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Contents

Editorial

Welcome to the November 2020 edition of the International Hydrographic Review! It was my hope that this edition would see all of us returning to normal day-to-day life, but we remain constrained and frustrated by the global pandemic. However, this has not stopped the business of hydrography—surveys are being conducted, charts are being produced and data is being made available. The IHO and member states have embraced online meetings to ensure the IHO work program continues; not an easy task across the world's time zones. Significantly, IHO has released a new edition of *Standards for Hydrographic Surveys* (S-44 Ed 6) that specifies a new "Exclusive" order and clarifies existing orders. I highly recommend a thorough review of S-44 Ed 6, which can be found here: https://iho.int/uploads/user/pubs/standards/s-44/S-44_Edition_6.0.0_EN.pdf.

Inside this edition, we start off with two articles that will be of great interest to hydrographic offices who are contemplating changes to chart schemes or establishment of a spatial data infrastructure. First, an article on NOAA's ambitious and complex ENC Re-scheming Plan, followed by an overview of Singapore's National Marine Spatial Data Infrastructure highlighting the motivation and challenges of establishing an MSDI. The next two articles provide insight and recommendations on the use of non-traditional sonars for hydrographic survey, including NOAA's Fisheries sonars and a Brazilian Navy Phase-Measuring Bathymetry Sidescan Sonar. The Universiti Teknologi Malaysia then shares their thoughts on the establishment and use of ellipsoidally referenced surveys for hydrographic surveys. The last three articles address the increasing importance of satellite data. The Canadian Hydrographic Service promotes accelerating the use of satellite based earth observation data; ARGANS, Ltd., provides a passionate argument for greater acceptance of satellite derived bathymetry as source data for nautical charts; and the Brazilian Navy shows the potential benefits of analyzing the relationship between satellite altimetry observations with bathymetry.

The six notes in this edition cover a wide range of topics, including education, remote surveying, survey specifications, and the current status of unmapped waters in the USA. Of particular interest is a best practice guide for the use of autonomous survey vessels in hydrographic survey-I am sure you will find it informative and helpful as you pursue use of these systems. Finally, the substantial work plan and activities of our colleagues in FIG Commission 4 (Hydrography) are presented.

I hope you enjoy the articles and notes in this edition; the topics addressed are wide-ranging, relevant, and reflective of the ever-growing knowledge and skill in our hydrographic community. Don't forget to submit articles for the May 2021 edition by January 31, 2021. A special edition of the IHR, celebrating 100 years of the IHO, is planned for release in April 2021, as well. A website dedicated to the IHR is also in the works with a goal to increase accessibility to both current and archived editions of the IHR. It's a great time to be a hydrographer!

Brian Connon
Editor

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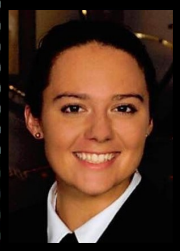
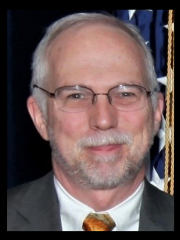
Articles



AN OVERVIEW OF THE NOAA ENC RE-SCHEMING PLAN

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Abstract

The scheme (or footprints) of NOAA Electronic Navigational Charts (ENCs) are based on traditional paper/raster charts from which they were derived. As a result, modernizing current ENC coverage to improve the way they are displayed in a digital environment, increase their level of detail, and incorporate additional survey data outside of the existing bounds is complex. As part of NOAA's "ENC-First" effort, a re-scheming approach was developed to provide a seamless, tiled coverage that can easily be segmented or extended based on geographic location, available data and scale. In this new regular gridded ENC coverage approach, fewer than a dozen chart scales are used (down from the current 130 scales used in the paper chart scheme). The re-scheme plan also aims to improve products for mariners who prefer paper charts. The uniform scales will enable mariners to create customized charts with a new online application. Additionally, NOAA has created one production line for both ENC and Raster Navigational Charts (RNCs) products that will reduce production resources for maintaining two chart products.

Key Words: Electronic Navigational Charts; Re-scheme; Marine Navigation; Chart Production; Production; Electronic Chart Display and Information System.

Résumé

Les schémas (ou empreintes) des cartes électroniques de navigation (ENC) de la NOAA sont basés sur les cartes traditionnelles papier/raster à partir desquelles ils ont été tirés. En conséquence, la modernisation de la couverture en ENC actuelle afin d'améliorer la manière dont ces dernières sont affichées dans un environnement numérique, d'accroître leur niveau de détail, et d'incorporer des données de levés supplémentaires au-delà des limites existantes, se révèle compliquée. Dans le cadre de l'initiative « ENC-First » de la NOAA, une approche de reschématisation a été développée afin de fournir une couverture maillée continue pouvant aisément être segmentée ou étendue en se basant sur la localisation géographique, les données disponibles et l'échelle. Dans le cadre de cette nouvelle approche d'une couverture en ENC maillée de manière régulière, moins d'une douzaine d'échelles cartographiques sont utilisées (bien moins que les 130 échelles actuellement utilisées dans le schéma de cartes papier). Le plan de re-schématisation vise également à améliorer les produits pour les navigateurs qui préfèrent les cartes papier. L'uniformité des échelles permettra aux navigateurs de créer des cartes personnalisées avec une nouvelle application en ligne. En outre, la NOAA a créé une ligne de production à la fois pour les produits ENC et pour les cartes de navigation raster (RNC), ce qui réduira les ressources de production pour la tenue à jour de deux produits cartographiques.

Mots clés : cartes électroniques de navigation ; re-schématisation ; navigation maritime ; production cartographique ; production ; système de visualisation des cartes électroniques et d'informations.

Resumen

El esquema (o el bosquejo) de las Cartas Náuticas Electrónicas (ENCs) de la NOAA se basa en las cartas tradicionales de papel/ráster de las que se derivaron. Como resultado, la modernización de la cobertura ENC actual para mejorar el modo en el que se visualizan en un entorno digital, aumentar su nivel de detalle e incorporar datos de levantamientos adicionales fuera de los límites existentes, es compleja. Como parte del esfuerzo de la NOAA «ENC-First», se desarrolló un enfoque en materia de restructuración para proporcionar una cobertura sin interrupciones y en forma de mosaico, que puede ser fácilmente segmentada o ampliada basándose en la ubicación geográfica, los datos disponibles y la escala. En este nuevo enfoque de cobertura ENC reticulada regular se utilizan menos de una docena de escalas de cartas (por debajo de las 130 escalas actuales utilizadas en el esquema de cartas de papel). El plan de restructuración también tiene por objeto mejorar los productos para los navegantes que prefieran las cartas de papel. Las escalas uniformes permitirán a los navegantes crear cartas personalizadas con una nueva aplicación en línea. Además, la NOAA ha creado una línea de producción para ambos productos, las cartas ENCs y Ráster (RNCs), que reducirá los recursos de producción para el mantenimiento de dos productos cartográficos.

Palabras clave: Cartas Náuticas Electrónicas; Restructuración; Navegación Marina; Producción de Cartas; Producción; Sistema de Información y Visualización de Cartas Electrónicas.

1. Introduction

The International Maritime Organization (IMO) requires commercial shipping to carry nautical charts and nautical publications for planning and displaying the ship's route for an intended voyage. The IMO has adopted the use of Electronic Navigational Charts (ENC), which are vector charts with a standardized content, structure and format described in the International Hydrographic Organization Standards Publication S-57 (IHO, 2000). ENCs are intended for use in an Electronic Chart Display and Information System (ECDIS), which is a geographic information display system used for nautical navigation and can also interface with other navigation systems, such as GPS, RADAR, and echosounders. The ECDIS itself has been adopted as part of carriage requirements for shipborne navigational systems and became mandatory for certain regulated vessels in July 2018 (IMO, 2012). Although paper charts are still in use, more and more mariners have switched to a digital form of these charts, known as Raster Navigational Charts (RNCs) that can also be loaded into ECDIS equipment and used together with an appropriate folio of up-to-date paper charts in the absence of ENC (IHO, 2018). However, RNCs only meet IMO carriage requirements where there is no ENC availa-bility. Similar to RNCs, ENCs are produced at various scales. However, while there can be any number of RNCs, produced at various scales, for any given area, ECDIS is limited to displaying no more than six different scale charts, one for each of the six ENC scale bands, - also called usage bands - in which only one chart at any scale can be produced over any given location. The division between the ECDIS scale bands is based on the intended navigational use: overview (Band 1), general (Band 2), coastal (Band 3), approach (Band 4), harbor (Band 5) and berthing (Band 6).

The format, information, and intended uses of NOAA charts, defined here as the RNC-First Approach, have not changed much over the past 150 years. Since NOAA introduced the ENC product, more than 20 years ago, the size of commercial vessels has increased more than four-fold (UNCTAD, 2017), modern navigational systems have become more sophisticated, and recreational boaters have joined professional mariners in using electronic chart displays. Marine and coastal users of all types are expecting more precision in the charted positions of features, higher resolution of depth information on electronic charts, and easier access to charts and chart updates that are more frequent.

In a digital production environment, the provision of data for many of the charted features can be streamlined into a hydrographic office (HO) in a digital format. Web services can provide shoreline and depth information as shapefiles, permits and other documents as scanned PDFs, and aids to navigation data as Excel spreadsheets. However, NOAA is currently managing two charting production lines that are not consistently harmonized with each other. As part of NOAA's ENC-First approach, it has been important to develop cartographic rules that will standardize charting products within the same scale band, independent of geographic location. It is also important to be aware of the technological advancements over the past 30 years of display systems on marine vessels, establishment of international distribution centers for ENCs, GIS portals, and non-navigation applications that only incorporate subsets of the charting products. As such, the goal of this report is to describe the benefits, challenges, and current results of NOAA's effort to re-scheme its ENC suite.

On March 8, 2017, NOAA invited the public to provide comments on a draft National Charting Plan (NCP). The NCP is a strategy to improve NOAA nautical chart coverage, products, and distribution. It consists of two parts: the first part describes the current set of NOAA nautical chart products and their distribution, and second part describes some of the steps proposed to improve those products, including changes to chart formats, scales, data compilation, and symbology. This paper quantifies and explains key topics mentioned in the NCP that include current challenges with the ENC products and cartographic rules to provide a seamless, tiled coverage that can easily be segmented or extended based on geographic location, available

data and scale. Examples of NOAA's regional chart coverage and charting of principle ports are presented in this paper to illustrate the ENC-First approach that standardizes 1,000+ irregularly shaped ENC cells using no more than 12 scales, instead of the current 100+.

2. Key issues resulting from ENCs derived from RNC Products

Most commercial ECDIS displays allow their users to select an ENC display according to usage bands. In order for a mariner to manage ENCs over the same area using different themes or navigational usage, IHO S-57 requires Hydrographic Offices (HOs) to identify a usage band for of their published ENC cells according to navigational purpose, depending on the scale of the source material used to compile them (IHO, 2000). The various ENC usage bands provide the mariner with different information based on the navigational purposes and detail preferred for display (IHO, 2002 and 2003). However, the S-57 ENC Product Specification does not provide guidance on the appropriate scale ranges to be used for each of the six Navigational Purposes. This issue was also identified in the context of controlling on-line generalization and multiscale ENC data management displayed in ECDIS using the SCAMIN (scale minimum) S-57 attribute (IHO, 2000; Leder, 2007). The SCAMIN attribute is the minimum scale at which an object may be used (e.g., for an ECDIS presentation) and allows optimal nautical data representation for any scale and purpose. Thus, an ENC is not cluttered when displayed at a smaller scale than the scale which the data was originally compiled (IHO, 2000).

