greater dynamic range (12-bit) (Rocchio, 2016). Recently, SDB was used in the Gulf of Guinea to extract UNCLOS baselines out of the surf bordering two adjacent African states (Geomares, 2015).

In short, SDB is gaining acceptance for daily use, not only as an operational exploration tool, but as a new technique that is capable of providing calibrated and validated depths to the marine cartographer.

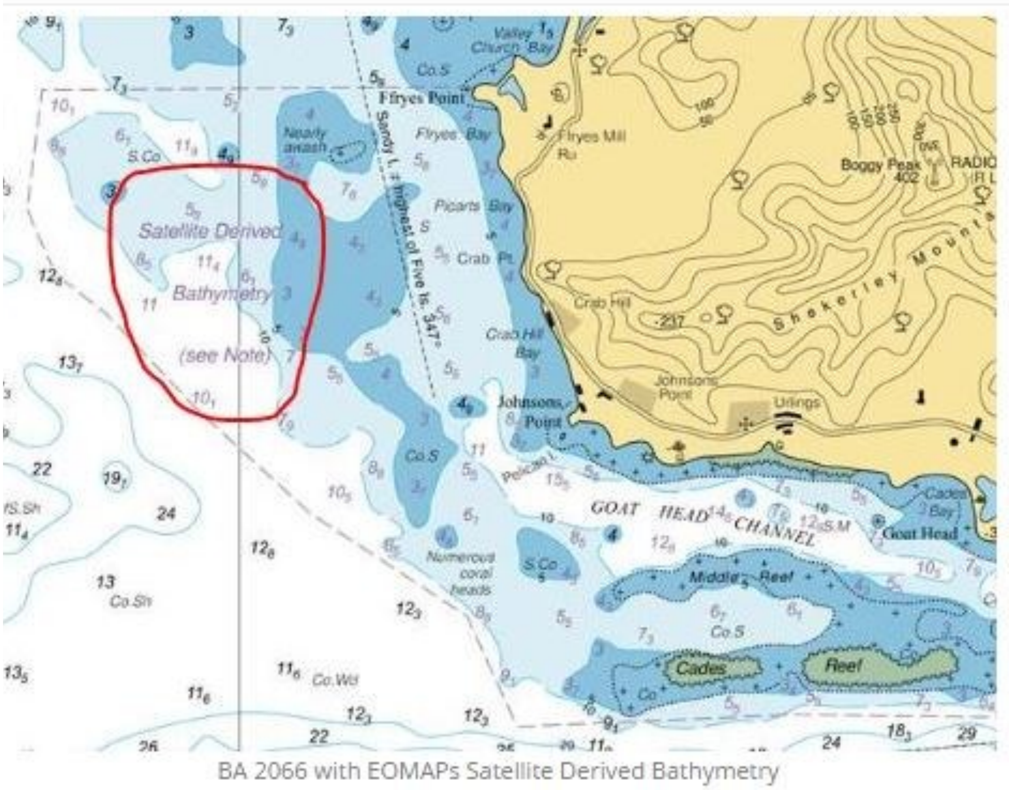

Figure 4: *Nautical Chart BA 2066, published with high resolution satellite derived shallow water bathymetry (www.eomap.com).*

4. Some Clues for Further Discussion

The global electronic cartography market can be broken into a number of Application markets *(**Figure 5**)* such as Marine - Commercial and Defense, Aviation – Commercial and Defence; Components - Systems, Charts; Marine Electronic Navigation Systems (ECDIS, ECS); Aviation Electronic Navigation Systems (Very Large Aircrafts, Wide Body Aircrafts, Narrow Body Aircrafts); Marine Electronic Charts Licensing Mode (PAYS, Direct). These markets operate across all geographic areas (i.e. APAC, Europe, North America, South America, Middle East and Africa). In all, the global market is forecasted to reach $21,267.60 million, growing with a compound annual growth rate (CAGR) of 1.46% from 2014 to 2020 (Electronic Cartography Market, 2014).

As the market demands increase and industry grows to support these markets, this drives an increased requirement for suitable hydrographic data and related nautical information - at a time when current budgets of national HOs are generally reducing. Hence, there is an urgency that is driven by the market, to meet its needs with reliable and up-to-date cartographic products over large sea areas. SDB is a relatively mature technique and due to its advantages, can contribute to safety of navigation issues. Further, imagery can provide surveyors with precise topographic data (i.e. coastlining, positioning of conspicuous points, etc.), bathymetric and benthos information and seabed sediment estimation, all of which are fundamental marine cartography features.

Obviously, the lack of up-to-date hydrographic data over huge regions with dynamic and changing shallow waters can be treated with fast and reliable SDB data, in conjunction with Satellite Positioning Systems (GNSS) and Satellite Communication Services. The aforementioned key elements expect to enhance the cartographic availability and safety of navigation procedures in future. Space-based, value-added technology, can provide the hydrographic community with trustworthy data (Lauzer, 2016). SDB will not substitute conventional hydrographic survey systems and methods, but as it is a "different" technology, it can be used as a complementary product to conventional survey data, satisfying *Order 1a* or *1b* IHO standards. The encoding and visualization of SDB with quality indicators is an important aspect of the use of SDB and the user's interpretation of bathymetric data quality. In certain circumstances, SDB techniques can also be used to provide reconnaissance information for follow-up survey tasks (Pe'eri *et al.* 2013).

Regardless of the abovementioned comments, it is crucial that further validation and research is undertaken to ensure that the SDB capability satisfies the accuracies specified in S-44.

Figure 5. *Marine Electronic Chart Market covers the needs of different applications, and users such as international shipping, leisure boats etc..*

5. Conclusions and proposals

Coastal environments are the most dynamic and constantly changing areas of the globe. Monitoring and depicting these rapidly changing environments on charts is critical to the safety of navigation where they relate to near-shore constructions, harbors, pipelines and other crucial infrastructures in the coastal zone or shallow off-shore areas. HOs strive to regularly survey and maintain their navigation products in coastal areas that often require *Special Order* and *Order 1a* surveys. As with all survey techniques, it is possible to gather data of varying quality using conventional surveys or SDB techniques. SDB has the potential to provide a key solution to updating charts of coastal waters that experience rapid seabed changes and in areas where little or no existing hydrographic data exists. Publications such as the IHO/IOC GEBCO Cook Book, provides a good introduction to implementing SDB data into a nautical chart production line, but it is only the start. Considering the potential advantages of satellite remote sensing for aiding the marine economy, the IHO is encouraged to continue to develop policy for the technical aspects and quality standards for adopting SDB data in navigational products.

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Article

AUTOMATED TOOLS TO IMPROVE THE PING-TO-CHART WORKFLOW

By M. Wilson [1], G. Masetti [2] , B.R. Calder [2]

Abstract

The review of hydrographic and cartographic data sets is still too often based on tedious and error-prone manual actions; however, these same characteristics make the work suitable for automation. As such, a software suite of task-specific solutions was developed to support the reviewer. The specific application of these tools to NOAA Coast Survey specifications as a case study highlighted improved quality, timeliness, and user confidence in the reviewed data, and provided a training resource for new personnel. Finally, the tools drove the algorithmic interpretation of agency specifications that can establish the foundation for a fully automated workflow.

Résumé

L'examen des lots de données hydrographiques et cartographiques repose encore trop souvent sur des actions manuelles fastidieuses et sujettes aux erreurs ; néanmoins, ces mêmes caractéristiques rendent le travail approprié à l'automatisation. A ce titre, une suite de logiciels proposant des solutions spécifiques à chaque tâche, a été développée à l'appui des travaux de l'examinateur. L'application spécifique de ces outils pour les spécifications relatives au service des levés côtiers de l'administration océanique et atmosphérique nationale (NOAA), en tant qu'étude de cas, a mis en exergue une qualité, une rapidité et une confiance des utilisateurs supérieures dans les données examinées, et a constitué une ressource pour la formation du nouveau personnel. Enfin, ces outils ont fourni l'interprétation algorithmique des spécifications de l'agence susceptible d'établir la base d'un processus entièrement automatisé.

Resumen

La revisión de las colecciones de datos hidrográficos y cartográficos sigue basándose demasiado a menudo en acciones manuales tediosas y expuestas a errores. Sin embargo, estas mismas características hacen que el trabajo sea adecuado para su automatización. Como tal, un paquete de programas de soluciones a tareas específicas fue desarrollado para apoyar al revisor. La aplicación específica de estas herramientas a las especificaciones de Coast Survey de la NOAA como estudio de caso destacó una calidad mejorada, una pertinencia y una confianza del usuario en los datos revisados, y proporcionó un recurso de formación para el nuevo personal. Finalmente, las herramientas dirigieron la interpretación algorítmica de las especificaciones de la agencia que pueden establecer la base para un flujo de trabajo totalmente automatizado.

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1. Introduction

Tedious and monotonous tasks are common in hydrographic data processing and nautical documentation update. If left to surveyors and cartographers to complete manually, these tasks are a poor use of human time, and the monotonous nature of the work is especially conducive to human error. These tasks typically arise when applying the very particular specifications of a hydrographic office (HO) to vast amounts of data. However, since many of these requirements are by design objective and quantitative, it is straightforward to interpret them algorithmically, and the monotonous nature of some actions performed by the reviewer makes them suitable for automation. This shift has the benefit of increasing accuracy and reproducibility due to the reduction of subjectivity and human errors, as well as faster overall ping-to-chart times. In addition to the benefits of efficiency, and improved data quality, the ability to provide algorithmic interpretation of specific requirements for hydrographic processing and cartographic generalization is an important step towards a fully automated workflow.

Having this kind of automation implemented in stand-alone tools – agnostic as to the underlying processing software – provides significant advantage: by acting like agents that inspect data products in their entirety, they help to increase confidence in the survey data. However, to enable these quality-control (QC) tools, the data created by the processing chain must be algorithmically accessible. The ocean mapping community has two existing popular open-source formats that facilitate this: the Open Navigation Surface Bathymetry Attributed Grid (BAG) format (Calder et al., 2005) for gridded bathymetric data, and the International Hydrographic Organization (IHO) S-57 format (IHO, 2000) for vector features. Additional proprietary data formats can be added, avoiding translation steps, so long as the manufacturer provides some access library.

The **QC Tools** package, described here, implements these ideas (Wilson et al., 2016). Written in Python (Python Software Foundation, https://www.python.org/), **QC Tools** are flexible, and Python's popularity in the scientific community may encourage engagement and additional development. Since it uses a highly modularized environment, each component of **QC Tools** can be easily customized (or even substituted) to meet agency-specific requirements without dependence on a software package-specific solution. To facilitate its implementation, **QC Tools** uses the HydrOffice (https://www.hydroffice.org/) project, a collaborative effort led by the Center for Coastal and Ocean Mapping (CCOM/JHC) to make available and easily accessible, several libraries likely to be useful in the construction of ocean mapping tools.

2. Common Challenges Conducive to Automation

A ping-to-chart workflow consists of many steps, each of which will usually require some level of user intervention. To avoid spreading user effort across all the data equally, a fundamental idea developed in the last decade is to prioritize areas of intervention and focus only on the data that requires remediation. In this mold, **QC Tools** considers bathymetric grids and feature files, which are now typical final products of a survey, and provides tools to address problems, which are common to these data products, irrespective of the particular hydrographic office (HO) specifications in force for a particular survey.

- *Fliers, Holidays, and Grid Data Quality Metrics*

Anomalous grid depth data, commonly described as "fliers", result when spurious soundings affect gridded bathymetry. Traditional methods of flier identification include 3D-viewers, shoal-biased sounding selections, and close examination of various grid metrics. However, these methods are far from foolproof, and it is quite common for fliers to be missed during a manual review. In 2015, it was reported that nearly 25% of the surveys received by the NOAA Hydrographic Surveys Division (HSD) were affected by fliers (Gonsalves, 2015). This perhaps should not be surprising. Even with 3D-views and statistical representations of grid nodes, it appears to be unreasonable to expect a human reviewer to have definitively identified all the fliers that might reside in grids that routinely consist of several millions of nodes. Some degree of automation to scan through the nodes would aid reviewers by flagging anomalies they may have missed, especially those of lesser magnitude, which are more difficult to detect manually.

Similarly, inspection to ensure that no grid data gaps or "holidays" exist is a task that is tedious to complete manually, and reviewers missing these also appears to be common. Given clear definitions of what constitutes a grid data holiday, it is possible to automatically scan for potential standards violations. Additionally, a review of "designated" soundings in a grid (i.e., soundings manually tagged by the reviewer as significant) may be required, for instance where HO specifications may exist to govern their proper use, or even to prevent their overuse. Such specifications often require tedious vertical or horizontal measuring by the reviewer, which can be easily and quickly accomplished by automated routines.

Finally, specifications from a HO might define statistical metrics for a bathymetric grid; for example, that the data density or uncertainty meets certain limits. Manufacturer-specific software solutions can compile many such metrics, but such solutions cannot be easily customized to follow HO specifications that may change year to year, or HO to HO. Automated routines created in-house can be tailored to the exact specifications which can provide an appropriate "pass" or "fail" indication to the reviewer.

- *Feature Validation*

Manual data entry (and the review of these entries) of mandatory attribution of feature objects can be extremely tedious, error-prone, and time consuming. Ensuring adherence to a multitude of rules and best practices that govern the proper cartographic attribution of the feature objects is similarly monotonous work. Many of these requirements are mechanical and therefore conducive to automation. Tests can be added, for example, to provide simple safeguards against attribute redundancy, or more complex use of contours and depth areas to validate attribution.

Numerous manufacturer-specific approaches to S-57 validation exist. The ability for an HO to develop specific validation tests is available in some systems – often the same as the production system. Alternatively, the HO will have to contract the manufacturer to develop them. In most cases, however, the HO uses several different software solutions to achieve an independent QC solution that covers all test scenarios. The structure of HydrOffice permits HO-specific feature validation checks (previously left to the human reviewer) to be algorithmically performed. For example, a common task is ensuring those feature objects that have the S-57 attribute VALSOU ("value of sounding") match the gridded bathymetry with respect to depth and position. This is simple for small numbers of features, but becomes not only tedious but a major waste of human resources as the feature-count increases. Automated checks can scan the gridded bathymetry to ensure that the grid and attributes are consistent.

- *Sounding Comparisons*

Throughout the charting process, it is often necessary to compare sounding selections. Generally, one set is a dense selection from the current survey, and the other is the older, sparse set of soundings and features that are currently charted. Sounding selections may be compared to quickly identify shoals and dangers to navigation not adequately represented in the current chart, or to validate a prospective set of new chart soundings with respect to the dense survey soundings from which it was derived, ensuring it adequately represents the most significant shoals from the dense selection. Since a dense selection of survey soundings routinely consists of tens of thousands of soundings, which are intended to supersede the hundreds of chart soundings, it is not reasonable to expect a reviewer to manually review all of the potential dangers to navigation, or shoals otherwise not well represented. Some degree of automation is critical for verification and to ensure no shoal points were missed.

3. Case Study: NOAA Coast Survey Workflow

The survey specifications and in-house best practices of the NOAA Office of Coast Survey have been used as a pilot study to guide the implementation of HydrOffice **QC Tools** in addressing the QC checks outlined previously. **QC Tools** provides an algorithmic interpretation of Coast Survey specifications (NOAA, 2016a), which can easily be adjusted as these specifications are revised. The tools can also be used to train new personnel: problems identified in the grid or feature data can aid the user to better understand HO specifications and their interpretation.

The **QC Tools** interface (***Figure 1***) has separate tabs for (reading from left to right on the top of the frame): Survey Review, Danger to Navigation scanning, Chart Review, and an information tab that includes a user manual, license information, etc. The Survey Review tab is shown here and has functions to (reading from left to right on the bottom of the frame): import data, detect anomalous grid data "fliers", detect grid data "holidays", ensure requirements for grid sounding density and uncertainty have been achieved, scan selected designated soundings to ensure their significance, implement an agreement check to ensure consistency between grids and features, and an export function for seabed area characteristics.

- *Grid Review Automation*

The first sub-package, "Detect Fliers" (***Figure 2***), automatically searches for anomalous depth values in dense gridded datavia five separate algorithms, some of which require an estimated search height. This search height may be derived automatically, based on the median grid depth, depth variability, and grid "roughness", and used for detection such that a relatively flat seafloor in shallow water would have a small detection height (making the algorithm sensitive to potential anomalies), whereas a deep water survey in a very dynamic area would have a large detection height to find the worst anomalies while guarding against excessive false positives. Automatically estimating an anomaly height has the benefit of standardizing this process throughout the various levels of review; it is still possible, although not recommended, to manually set the detection height.