An official IHO recommendation for scale ranges and usage band was published in 2004, several years after some leading HOs had already decided on their own national usage bands and started to compile their ENCs accordingly (IHO, 2004a, b). Two IHO publications that were approved at that time (IHO S-65 and a SCAMIN paper) strongly recommend HOs assign each ENC to a navigational purpose based on the ENC's compilation scale (***Table 1***). With that said, the inter-relationship and interaction between usage bands, SCAMIN, and compilation scale are particularly problematic and it is difficult to formulate voluntary guidelines that resolve all of the problems and that are acceptable to all HOs with differing views of these issues (Pharaoh, 2007). For example, ***Table 2*** presents the different definition of the usage bands by NOAA and the Canadian Hydrographic Office.

Table 1. Interdependence of usage band, navigational purpose, scale range, compilation scale and radar range (according to IHO, 2004a and b).

Usage Band	Navigational Purpose	IHO Recommended Scale Ranges (1:)	Radar Ranges (NM)	Available compilation scales (1:)
6	Berthing	> 4,000	< 0.25	
5	Harbour	4,000 – 21,999	0.25 - 0.75	8,000 12,000
4	Approach	22,000 – 89,999	1.5 - 3	22,000 45,000
3	Coastal	90,000 – 349,000	6 - 12	90,000 180,000
2	General	350,000 – 1,499,999	24 - 48	350,000 700,000
1	Overview	< 1,499,999	96 - 200	1,500,000 3,000,000

Table 2. Interdependence of usage band, navigational purpose, scale range, compilation scale and radar range (according to IHO, 2004a and b).

Usage Band	Navigational Purpose	NOAA Scale Ranges (1:)	CHS Scale Ranges (1:)	IHO Recommended Scale Ranges (1:)
6	Berthing	> 5,000	> 2,000	> 4,000
5	Harbour	5,001 – 50,000	2,001 – 20,000	4,000 – 21,999
4	Approach	50,001 – 150,000	20,001 – 50,000	22,000 – 89,999
3	Coastal	150,001- 600,000	50,001 – 150,000	90,000 – 349,000
2	General	600,001 – 1,500,000	150,001 – 500,000	350,000 – 1,499,999
1	Overview	< 1,500,001	< 500,001	< 1,500,000

As a result, NOAA's RNC-First Approach and interaction between usage bands, SCAMIN, and compilation scale created several key issues with NOAA's current nautical chart products and their distribution (NOAA, 2017):

- Too many alarms on caution areas are shown in ECDIS.
- Uncertainty values associated with "reported," "existence doubtful," and "position approximate" dangers are not well defined.
- Limited description of depth areas in key locations that require more detail for the mariner.
- Irregularly shaped ENC cells compiled at over 100 different scales that result with many discontinuities between neighboring charts on the same scale band.
- Current attributes to NOAA chart features are mainly good for SOLAS mariners, but not good for recreational mariners.

3. Re-Scheme Plan for NOAA'S Charting Products

3.1 Standardizing Scales

In order for NOAA's charts to comply with international standards, NOAA adopted IHO recommended usage bands with two compilation scales in each usage band (***Table 1***). However, binary -dependent compilation scales were selected for NOAA's ENCs instead of the compilation scales that are dependent on radar ranges (***Table 3***). Use of binary dependent scales will simplify the display of charts in ECS displays and different web-services. Also, it is simpler to sample key vertex points when generalizing a larger scale chart to a smaller scale binary-dependent chart. The only difference between the IHO recommended usage bands and NOAA's usage bands is the scale division between Band 5 (Harbor) and Band 6 (Berthing). NOAA chooses to divide the scales at 1:5,000 instead of 1:4,000. ***Table 3*** shows four common binary scale lists for the transition between large-scale to small-scale charts (i.e., Google Maps scale, 5-10-20, 12-48-96, and 25-50-100). Because of the large number of ENCs (more than 50) currently available at 1:10,000, 1:20,000, 1:40,000, and 1:80,000 scales, the use of the 5-10-20 scale list (NOAA Binary 1 in ***Table 3***) seemed to be most appropriate for NOAA's new re-schemed ENC scales. As a result, fewer charts will need to be rescaled and compiled to the new binary scale list, i.e., many feature can directly transfer from current NOAA charts into the new re-schemed charts. NOAA is currently focusing on producing continuous coverage of Scale Band 4 along all of the US and its territories (within NOAA's charting responsibilities), where approaches to ports will be at 1:40,000

scale. Principal ports (based on cargo, fisheries and tourism) will be covered at scale band 5, i.e., 1:10,000 scale or 1:20,000 scale.

Table 3. . Common binary compilation scales divided according to IHO's recommended usage bands. Gmap – Google Map Scale (Lee et al., 2016).

Navigational Purpose	NOAA Adaptation* of IHO Recommended Scale Ranges (1:)	Gmap (rounded) (1:)	NOAA Binary 1 (1:)	NOAA Binary 2 (1:)	NOAA Binary 3 (1:)
Berthing*	> 5,000	2,250 4,500	2,500 5,000	3,000	3,125
Harbour*	5,001 – 21,999	9,000 18,000	10,000 20,000	6,000 12,000	6,250 12,500
Approach	22,000 – 89,999	36,000 72,000	40,000 80,000	24,000 48,000	25,000 50,000
Coastal	90,000 – 349,000	144,000 288,000	160,000 320,000	96,000 192,000	100,000 200,000
General	350,000 – 1,499,999	576,000 1,152,000	640,000 1,280,000	384,000 768,000	400,000 800,000
Overview	< 1,499,999	2,304,000 4,608,000	2,560,000 5,760,000	1,536,000 3,072,000	1,600,000 3,200,000

* NOAA divides the scales between Berthing and Harbour at 1:5,000 instead of 1:4,000 as recommended by IHO (see ***Table 2***).

3.2 Improving Charts Schemes

The second element of the plan is the footprint (scheme) of the charts. NOAA and many other HOs built their ENCs by digitizing paper nautical charts in order to get them done quickly and to ensure that the two products matched each other. In the new ENC-First paradigm, it is important to point out that ENCs do not need to follow traditional raster chart limits and are solely limited by the 5 MB ENC file size restriction (IHO, 2000). As such, it is possible to use a gridded system with fixed cell sizes and standardized scales. A statistical analysis of NOAA's current ENC cells over the continental US showed that the calculated cell boundaries along the width and height are linearly dependent on the scale, i.e., progressively larger scale usage bands cells will nest within the (larger size) smaller scale cells (***Figure 1***). The reason for excluding Pacific Islands and the State of Alaska was to avoid the introduction of unique small inset island charts and high-latitude charts that contain distortion, respectively. A reference fishnet has been created for each usage band. All re-schemed ENC cell boundaries follow lines of longitude and latitude and will appear rectangular in a Mercator projection. The reference fishnet's center of reference is at 0°N and 0°E for each of the usage bands, and it is possible to add more ENC cells to the chart suite by copying the footprint from the fishnet for any location on Earth. The geographic ENC size for each usage band was calculated based on data volume restriction of not being over 5 Mb (***Table 1).***

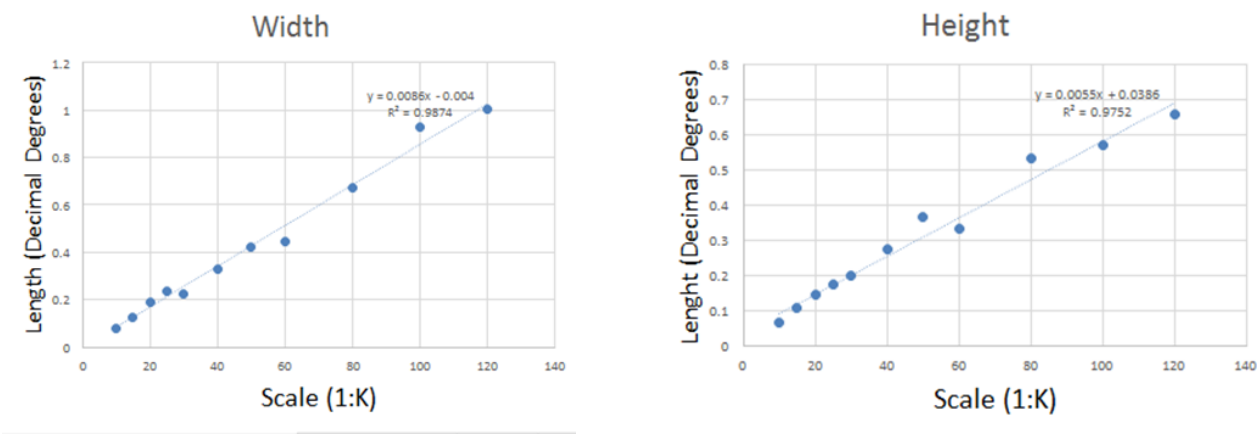

Figure 1. Scatter plots of average NOAA ENC width (along latitude), height (along longitude) and area as function of scale.

In the past, each ENC cell was maintained within its own individual database, which made re-scheming ENCs difficult, but now all NOAA ENCs are maintained within a single, seamless database called the Nautical Information System (NIS). The NIS database simplifies many ENC enhancements, such as the edge matching of data on adjacent cells of the same or similar scales, and increasing the conformity of feature compilations on different scale ENCs. ENC footprint dimensions are separated into three geographic zones (***Figure 2):*** low-latitudes (48˚S to 48˚N), mid-latitudes (48˚N to 64˚N) and high-latitudes (64˚N to 80˚N). The separation is based on the distortion at high-latitude caused by the projection used to display the charts. To accommodate this, the width of the ENC cells is doubled from low-latitudes to mid-latitudes, and doubled again from mid-latitudes to high-latitudes. For example, a Band 5 ENC cell's width is 0.075˚ at low-latitudes, 0.15˚ at mid-latitudes, and 0.30˚ at high-latitudes.

Width Zone	Latitude Extent
III	64˚N - 80˚N
II	48˚N - 64˚N
I	0˚ - 48˚N
	Equator
	0˚ - 48˚S
II	48˚S - 64˚S
III	64˚S - 80˚S

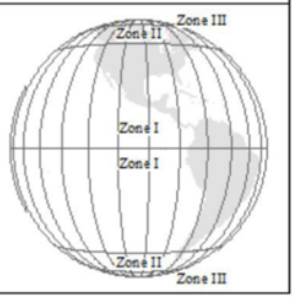

Figure 2. Schematic illustration of the three geographic zones based on latitude for defining the dimension of NOAA's ENCs.

The United Nations Code for Trade and Transport Locations (UN/LOCODE) was used to identify each port by a unique three letter identifier in order to differentiate the US Principle Ports from the rest of the re-schemed ENC cells at the same scale band. The US port list is the official short name in English as referenced in ISO 3166, where the two-letter identifier of the country (i.e., US) were ignored. Thus, the Principle Port ENC cells utilize the three-letter port code for the fourth, fifth and sixth characters. The last two characters are determined by the cell location with respect to a given reference. The southwestern corner of the ENC cell grid is the origin ("AA"), where the seventh and eighth character represents distance from the origin in latitude and longitude, respectively (***Figure 2***). In non-principle port ENCs, the U.S. state represents the fourth and fifth characters, followed by an integer delineating a zone within the state for the sixth character.

The seventh and eighth characters are the cell location with respect to a given reference. The port list was obtained from the UN/LOCODE Code List 2017-1 for each country (current version was published in July 2017): http://www.unece.org/cefact/locode/service/location.html. In cases where there are two or more Principle Ports next to each other, only the three letter UN code of the largest Principle Port will be used for the ENC grid.

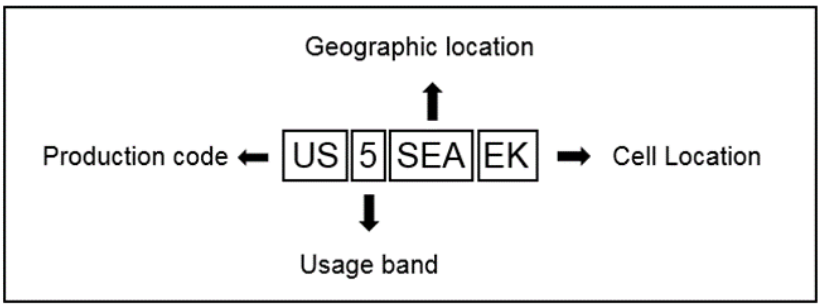

Figure 3. Naming convention for re-schemed ENC cell names.

3.3 Generalization

NOAA's generalization rules follow legacy best practices used in RNC production. IHO S-58 (IHO, 2018b) also uses a validation check – "For each edge which contains vertices at a density Greater than 0.3mm at compilation scale." As such, key generalization rules used in ENC production during the re-scheming process included: 1) minimum vertex density greater than 0.3 mm/scale, 2) double-line features become a single-line feature when the distances between the lines are less than 0.3 mm/scale, 3) and any branch line feature (e.g., pier or a stream) perpendicular to the trunk feature (e.g., shoreline or rivers) and is less than 0.8mm/scale will be omitted from the data. It is important to note that the IHO S-58 refers to the native spatial representation of the ENC features, i.e. is geographic WGS-84. However, ESRI and other GIS software encounter truncation issues with meter-level calculations (six digits after the decimal point). In order to avoid potential GIS algorithms, NOAA validated and generalizes vertex points along the same feature or the distance between two line features using a 0.4 mm/scale threshold in a metric projection (e.g., Universal Transverse Mercator) (**Table 4**). The output is an ENC product in geographic coordinate system with vertex density less than 0.3 mm/scale.

Table 4. NOAA's recommended vertex and line distance density of features for GIS tools using metric projection.

Scale	Vertex density and singleline threshold (0.4 mm/scale)	Perpendicular line feature threshold (0.8 mm/scale)
1:10,000	4 m	8 m
1:20,000	8 m	16 m
1:40,000	16 m	32 m
1:80,000	32 m	64 m
1:160,000	64 m	128 m
1:320,000	128 m	256 m
1:640,000	256 m	512 m
1:1,280,000	512 m	1,024 m
1:2,560,000	1,024 m	2,048 m
1:5,120,000	2,048 m	4,096 m

4. Results

4.1 Current production effort

NOAA's Marine Chart Division (MCD) has worked to address the re-scheming challenge through a series of production steps that are separated by phases. The first edition of a re-schemed NOAA ENC should have an authorization letter that is registered in the MCD tracking system. Following this, production of re-schemed ENCs includes: 1) generalizing shoreline to the appropriate scale, 2) compiling features as function of scale, 3) matching feature edges to ensure connection of contours, shoreline, depth areas, etc., and 4) applying new cell boundaries and chart note files. Furthermore, an Edition one re-schemed ENC should comply with MCD's current vertex density rules of no more than 200 vertex density warnings for vertices closer than 0.3mm at compilation scale (IHO, 2018b). Phase two of a re-schemed ENC will include updated and recompiled hydrographic contours. The recompilation will take advantage of NOAA's new National Bathymetric Source (NBS) database, which will assist in the transformation to metric soundings and contours (currently, compiled in feet and fathoms, and converted to meters for ENC production) and ensure that the latest data is applied to re-schemed areas (Rice et al., 2020). The NBS will ensure that the latest data is used to compile the new products while also maintaining proper supersession rules between different survey data sources. The NBS's automated approach will save countless cartographic compilation hours while improving the data quality of the ENCs. Edition three, the final step in the re-scheming process, will include the addition of topographic contours and feature place names, road networks and other land features. Once edition three is complete, the cell will be in a maintenance mode. Each new edition intends to provide the maximum incremental benefit to the public without having to wait for the entire re-scheming process to be completed.

According to NOAA's re-scheme plan (NOAA, 2017), NOAA has started its re-scheming effort in the band 4 space in order to produce continuous coverage along all of the US and its territories (within NOAA's charting responsibilities), Two additional reasons were: 1) the ease of transition due to existing coverage in a corresponding scale, available data (shoreline and bathymetry) for the new coverage, and 2) Approach scale charts at the 1:80,000 serve as a mid-scale product for use in confined bodies of water, and with NOAA's extended re-schemed coverage can be used for coastal navigation in the electronic environment. ***Figure 4*** illustrates NOAA's re-scheme plan for the Great Lakes. NOAA has also started working on band 5 coverage in some areas and intends to work on band 3 in the near future. As shown in ***Figure 5***, the MCD is working in several different geographic areas around the country to re-scheme the charts. The main reason for this is to ensure that each of the six regionally-based cartographic teams builds expertise simultaneously while working to demonstrate the benefits to a more regionally diverse set of customers.

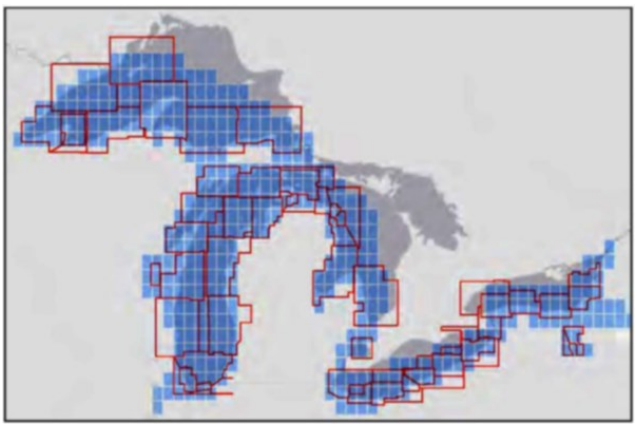

Figure 4. NOAA's re-scheme plan for the Great Lakes (Band 4). Red polygons represent the legacy ENC footprint and the blue rectangles represent the new re-schemed ENC cells.

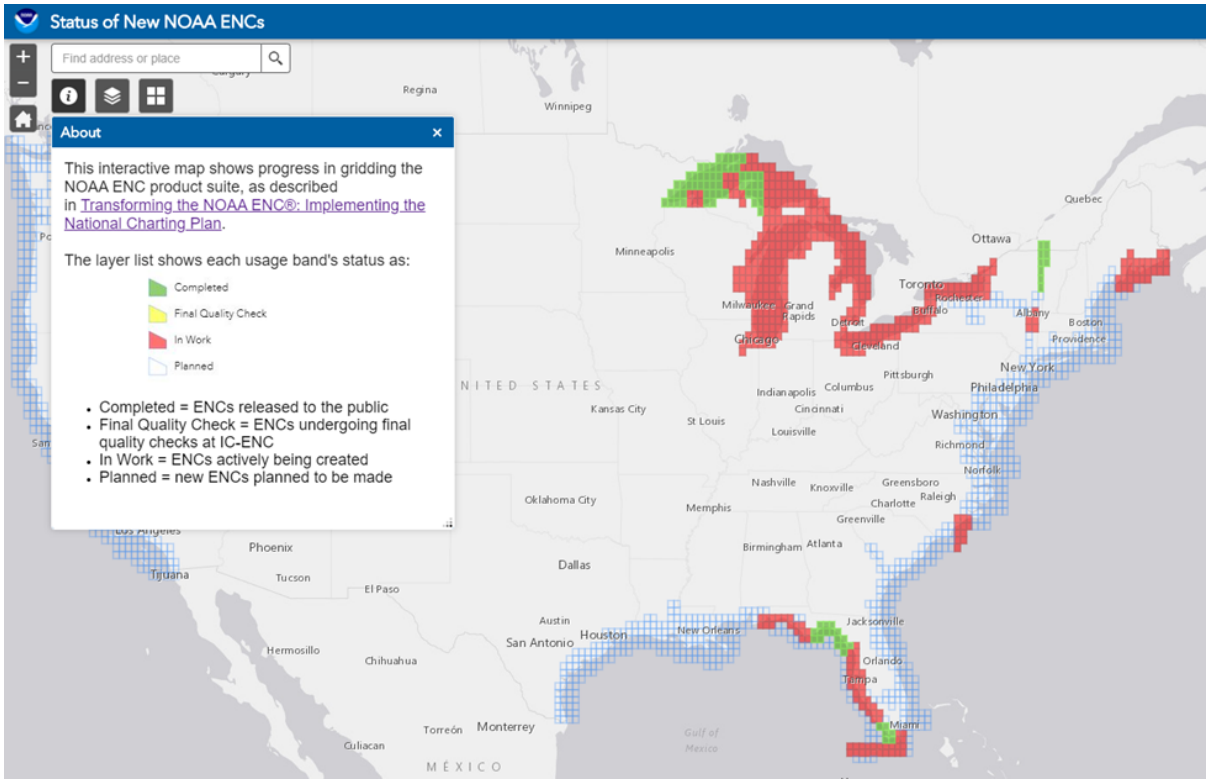

Figure 5. Online GIS used to display progress of creating re-schemed ENC coverage.

4.2 Challenges in production

Coordinating the production and release of a re-schemed chart while ensuring that the mariner has access to a current the pre-re-schemed chart is akin to changing a car tire while the car is moving. Large amounts of data must be applied to both current and new products while the new charts are being built; the old chart must be retired or cut to new extents, simultaneously with the new ENC release, or overlap errors will occur. Additionally, when charts are retired by area (rather than individual cell) communication with the mariner is critical. Other key challenges in production are as follows:

Bathymetry – Applying bathymetry is one of the most challenging aspects of the re-scheming project. NOAA's aim to apply the most accurate data available while converting the contours to metric requires complete recompilation in many areas. The challenge of finding shore-to-shore coverage that is deemed acceptable to support navigation is frequently impossible and often requires additional data collection. The use of non-traditional means of gathering data, including Airborne LiDAR Bathymetry and Satellite-Derived Bathymetry, are employed. However, this type of data are only useful when the waters are optically clear to detect the bottom at depths deeper than 6 m (Pe'eri et al., 2014). This issue of charted areas lacking bathymetry also presents the challenge of creating larger scale products as part of the re-schemed plan that do not currently exist. Creating approximate, dashed line, contours from smaller scale data to update larger scale chart production (example: 1:40,000 data creating a new 1:10,000 scale chart) is not preferred but is possible. The same approach cannot be used to produce the desired spacing or horizontal accuracy for soundings on larger scale charts. An interim solution of updating chart notes to warn the mariner was coordinated with IC-ENC. NOAA is enthusiastically working on deploying its National Bathymetry Source database (Rice et al., 2020), which is expected to significantly expedite the compilation process by automating data precedent and sounding selection.