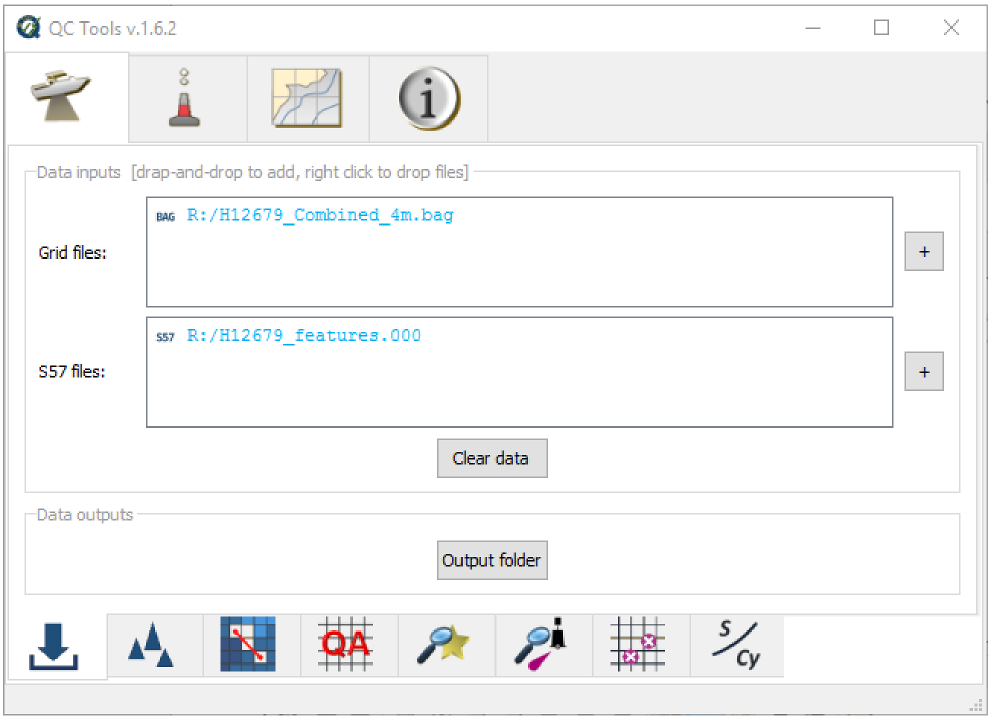

***Figure 1**: HydrOffice QC Tools interface*

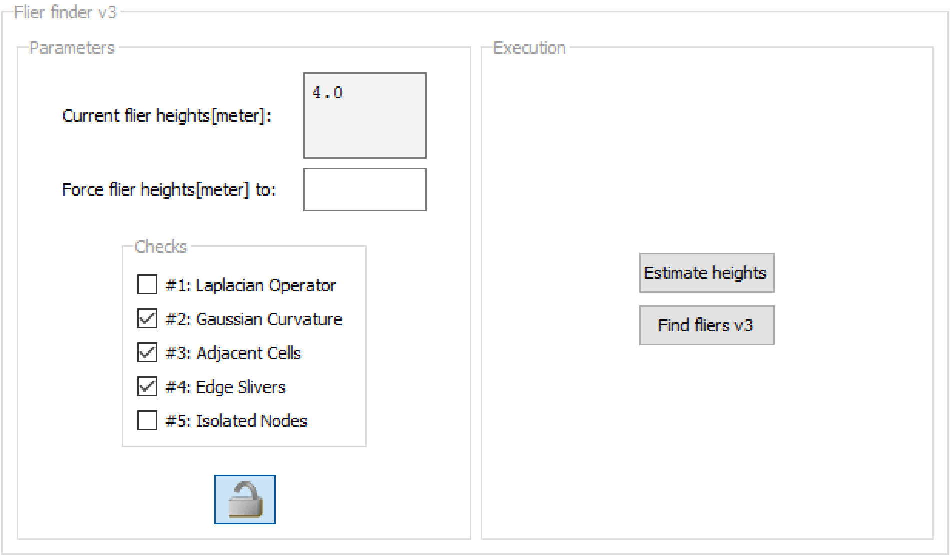

Figure 2: *QC Tools Flier Finder.*

Typical problems in a grid include shoal or deep spikes (***Figure 3***), isolated nodes occurring along grid edges, or nodes detached from the grid altogether; separate algorithms were developed to identify these. The given algorithms may be enabled or disabled for customized flier search and identification. Algorithms 1-3 use various means to detect shoal or deep spikes in the grid, whereas algorithm 4 finds fliers on grid edges (common in sparse data), and algorithm 5 detects isolated nodes detached from a grid, which are often hard to detect manually.

An estimated height for the fliers is derived automatically, based on the median grid depth, depth variability, and grid "roughness", and used for detection such that a relatively flat seafloor in shallow water would have a small detection height (making the algorithm sensitive to potential anomalies), whereas a deep water survey in a very dynamic area would have a large detection height to find the worst anomalies while guarding against excessive false positives. Automatically estimating an anomaly height has the benefit of standardizing this process throughout the various levels of review; it is still possible, although not recommended, to manually set the detection height.

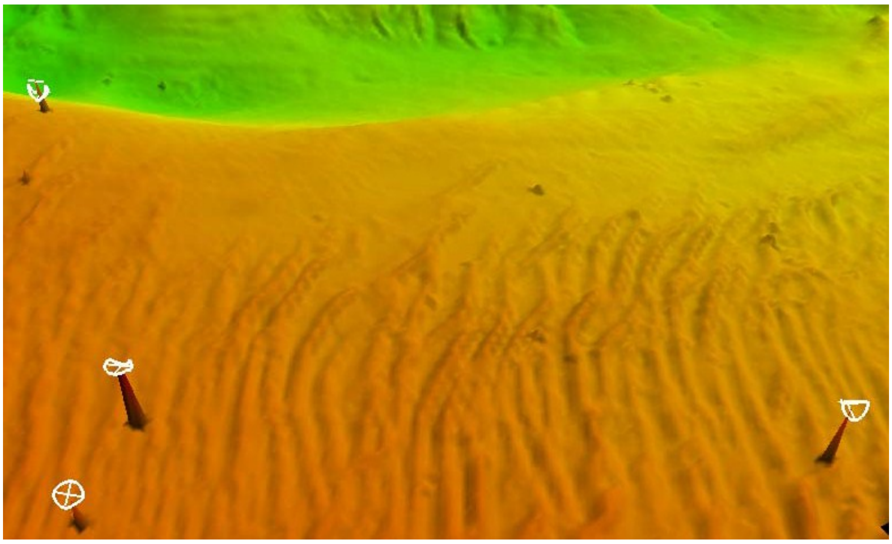

Figure 3*: The output of QC Tools Flier Finder is an S-57 layer (white targets) that the user may overlay on a grid to isolate the anomalous data fliers. Shown here is a grid and S-57 output layer in 3D view.*

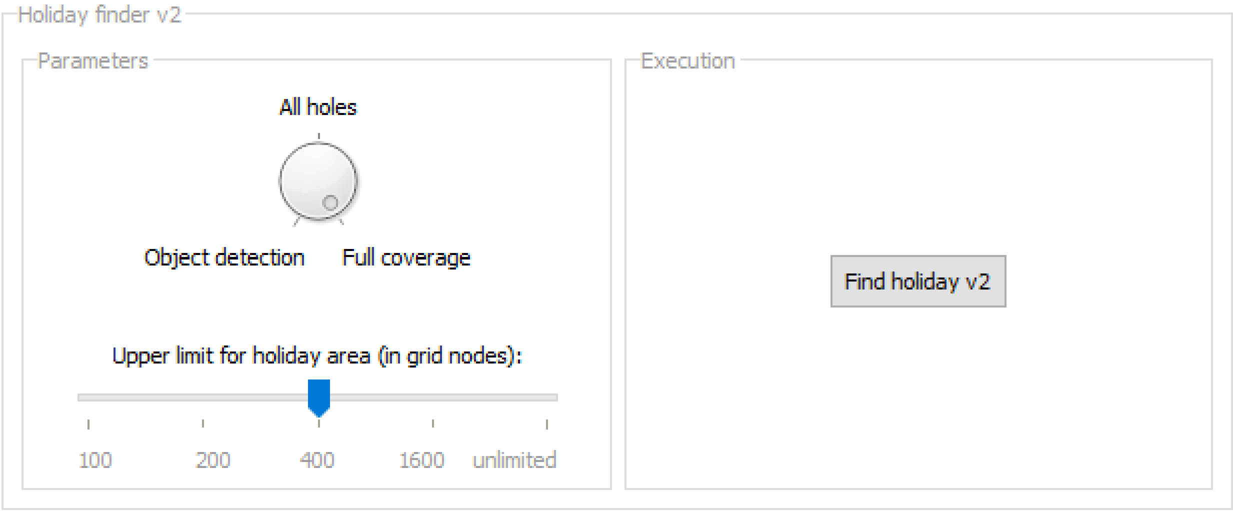

Figure 4: *QC Tools Holiday Finder can be customized to HO specifications.*

"Detect Holidays" (***Figure 4***) scans for (one or more) unpopulated nodes, or "holidays". Parameters may be set such that all holidays are identified, regardless of their size, or so that just those holidays defined by specification are detected. In Coast Survey, holidays are defined by multibeam echosounder coverage requirements.

Data density and uncertainty requirements are also specified (NOAA, 2016a), and "Grid QA" identifies areas failing these metrics. The output shown in ***Figure 5*** plots the ratio of computed uncertainty to allowable uncertainty, summarized over all grid nodes. The red space exceeds tolerance according to Coast Survey standards; in this case, more than 99.5% of the nodes meet the specification. The evaluation criteria can be easily adjusted to meet any specification.

Finally, "Scan Designated" validates the hand-selected soundings (considered to be hydrographically significant by the data processor) against the grid according to Coast Survey specifications to ensure their significance. In all cases, any discrepancies are automatically highlighted for the reviewer.

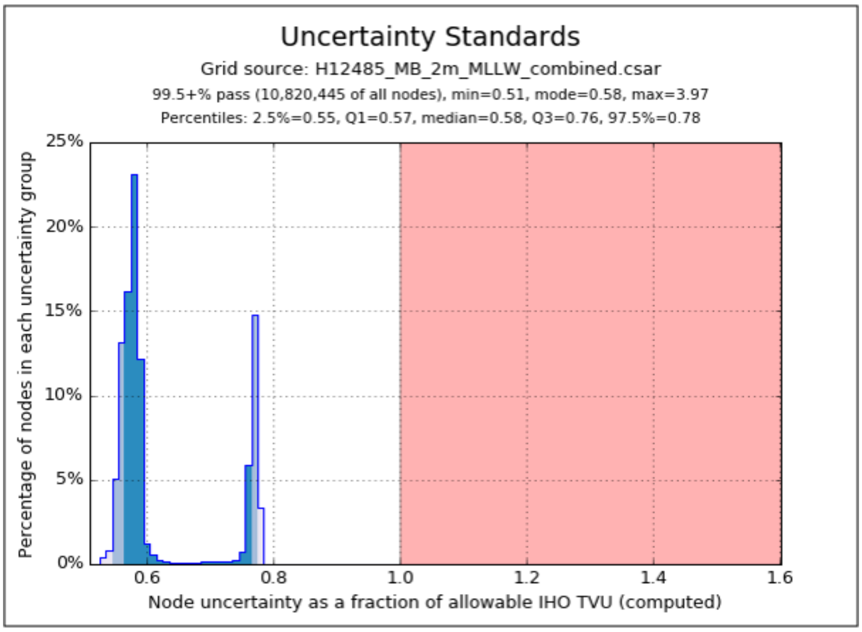

Figure 5: *One of several output plots from QC Tools Grid QA.*

- *Feature Review Automation*

QC Tools provides a "Scan Features" module, which has required S-57 attribution checks coded per hydrographic requirements (NOAA, 2016a), and a separate test to meet cartographic requirements (NOAA, 2016b), which are used at different points along the charting process. User parameters allow for further customization based on whether field or office review is being conducted, or which year of the specification is to be applied. The "Check VALSOU" module scans the gridded bathymetry to ensure a grid node is found for each feature object, and that the depth and position of the grid node match (to a specified precision) that of the feature's VALSOU attribute and declared position.

- *Sounding Comparison Automation*

QC Tools implements a longstanding best practice in Coast Survey for comparison of sounding sets. Informally called the "Triangle Rule", this algorithm builds a triangulated irregular network (TIN) (*Figure 6*) from existing chart soundings and features (in black), then matches the dense set of survey soundings (in blue) within the triangles of the TIN; any survey sounding shoaler (in red (high priority) and beige (lower priority)) than any of the three vertices of its containing triangle is marked as a potential problem. The **QC Tools** implementation also computes the magnitude of the discrepancy against the chart and adds it as an S-57 attribute, allowing the identified soundings to be sorted. In this manner, the most significant discrepancies (and potential dangers to navigation) are identified immediately. The Triangle Rule, as a method of sounding comparison, has two implementations in **QC Tools**, one to be used during survey review as a quick identification of dangers to navigation, and one to be used during chart review as a method of validating a prospective chart sounding selection prior to its application.

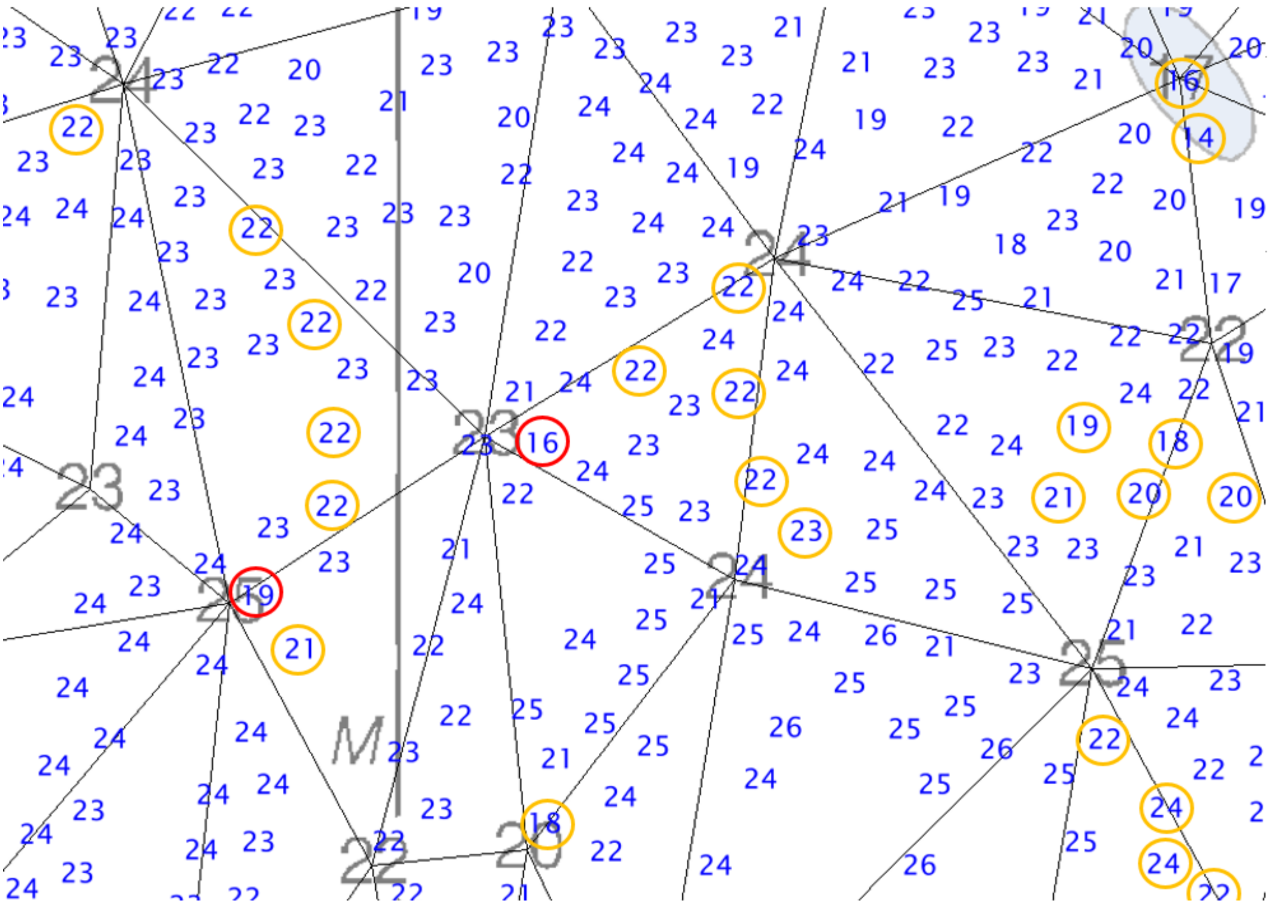

Figure 6: *Example of the Triangle Rule applied to real data.*

4. Conclusions

QC Tools highlighted several common challenges in the charting workflow. These are illustrated in the Coast Survey processing and validation chain, but are generically applicable to other HOs. The modular software architecture of HydrOffice eases the customization of tools to a specification, as the code describing the specification is largely separate from the graphical user interface and so is easily modified or replaced. For the same reason, the specifications implemented are easily updated as they evolve. **QC Tools** provides an alternative to relying on software manufacturers who may be unable, or unwilling, to accede to requests for customization of their software for a particular HO's requirements.