Digitized line and polygon features – As mentioned above, most ENCs were digitized from raster products, resulting in severe over compilation of features, such as shoreline. In many cases, the vertices are closer than 0.3mm/scale (IHO, 2018b). Another issue is fragmented line features that represent only a single feature. This level of detail is not visible when viewing ENCs at the proper zoom level and requires more effort on an ECDIS to display these features. As such, many charts can receive hundreds or even thousands of S-58 warnings during the chart validation process. In addition, there might be Group 1 ("Skin of the Earth") errors due to gaps between the depth and land areas. Although there are several automated generalization tools, there is a need for manual editing to reduce these errors and warnings, while also amending topology of all the Group 1 bounding features that interact with land areas, depth areas, sea areas (e.g., shoreline). As a result, production time is drastically increased for generating ENC products. Several possible solutions are being tested to reduce the effort of this generalization process, but a final solution has not yet been implemented into the workflow.

Communication – Although communication with the public and key stake holders has been a challenge, it has been met through a series of internet blog posts and customer interaction through NOAA's regional navigation managers. NOAA also employs an online "Status of New NOAA ENCs" web map (https://distribution.charts.noaa.gov/ENC/rescheme/) that shows areas where re-scheming is planned, in work, in final quality check or completed. It should be noted that plans for the new ENC scheme are subject to change, and may be modified to meet user needs. The coverage and/or the scale may end up being significantly larger or slightly smaller. The web map will reflect changes to the planned layout as they are made.

5. Discussion

5.1 Rasterization HD Charts

Despite the re-scheme plan described here, raster format charts are still preferred by many mariners. With NOAA's new plan to standardize a consistent gridded framework that is optimized for digital displays, the question is what is the future of paper charts, or raster images that are used in navigation systems? In order to allow a raster-based maintenance system, it is now possible to translate encoding attributes of vector objects into standardized chart symbols and labels, and therefore simplifying workflow processes for raster chart production (Ence and Pe'eri, 2019). One of the great side benefits of the re-scheming project is that it will significantly improve another charting service that NOAA is providing, the NOAA Custom Chart (NCC) application (https://devgis.charttools.noaa.gov/pod/). The NCC allows users to define their desired footprint for a paper chart and includes customizable settings, such as paper size, scale, and safety contour to name a few. Since the NCC uses the NOAA ENC suite as its base data, the output is greatly improved when the ENC suite is uniform in scale. If, for example, one wishes to produce a chart at 1:40,000, but half of the area covered is only available at 1:80,000, then that portion of the paper output will only show half the level of detail as the area that has the 1:40,000 scale data available. Also, features like depth contours and depth areas may not be aligned or suddenly end. The use of only one or two scales for each usage band throughout the re-scheme effort should resolve these issues.

5.2 Re-schemed products Dissemination

NOAA is a member of the International Centre for Electronic Navigational Charts (IC-ENC). This is a Regional ENC Coordinating Centre (RENC), which supports the IHO Worldwide Electronic Navigational Chart Database (WEND) principles. The IC-ENC validates NOAA ENCs according to the IHO S-58 check list and distributes the chart products. IC-ENC is acutely involved in NOAA's re-scheming process for a number of reasons: 1.) Validating new, first edition, ENCs takes considerably more effort than validating new editions of existing ENCs. Since every new

re-schemed ENC is a first edition chart, the re-scheming workflow has increased the IC-ENC workload considerably. Additionally, these new cells may be created in areas which have not been subject to a new edition for some time, and so there is the opportunity to update content and encoding to reflect the latest "best practice"; 2.) IC-ENC carries out a vital function in coordinating the exchange between new and old cells. This RENC maintains a critical part of the communication chain during a cell re-scheming. This ensures that mariners on the bridge of a ship are provided with a seamless coverage, and the 'old' is replaced by the 'new'; 3.) The new chart scheme dramatically increases the number of ENCs in the US suite (***Figure 4***). While this increases safety, among other things, it also increases the cost of management due to the complexity of accounting (i.e., storage space, coordination, and distribution management, such as supply and user permit generation). As part of the re-scheme workflow, NOAA provided resources and personnel to coordinate the communication with IC-ENC to maintain a steady, secure production line that can reliably deliver the latest data to ships operating in US ports.

6. Conclusions

NOAA's "ENC-First" initiative includes a multi-year re-scheming project that will result in a seamless, grid based coverage that can easily be segmented or extended based on geographic location, available data and scale. A new naming convention will be used for the re-schemed cells, retiring the old names associated with the raster-based ENC cells. NOAA has started by re-scheming the band 4 space in order to produce continuous coverage in the US and its territories (within NOAA's charting responsibilities). Additional band 5 coverage re-scheming efforts will be conducted in key U.S. ports, but in the future, NOAA expects to work to complete large regional areas in all usage bands, as it works around the country. During the project's initial period, NOAA is working through multiple challenges along the production pipeline that include: manual work generalizing line and polygon features (e.g., shoreline and inland water bodies), gaps in bathymetry due to the compilation of larger-scale products from smaller-scale sources, and more effort in conducting validation for new ENC cells. However, the expected result will allow for many automated cartographic processes that are currently manual and provide updates to charts through the scales in a much faster time. The end goal is provide seamless sets of uniform data throughout US waters that will improve electronic navigation through uniform coding practices and standard scales while also greatly improving the ability to produce customizable charts for printing using ENC data as source.

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8. Authors Biographies

John Nyberg is the Deputy National Hydrographer at NOAA's Office of Coast Survey. Nyberg's previous positions at NOAA include chief and deputy chief of the Marine Chart Division from 2010 to 2020, where he directed Coast Survey's chart modernization to digital products, changing the operational focus from paper-based chart compilation to electronic navigational charts. Prior to his work in the Marine Chart Division, Nyberg spent 12 years in Coast Survey's Navigation Services Division, moving from United States Coast Pilot ® cartographer to deputy division chief where he managed the procurement of the research vessel *Bay Hydrographer II* and initiated the modernization of the Coast Pilot's production system.
Nyberg has a bachelor's degree from the University of Florida, with a major in geography, a master's in international management from the University of Maryland, and is currently working on a PhD in geographic science at George Mason University. He is presently living in Key West, Florida.

Dr. Shachak Pe'eri is the currrent Division Chief of Coast Survey Development Lab at NOAA. Dr. Pe'eri's previous positions at NOAA, included Branch Chief of the Chart Standards Group and Chief of the Cartographic Support Branch within the Marine Chart Division. Dr. Pe'eri earned his PhD in Geophysics from Tel Aviv University, Israel. Dr. Pe'eri is also affiliated with Center of Coastal and Ocean Mapping (CCOM), University of New Hampshire (UNH), NH USA and George Mason University, VA, USA.

Colby Harmon is a staff cartographer and project manager in the National Oceanic and Atmospheric Administration's Office of Coast Survey. Previously, he worked at the National Geospatial-Intelligence Agency and its predecessor organizations. He has been involved in developing and maintaining specifications for several digital map and chart products and their symbolization throughout his career. He received a Bachelor of Arts degree in Geography from the University of Connecticut and a Masters of Science in Strategic Intelligence from the U.S. Joint Military Intelligence College. Prior to obtaining his undergraduate degree, Mr. Harmon served in the U.S. Air Force as a geodetic surveyor.

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Articles

SINGAPORE'S NATIONAL MARINE SPATIAL DATA INFRASTRUCTURE "GEOSPACE-SEA" : Enabling Hydrospatial Context and Applications in a Changing Ocean and Seascape

By P. Y. Pang[1,2] and P. Oei[1,2]

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Abstract

The establishment of national Marine Spatial Data Infrastructures (MSDI) have been geographically uneven due to challenges such as funding, political will and human capital. Furthermore, actualising MSDI benefits; enabling and supporting hydrospatial applications, poses another set of challenges. Using Singapore's national MSDI – GeoSpace-Sea, this paper uncovers four catalysts of GeoSpace-Sea's development and describes three challenges an emerging national MSDI confronts when actualising its envisaged benefits. These challenges could vary over time, space and the MSDI's maturity. Along with integrated hydrospatial and geospatial management, MSDIs would foreseeably continue to be key to unlocking the value of spatial data and in revealing insights into the past, present and future.

Résumé

La mise en place d'infrastructures de données spatiales maritimes (MSDI) nationales a été inégale sur le plan géographique en raison de défis tels que le financement, la volonté politique et les ressources humaines. En outre, l'actualisation des avantages des MSDI, la facilitation et le soutien d'applications hydrospatiales, représentent un autre défi. En utilisant la MSDI nationale de Singapour – GeoSpace-Sea, cet article dévoile quatre catalyseurs du développement de GeoSpace-Sea et décrit trois défis auxquels est confrontée une MSDI nationale émergente lors de l'actualisation de ses avantages envisagés. Ces défis peuvent varier dans le temps, l'espace et selon la maturité de la MSDI. Parallèlement à la gestion hydrospatiale et géospatiale intégrée, les MSDI continueraient probablement à être essentielles en vue de libérer la valeur des données spatiales et de révéler des perspectives passées, présentes et futures.

Resumen

El establecimiento de las Infraestructuras Nacionales de Datos Espaciales Marinos (MSDIs) ha sido geográficamente desigual debido a desafíos como la financiación, la voluntad política y el capital humano. Además, la actualización de los beneficios de las MSDIs; la activación y el apoyo a las aplicaciones hidroespaciales, plantean otra serie de desafíos. Al utilizar la MSDI nacional de Singapur - *GeoSpace-Sea*, este documento revela cuatro catalizadores del desarrollo de *GeoSpace-Sea* y describe tres retos a los que se enfrenta una MSDI nacional emergente a la hora de actualizar sus beneficios esperados. Estos desafíos podrían variar con el tiempo, el espacio y la madurez de la MSDI. Junto con la gestión hidroespacial y geoespacial integrada, es previsible que las MSDIs sigan siendo fundamentales para desentrañar el valor de los datos espaciales y para desbloquear el valor de los datos espaciales y revelar perspectivas sobre el pasado, el presente y el futuro.

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1. Introduction

At Singapore's World Hydrography Day celebrations in June 2019, the Maritime and Port Authority of Singapore (MPA) officially announced the setting up of our national Marine Spatial Data Infrastructure (MSDI) initiative, called 'GeoSpace-Sea' (Maritime and Port Authority of Singapore, 2019a). This initiative complements Singapore's terrestrial-based spatial data infrastructure (SDI). The MPA collaborated with 11 other government agencies and academic representatives to deliver the marine component of the national SDI, and in doing so, bridge the land-and-sea information gap through data harmonisation and interoperable standards, in particular those that are Open Geospatial Consortium (OGC) approved.

At the national level it was agreed that a continuous land to sea surface model would be fundamental to addressing issues such as sea level rise and coastal adaptation. The first phase of GeoSpace-Sea aimed to establish partnerships, implement the Geographic Information System (GIS) infrastructure and provide access to government stakeholders. The next phase is expected to create access for institutes of higher learnings and public end-user groups, enhance the repository with the integration of near real-time data, and enable hydrospatial end-user applications.

MSDIs are an embodiment and enabler of hydrospatial applications; harmonising and distributing marine and coastal spatial data and information to support a wide range of applications beyond safety and efficiency of navigation, such as marine and coastal spatial planning, marine science research and development, climate change research, and disaster response. 'Hydrospatial' is a new proposed branch of applied science to study the evolving marine and coastal spatial objects in the ocean and sea space, and how they are applied to serve agendas like a sustainable Blue Economy (Ponce, 2019; Hains, 2020). A key advantage of geospatial data is providing the geographical context to observations, likewise, hydrospatial data will emphasise the geography of the oceans and seas in the marine and coastal data and information acquired.

Using Singapore's national MSDI – GeoSpace-Sea – as a case study, this paper aims to, firstly, uncover the catalysts for the development of a national MSDI in this time, and secondly, describe key challenges an emerging national MSDI would confront in order to actualise the benefit of enabling and supporting hydrospatial end-user applications.

2. Why the need for GeoSpace-Sea for Singapore?

Maritime, marine and coastal activities have significant socio-economic impact to Singapore. The maritime industry alone contributes 7% of Singapore's Gross Domestic Product (GDP) and employs over 170,000 people (Maritime and Port Authority of Singapore, 2018). Located at the crossroads of major shipping routes, Singapore's sea space is one of the world's busiest. At any one time, there are about 1,000 vessels in the Singapore port and every 2 to 3 minutes, a ship arrives or leaves Singapore.

Despite the busy waters, Singapore's sea space is home to about a third of the world's hermatypic coral species and at least 994 marine intertidal species (Chou, et al., 2012; Lim, et al., 2020). In 2014, southern islands Small Sister's Island and Big Sister's Island, and the western reefs of St John's Island and *Pulau Tekukor*, were officially designated as Singapore's first Marine Park (Koh, 2015). Recently, Singapore also announced its expansion of aquaculture to the southern waters (Tan, 2020). Other uses and needs of Singapore's sea space include recreational activities and coastal development. In the future, Singapore residents could even be living in floating apartments (Paulo & Mak, 2019).

Singapore is not spared from the potential impacts of climate change and is at risk from more frequent and extreme rainfall events, storm surges, and sea level rise, which is projected to continue beyond 2100, even if global warming is limited to 1.5°C in the 21st century (*high confidence*) (National Environment Agency, 2018; IPCC, 2018). As a densely populated, low-lying, small island city-state with limited resources, sustainable development and science-based climate change adaptation and mitigation strategies continue to be a focal point of Singapore's story.

3. Catalysts of a national MSDI

While the benefits of MSDIs are endless, the implementation of government-led MSDIs have been geographically uneven due to challenges such as funding, political will and human capital. However, countries and governmental bodies have shown heightened interest in MSDIs, especially in recent years. This is evident from the growing IHO MSDI WG Member States' membership from 2008 to 2020 which has grown from 22 to 29. The total number of participants inclusive of Member States, IHO secretariat and expert contributors has also steadily increased from 14 in 2008, to 35 in 2019, and 58 in 2020.

Due to increased interests in the marine domain, the OGC in 2016 established a Marine Domain Working Group (OGC Marine DWG). With support from IHO Member States, the United Nations Global Geospatial Information Management Working Group on Marine Geospatial Information (UN-GGIM MGI WG) was also established in 2017 and held its inaugural face-to-face meeting in Busan, Republic of Korea, in 2019. Singapore's timely establishment of a national MSDI is in line with these positive international trends.

This section describes four catalysts that led to the establishment of GeoSpace-Sea: the changing ocean and seascape, regional and global agendas, the role of the national hydrographic office, and the advancements and availability of standards and frameworks.

3.1 Changing ocean and seascape

The changing local seascape coupled with threats of climate change impacts were drivers for Singapore's GeoSpace-Sea initiative. Our seascape involves diverse stakeholders that can be categorised to government, industry, academia and public users, and further broken down into diverse use-cases and activities (***Figure 1***). Although most of Singapore's sea space are port waters, with its expanding users and uses, policymakers recognised the need to move beyond port planning and to produce a more comprehensive marine spatial plan and integrated urban coastal zone management. Mr Khoo Teng Chye, Executive Director, Centre for Liveable Cities, highlighted that planning requires an inventory of historical and present information and Professor Lui Pao Chuen, adviser to the Ministry of National Development and National Research Foundation, supported that "GeoSpace-Sea would be the source for integrated knowledge-based planning and development of Singapore, and the instrument for the modelling of Singapore for various applications" (Maritime and Port Authority of Singapore, 2019b). The local scientists and community have also recommended, through 'The Singapore Blue Plan 2018', that a coordinated marine database for Singapore is required for the sustainable management of Singapore's sea space (Jaafar, et al., 2018)

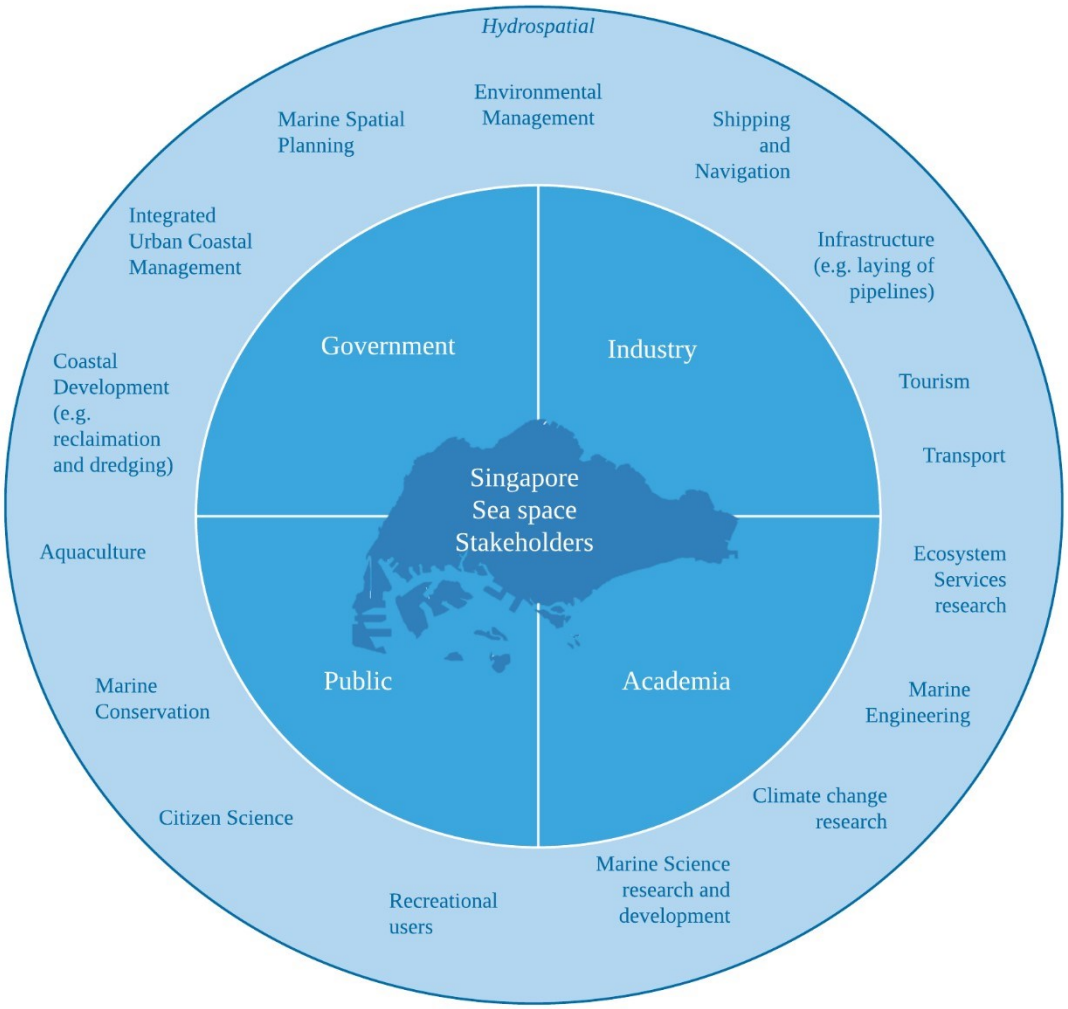

Figure 1: *Singapore's sea space stakeholders*

The threat and experience of climate change impacts were also push-factors for GeoSpace-Sea. Prolonged sea surface warming caused major coral bleaching events in 1998, 2010 and 2016 whereby 60% to 90% of surveyed corals were bleached (Chou, et al., 2019), and the absence of coral reefs could consequently have dire impact on ecosystem services such as food (fish) security (Friess, 2017). Furthermore, sea level rise and the more frequent and intense climate-change extreme events are expected to be a strong external physical stressor on Singapore's resilience (Chow, 2018). In the worst case scenario of 0.87m sea level rise, adaptation strategies (construction and maintenance) are projected to cost US$ 5.7 million and US$ 16.8 million by 2050 and 2100, respectively (Ng & Mendelsohn, 2005). Data is needed to study how local extreme events are related to global-scale climate change, monitor regional hydro-climate phenomena (e.g. ocean acidification, ocean warming and tropical cyclones) and local geographical changes (e.g. tidal heights and coastal development). Monitoring and understanding the risks of hydro-climate hazards, such as storm surge impacts, would contribute to the knowledge production chain and produce more robust science-based adaptation, mitigation and response strategies.

3.2 Regional and global agendas

Singapore's commitment to global agendas, such as the Paris Climate Agreement and United Nations (UN) 2030 Agenda, including the UN Decade of Ocean Science 2030 complemented by The Nippon Foundation-General Bathymetric Chart of the Oceans (GEBCO) Seabed 2030 Project, and membership to regional and international organisations, such as East Asia Hydrographic Commission (EAHC) and International Hydrographic Organization (IHO), were also catalysts to the establishment of GeoSpace-Sea.

The ocean is one giant conveyor belt of dynamic ocean currents, nutrients, including pollutants, therefore, global and regional action and data is required to address marine environmental management, especially for confined and busy waterways used for international navigation like the Singapore and Malacca Straits. GeoSpace-Sea is envisaged to ultimately contribute to the global marine and coastal data ecosystem for sustainable development. Singapore updated its climate pledge under the Paris Agreement and reaffirmed its commitment to the UN 2030 Agenda through a voluntary national review report at the UN High-Level Political Forum on Sustainable Development (Ministry of Foreign Affairs, 2018; Ministry of the Environment and Water Resources, 2019). The UN 2030 Agenda is a global development framework adopted by World Leaders, including Singapore, at the UN Sustainable Development Summit in September 2015. The 2030 Agenda comprises 17 Sustainable Development Goals (SDG). Open hydrographic and marine spatial information is expected to contribute to not only hydro-related SDG 14 (Life below water) and SDG 6 (Ensure availability and sustainable management of water and sanitation for all), but also others like SDG 13 (Climate action), SDG 11 (Sustainable Cities and Communities), and SDG 15 (Life on land).

Regionally, Singapore is also an active member of the EAHC MSDI WG which includes a total of 10 Member States and 1 observer from the region: Brunei Darussalam, China, DPRK, Japan, Indonesia, Malaysia, Philippines, Republic of Korea, Singapore, Thailand and Vietnam. One of EAHC MSDI WG's key tasks is to implement a regional EAHC MSDI in order to share and exchange marine spatial data.

A national MSDI is now almost necessary for countries to address, demonstrate and fulfil its regional and global commitments for sustainable development and climate action. The list of MSDIs have been growing and as of 31 March 2020, 66 MSDI/SDI portals, across 41 countries have been reportedly established (International Hydrographic Organization, 2020a).

3.3 The role of Singapore's hydrographic division

Hydrographic offices (HO) play an important role in driving the development of a national MSDI and in being national custodians of marine and coastal data. Having been an integral part of Singapore's marine and coastal spatial data life cycle, the MPA's Hydrographic Division is spearheading this national initiative. Over the years, the difficulties in ocean data acquisition, big 3D marine data processing and enabling marine GIS applications has diminished alongside advancements in technology and digitalisation of the hydrospace (Li & Saxena, 1993). Today, HOs like Singapore's which have been acquiring, processing and distributing navigational products have become valuable sources of high quality, long-term, fundamental marine and coastal spatial data such as bathymetry, coastline and tidal heights (International Hydrographic Organization, 2017a; Ponce, 2019). Being custodians of most of the fundamental marine and coastal data and having the experience of handling these spatial data formed the foundation of the GeoSpace-Sea initiative.