Instead of attempting to replace large portions of a standard workflow with a monolithic application, **QC Tools** adopts a divide-and-conquer approach that focuses on the most time critical and error prone steps, as discovered through user experience and feedback. By design, **QC Tools** will not now, or in the future, substitute an existing processing chain, but is intended to be complementary to it, providing valuable (even critical) supplementation of operator assessment with automated scanning over large data sets.

The results in Coast Survey are quite positive, with the project receiving enthusiastic feedback from field users. Recent observations have cited an increase in Coast Survey data quality and timeliness, in part attributed to the field implementation of these tools (Evans, 2017). Use of **QC Tools** instills confidence that survey products have been thoroughly reviewed, and that they adhere to specifications. **QC Tools** can also be used as a training tool for HO-specific requirements for new hires.

Finally, **QC Tools** inherently provides algorithmic interpretation of HO specifications, making them available for future tools and further automation. Having a solid base of version-controlled algorithms allows for stable expansion to further automation in the future.

5. Acknowledgments

The authors would like to thank NOAA Coast Survey and UNH CCOM/JHC for actively supporting new products and innovation. We also acknowledge NOAA users for their endless enthusiasm in testing and providing feedback to improve HydrOffice **QC Tools**, and to the Coast Survey Hydrographic Systems and Technology Branch for the help in the integration within their software distribution. This work was partially supported by NOAA grants NA10NOS4000073 and NA15NOS4000200.

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Article

SOUND SPEED MANAGER:

An open-source application to manage sound speed profiles

By G. Masetti [1], B. Gallagher [2] , B.R. Calder [1] , C. Zhang [2], M. Wilson [3]

Abstract

The execution of a modern survey using acoustic sensors cannot overlook an accurate environmental characterization of the water column. In particular, the selected sound speed profile is critical for ray tracing, while knowing the temperature and the salinity variability is crucial in the calculation of valid absorption coefficients.

Built on decades of experience and feedback from hydrographic surveyors, **Sound Speed Manager** provides a streamlined workflow that guides the user to perform accurate processing and management of sound speed profiles. Developed following criteria of simplicity of use, robustness of results, and openness of the chosen solutions, **Sound Speed *Manager*** *is a ready-for-use but customizable application, with a long-term support plan, made freely available to the hydrographic community under an open source license model.*

Résumé

L'exécution de levés modernes à l'aide de capteurs acoustiques ne peut pas se dispenser d'une caractérisation environnementale exacte de la colonne d'eau. En particulier, le profil de vitesse de son sélectionné est un élément critique du tracé des rayons, de la même manière que la connaissance de la variabilité de la température et de la salinité est indispensable pour le calcul de coefficients d'absorption corrects.

Sur la base de dizaines d'années d'expérience et des retours des hydrographes, **Sound Speed Manager** fournit un processus optimisé qui guide l'utilisateur afin qu'il soit en mesure de traiter et de gérer de manière précise les profils de vitesse du son. Elaboré selon des critères de simplicité d'utilisation, de robustesse des résultats, et d'ouverture aux solutions choisies, **Sound Speed Manager** est une application prête à l'emploi mais personnalisable, associée à un plan de soutien à long terme, mise gracieusement à la disposition de la communauté hydrographique sous un modèle de licence open source.

Resumen

La ejecución de un levantamiento moderno utilizando sensores acústicos no puede pasar por alto una caracterización ambiental precisa de la columna de agua. En particular, el perfil de la velocidad del sonido seleccionado es crítico para el trazado de los haces, mientras que el conocimiento de la temperatura y de la variabilidad de la salinidad es crucial en el cálculo de los coeficientes de absorción válidos.

Creado basándose en décadas de experiencia y de contribuciones de hidrógrafos, el **Administrador de la Velocidad del Sonido** proporciona un flujo de trabajo dirigido que orienta al usuario para que pueda ejecutar un proceso preciso y administrar los perfiles de la velocidad del sonido. Elaborado siguiendo criterios de simplicidad en su uso, solidez de los resultados, y una apertura de las soluciones elegidas, el **Administrador de la Velocidad del Sonido** es una aplicación lista para su uso pero personalizable, con un plan de asistencia a largo plazo, disponible gratuitamente para la comunidad hidrográfica bajo un modelo de licencia de fuente abierta.

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1. Introduction

For the last few decades, hydrographic surveyors have adopted a variety of partial, manufacturer-specific, and hand-made solutions to prepare the sound speed profiles for use in acquisition and post-processing applications. Far from optimal, this approach carries a number of disadvantages like being error prone and inconsistent among different sound speed profile systems. Practically, the requirements for a modern survey using acoustic means cannot overlook the accurate environmental characterization of the water column. Approximate or erroneous characterization heavily affects all survey products from the bathymetry and backscatter mosaic through the water column imagery. The sound speed profile is critical for ray tracing, whilst the temperature and the salinity variability through the water column is crucial in the calculation of realistic absorption coefficients.

NOAA Coast Survey has developed over the years, for internal use, a series of applications (the latest one named Pydro Velocipy) to perform the sound speed profiling task and other agency-specific quality control functionalities. In 2012, UNH's Center for Coastal and Ocean Mapping (CCOM), through the NSF-founded MAC (Multibeam Advisory Committee) project, developed SVP Editor. This application was officially adopted by the University-National Oceanographic Laboratory System (UNOLS) vessels to homogenize the use of sound speed for multibeam acquisition across the fleet (Beaudoin et al., 2011; Johnson et al., 2012). In 2014, the original MAC application evolved into HydrOffice SSP Manager that, among other improvements, enriched the SVP Editor functionalities with a relational database to provide data persistency, and to track the changes applied to the imported raw values.

In 2016, NOAA Coast Survey and CCOM decided to collaborate on the joint development of an open-source application to provide a long-term and reliable solution for sound speed profile processing and management known as **Sound Speed Manager**. Among the many advantages of such a move, the merge of the many overlapping functionalities between Velocipy and SSP Manager provides a simplified, single, feature-rich application with a larger community of users, a long-term support plan, and accommodation of the operational and scientific needs of both NOAA and UNOLS. Since inception, the main aim of the joint development has been to create an application that fulfills the accuracy and validity requirements of a modern survey workflow. In January 2017, after a few months of testing, **Sound Speed Manager** was officially deployed to be used as an official tool for the 2017 field season by NOAA vessels (Gallagher et al., 2017), and is available for use by the UNOLS fleet.

2. Main application functionalities

Sound Speed Manager reads data collected in various formats from CTDs, velocimeters, Expendable Bathythermographs (XBT), Moving Vessel Profilers (MVP) etc. The user can enhance the profiles (e.g., extension from oceanographic atlases) and export the processed data in formats that are ready to be used by commonly used hydrographic (acquisition and processing) applications. As shown in ***Figure 1***, when a new cast is imported, **Sound Speed Manager** presents an intuitive, but feature-rich interface that guides the user through the processing steps required to deliver an enhanced profile to the acquisition system. In this specific example, an XBT cast is imported. In the right pane, the single salinity value stored in the cast (in solid blue) is shown, but is expected to be substituted by the model-retrieved salinity (in dashed orange). This operation also triggers the recalculation of the sound speed values.

3. Input data sources

Sound Speed Manager currently supports raw data formats used by the most common sound speed, XBT and CTD probes (e.g., Castaway, Digibar, Seabird, Sippican, Sonardyne, Turo and Valeport). It also supports network reception of data currently from Sippican and MVP systems. ***Figure 2*** shows the "Import file" section listing the file formats that **Sound Speed Manager** recognizes. The "Retrieve from" section provides buttons to retrieve the

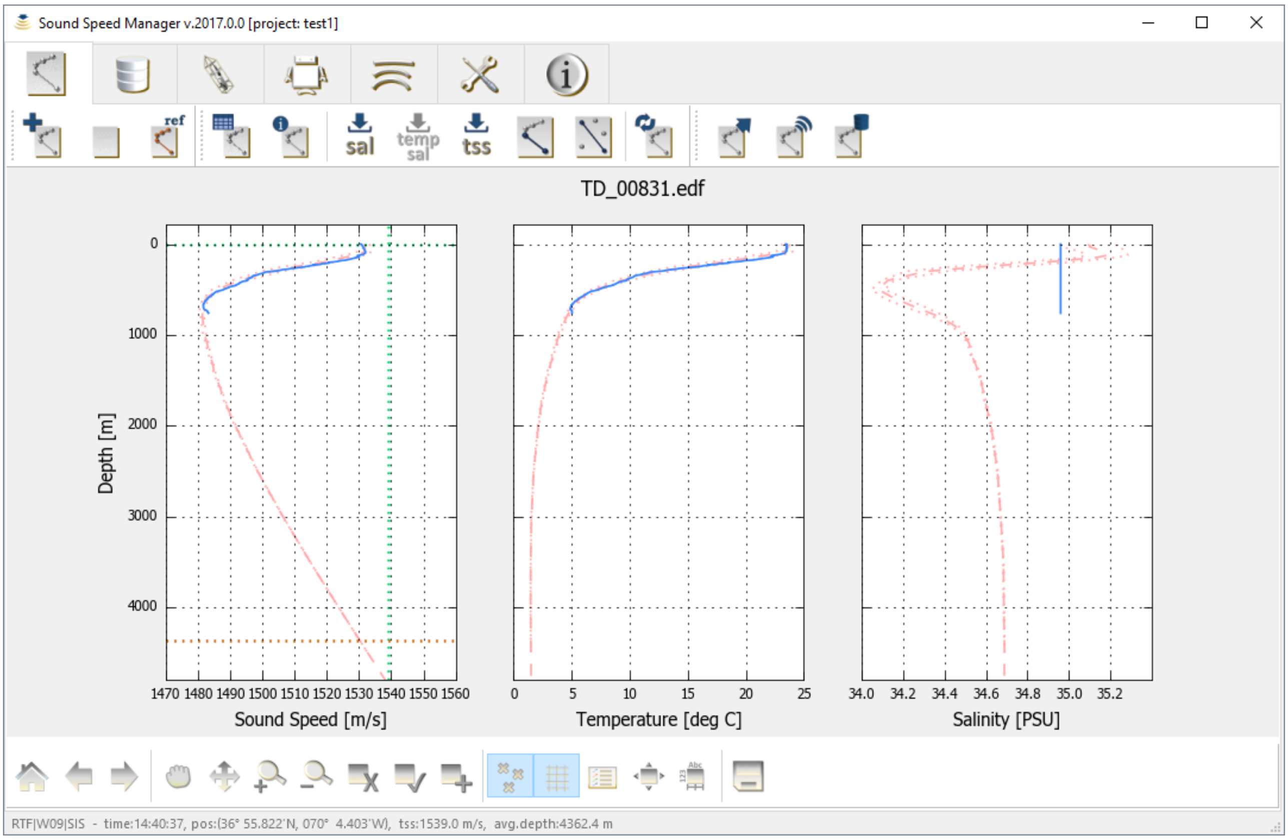

***Figure 1**. Sound Speed Manager primary interface.*

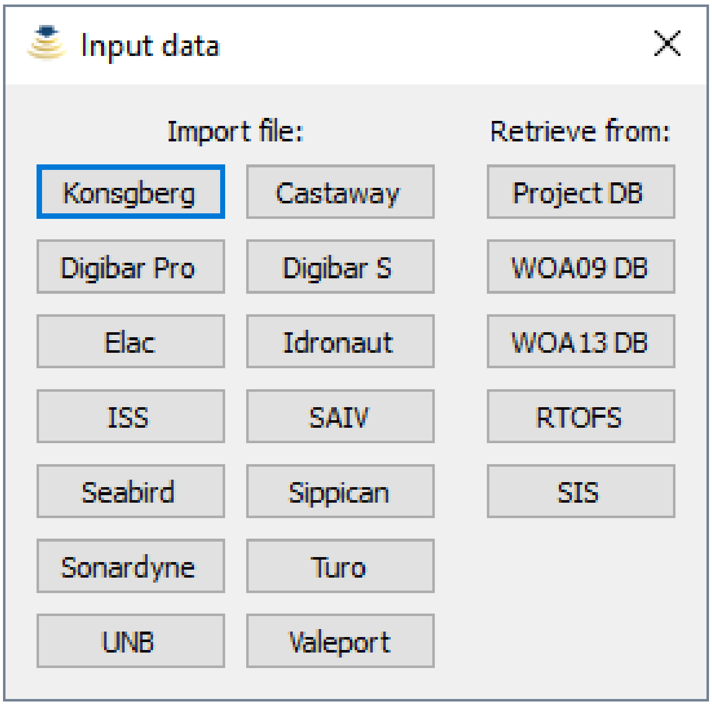

***Figure 2** : The Input Data dialog demonstrates the different available input data sources.*

profile data from databases and through a network connection from Kongsberg SIS. Note that in the Figure, the user has the option to retrieve a synthetic profile from both the WOA 2013 database and the from the older, but smaller WOA 2009 database (~500 MB vs. 17 GB for WOA13).

In addition, the application can retrieve 'synthetic' profiles from oceanographic databases, such as the NOAA World Ocean Atlas (WOA) (Levitus et al. 2013), or modeling forecasts (e.g. the NCEP Global Real-Time Forecast System) (Spindler et al. 2006; Mehra et al. 2011). These profiles can be used to extend to a deeper depth, samples collected by devices, complement the values of environmental variables that are not directly measured, such as the salinity for XBTs, or model profile information when no profile sampling effort is made (e.g., transit surveys).

Customization is one of the key points of **Sound Speed Manager**. Straightforward inheritance models have been implemented to ease the creation of new format drivers (for both input and output files) and data listeners (network based, using UDP packets) as well as the support of institute-specific oceanographic databases. These oceanographic databases are usually built by oceanographic data centers through analyzing and synthesizing data sets with a large number of profiles.

The adoption of an open source paradigm provides several advantages from a user perspective. First, the user has direct access to the source code, allowing them to learn what the application is actually doing to the data (https://github.com/hydroffice/hyo_soundspeed). Many details cannot be integrated in the documentation without making it lengthy, verbose, and too difficult to track development changes. Access to the code 'recipe' can provide the interested user with all the required levels of information. Further, access to the source code makes it possible for users to directly modify and extend the available functionalities. **Sound Speed Manager** is implemented in Python (Python Software Foundation, https://www.python.org/). Python is a very popular language, and widely used in the scientific community, so the decision to implement **Sound Speed Manager** in Python was specifically taken to make it easy to extend. The same level of flexibility is not available in proprietary applications, where the user only has the option of asking the developers to fix a bug, or to add functionality - a process which is subject to the timelines and priorities of the developers, rather than the users.

4. Profile Processing

Once raw data are imported, three plots (sound speed, temperature, and salinity) are presented to the user, with an overview of all of the imported data, for visual inspection. When active and available, data closest to the profile from oceanographic databases/models are also displayed to assist in evaluation of the quality of the imported profile. In case of multiple available options, the user can select which salinity, temperature, and sound speed 'synthetic' data to use to enhance the original raw data and to extend the depth profile as required by the output format (e.g. to 12,000 meters for Kongsberg systems) to ensure correct ray-tracing of the soundings.

The application provides an intuitive way to perform interactive graphical inspection (e.g., outlier removal, point additions) of sound speed, temperature, and salinity profiles. Augmentation of the sound speed profile surface layer with measured sound speed values is provided both manually, or by retrieving this information over a network.

The user can visualize and edit the data in a tabular form, and edit the profile metadata. To avoid the execution of repetitive operations, it is possible to define a set of default metadata (e.g., the institution, the survey name, the vessel) to be applied to each new imported profile. The graphic interface allows easy and intuitive validation of any user input.

5. Project Database

Although it is possible to use **Sound Speed Manager** in a memory-less mode (i.e., loading, processing, and transmitting each profile individually without keeping any record of the data), the storage of the processed profile data in a per-project local SQLite database is recommended (***Figure 3***). Once stored in the database, the system provides analysis functions and tools to manage the collected profiles.

Database storage empowers the users with a large number of functionalities. This includes re-loading previous profiles so as to evaluate the evolution of the sampled water column environment (***Figure 4***) through comparison plots. In particular, the database is structured so that each profile may contain three types of stored data: the raw data (enabling reprocessing of the profile from scratch); the processed samples (with flags to identify the various different source of data); and an optional SIS profile (which represents the result of the data reduction, or thinning, process required by Kongsberg SIS).

The adoption of a SQLite-based technology makes the databases both robust and cross-platform. Functionality was also incorporated to ease the transfer of profiles between databases. A possible use case of such functionality is the collection of profiles from multiple survey launches and their subsequent transfer to the mother vessel at the end of the survey day.

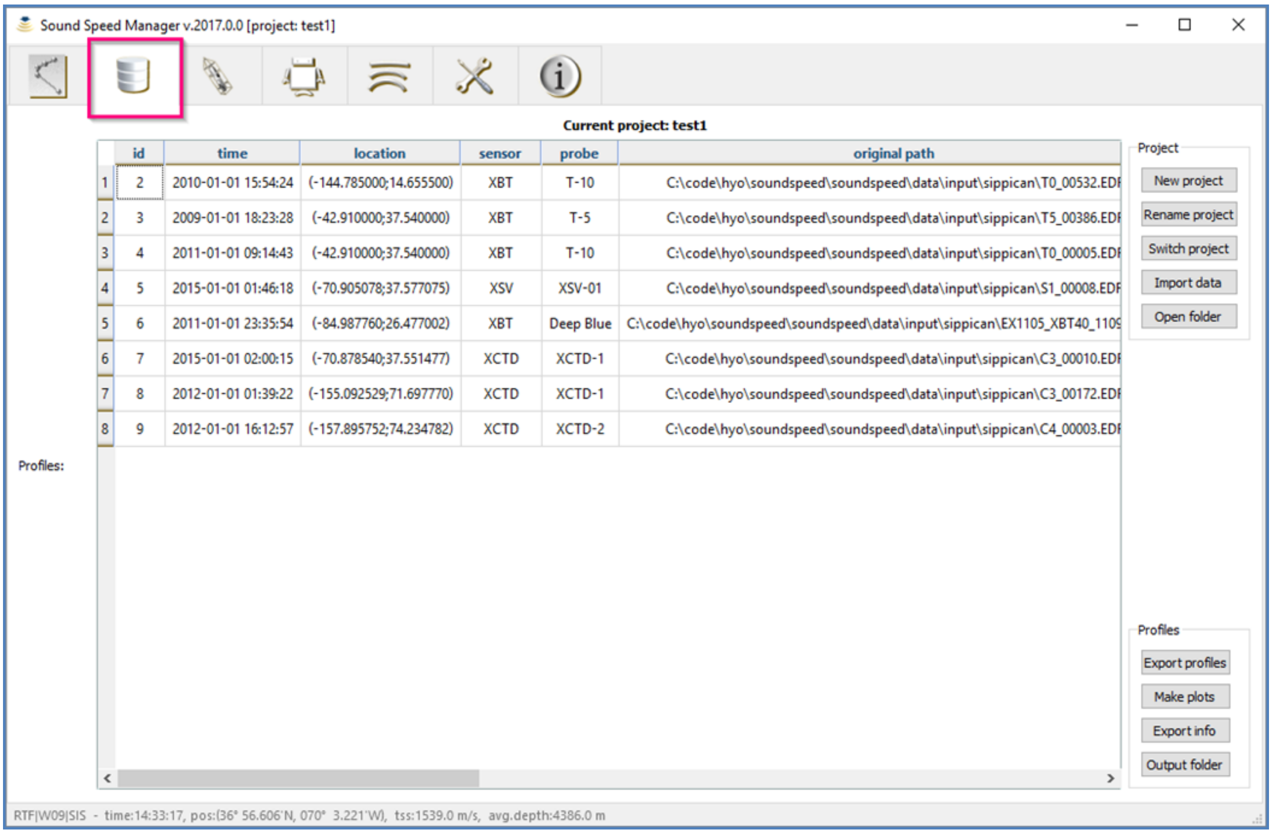

***Figure 3** : Sound Speed Manager's Database tab.*

6. Output Creation

Given the limitation in the number of samples accepted in a single profile by some echo sounders, after being enhanced and extended, a profile may also need to be sub-sampled before use. This task is performed using a variant of the Douglas-Peucker algorithm (Douglas and Peucker, 1973). It is also possible to preview the thinned profile resulting from of this operation so that the user can verify that the generalized profile adequately represents the original data.

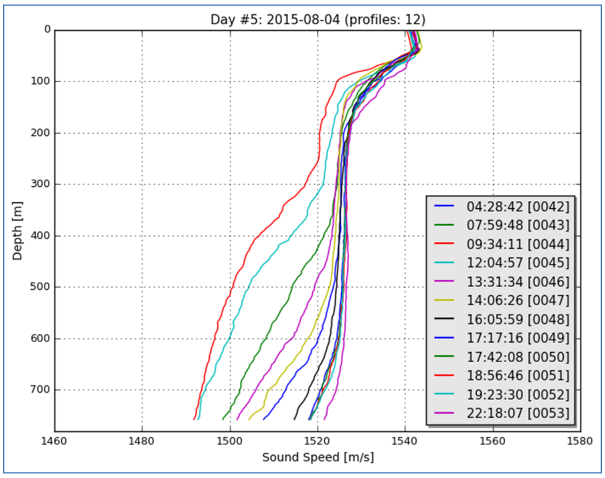

***Figure 4** : Example of a daily plot that can be created from the profiles stored in the Sound Speed Manager project database.*

Sound Speed Manager can export the resulting processed data to disk in a large variety of data formats (e.g., multiple cast CARIS HIPS V2, Elac, Hypack, Kongsberg, Sonardyne) or transmit them to well known hydrographic data acquisition systems (Hypack, Reson PDS2000, QPS QINSy, and Kongsberg SIS), or any application that supports network transport of profiles using UDP data packets. Of particular scientific relevance in this context, is the format used by the NOAA National Center for Environmental Information (NCEI). **Sound Speed Manager** offers an easy way to prepare a set of profiles with all the metadata required by this net CDF-based format so that new data can be submitted to NCEI to feed the creation of future oceanographic models (see https://www.nodc.noaa.gov/submit/index.html for submission details).

It is also possible to visualize the georeferenced metadata (***Figure 5***), or to export them in several popular formats (***Figure 6***).

7. Synthetic-profile Server Mode

Currently, **Sound Speed Manager** can operate in two mutually exclusive modes: Operator mode, and Synthetic-profile Server mode. In most cases, Operator mode as described in the previous sections, is used.

To enable better results from opportunistic mapping when no profiles are acquired, the Synthetic-profile Server mode was developed to deliver WOA/RTOFS-derived synthetic sound speed profiles to one or more network clients in a continuous manner. Given the potential for biases inherent in such an approach, this mode is expected to only be used in transit, capturing the current position from network broadcast packets, and using it as input to lookup reference data from the selected oceanographic model.

8. Plugin Architecture

Sound Speed Manager provides functionalities to help bridge the gap between sound speed profiling instrumentation and acquisition systems. As such, it currently provides a large number of drivers to read file formats and to listen to network UDP packets. However, these two kinds of data feeds are not the only ones available, so a plugin architecture has also been developed so that additional custom data sources can be integrated.

The pilot plugin used to test the architecture was to directly interact with Sea-Bird SeaCAT CTD profilers via an RS-232 serial interface. Other plugins are currently in development, and advanced users are encouraged to contribute back to the project any newly developed plugins.

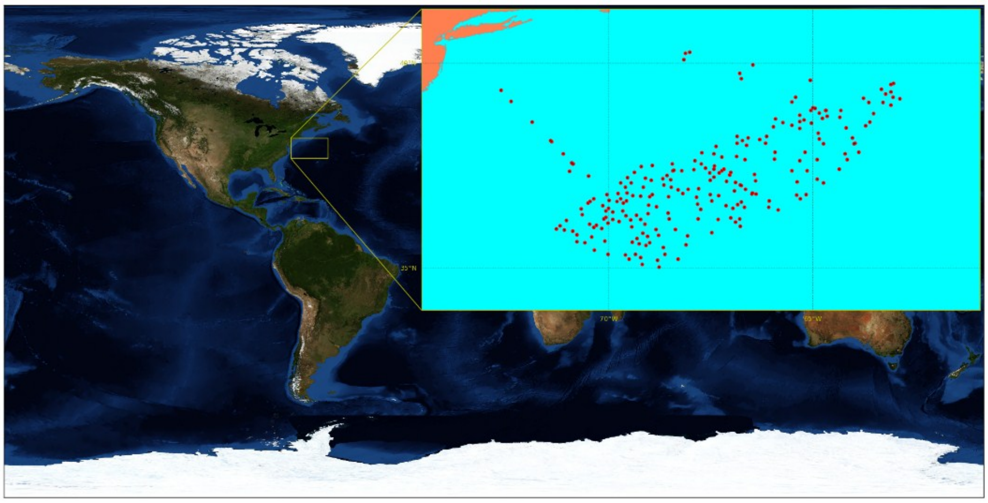

Figure 5 *: Sound Speed Manager has embedded functionalities to create maps that geolocate the processed sound speed casts*

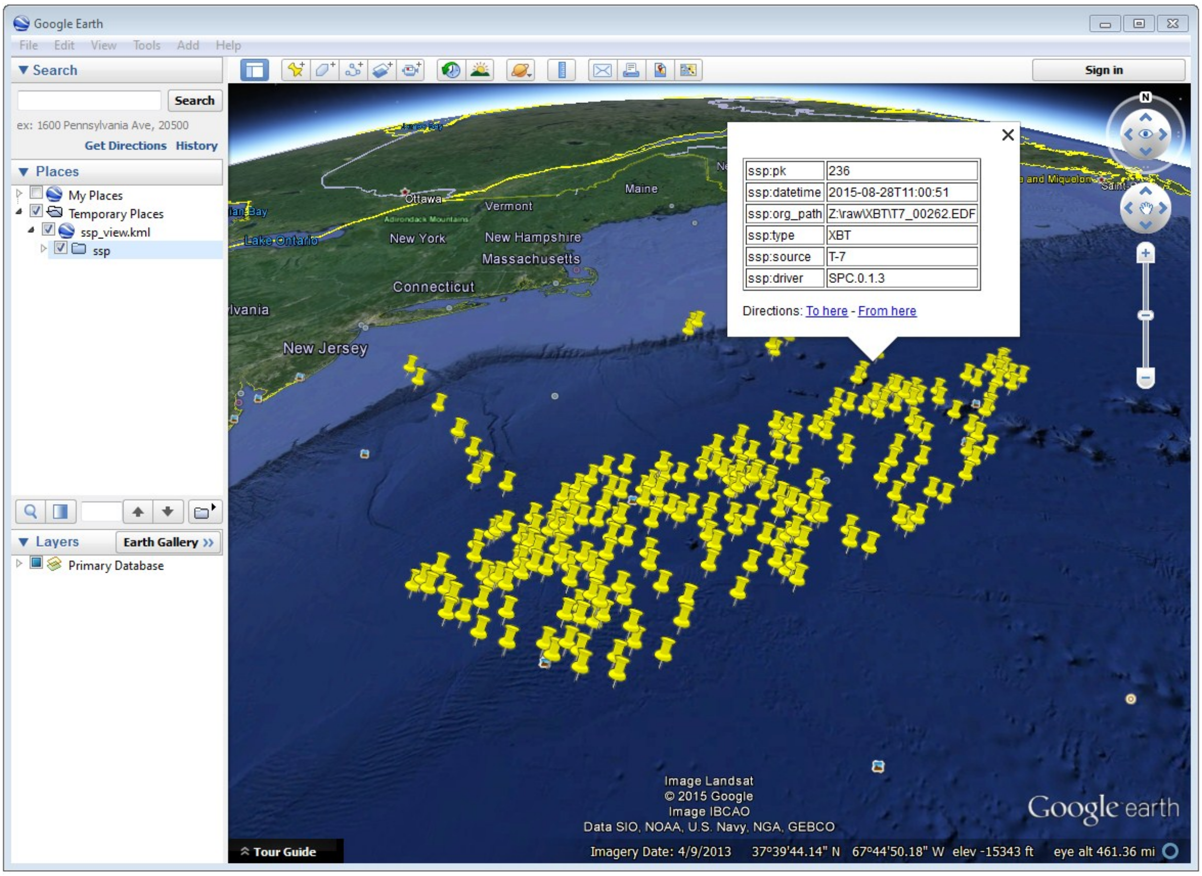

Figure 6 *: Loading result of the exported metadata, using KML, in Google Earth*

9. Technical requirements and documentation

Sound Speed Manager is publicly available as both a stand-alone application and a Python package (https://github.com/hydroffice/hyo_soundspeed).In this latter form, it is already integrated in Pydro, a NOAA-specific Python application set and software distribution.

The stand-alone application is made available as a portable (that is, not requiring an installer) zipped archive on the official webpage (http://www.hydroffice.org/soundspeed/main). This solution is ideal for users that simply want to use the application, without any interest in extending it with custom functionality.

Thanks to the selection of Python as the development language, **Sound Speed Manager** can also be installed on a wide variety of platforms. It has been tested on various Windows versions (XP, 7, 10), Linux (Ubuntu, Mint) and macOS (Yosemite), using both 32- and 64-bit binary models. Being open source, it can be installed in development mode so that an advanced user, or an oceanographic institute, can modify the source code to specific requirements. A graphical user interface "look-and-feel" that is consistent with the host operating system is made possible by the use of PySide, an LGPL Python binding of the popular Qt graphic library (https://github.com/pyside/PySide).

Sound Speed Manager is documented in a PDF manual (embedded with the library) and online as 'live' html-based documentation set (https://www.hydroffice.org/manuals/soundspeed/index.html).

10. Conclusions

Sound Speed Manager is the result of a project jointly developed by NOAA Coast Survey and UNH CCOM. It has already been adopted as the preferred tool to process sound speed profiles onboard a large number of NOAA and UNOLS vessels.

Sound Speed Manager has been designed to ease integration into existing data acquisition workflows. The liberal open source license used by the project (specifically, GNU LGPL) provides for understanding of the chosen processing solutions through ready inspection of the source code, as well as the ability to adapt the application to specific organization needs. This adaptation is eased by the modular design of the application, with the NOAA-specific functionalities organized so that they can be easily deactivated for non-NOAA users. The main functionalities include: wide support of commonly-used sound speed profile formats in input and output, full integration with common data acquisition/integration applications (e.g., Kongsberg SIS), profile enhancement based on real-time and climatologic models, and database management of the collected data with built-in functionalities for analysis and visualization.

With a long-term support and development plan, **Sound Speed Manager** is a turnkey application ready to be used (and extended) by professionals and institutions in the hydrographic community.

11. Acknowledgments

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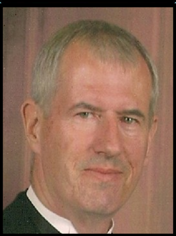

Article

NAVIGATION SONAR: MORE THAN UNDERWATER RADAR

Realizing the full potential of navigation and obstacle avoidance sonar

By I. Russel ***(FRICS, MINI-UK)*** and
R. G. Wright (*GMATEK, Inc., USA/World Maritime University, SE*)

Abstract

At least half the world's coastal waterways are inadequately surveyed or not surveyed at all. Coverage is particularly poor in the Caribbean, the Indian and Pacific Oceans and the Polar regions. Recent accounts of vessels grounding on uncharted seabed features reflect this situation. Advances in three dimensional (3D) Navigation Sonar that can reduce vessel risk in such areas are described. This technology has the potential to enhance the safety of navigation for vessels and for those that follow in their wake. New generations of coastal trading vessels, cruise and adventure ships together with a variety of government vessels can all benefit from this technology.