Before 2018, Singapore Hydrographic Division's role and core functions like many of HOs remained largely to support safety of life at sea (SOLAS): (1) conduct hydrographic surveys; (2) publication of nautical charts; (3) provide, install and maintain aids to navigation (Oei,1991).

However, the changing local, regional and global ocean and seascape has served as impetus for the Singapore's Hydrographic Division to expand its role and core functions.

In July 2018, the 'GeoSpace-Sea' section of Singapore's Hydrographic Department was set up to dedicate resources to the development of GeoSpace-Sea, and on 1 April 2019, the Hydrographic Division was upgraded to a Division. Presently, Singapore's Hydrographic Division consists of four departments: Survey, Cartographic, Aids to Navigation and GeoSpace-Sea. Its role now encompasses serving a wider range of applications and users beyond safety of navigation and mariners. Its additional functions include maintenance of data and marine GIS, namely Singapore's Integrated Hydrographic Management System (IHMS) and GeoSpace-Sea. By supporting safe navigation, and preventing collisions and oil spills, Singapore's Hydrographic Division has been protecting the marine environment (Oei, 2010), but it is now taking the next step to enable more to contribute to this mission.

In May 2020, the co-author and author accepted to join the volunteer "Hydrospatial Movement Club and Community (HMCC)", as the Asian Node; to be the voice of Hydrospatial as the foundation of any activity in the oceans, seas, lakes and rivers with emphasis on the Blue Economy for Sustainable Development.

3.4 Advancements and availability of standards and frameworks

The advancements and availability of MSDI standards and frameworks was also a driver for the timely establishing the GeoSpace-Sea. The IHO MSDI WG, OGC Marine DWG and UN-GGIM MGI WG have been providing technical guidance and standards on MSDIs and supporting the development of innovative solutions to MSDI challenges, most notably, data interoperability.

Frameworks are useful to establish and periodically assess the state of a national MSDI. MSDIs must be reliable in order to enable and support the broader hydrospatial context and its applications. Two complementary conceptual frameworks have been adopted for GeoSpace-Sea. The first, is the IHO MSDI WG recommended 'Four Pillars of MSDI': (1) Policy and Governance (People); (2) Technical Standards (Standards); (3) Geographic Content (Data); and (4) Information Systems (ICT) (***Figure 2***). The four pillars of MSDI have been useful in organising the resources required to establish and monitor the progress of GeoSpace-Sea.

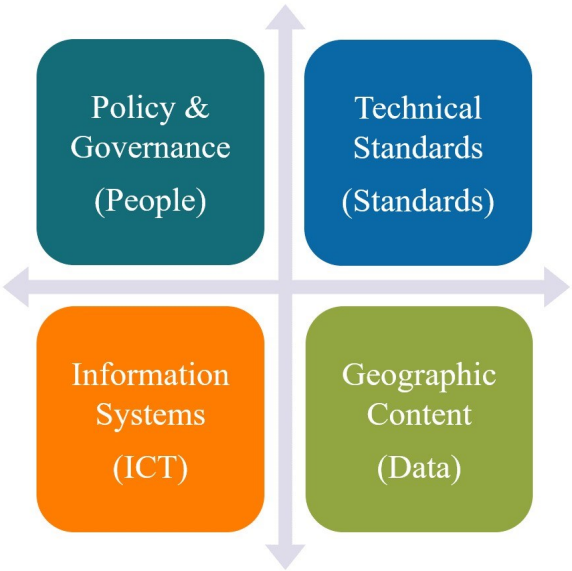

Figure 2: *The Four Pillars of MSDI (International Hydrographic Organization, 2017b, p. 6)*

The second framework adopted is the UN-GGIM Integrated Geographic Information Framework (IGIF) and its nine strategic pathways, which could be useful particularly for long-term strategic plans (***Figure 3***). The four pillars of MSDI is complementary and can be easily mapped to the nine strategic pathways (***Table 1***). It is noteworthy that the 'innovation' centre puzzle piece is intended to be applied across all other pieces.

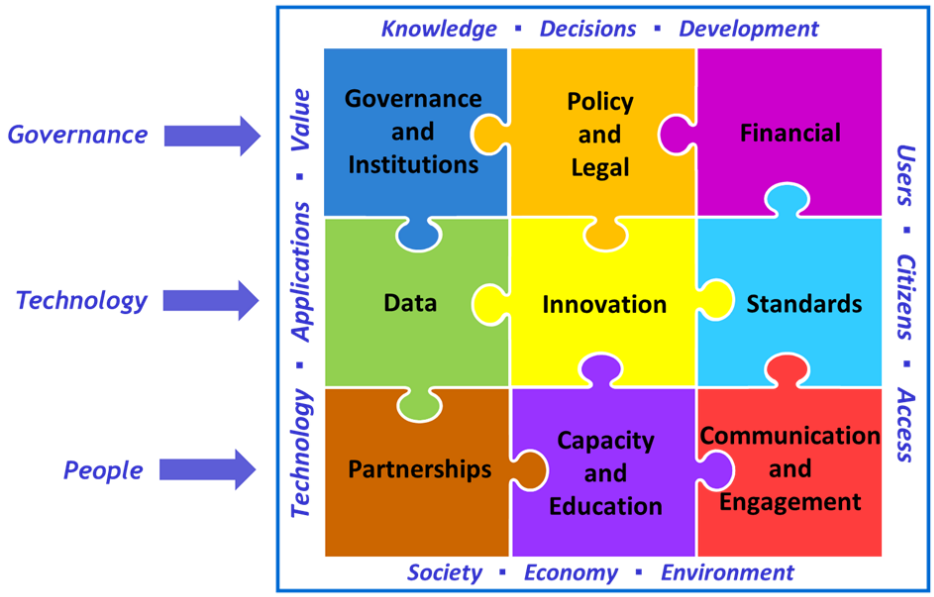

Figure 3: *UN-GGIM IGIF Nine Strategic Pathways (UN-GGIM, 2018, p. 21)*

Table 1: How the four pillars of MSDI and IGIF nine strategic pathways are complementary

The Four Pillars of MSDI	UN-GGIM IGIF Nine Strategic Pathways
Technical Standards (Standards)	Standards
Geographic Content (Data)	Data
Information Systems (ICT)	Innovation (particularly for ICT)
Policy and Governance (People)	Governance and Institutions Policy and Legal Financial Partnerships Capacity and Education Communication and Engagement

Open standards that MSDIs could adopt are also available to ensure data and system interoperability, for instance those approved by OGC. The marine and maritime community is currently working towards producing and implementing a suite of product specifications to promote data standardisation and interoperability for hydrospatial services such as e-navigation (***Table 2***). At present, it appears that MSDIs could be both at the receiving end and producers of these products. The adoption of these advancing common standards and technology could enhance the mission of MSDIs in enabling a wider range of hydrospatial applications.

Table 2: List of Planned Marine Data Product Specifications (International Hydrographic Organization, 2020b)

Organisation In-charge	Product Specification Series	Planned Product Specifications
International Hydrographic Organization (IHO)	S-1xx	S-101 Electronic Navigational Chart (ENC) S-102 Bathymetric Surface S-103 Sub-surface Navigation S-104 Water Level Information for Surface Navigation S-111 Surface Currents S-112 Open - (See Decision HSSC9/38) S-121 Maritime Limits and Boundaries S-122 Marine Protected Areas S-123 Marine Radio Services S-124 Navigational Warnings S-125 Marine Navigational Services S-126 Marine Physical Environment S-127 Marine Traffic Management S-128 Catalogue of Nautical Products S-129 Under Keel Clearance Management (UKCM)
International Association of Light Authorities (IALA)	S-2xx	S-201 Aids to Navigation Information S-210 Inter-VTS Exchange Format S-211 Port Call Message Format S-230 Application Specific Messages S-240 DGNSS Station Almanac S-245 eLoran ASF Data S-246 eLoran Station Almanac S-247 Differential eLoran Reference Station Almanac
Intergovernmental Oceano-graphic Commission (IOC)	S-3xx	None proposed yet
Inland ENC Harmonization Group (IEHG)	S-401 to S-402	S-401 IEHG Inland ENC S-402 IEHG Bathymetric Inland ENC
Joint Technical Commission for Oceanography and Marine Meteorology (WMO/IOC JCOMM)	S-411 to S-421	S-411 JCOMM Ice Information S-412 JCOMM Weather Overlay S-413 Weather and Wave Conditions S-414 Weather and Wave Observations
International Electrotechnical Commission - Technical Committee 80 (IEC-TC80) Numbers	S-421 to S-430	S-421 Rout Exchange Format

4. MSDIs enabling hydrospatial context and applications

The MSDI road map does not stop at implementing policies, infrastructure and a portal for data consolidation, harmonisation and access. The process of actualising its anticipated benefits; enabling and supporting the hydrospatial context and wide-range of applications, poses another set of challenges MSDIs have to address. This section identifies and describes three key challenges GeoSpace-Sea has and would continue to confront in order to enable and support hydrospatial context and applications such as climate change research, marine spatial planning, coastal zone management, environmental impact assessments, incident reporting, environmental management, or maritime automated surface ships.

4.1 Partnerships

MSDI is a coordinated effort to collect, integrate, use and re-use marine and coastal spatial data. In order to establish and sustain the data lake of MSDIs, partnerships play a pivotal role in securing data sources and channels. Arguably, the biggest challenge of establishing GeoSpace-Sea was neither a technical one nor about data availability, it was about building partnerships and sharing of common goals. These partnerships extended across the national, regional and international scales. However, in order to enable and support hydrospatial context and applications, these partnerships would need to be sustainable, developmental and diversified.

At the national scale, a user-centric approach was adopted in the development of GeoSpace-Sea. A governance structure involving a steering committee, working committee and two technical committees were set up to support decision and policymaking. In its initial stages, an end-user application exercise was conducted between the government agencies to map out stakeholder user needs and commitment (***Figure 4***). Representatives from government agencies listed end-user applications and the data or resources required. At the same time, they stated data or re-sources they could offer to the rest of the stakeholders. The inputs were mapped and the outputs of the exercise were: (1) a base data inventory of data required and can be made accessible, and (2) a wish list of data that were presently neither available nor accessible. Ultimately, MSDI is a balancing act between user needs and concerns about data exchange and sharing, and its role is to maximise each user group's mission without compromising the strategic interest of another. An end-user application exercise makes this decision-making process transparent.