Résumé

Au moins la moitié des voies navigables côtières du monde sont inadéquatement hydrographiées voire pas du tout. La couverture est particulièrement médiocre dans les Caraïbes, dans les océans Indien et Pacifique et dans les régions polaires. De récents exemples d'échouements de navires sur des éléments du fond marin non cartographiés, reflètent cette situation. Les avancées des sonars de navigation tridimensionnels (3D) susceptibles de réduire les risques pour les navires dans ces zones sont décrites. Cette technologie a le potentiel d'améliorer la sécurité de la navigation pour les navires et pour ceux qui naviguent dans leur sillage. Les nouvelles générations de navires marchands côtiers, de paquebots de croisière et de navires de plaisance et d'expéditions ainsi que différents bâtiments gouvernementaux peuvent tous bénéficier de cette technologie.

Resumen

Por lo menos la mitad de las vías navegables costeras del mundo están levantadas de forma inadecuada o no están levantadas en absoluto. La cobertura es particularmente escasa en el Caribe, en los océanos Índico y Pacífico y en las regiones Polares. Los informes recientes de buques que han encallado en formas del relieve del fondo marino no cartografiadas reflejan esta situación. Se describen los avances en el Sonar de Navegación Tridimensional (3D) que puede reducir los riesgos para los buques en dichas áreas. Esta tecnología tiene el potencial de mejorar la seguridad de la navegación para los buques y para los que siguen su estela. Las nuevas generaciones de naves de cabotaje costeras, cruceros y buques de aventura, junto con una variedad de buques gubernamentales pueden beneficiarse de esta tecnología.

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1. Introduction

The International Hydrographic Organization (IHO) was established to support safety of navigation and the protection of the marine environment. This involves the coordination of the activities of national hydrographic offices in the production of nautical charts and documents derived from hydrographic surveys and other information. The status of hydrographic surveying and nautical charting worldwide is promulgated in IHO Publication C-55 (IHO, 2016a). This document reveals that many of the world's coastal waterways, including those of a number of developed States, the Caribbean, Indian Ocean and the Polar regions are still inadequately surveyed for contemporary needs, or not surveyed at all.

Recognising this situation, the chosen theme for World Hydrography Day 2016 was;

Hydrography - "the Key to well managed seas and waterways"

The following statement promoting this day is in many ways relevant to the proposition in this article.

> "The theme for 2016 is intended to focus attention on the fundamental importance of hydrography and our knowledge of the shape, nature and depth of the seafloor as a fundamental requirement for the proper, safe, sustainable and cost effective use of the world's seas, oceans and waterways." (IHO, 2016b)

With few exceptions and by the end of the current decade, vessels engaged in international voyaging will be navigating with an Electronic Chart Display and Information System (ECDIS). However, in many areas now opening up to navigation, the key component of the system, the Electronic Navigation Chart (ENC), will not be fit for purpose as the ENC will not necessarily contain the required data content to ensure safe navigation. Fortunately, responsible owners who intend to operate ships in such waters now have the opportunity to remedy the situation by installing a Navigation and Obstacle Avoidance Sonar hereafter referred to as Navigation Sonar.

With the use of Navigation Sonar, the shape, nature and depth of the seafloor ahead of a vessel can be determined in real time – effectively it is a forward looking multi-beam echo sounder. Contemporary systems maintain an effective watch below the waterline similar to that of radar above water. The sonar image can serve as a check on charted bathymetry, thereby contributing an additional dimension to situation awareness. Navigation personnel are made aware of the true nature of the seabed ahead of the vessel. The timely detection of uncharted shoals, reefs and other hazards to navigation enables evasive action to be initiated to avoid groundings altogether or lessen their consequences. The data acquired may also have potential to provide an independent source of high-resolution full-swath bathymetry that can, once validated, make a significant contribution to crowd-sourced bathymetry.

A previous article in this journal (Russell, 2014a) reviewed a number of groundings on uncharted seabed features, some of which might have been averted or their consequences mitigated had the casualties been equipped with Navigational Sonar. This article describes further developments that may increase the potential for integrating data products obtained from Navigation Sonar with crowd-sourcing initiatives to improve navigation charts for all. An additional benefit may include the capability for real time detection of changes in the seabed that have occurred since the revision of the current chart.

2. Background

The first edition of the Admiralty Manual of Scientific Enquiry, published in 1849, included at Appendix No.1 an abstract from a "Return" to the House of Commons prepared under the Hydrographer Francis Beaufort in 1848. This was entitled *Coasts and Islands of which our Hydrographic Knowledge is imperfect.* Supplements to this initial account, provided by the Hydrographers of the day, dated 1858, 1871 and 1885 appeared in later editions of the manual. They record the heroic efforts of hydrographers of many nations to chart the arteries of ever expanding commerce with, it may be said, no little success. Among areas still suffering from a lack of modern survey coverage, were the western portion of the Pacific Ocean and the Seychelles Bank, two locations which saw fatal groundings in 2000 and 1970 respectively (Russell, *ibid.*).

The supplement of 1885 notes that the *West Indies are probably as well charted as any part of the world.* These optimistic assessments sadly only held good for the shipping needs at the time of writing. Witness the loss in the Windward Isles of a French cruise liner in 1971 (Russell, *ibid*.). In contrast, the charting of the *Dutch Archipelago* was adjudged to be *still imperfect. Though many additions have been made, these have not been of a detailed character*. This *caveat* still applies to some of Indonesia's waters; where a bulk carrier, shown in ***Figure 1***, grounded on an uncharted pinnacle in 2010 (Russell, *ibid*.).

Figure 1: *Handymax bulk carrier NOBLE HAWK aground on an uncharted pinnacle in E. Indonesia 2010.*

Photo by Captain N Haslam, LOC Group Ltd, who attended the casualty as owner's special representative

By the time the fifth edition of the manual was published in 1886 the transition from sail to steam was effectively complete and the opening paragraph of the supplement has a familiar ring;

> *"Great as has been the advance in the publication of accurate charts of the globe made since the last revision of the Admiralty Manual in 1871, the needs of navigation have increased more rapidly".*

These new demands required significant allocation of hydrographic resources to re-survey coastal areas hitherto regarded as adequately charted. This was something which could only be achieved at the expense of surveys in less well frequented areas – a situation just as familiar today as the rationale for World Hydrography Day 2016 attests.

A telling example of this recurrent theme is the exponential increase in the tonnage and draughts of Large Crude Carriers towards the end of the 1960's. Prior to 1960, the depth criterion for dangerous wrecks on Admiralty charts was 8 fathoms (14.6m). In that year this was increased to 10 fathoms (18m) and only 3 years later to 11 fathoms (20m). Since 1968 a wreck with less than 28m (15 fathoms) of water over it has been charted as dangerous.

The upward trend in vessel dimensions is continuing, patterns of trade are changing and cruise operators are offering more venturesome itineraries (Russell, *ibid*.) Together with the opening up of the Northwest Passage and Northern Sea Route these trends present an intolerable demand on the diminishing survey resources of national Hydrographic Agencies. The wider adoption of Navigation Sonar might contribute towards the alleviation of this pressing problem.

3. Developments in Sonar Technology

The use of sonar (SOund Navigation And Ranging) to detect underwater obstructions is not new. Its navigational purpose has been implicit from conception. Most of the early sound work was devoted to horizontal propagation and the detection of objects in the water. Development of transducers gained impetus following the *Titanic* disaster and the outbreak of World War I in order to detect submarines. In 1914 an oscillator invented by Reginald Fessenden installed in the USCG Cutter *Miami,* detected an iceberg over 20km away. A seabed return noted at the same time paved the way for rapid advances in sounding technology (Theberge, 1989). In 1922, French and American vessels equipped with the first echo sounders, obtained lines of soundings in the Atlantic and Mediterranean respectively.

The first bathymetric chart to be produced solely from acoustic soundings was published in 1923 (Dierssen and Theberge, 2014).

4. Historical perspective

The first echo sounders only obtained individual depths, as had lead lines and sounding machines. They did not perform satisfactorily in shallow water so that traditional methods were retained for boat sounding until the 1950's and beyond this for some port applications. Once reliable paper recorders were perfected and continuous all weather electronic fixing became available a step change improvement in productivity was realised. Thought was directed to the possibility of scanning between the lines of soundings to detect wrecks and rock pinnacles which might otherwise have been missed (Morris, 1995). This resulted in Royal Naval survey ships, converted from anti-submarine frigates, making routine use of their World War II era scanning sonars to sweep ahead, along and across track. In 1961 fisherman's sonars were retro-fitted to existing inshore survey craft and subsequently in new build ocean and coastal survey vessels. This was mainly used for wreck location and examination. In seeking to "broaden the furrow" of depth data provided by the single beam echo sounder hydrographers looked to other sonar applications. This was with a view not only to detect underwater obstructions; but to provide depth data between survey lines as well.

A sector scanning sonar, Hydrosearch, was introduced into the British Royal Naval Hydrographic Service in 1979. Its operating principles were those of the sonar developed in the 1950s at the UK's Admiralty Research Laboratory for detection of ground mines. Hydrosearch fulfilled its purpose for wreck investigation but not for area sweeping or depth measurement. The acoustic operating concept was technically successful; but the limitations of contemporary deployment mechanisms and computer capacity meant that the system was ahead of its time. Multi beam echo sounding and sidescan sonar then superseded Hydrosearch, thus achieving total seabed insonification and depth measurement; but forfeiting the forward looking capability.

In the late 1990s the Petrel TSM 5424 3D sonar, with a claimed range of about 1000m, was developed by the Royal Australian Navy as a mine and obstacle avoidance system for littoral warfare and for optimised navigation in poorly charted waters. Regrettably, this system did not meet expectations and is no longer supported in fleet units. However, it still fulfils a limited navigational function for inshore hydrographic survey vessels in the reef strewn waters of Northern Australia. The system supposedly had a depth data logging capability; but this was not realised satisfactorily. Consequently it was only ever used for obstruction detection and avoidance.

5. Recent initiatives

In 2007 the US National Institute of Standards and Technology (NIST), funded FarSounder Inc. for a three year project to develop a Forward Looking 3D Sonar System for navigation and collision avoidance, in order to improve the efficiency and safety of marine cargo transport (NIST, 2007). The optimal system design parameters were for applications that would be effective at long range (two miles) and high speed (35 knots). The speed criteria - up to 32 knots – have been realised in terms of the robustness and hydrodynamics of the installation and transducer design. However, current production systems only have a maximum range of 1,000m.

In 2009, the owners of a tanker fleet contracted with Marine Electronics Ltd for the development of navigation sonar with a 1,000m detection range and installed the prototype in one of their vessels (Hydro International, 2009). Although the project was subsequently abandoned, for commercial rather than technical reasons, it still indicates that in some commercial quarters at least, the benefit of navigation sonar has received serious consideration.

Between 2015 and 2016 research explored the utility of navigation sonar as a means to avoid hazards to navigation in a simulation of the *Costa Concordia* disaster and several other groundings (Wright and Baldauf, 2015; 2016). Its use as a means to perform hydrographic survey has also been evaluated against IHO minimum standards for Hydrographic Surveys (Wright and Zimmerman, 2015; Wright and Baldauf, 2016a). This research demonstrated the potential of navigation sonar to accomplish swath survey coverage for the route of transit with horizontal and vertical accuracies approximating IHO S-44 standards order 1a (IHO, 2008).

In December 2016, FarSounder Inc. (FarSounder, 2017a) performed sea trials using their FS-500 3D forward looking sonar that included comparisons with the U.S. National Oceanic and Atmospheric Administration (NOAA) multibeam data from a relatively recent survey shown in ***Figure 2*** (NOAA, 2009). Corrections were made for tide, position, heading, course over ground, speed over ground, and rate of turn information were recorded. Grid size was set to match the NOAA grid size of 4m grid spacing and aligned, resulting in 1911 grid locations that overlapped between the FarSounder data and the NOAA data. High performance Real Time Kinematic (RTK) GPS was not used for positioning nor was heave measured or heave compensation performed. An iso-velocity sound speed of 1500m/s was assumed for all depths, and it is not known whether any sedimentation or scouring had occurred since the NOAA survey causing any changes to the measured depths. Given these conditions FS-500 depth measurements were found to have an average depth difference of 3.31% relative to the NOAA data with a standard deviation of 2.40%. The bathymetry output was produced in real time using an entirely automated process with no manual data cleaning.

In 2016, the Australian Hydrographic Service contracted for the replacement of the ageing Petrel sonars with FarSounder's FS-1000 3D sonars. The first unit should be installed in an inshore survey vessel early in 2017. The rest will be progressively installed when craft are next taken in hand for refit. The new sonar has the capability to collect swath bathymetry ahead of the vessel.

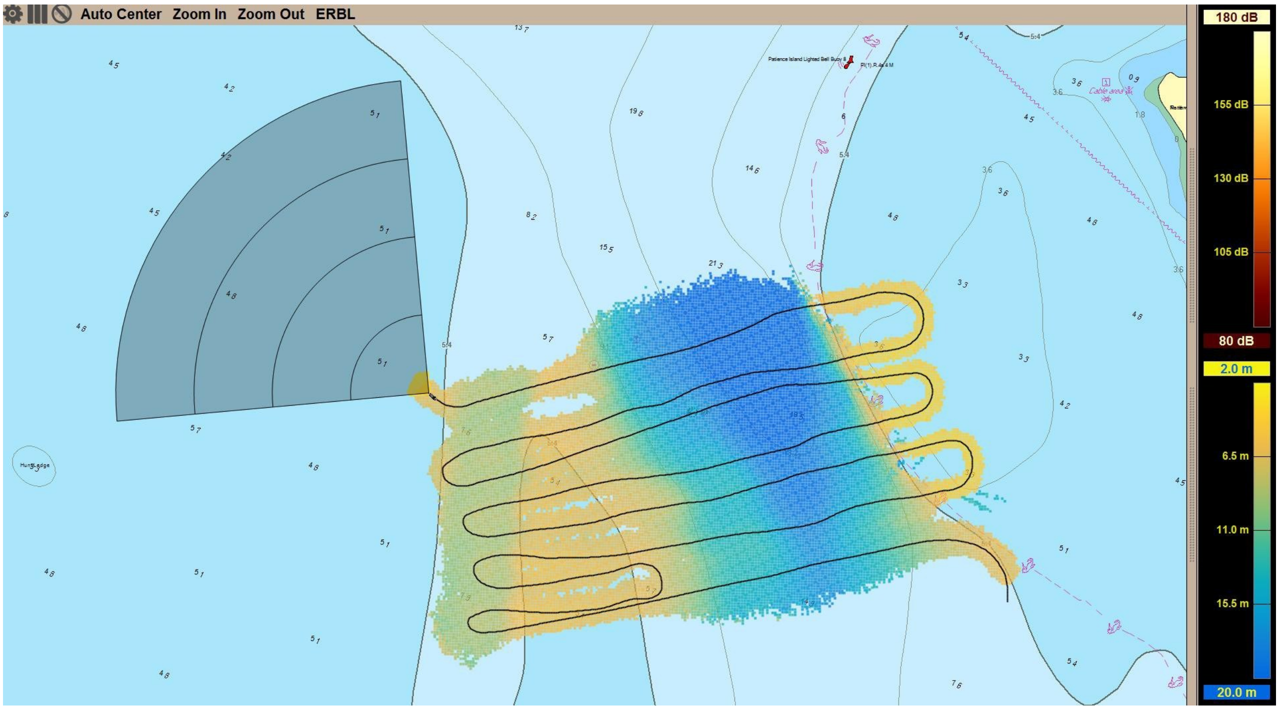

Figure 2 *Navigation Sonar swath data closely corresponds to 2009 NOAA Multibeam echo sounder survey results*

Image courtesy of FarSounder

In 2017 WESMAR will be supplying the first of six military versions of its EV850/110-10 sonar for new Arctic offshore ships being built for the Canadian Navy. This sonar operates at 110 kHz and has a nominal range of 2,000m. These vessels will enhance Canada's support for growing Northwest Passage usage, resource exploitation and territorial claims under the United Nations Convention on the Law of the Sea (UNCLOS).