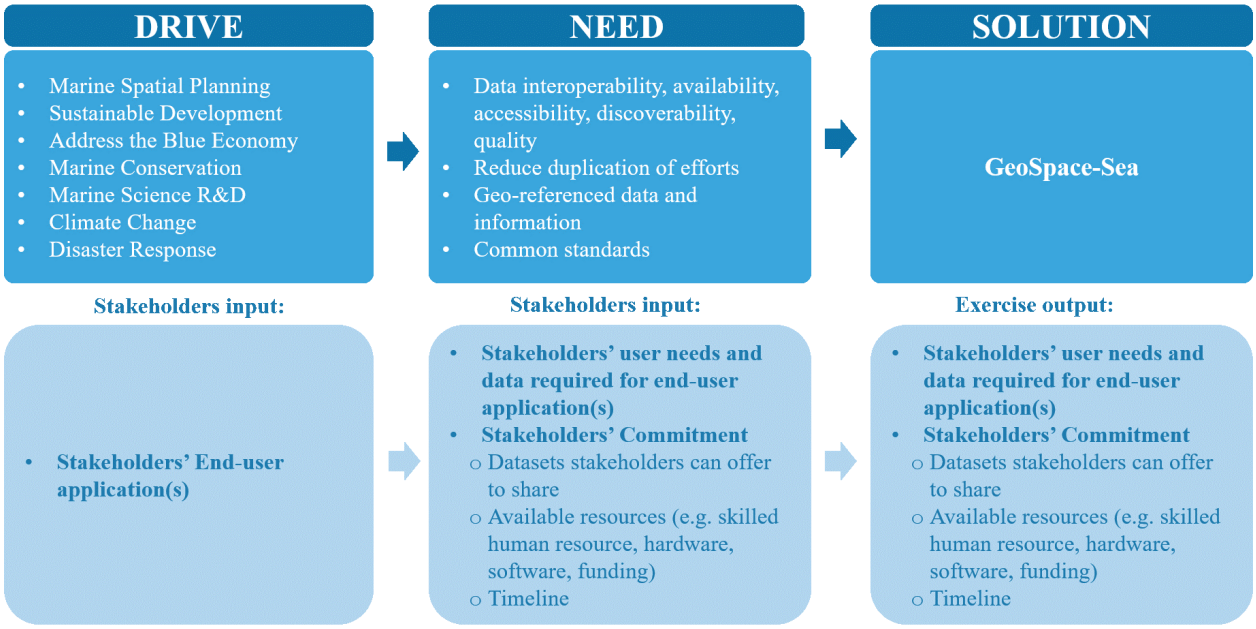

Figure 4: *GeoSpace-Sea end-user application exercise overview*

Apart from the technological infrastructure that has brought data together, GeoSpace-Sea has also formed a network of local sea space stakeholders. This network is expected to grow and become more diverse as GeoSpace-Sea continues engaging various groups and enabling more hydrospatial applications. The GeoSpace-Sea committees notably include representatives from academia too, and the stakeholder group would likely expand in the next phase which aims to create access for academia and public end-user groups. Government-academic-industry

partnerships have notable benefits of improving the quality of marine science research and development, increasing the efficiency of translating standards into industry-ready technologies or products, and potentially bridging the science and policy gap.

Partnerships beyond national scale are also required to build a regional and global marine and coastal data ecosystem. In its mission to promote safe navigation, the importance of international cooperation and exchange of best practices has been entrenched in the international hydrographic community. Since 2007, these principles have been extended to the IHO MSDI WG. IHO MSDI WG and regional MSDI working groups, such as the EAHC MSDI WG, have annual meetings to build these partnerships. At the meetings, sharing of national reports and discussions on common standards foster these connections.

4.2 Authoritative data and metadata

With data flows secured, another challenge is how MSDIs define and maintain the "authoritativeness" and quality of data for the hydrospatial context and wide range of applications it intends to enable and support. MSDIs, including GeoSpace-Sea, aim to promote the use and re-use of "authoritative" marine and coastal data. Authoritative data is often understood as data obtained with "formal quality assurance procedures", and traditionally, government agencies and reputable mapping companies have been sources of these data (Du, et al., 2016, p. 1). Presently, GeoSpace-Sea's base data inventory includes authoritative hydrographic, coastal geography, environmental, species distribution and habitat, meteorological and infrastructure data from government sources.

A dataset's quality can be assessed for either its internal characteristics (i.e. internal quality) or its 'fitness for use' (i.e. external quality). Typically, standardisation bodies develop internal quality assessments that consists of five to eight parameters, and users take these parameters to assess if the data is fit for use or purpose (Devillers, et al., 2005):

- Lineage/Source
- Spatial/Positional Accuracy
- Attribute Accuracy
- Semantic Accuracy
- Thematic Accuracy
- Completeness
- Logical Consistency
- Temporal Information/Accuracy.

HOs will be familiar with the production and distribution of authoritative data and information through Electronic Navigational Charts (ENCs) and paper nautical charts. For the production of these products, most marine GIS are equipped with IHO S-58 validation tools and marine cartographers are trained to ensure data quality from a mariner's perspective and for safe navigation. There are acceptable inaccuracies of data in charts, for instance, the generalisation of depth contours on the "safe side". For effective communication, spatial data and information are representations of reality, and are only as accurate as the elements selected to represent it. However, assessing data quality and 'fit for purpose' from a MSDI perspective is difficult because the use-cases and users are intentionally broad and diverse.

Instead of ensuring data is fit for purpose, MSDIs can focus on ensuring internal data quality is up to date. If the MSDI policy entails that data's 'fit for purpose'-ness should be determined by users, MSDIs have the responsibility of providing good quality and up-to-date metadata to support users' in this decision-making process. GeoSpace-Sea's metadata is aligned with its terrestrial

counterpart and both systems adopt a national 'GeospatialSG Data Standards' framework that is based on ISO 19100 standards.

In the near future, MSDIs may also have to consider the "authoritativeness" of crowd-sourced data. The data collected through volunteer GIS, mobile applications or as a bi-product of other processes could contribute to policy-making (Goodchild, 2007; Du, et al., 2016). For instance, as a bi-product of shipping and navigation, crowd-sourced bathymetry data are being contributed to The Nippon Foundation-GEBCO Seabed 2030 Project. There are also researcher-validated crowd-sourced biodiversity records, such as those in the 'Wild book for Whale Sharks' available in the International Union for Conservation of Nature (IUCN) open-source database (Morales-Ramirez & Pang, 2018). GeoSpace-Sea could also in future consider incorporating researcher-validated citizen science biodiversity records. These data, albeit not from traditional sources of authoritative data, could meet a data quality criterion and be approved for sharing in MSDIs.

4.3 Funding and operational sustainability

A MSDI questionnaire completed by IHO Member States revealed that majority of MSDIs are funded by 'task of an organisation'. The ownership and willingness to fund MSDIs is a recognition of the benefits of MSDIs, however, it is important to quantify its benefits, and translate them into cost-benefit analysis so as to justify its longer-term funding and operational sustainability. To enable and support the hydrospatial context and various applications, the MSDI itself needs to be sustainable and reliable.

While the direct costs of MSDIs and, fundamentally, sharing of open data could be justified with qualitative potential benefits (Johnson, et al., 2017), quantification of potential and actualised benefits is a challenge to overcome. These benefits include operational cost-savings, such as reduction in duplication of data collection and improved decision-making, and socio-economic and environmental benefits both in the short term and long term. Griffin, Coote and Crompvoets (2019) found that direct costs of MSDIs could result in a net benefit; for every US dollar invested, it is predicted that 2 to 18 US dollars would be returned. However, the authors also highlighted that these are projected figures and the evaluation of the actual effectiveness of MSDIs remain a knowledge gap.

Data being the currency of MSDI has value and MSDI could become a source of revenue too. Value-added data could be produced in the process of harmonising data from various sources. Encouraging the re-use of data also serves to maximise the lifespan of data collected and enhances its value when a wider range of applications depend on it. The higher value of this data eventually asserts the mandate of the data source and its acquiring cost (Garavelli, 2018). The United Kingdom (UK) Hydrographic Office Admiralty Marine Data Portal has 'paid Admiralty data services' which currently includes five data layers: 'offshore infrastructure', 'Vertical Offshore Reference Frames (VORF)', 'wrecks and obstructions', 'seabed composition' and 'HMNAO Astronomical and Calendar Information' (UK Hydrographic Office, 2019). In order to do so, pricing mechanisms and models are required to quantify and assign a monetary value to data, possibly by the 'age' of the dataset or the 'demand' for it.

5. Conclusion: Looking ahead

This paper has described the four catalysts that led to the establishment of Singapore's GeoSpace-Sea. It has also identified three key challenges that an emerging national MSDI may confront in the process of actualising its envisaged benefits. Catalysts and ease of establishing a national MSDI could vary over time and space depending on the country's funding priorities and the spatial data policies enacted. For instance, countries without an open geospatial data policy

or with restricted funding opportunities may have to seek more commercially driven catalysts. This is especially so with the economic impacts arising from the global pandemic, funding could surface as a more immediate challenge in the establishment of a national MSDI.

Similarly, MSDIs could face additional challenges in enabling hydrospatial context and applications depending on its maturity. For example, mature MSDIs may be required to upgrade and be kept up to date with the latest S-100, S-200, S-300 and S-400 standards. There are various challenges in implementing these standards that would involve standards organisations who are producing these standards, the industry translating these standards into operational tools for production, and the HOs which must seek an opportune time and source of funding to upgrade the specifications of their MSDI. For HO-led MSDIs, partnerships remain essential in the implementation of these S-100 product standards too because the process could involve transforming data and workflows beyond the hydrographic domain. Looking ahead, identifying MSDI-relevant product specifications, an implementation roadmap for MSDI and continued exchange of tangible benefits from MSDIs to justify investments would be needed.

In an increasingly digital hydrospace, MSDIs would foreseeably continue to play a key role in unlocking the value of hydrospatial data, and reveal insights through data integration, hydrospatial analysis and applications. To sustain MSDIs and enable it to support the hydrospatial context and wide-range of applications in the medium and long-run require integrated hydrospatial (geospatial) information management that strategically considers data, metadata, people (partnerships and capacity building), governance, and how to exploit opportunities arising from present crises and disruptive future technological and non-technological trends, for instance, Artificial Intelligence (AI) and the demand for digitalisation. Ultimately, when national MSDIs, regional MSDIs and other domain SDIs agree to better cooperation and collaboration on data sharing and exchange, we could develop and visualise a more holistic view of water movements and impact on our earth. This would enable functions akin to the development of a time machine where users can dynamically and more accurately model the past, present and future. In other words, we could be more proactive than reactive in managing our marine environment.

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Articles

HYDROGRAPHY FROM FISHERIES SURVEYS
Filling coverage gaps with bathymetry extracted from Simrad EK60 water column data

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Abstract

The collection of available fisheries acoustic data holds significant seafloor mapping potential. We estimate that in the Northeast United States, Simrad EK60 data from the NOAA Fisheries fleet could increase bathymetric coverage by as much as nine percent. This article describes initial automated processes and techniques used to: extract the seafloor from Simrad EK60 water column data collected with NOAA Fisheries vessels, obtain and apply best available information to realize the seafloor relative to chart datum, and verify the outcome with existing qualified bathymetry.

Résumé

L'ensemble disponible de données acoustiques issues de la pêche représente un potentiel significatif pour la cartographie du fond marin. Nous estimons que dans le nord-est des Etats-Unis, les données Simrad EK60 issues de la flotte de pêche de la NOAA pourraient accroître la couverture bathymétrique jusqu'à neuf pourcent. Le présent article décrit les processus et techniques automatisés initiaux utilisés pour : extraire les données relatives au fond marin à partir des données de la colonne d'eau Simrad EK60 qui sont collectées par les navires de pêche de la NOAA, obtenir et appliquer les meilleures informations disponibles pour réaliser la cartographie du fond marin par rapport au zéro des cartes, et vérifier le résultat avec les données bathymétriques homologuées existantes.