6. Navigation Sonar installations

Two types of Navigation Sonar systems presently exist, each utilizing different approaches to accomplish the same goals. One type uses a searchlight approach, steering the sonar beam scanning forward of the vessel and streaming soundings on a continuous basis. The second type uses a single ping to capture acoustic data which is then analysed to extract soundings from the data, and a swath of soundings is acquired using a series of pings. The number of beams emanating from either one or two sonar transducers, depending on manufacturer, can also vary widely. The same can be said for performance specifications with useful depths ranging from 50 to 200m and forward range extending from 200 to 2,000m. These systems are being installed in cruise ships, luxury yachts, hydrographic and other vessels.

7. Cruise and Expedition Vessels in Polar Regions and Transits

While some experienced ice navigators discount the effectiveness of navigation sonar for the detection of drifting ice (Toomey, 2012) there is support for its use in the detection of hazardous seabed features in polar seas. For several existing adventure cruise ships operating in Polar Regions, sonar is already making a significant contribution to ship safety (Skog, 2014, 2015). At present more than 50 cruise ships are active in the Polar cruise markets (Wright, 2017).

These vessels usually visit exotic tropical locations when transiting to and from polar cruising grounds. The Expedition vessel, *World Discoverer* (l.o.a. 88m, 3724 grt), was not fitted with any navigation sonar capability and grounded in Sandfly Passage, Solomon Islands in 2000 (Russell, 2014b). Following an aborted salvage attempt she remains where her master beached her to save his ship and passengers. In response to demand, replacement vessels are planned and under construction for the ageing fleet of conversions from Russian research ships, ferries and Nordic passenger ships. Many of these are expected to have Navigation Sonars installed.

In August 2016 the cruise ship Crystal Serenity (l.o.a. 238m, 69,000 grt) shown in ***Figure 3***, made a successful transit of the North West Passage with 1,600 passengers and crew and escorted by the ice strengthened RRS *Ernest Shackleton* (Thiessen, 2016). Before undertaking this voyage owners sanctioned the fitting of a WESMAR scanning sonar and arranged for bridge personnel to receive onboard training in its operation. Larger traditional cruise ships, each with 500 to 3000 passengers routinely visit both Arctic and Antarctic waters. *Celebrity Infinity* (l.o.a. 294m, 91,000 grt) regularly takes 2,000 passengers on a cruise-by voyage past the Antarctic Peninsula, while the *Costa Deliziosa* (l.o.a. 294m, 92,700 grt) has carried nearly 3,000 to Greenland. In January 2017, *The World*, (l.o.a. 196m, 43,188 grt) a private residential cruise ship carrying 145 residents and guests and 272 crew, broke the record for the most southerly navigation reaching 78° 43•997´S and 163°41•421´W at the Bay of Whales in Antarctica's Ross Sea (Maritime Executive, 2017). She is equipped with an FS-1000 Navigation Sonar (FarSounder, 2017b).

Figure 3: *Crystal Serenity transiting the North West Passage in 2016. (Cruise-advisor 2017).*

According to the Cruise Line Industry Association (CLIA), adventure cruise travel is growing at a record pace and expedition cruising to remote locations is seeing the impact of this trend (CLIA, 2016). At present there are 55 expedition, 548 motor and 75 sailing yachts of greater than 24m on order in 2017, many of which will transport thousands of passengers and crew to remote regions (Informer, 2017). The owners of these expedition vessels and luxury yachts are increasingly installing navigation sonar. This will safeguard the latter's expensive acquisitions as they seek to provide unique experiences for their guests in remote and exotic areas where charting may be inadequate or non-existent. Such experiences have included transits of the NW passage. Expedition cruise providers cite the availability of navigation sonar as an additional safety feature to reassure prospective passengers.

Compagnie du Ponant installed short range (440m/500m) navigation sonar in its four Le Boréal class expedition ships (l.o.a. 142m and 11,000 grt). It is understood that the "Explorer" class of four smaller vessels (l.o.a. 131m and 10,000 grt) which will enter service progressively from 2018 (Ponant, 2016) will feature FS -1000 sonars. In the USA, all Sunstone Ships Inc. expedition vessels have scanning navigation sonar and the company's design of a purpose built series of 300 passenger capacity polar class expedition ships also specifies navigation sonar. They have good reason for this investment as ***Figure 4*** illustrates.

Figure 4: *Reef awash in Antarctica a serious hazard in poor visibility or if masked by ice*

Taken from Land Information New Zealand survey report 2002. Used with permission.

8. Hydrographic Surveying and Research

The Australian Hydrographic Service (AHS) has long recognised the benefits of navigation sonar and is upgrading the systems in its four inshore survey vessels. The two larger hydrographic survey vessels are fitted with the longer range (3,000m) C-Tech CMAS 36 kHz scanning navigation sonar.

Various shorter range systems are fitted in the UK and Irish General Lighthouse Authority's vessels. Navigation sonar has been specified by the British Antarctic Survey for inclusion in the bridge system of RRS *Sir Richard Attenborough* and one may be retro-fitted in RRS *James Clark Ross*.

9. Navigating the "White Spaces"

- *A Case Study*

Although the illustrations in the following discussion are relevant to Polar regions, the principles are equally applicable wherever depth data is sporadic, uncertain or absent. In 2010, the Expedition Cruise vessel *Clipper Adventurer* ran aground in Coronation Gulf in the Canadian Arctic whilst following a single line of soundings acquired in 1965 (see ***Figure 5***). In 2007, a previously unknown shoal had been detected adjacent to this line. However it had not been charted as the vicinity of the shoal had not yet been surveyed to Canadian Hydrographic Service (CHS) standards. Instead, its position and reported least depth had been posted as a Notification to Shipping (NOTSHIP). The officers of *Clipper Adventurer* had not made themselves aware of this notice.

Although the *Clipper Adventurer* was equipped with a navigation sonar, it was unserviceable at the time. It was not due for repair until the end of the northern cruising season as its carriage was not required by either international or Canadian regulations for Polar voyages. The system was replaced at the docking which followed the grounding. The subsequent accident investigation report (TSB, 2012) noted that:

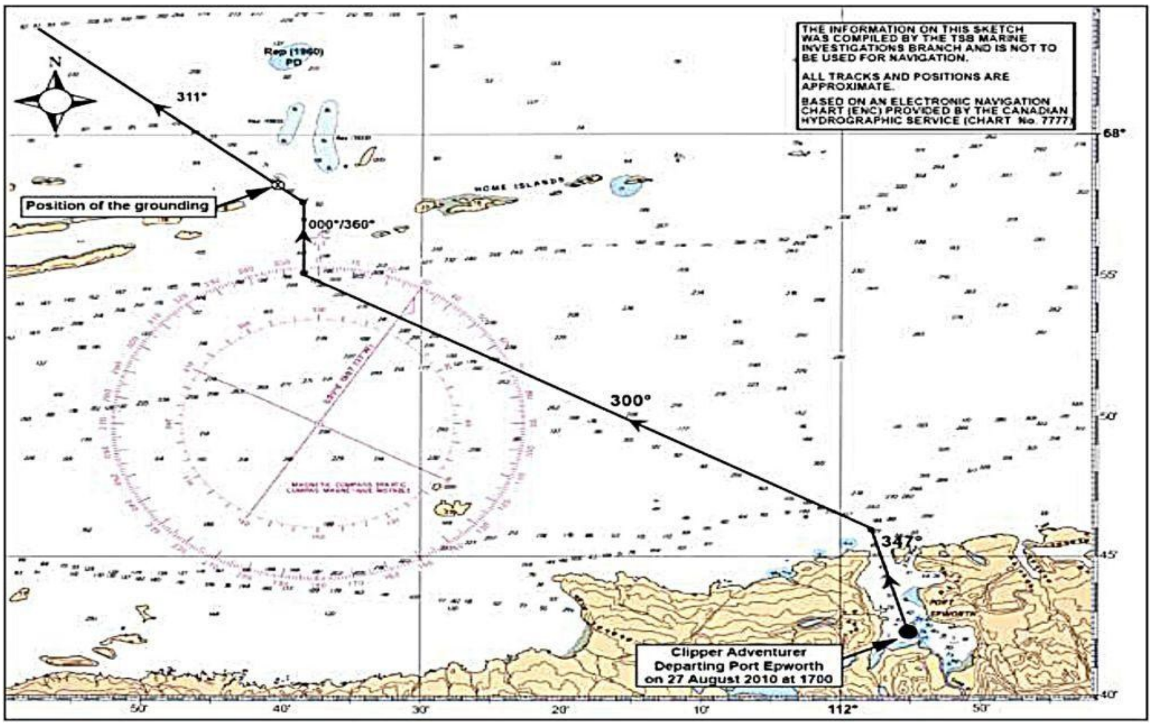

Figure 5: *Portion of CHS Chart 7777 showing "passage soundings" and vessel's planned track* (TSB, 2012).

The unserviceable condition of the forward looking sonar deprived the bridge team of an additional source of valuable information. Forward looking sonars are designed to provide safety critical information regarding underwater obstructions ahead of ships, and provide automatic navigation alerts to bridge teams.

The report concluded:

1. The Clipper Adventurer ran aground on an uncharted shoal ***(Figures 6** and **7)*** after the bridge team chose to navigate a route on an inadequately surveyed single line of soundings.

2. Despite having a non-functional navigation sonar and not using any other means to assess the water depths ahead of the vessel, the Clipper Adventurer was proceeding at full sea speed (13.9 knots).

Figure 6 shows a shoal between the Lawson Islands and the Home Islands in the Southern Coronation Gulf in position 67° 58.25′ N, 112° 40.39′ W. Charted depth in area 29 m. Least depth found 3.3 m.

Figure 7 shows the *Clipper Adventurer* grounded on a hard rock shelf from approximately the forepeak to amidships. The weather deteriorated shortly after the grounding, hampering the salvage effort. Fortunately a survey vessel was on hand to provide salvors with updated depth data.

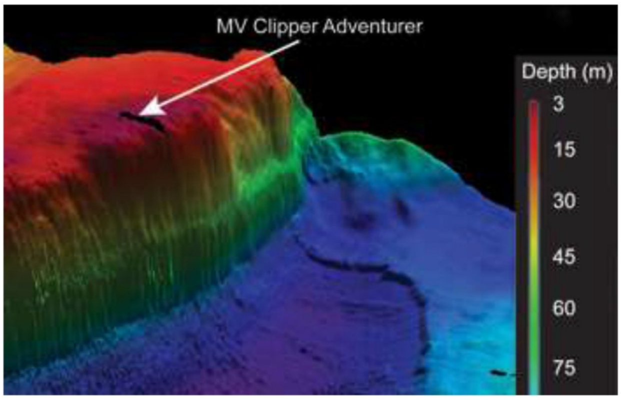

Figure 6 : *Isolated rock shoal (TSB, 2012).*

As the maximum nominal range of the sonar was 440m, the safe speed for its effective use would have been about 6 knots accompanied by heightened vigilance on the bridge. The decision to embark on a season of Arctic voyaging, when the charts were known to be inadequate; rather than reschedule the cruise programme and repair the sonar, was ill advised. It was also disproportionately costly to the company. Not only did it lose a substantial compensation claim against the Canadian government; but it will have to pay nearly $500,000 in environmental costs (Maritime Executive, 2017a).

Figure 7 : *Clipper Adventurer aground and listed 5 ° to port.* (CCG, 2010)

♦ *Polar Regions*

In Antarctic waters the present day charts contain an alarming number of white spaces as ***Figure 8*** shows. The surveys cited were undertaken by RV *Tangaroa* of the National Institute of Water & Atmospheric Research (NIWA) of New Zealand (Ching and Mitchell, 2006). The ship used multi-beam echo sounding (MBES) in water depths over 75m. Elsewhere a survey launch with a single beam echo sounder (SBES) and sidescan sonar completed the work, where ice conditions allowed. MBES is the only reliable means of disproving dangers where ice conditions effectively preclude the deployment of sidescan-sonar. There is limited access to open water in the short summer season; but weather conditions can still be adverse. Traditionally throughout Antarctica, large scale SBES coverage has mainly focused on the approaches to scientific bases. Increasingly research ships equipped with MBES are supplementing the limited deployments of dedicated survey vessels.

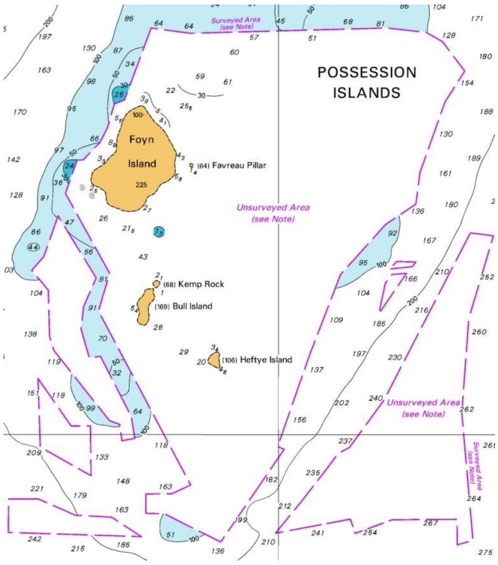

Figure 8 : *Portion of Chart NZ 14907 Antarctica – Ross Sea - Possession Islands*

First published 2003 New Edn.2006 from Surveys 2001 and 2004 to provide safety of navigation for cruise and scientific ships travelling to Antarctica.

“Source: Land Information New Zealand (LINZ) and licensed by LINZ for re-use under the Creative Commons Attribution 4.0 International licence (link is external)

While the proximity of the Ross Sea coasts and islands to New Zealand and Australia attracts some cruise activity, the principal cruise destination is the western side of the Antarctic Peninsula. Here, the British Antarctic survey and British naval survey parties embarked in a succession of Ice Patrol naval vessels have been active since the middle of the last century. Yet only 13% of waters less than 200m deep have been adequately surveyed (IHO, 2016a). Cruise vessels, both independently and as part of a United Kingdom Hydrographic Office (UKHO)/International Association of Antarctic Tour Operators (IAATO) initiative, have had to resort to developing their own safe routes and anchorages using SBES. Some British Admiralty charts published in 2015 now show navigation corridors established by crowd -sourcing over the previous 10 years (Skog, 2017).

In northern waters the Northwest Passage with its adjacent sea areas and Russia's Northern Sea Route (NSR) have not been properly charted. In the US the area of the Bering Sea is "only partially surveyed, and the charts must not be relied upon too closely, especially near shore". "Off the Arctic coast of Alaska depths near shore may change as much as 6 feet (1.8m) because of ice gouging; storms also shift the sands in shallow water" (NOAA 2016). Following the adoption of a region specific Risk Assessment Methodology survey effort is focusing on heavily transited areas of high concern and development of offshore transit corridors (Gonsalves *et al.*, 2015).

Only approximately 32% of Canada's Arctic marine corridors are adequately surveyed, with an additional 3% surveyed to modern standards (CHS, 2015). There are many places along the coast of Greenland, where no systematic and comprehensive surveys have been carried out. A prioritised programme is in force to resurvey navigable routes to and between populated areas on the West Coast of Greenland to modern standards (Danish Geodata Agency, 2017). Russia announced plans to commission hydrographic surveys of the NSR to accommodate large ships (World Maritime News, 2012), but progress appears to be unsatisfactory (Gunnarsson, 2016).

Eight vessels, all members of the Association of Expedition Cruise Operators (AECO) contribute SBES soundings to the Olex system. This is a global data base of passage soundings mainly originating from fishing vessels. Individual depth data sets are generally downloaded at the end of the Arctic or Antarctic cruising season. These are then verified and can be uploaded by all users at the start of the following season. Safety critical information is reported immediately to the charting authorities and notified to other vessels in the vicinity (Skog, *ibid.*).

- *South West Pacific*

Another increasingly popular cruise destination from Australia is Vanuatu; where 55% of its water area under 200m deep strictly requires resurvey at larger scale or to modern standards (IHO, 2016a). In recognition of this, New Zealand carried out an IHO endorsed hydrographic risk assessment (Marico Marine NZ, 2013). The recommendations reduced the scope of the required survey effort by linking areas of marine activity with areas of demonstrated environmental and cultural value. Four critical areas were identified and these were surveyed in 2014 (Hydro International, 2014). An Australian cruise operator had previously commissioned surveys to improve access to some of the southern Islands of Vanuatu, for cruise landing access. Further assessments under the South West Pacific Regional Hydrography Programme have been undertaken for Tonga, the Cook Islands and most recently Niue (IHO, 2016c). They provide a more nuanced appreciation of the status of survey and charting from which to determine the extent and focus of remedial measures than the more generalised percentages stated in IHO C-55.

Regardless of where cruise ships operate the provision of depth information on charts covering unfrequented areas will continue to depend on opportunistic survey tracks for the foreseeable future. The capability of Navigation Sonar to provide a swath of soundings rather than a single profile should be exploited to the full. In effect this would develop a series of swept channels. Subsequent use of these would allow some flexibility in course keeping and provide a greater measure of reassurance to navigators than single lines of sounding.

10. Crowd sourcing bathymetry

- *IHO and other Initiatives*

NOAA and the IHO are collaborating on a project to improve the IHO Data Centre for Digital Bathymetry (DCDB) through the collection of crowd-sourced bathymetry (CSB). Ultimately the public will be able to upload, discover, display and download bathymetric data via a web-based interface. Integral to CSB is the establishment by the IHO of the Crowd-Sourced Bathymetry Working Group (CSBWG) that is tasked to develop a guidance document for the collection and submission of CSB data (Robertson, 2016).

Other projects underway include:

- Rose Point Navigation Systems coordinating with NOAA to allow users of their Coastal Explorer product to send anonymous GPS position and soundings data to a new international database managed by the NOAA Centres for Environmental Information (NCEI) (Reed, 2016).
- the TeamSurv BASE Platform project, funded by the European Union's Horizon 2020 program, combines crowd-sourced with satellite derived bathymetry to enhance seafloor mapping (TeamSurv, 2016).
- The Sea ID project, which is developing a mass-available bathymetry survey platform with the IHO and the Google Ocean Program (Sea ID, 2017).
- The European Marine Observation and Data Network (EMODnet), which is building a Bathymetry portal data infrastructure with full coverage of all European sea-basins (EMODnet, 2016).

There is significant potential for the integration of the data products obtained from Navigation Sonar under crowd sourcing initiatives to improve the content of navigation charts. This is especially significant in poorly charted regions. Even a small percentage of the 678 expedition, sailing and motor yachts over 24m on order in 2017 would represent a substantial fleet of vessels of opportunity that could participate in crowd-sourcing initiatives.

11. Navigation Sonar Bathymetry

Data products produced by navigation sonar systems can range from non-existent, providing only a raster image, to a full and comprehensive representation of the acoustic environment from which the data from an entire voyage may be recreated. The comprehensive representation is exceptionally memory intensive, often resulting in 10 megabytes of data or more for each ping (Wright and Baldauf, 2016a). With a new ping every other second or so, data storage requirements can build up rapidly to where gigabytes of data are created for every few minutes of use. In addition, the formats and contents of these data are generally proprietary to each manufacturer. However, each of these systems render an image from the transducer data they collect that depicts a representation of a swath of soundings within the range of the system that is georeferenced with respect to the position of the vessel. A 2-dimensional image shown in ***Figure 9*** can be shown as an overlay on a chart showing the bathymetric swath collected along and adjacent the vessel's route.

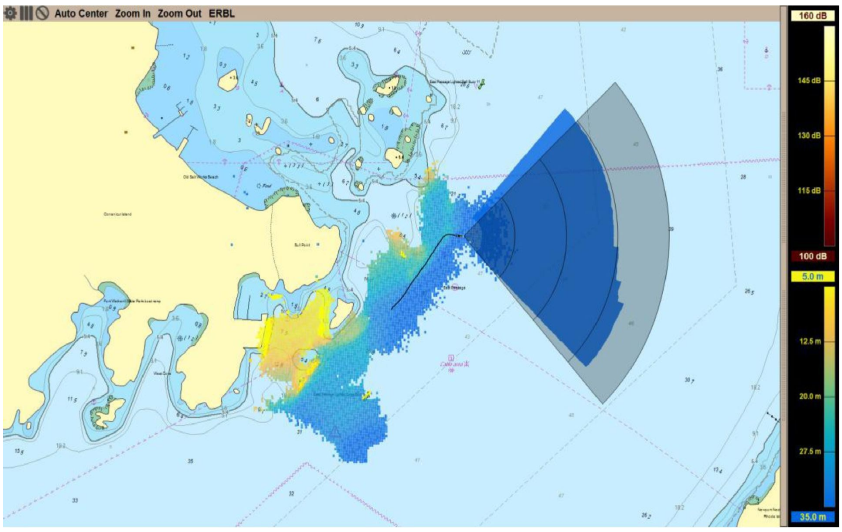

***Figure 9**: 2-dimensional Navigation Sonar Imagery Showing Recent Voyage Soundings History*

(Image courtesy of FarSounder, Inc.)

♦ *Data extraction*

It is necessary to identify a basis upon which these common data may be derived from the individual formats in which they are created, rather than to attempt to use the data in their native, proprietary and diverse formats. Doing so will facilitate the extraction of only the actual data required for crowd sourcing, reducing the file size for one ping from its original size of greater than 10 megabytes to 6 kilobytes or less as the file would only contain text similar to the proposed data format being considered by the IHO CSBWG (Robertson, *ibid.*). ***Figure 10*** provides an initial draft of a data specification that would be available from a ping-type of navigation sonar whereby one ping represents data simultaneously from many hydrophones, often numbering 200 or more. A different format would be required for searchlight sonars that would be similar to a data stream of a single beam echo sounder.

A record of data obtained would include metadata regarding the origin of the data and some of the characteristics of this source. This metadata need only be acquired once, whereby it can be attached as a header that accompanies all subsequent bathymetry data contained in a record comprising a set of files, with one file anticipated to be produced for each ping. The file name should ideally contain date and time information, plus any Unique ID that may be desired for identifying and managing the data (IHO, 2016d). Each ping file contains the sounding information derived from each active hydrophone, from 1 to the last hydrophone, e.g., 256, 512 or other value. The x,y,z values associated with latitude, longitude and depth from each hydrophone are contained in this file.

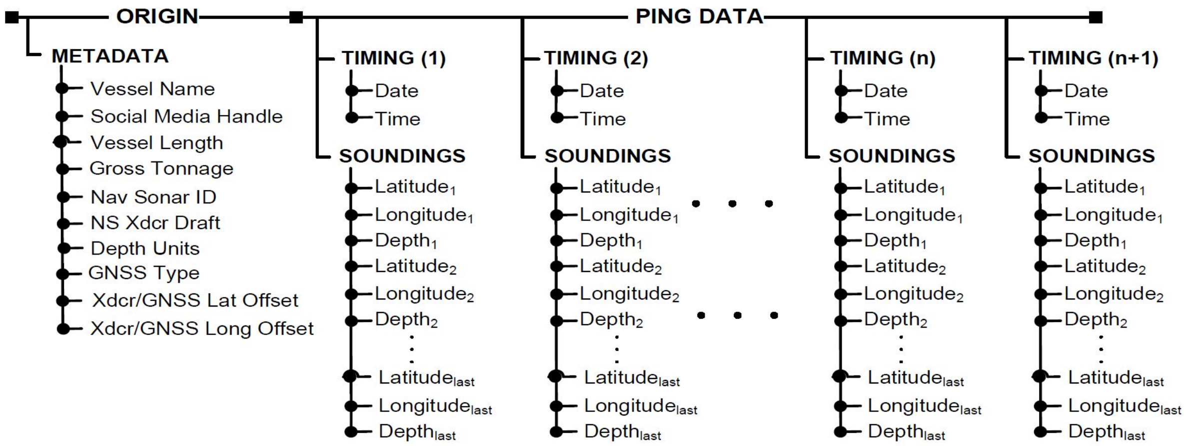

Figure 10 : *Sample Navigation Sonar Data Specification*

A complete record would consist of a header and the total number of files that represents pings over a specific period of time. This time-segmenting of the data is intended to facilitate ease of their transmission via existing communication channels. It also provides protection in the event data is lost to prevent the loss of entire data sets. It is not necessary or even desirable to capture all soundings from all hydrophones obtained during each ping. It is likely that a few hydrophones at the fringes and the corners of the transducer are likely to produce results that are statistically less accurate than in other areas. Indeed, there is a zone of between approximately 20 to 75 percent of the sonar cone distance that provides the most highly sampled and accurate soundings that should form the basis for the crowd sourcing of these data. This phenomenon is illustrated at the top of ***Figure 11*** and is based upon the existence of a great deal of overlap between pings.

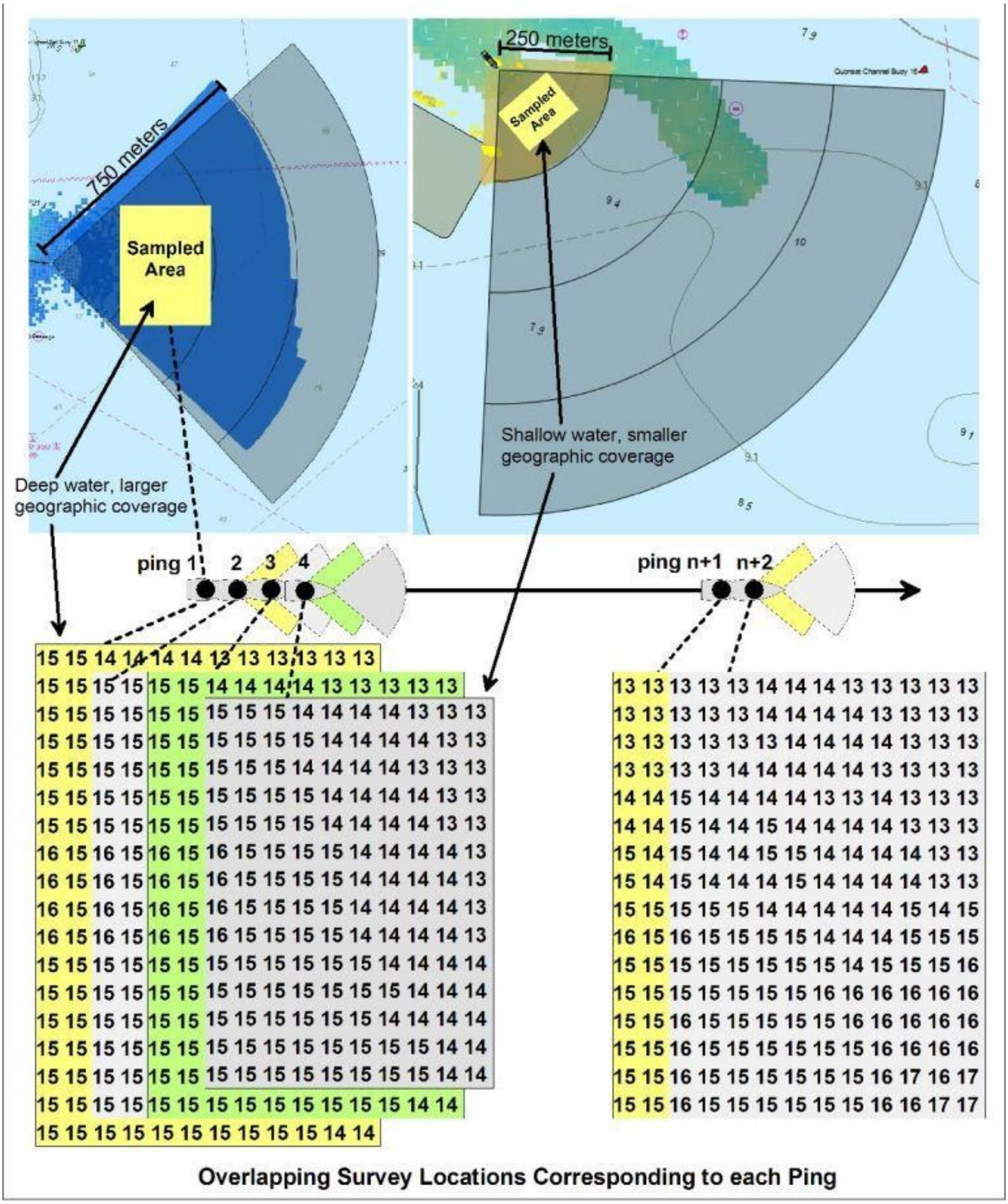

Figure 11 **:** *Sample areas within the sonar cone providing the most accurate soundings. Overlap of soundings between pings is also illustrated.*

(Image courtesy of FarSounder, Inc., annotated by authors)

Also, the number of hydrophones providing useful data can vary as a factor of depth where shallow water can result in the acquisition of accurate but less useful data than would be possible in deeper water since spacing between soundings may be unnecessarily close. A statistical sampling of these soundings across multiple pings may be accomplished to determine their accuracy for each geographical area. This approach can also identify those areas that have been most sampled. Using this technique it is possible that the total record size for one hour of useful soundings data can be reduced to a few megabytes of data that can be easily transmitted via broadband cellular and satellite communications channels.

12. Navigation Sonar as a new method for ship navigation

The use of depth information and the marking of minimum depth contours to navigate has been a basic piloting skill for centuries. Navigation Sonar may also provide new capabilities to navigate vessels by providing the ability to view landmarks along the bottom and to navigate by georeferencing their position relative to that of the vessel. It may also provide new capabilities for the real time detection of changes in the seabed that have occurred since the revision of the current chart.

The availability of Global Navigation Satellite System (GNSS) delivering constant position, navigation and timing (PNT) in most navigable waters world wide has revolutionised navigation. In combination with the ENC, the look ahead and safe depth settings in ECDIS with associated alarms, can now automatically alert mariners to the proximity of shoal water and underwater hazards.

There are however *caveats*. To be fully effective, the ENC must be derived from recent and comprehensive surveys. Mariners therefore need to be aware of the limitations which may exist in areas where recent and comprehensive surveys do not exist, through a thorough understanding of Zones of Confidence (ZOC) used to convey the quality of charted information within ENC.

♦ *Complementing the Navigation Suite*

By providing 3D visibility into the waters ahead of the bow, Navigation Sonar can compensate for limitations in charted detail. Current systems have a range of 1,000m and scanning sonars normally operate at 1,500m or more. Consequently, provided a vessel's speed is commensurate with the navigational situation and her manoeuvrability and the bridge watch is alert, timely avoidance action can be taken to prevent a grounding. In some ECDIS systems, the sonar display can be integrated with the ENC display.

However, changes are also in store for ENC as well. Many new capabilities for Navigation Sonar can become available by having higher resolution survey data with greater levels of detail contained within the ENC itself. This is presently being accomplished as a result of detailed hydrography data that is integrated within the IHO S-100 framework standard Universal Hydrographic Data Model. Specifically, the S-102 high definition gridded Bathymetry standard (IHO, 2012) supports development of new navigation products not possible under S-57 and previous standards.

♦ *Navigation by Georeferencing*

In the same way that a radar overlay and comparison against charted above-water features can be used to address known or suspected GNSS failure, a novel approach to ship navigation becomes possible with the use of Navigation Sonar. This involves a comparison between real time live seascape features and elevations, and those represented within an ENC. A "ship-centric" methodology is followed such that vessels may safely navigate using real-time information supplied by the vessel's own sensors (Wright and Baldauf, 2015). This approach is based upon the premise that, given a specific geographic position, the corresponding position on a nautical chart should accurately represent the depth and bottom configuration of that position. Conversely, should the observed seascape via the Navigation Sonar differ markedly from charted depths and contours in the ENC (and particularly future high definition gridded bathymetry) then this would provide a clear indication that the ship's position was in doubt.

With the potential availability of high density gridded bathymetry, this discrepancy detection could be taken one step further. While the shape of the seabed is described in fairly coarse terms in a traditional ENC (as a carry over from paper chart compilation practices), the much higher resolution that will be available in S-102 gridded bathymetry will enable much finer discrepancy detection. This will potentially include differences in seabed slope and rate of change of slope.

- *Real-time detection of changes in bottom configuration*

Further capitalizing upon the greater resolution and detail contained within ENC in accordance with IHO S-102, is the prospect of Navigation Sonar being able to detect in real time, changes in bottom configuration between that sensed by live rendering and that contained within the ENC. This can be accomplished by placing an overlay of the 3D model created by Navigation Sonar onto a 3D bathymetry model created from ENC, and highlighting areas of the bottom that show differences between the two models. Such information can be very useful in highly transited areas, especially after storms and other events that may drastically alter bottom topography.

13. Conclusions

Evidence points to a steady increase in both adventure and regular cruising in Polar and other less frequented waters. In particular, given the unsatisfactory state of nautical charting in many polar cruising areas, these trends are concerning. As grounding is the most likely cause of a marine casualty, the provisions of the Polar Code (IMO, 2016) may mitigate the consequences of such an incident, but will not prevent one. Navigation Sonar is already fitted in a variety of vessels and is being specified for new build adventure cruise ships, luxury yachts and research vessels. These vessels are more manoeuvrable than crude carriers and pose less of a threat to the environment if grounded. Nonetheless, the financial and human cost of a major casualty could be just as significant. Assessment of the benefits of installing Navigation Sonar should include the nature and location of the vessel's area of operation, the status of charting, the distance from Search and Rescue services, climate, and environmental sensitivity. An effective sonar range of 1,000m should prove sufficient for vessels up to 200m in length, provided their speed and situation awareness are commensurate with the threat of encountering uncharted hazards.

While Navigation Sonar alone cannot guarantee a vessel's safety in uncharted or inadequately charted waters, it can provide an important addition to the navigation suite. There is qualified support for this view in which issues of training, integration with existing navigation systems and cost effectiveness are recurrent concerns. At the same time there is no doubt that for certain applications such as coastal hydrographic surveying, littoral warfare and expedition cruising in Polar Regions and less frequented tropical seas, Navigation Sonar can be an invaluable aid to safer navigation. Installations in super yachts point to the possibility of improved integration of Navigation Sonar displays and intuitive operation. In common with observed development trends in technology, Navigation Sonar unit costs can be expected to reduce and capabilities and functionality increase.

With increased resolution and range, Navigation Sonar will help bridge watch keepers to maintain an effective watch below the waterline in the same way as radar enhances situational awareness on the surface. Integration into ECDIS will further enhance the utility of these systems. High resolution three-dimensional forward looking sonar can also acquire swath bathymetry. As bottom features become better surveyed and delineated, feature-based navigation using forward looking sonar will become more feasible; thereby lessening the dependence on GNSS as a primary means of geo-referencing. Navigation Sonar is already proving its worth in specific obstacle avoidance applications as is scanning sonar. In addition there is the potential for Navigation Sonar to make a significant contribution to Crowd Sourced Bathymetry.

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Notes

COMPLETION OF THE CHARTING COVERAGE OF THE INTERIOR WATER'S COMMERCIAL NAVIGATION ROUTE

By the Chilean Navy Hydrographic and Oceanographic Service (SHOA)

Background

The Chilean Navy Hydrographic and Oceanographic Service (SHOA) is the official technical and permanent agency of the State of Chile in charge of production and maintenance of the national Nautical Charts. In this role, SHOA contributes directly to national development, providing safety to navigation on the different navigation routes that interconnect the Chilean ports, and connect these ports with others abroad. One of the most important routes is known as "Interior Water's Commercial Navigation Route", which allows navigation through the numerous channels and narrows that exist between the Chacao Channel and Punta Arenas in the Strait of Magellan.

In January 2017, SHOA accomplished the challenging goal of completing the paper chart and ENC cartographic coverage to improve safe navigation through the Interior Water's Commercial Navigation Route, (from now on described as the "Commercial Route"). The availability of the ENCs now enables ships to comply with IMO requirements set in SOLAS regulations. These regulations require that all ships over 500 tons must be fitted with a compliant ECDIS prior to July 2018.

The charting of the commercial route comprises 198 ENC cells, equivalent to 113 paper nautical charts and compiled at different scales. To achieve the completeness of the commercial route, it was necessary to conduct several hydrographic surveys to gather the data to enable the Lab Work to compile, validate and publish the new editions of the corresponding nautical charts. All this took SHOA several years of hard and coordinated work.

The Commercial Route

The Commercial Route is the route established by the Pilotage's Regulation. This identifies the channels and other water bodies authorized to be navigated continuously by vessels from the occidental entrance to the Chacao Channel, to the oriental access to the Strait of Magellan (see ***Figure 1***). This route is divided into 5 components:

- ⇒ Route to Puerto Montt through Chacao Channel
- ⇒ Route Interior Channels of Chile
- ⇒ Route through Chonos' Archipelago
- ⇒ Channels' Route from Tamar Cape to San Pedro Island
- ⇒ Strait of Magellan Route

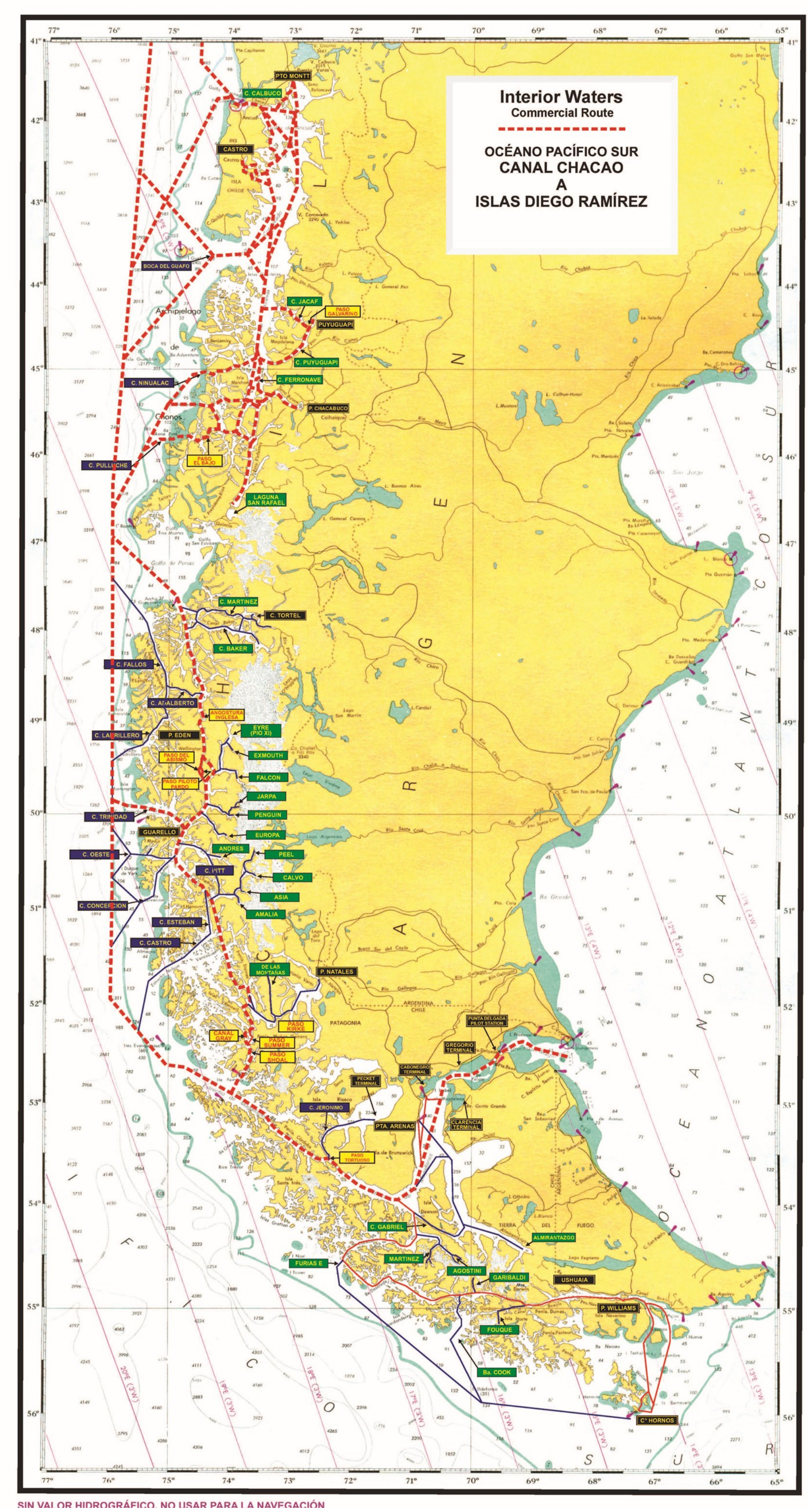

***Figure 1**: Navigation Routes from occidental entrance to Chacao Channel to the oriental access to the Strait of Magellan.*

To achieve this goal, updated information was obtained during several hydrographic surveys conducted by the Navy Hydrographic units. The field data was then merged with information obtained from processing satellite images. This data was then included in the hydro-cartographic database, where it was validated and finally compiled in the new edition processes for both the paper chart and the ENC.

With the publication of the new charts that complete chart coverage of the Commercial Route, all merchant vessels can benefit from the availability of the paper charts as well as their ENC versions. The improvement to navigational safety now allows shipping from Chacao Channel to and through the Strait of Magellan route and vice-versa. This avoids the need to navigate through open seas where it is normal to experience unpleasant sea conditions.

Having achieved this goal does not mean that the work is over. Future tasks include updating the coverage of the main commercial route as well as the execution of new hydrographic surveys to establish an alternative commercial route.

Conclusions

New technologies allow a more effective and efficient way to gather the relevant information to meet cartographic needs. In SHOA's case, when combined with well trained and qualified personnel, the survey and charting coverage of the main commercial route of the Chilean southern channels has been achieved successfully. The resulting outcome constitutes a direct contribution to safety of navigation.

This experience is both motivational and also a challenge. It shows that progress can be reached if the knowledge level and access to technology are given priority. Some years ago, it would not have been possible to collect, interpret, manage and process the volumes of data to the required quality of the information.

Finally, fulfilling this goal, places SHOA much closer to fully achieving its mission and objectives as the State of Chile's technical and permanent service with responsibilities to provide data, information, products and services associated to hydrography, nautical cartography and other related disciplines, thus contributing to national and international policies in force.

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Notes

THE AMENDMENTS TO THE CONVENTION ON THE IHO AND ITS SUPPORTING BASIC DOCUMENTS ENTERED INTO FORCE (8 NOVEMBER 2016)

By the IHO Secretariat

In 1997, a Strategic Planning Working Group (SPWG) was formed by the 15th International Hydrographic Conference (IHC) with two main objectives. The first one was to develop a Strategic Plan and Work Programme for the International Hydrographic Organization (IHO) and the second one was to review the structure and effectiveness of the Organization. The first objective was the focus of the work of the SPWG in 1998 and 1999 and resulted in the adoption of the IHO Strategic Plan and the IHO inter-sessional Work Programme and Priorities for 2000-2004 by the Second Extraordinary International Hydrographic Conference (EIHC) in 2000.

In April 2002, the 16th IHC considered the progress reported by the SPWG and tasked the Working Group to carry out a study on the need to revise the IHO Convention, to consider the harmonization of the texts of the IHO Basic Documents and to present the results of these studies to the Directing Committee of the International Hydrographic Bureau (IHB) that would then circulate the report to Member States by December 2003. The Conference tasked the SPWG to co-ordinate the comments on the interim report and produce a final version for consideration by the 3rd Extraordinary International Hydrographic Conference (EIHC) in April 2005.

The 16th IHC also decided that the SPWG would include representatives designated by the Regional Hydrographic Commissions (RHC). The Conference elected a Chair, Mr Frode Klepsvik (Norway) and two Vice-Chairs, Dr Wyn Williams (UK) and Mr Hideo Nishida (Japan) for the SPWG, and asked the President of the IHB Directing Committee (Rear Admiral Giuseppe Angrisano, succeeded by Vice Admiral Alexandros Maratos on 1 September 2002) to represent the IHB and to provide a Secretary (Captain Federico Bermejo). The SPWG met in full plenary sessions on five occasions to address its tasks; all the RHCs and several individual Member States contributed strongly to the debates.

Participants at the 4th SPWG Meeting Singapore 9-11 October 2003

A holistic approach to the tasks was adopted to ensure a structured, logical and rigorous review. The SPWG established an image of the future IHO defined through statements of its Vision, Mission and Objectives. It determined, through a review of past documents and a survey of Member States' opinions, what strengths and weaknesses the IHO possessed which would help or hinder it from achieving the Vision, Mission & Objectives. After assessing and debating many potential candidates for an IHO structure, the SPWG proposed a structure and a set of operational procedures which it believed were best suited to maintain the strengths, overcome the weaknesses and achieve the Mission, Vision and Objectives. It took into account the need to show increased effectiveness and cost-effectiveness and to maintain the IHO's status as a competent international organization.

After two years of intensive work, the SPWG completed its tasks and the Chair of the SPWG submitted the Final Report to the IHB Directing Committee in April 2004. The IHB Directing Committee then issued a Conference Circular Letter (CCL-2) on 10 May 2004 and forwarded the SPWG Report and its annexed documents for the consideration of the IHO Member States. The Report included the following documents:

1. A Study into the Organizational Structure and Procedures of the IHO.
2. Convention on the IHO *(Consolidated Version).*
3. Draft Basic Documents *(General and Financial Regulations of the IHO)* (Provided Later).
4. Protocol of Proposed Amendments to the Convention on IHO.
5. Proposals to the 3rd EIHC.

The General and Financial Regulations were circulated later and provided as Information Documents, since the texts would have to be finalized after the 3rd EIHC, subject to the amendments to the Convention accepted by the Conference.

The Directing Committee invited all IHO Member States to carefully study the SPWG Report and the proposals submitted, in order to facilitate the debate, aiming to reach agreement at the 3rd EIHC, highlighting that the amendments, among other innovative ideas, proposed the following: update the objectives of the Organization, consider more frequent meetings of the Conference (every three years), establish a new organ - the Council, replace the Directing Committee with a Secretary-General and Directors, developing the IHB into the IHO Secretariat, and simplify the procedures to become a Member of the Organization.

All Member States were requested to provide their comments on the Proposals, including any alternative or amendment to the texts proposed, to the IHB by September 2004. The IHB then collated the responses and comments and circulated the "Red Book of Proposals to the 3rd Extraordinary International Hydrographic Conference" in December 2004 (CCL-12).

The 3rd EIHC held in April 2005 agreed a Protocol of Amendments to the Convention on the IHO (Decision 2). Subsequently, the 17th IHC that took place in May 2007 approved the supporting Basic Documents.

Delegates of the 3rd Extraordinary International Hydrographic Conference, 11 April 2005

In order for the Amended Convention and the supporting Basic Documents to enter into force, the approvals of at least 48 existing Member States, being two-thirds of the Member States entitled to vote at the time of the 3rd EIHC, were required. This process, involving the approval by individual Governments and formal notification through diplomatic channels, took 11 years before the Government of Monaco was able to inform the IHB Directing Committee that it was formally notified of the approval of the 48th Member State on 8 August 2016. In accordance with the terms of the Protocol, this meant that the Amended Convention on the IHO and its supporting Basic Documents entered into force three months later, this being on 8 November 2016.

As a result of the entry into force of the revised IHO Convention and its supporting Basic Documents, a number of changes to the organization of the IHO took effect from 8 November 2016. The most significant of these changes included:

- the term *International Hydrographic Bureau (IHB)* used to describe the headquarters and the secretariat of the IHO ceased to be used and was replaced by the term *IHO Secretariat*;

- the Directing Committee, comprising a President and two Directors ceased to lead the IHB (Secretariat of the IHO). Instead, the Secretariat of the IHO was thereafter led by a Secretary-General assisted by two subordinate Directors;

- the term *International Hydrographic Conference* used to designate the principal organ of the Organization, composed of all Member States, was replaced by the term *Assembly*. The ordinary sessions of the Assembly would be held every three years instead of every five years for the Conference. The first session of the IHO Assembly (A-1) would be held in Monaco from 24 to 28 April 2017, at which time an IHO Council would be established. In order to provide a logical and sequential timetable for decision making, the first meeting of the Council (C-1) was scheduled to take place from 17 to 19 October 2017 and annually thereafter. The second session of the Assembly (A-2) would take place in April 2020;

- the subsidiary organs would report to the Council that will then refer their proposals to the Assembly or to the Member States, for adoption, through correspondence;
- the planning cycle for the IHO work programme and budget changed from a five-year to a three-year cycle. The first cycle would run from 2018 to 2020.
- for States wishing to join the IHO that are already Member States of the United Nations there would be no requirement to seek the approval of existing Member States of the IHO;
- the strict eligibility requirements for candidates seeking election as the Secretary-General or a Director were relaxed; and
- where voting by correspondence is required, through the Council, decisions would, in future, be taken based on a majority of the Member States that cast a vote, rather than the previous arrangement where a majority of all the Member States entitled to vote were required. Under the new arrangements, a minimum number of at least one-third of all Member States eligible to vote must vote positively for a vote by correspondence to stand.

In addition, a significant number of editorial amendments were required to IHO Resolutions to reflect the above and other changes. As a result, the Directing Committee presented the required consequential changes to the Resolutions (Proposal 9) to the first session of the Assembly for consideration in April 2017.