Resumen

La recopilación de los datos acústicos disponibles sobre pesca encierra un importante potencial de cartografía de los fondos marinos. Estimamos que en el Noreste de los Estados Unidos, los datos del Simrad EK60 de la flota pesquera de la NOAA podrían aumentar la cobertura batimétrica hasta un 9%. Este artículo describe los procesos y técnicas automatizados iniciales utilizados para: extraer el fondo marino desde los datos de la columna registrados por el Simrad EK60 recogidos con los barcos de pesca de la NOAA, obtener y aplicar la mejor información disponible para reconocer el fondo marino en relación con el datum de la carta y verificar el resultado con la batimetría cualificada existente

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1. Introduction

As of January 2020, the National Oceanic and Atmospheric Administration (NOAA) has classified 54% of the United States coastal, ocean, and Great Lakes waters as unmapped (Office of Coast Survey, 2020). Worldwide, bathymetry is used for charting, modeling, and coastal and ocean zone management purposes. Global bathymetric coverage has numerous scientific and economic applications which are highlighted by the need to understand an ever-changing ocean floor. In 2011, National Centers for Environmental Information (NCEI) partnered with NOAA's National Marine Fisheries Service (NMFS) and the Joint Hydrographic Center to create an archive for water column data collected by government, academic and international vessels. Water column data is the full acoustic time series of an underwater echo sounder. This archive (*NOAA Water Column Sonar Data*) includes data from various areas around the United States Exclusive Economic Zone (EEZ) and provides RAW data files for public use (National Centers for Environmental Information, 2011). NMFS often uses the Simrad EK60 split beam echo sounder during fisheries surveys to observe biological attributes such as marine habitat and animal populations in the water column. Fortunately, this water column data often includes the seafloor and can be used to increase the overall mapped area of the EEZ (National Centers for Environmental Information, 2011).

In 2019, NOAA Office of Coast Survey (OCS) and Coastal Survey Development Lab (CSDL) took an interest in using the NMFS water column data to update coastal bathymetric charts. The National Bathymetric Source (NBS) project has begun to highlight gaps in coverage in the New England region and is motivated to fill these gaps with the best available bathymetry (Wyllie and Rice, 2020). The EK60 data from fisheries surveys was recognized as a potential source for filling these gaps thanks to previous collaboration with Pacific Marine and Environmental Laboratory (PMEL), NMFS, and Saildrone in the Bering Sea (Office of Coast Survey, 2017). Because of ties to the NBS project, Northeast United States waters are the focus region for this work.

Often, hydrographic acoustic survey data is processed in manual steps to integrate supporting information and to derive depths. While supervised processing can be effective for single cruise datasets, a procedure for automating the process for significant amounts of RAW EK60 data is needed. The NOAA Hydrographic Systems and Technologies Branch (HSTB), along with contractors from Earth Resources Technologies (ERT), developed and tested a Python script for batch processing the water column data for derived depths on chart datum. The project's ultimate goal was to develop a way for the EK60 data to be automatically synthesized into forms easily consumable by the OCS External Source Data team, thus enabling efficient access for the national bathymetry and the chart. This paper illustrates the process and describes the current results of these efforts.

The Simrad EK60 is a scientific split beam echosounder specifically intended for observing the water column with multiple frequencies. A split beam echosounder is a single beam echosounder, which is to say an acoustic transducer with a beam pattern that defines a single primary beam, but is capable of determining the angle to a target within the beam. Given multiple frequencies, it is possible to observe and discriminate between mid-water marine organisms, such as schools of fish and plankton, or map for gas seeps and oil spills (National Centers for Environmental Information, 2011). For this study we use the EK60 as a single beam echosounder. While the majority of hydrographic surveys use a swath sonar for more efficient and complete bathymetric coverage, single beam sonars are still capable of recording bathymetry while surveying the water column (***Figure 1***). The majority of the data processed includes information from five transducers with discrete frequencies: 18kHz, 38 kHz, 70 kHz, 120 kHz, and 200 kHz. These discrete frequencies allow for duplicate observations of the seafloor, potentially improving the information available to a seafloor detection algorithm. The EK60 data has largely been collected in the last 20 years, making it particularly useful for updating bathymetric charts in areas where the latest survey may have been over 100 years ago. There are currently 401 cruises from 2003 to 2019

with available EK60 data, spanning a total of 1.1 million linear nautical miles of data. Of these EK60 cruises, NMFS vessels have collected 222 cruises for 811 thousand linear miles (National Centers for Environmental Information, 2011). The cumulative geographical scope of these surveys makes them particularly useful for hydrographic mapping (***Figure 2***).

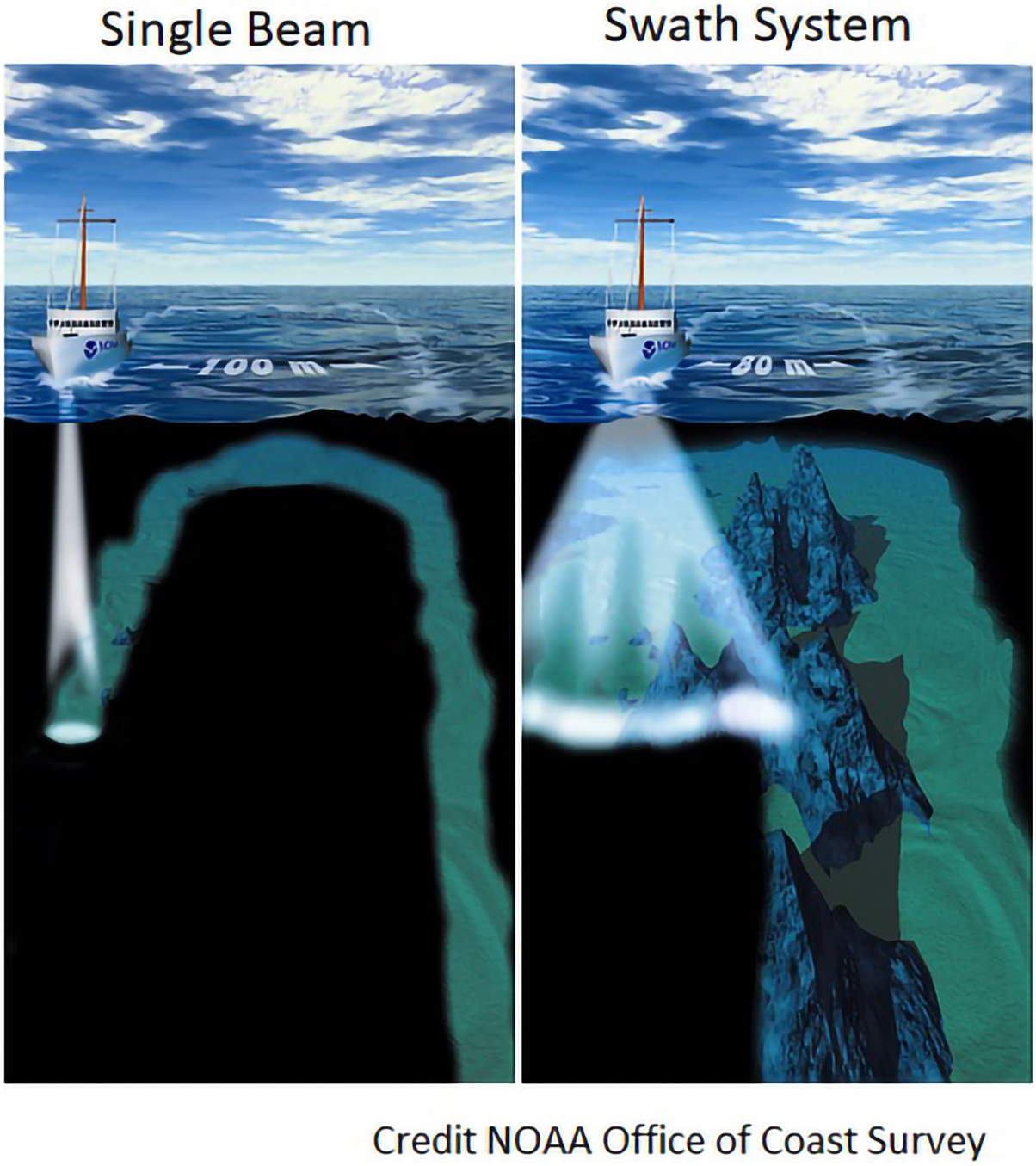

Figure 1*: Single beam echo sounder compared to swath echo sounder. Both methods record the bathymetry of the seafloor. The EK60 echosounder is represented by the single beam.*

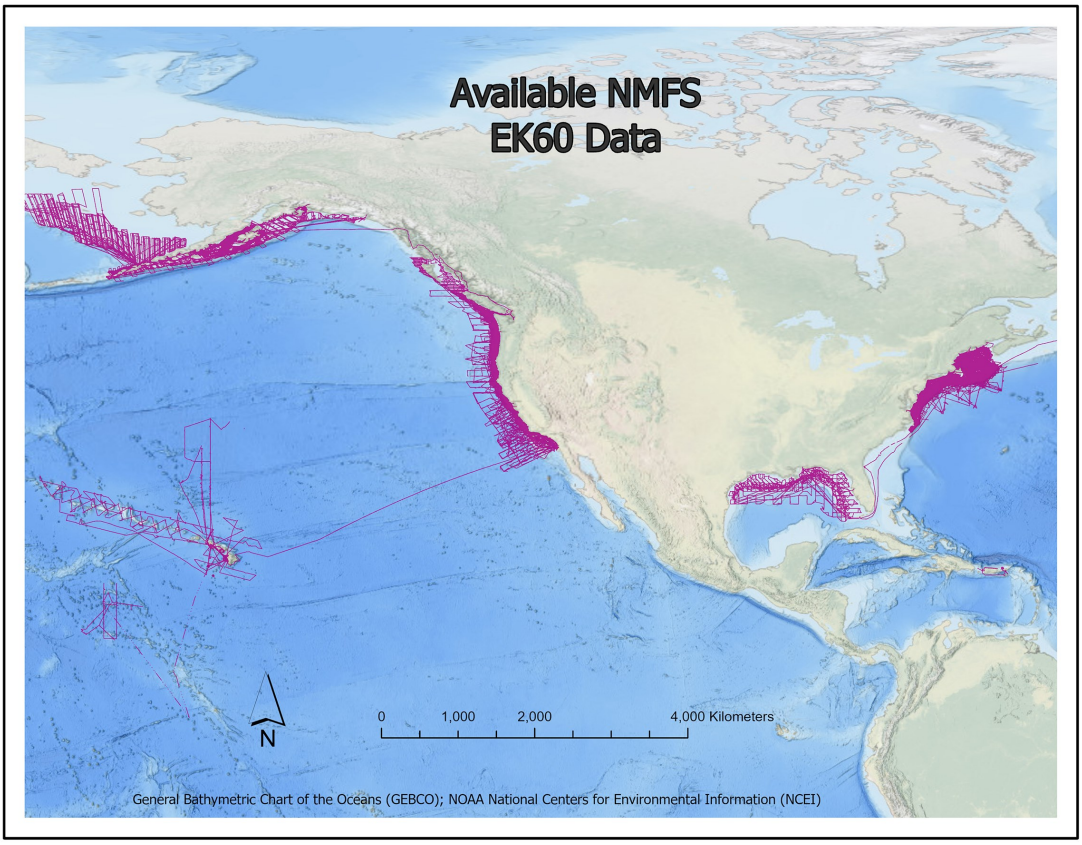

***Figure 2**: Available NMFS EK60 data for the entire US Exclusive Economic Zone from 2003-2019 (National Centers for Environmental Information, 2011).*

As demonstrated in our test area of the Northeast United States, the expanse of the EK60 surveys has the potential to contribute to unmapped areas of the US EEZ (***Figure 3***).

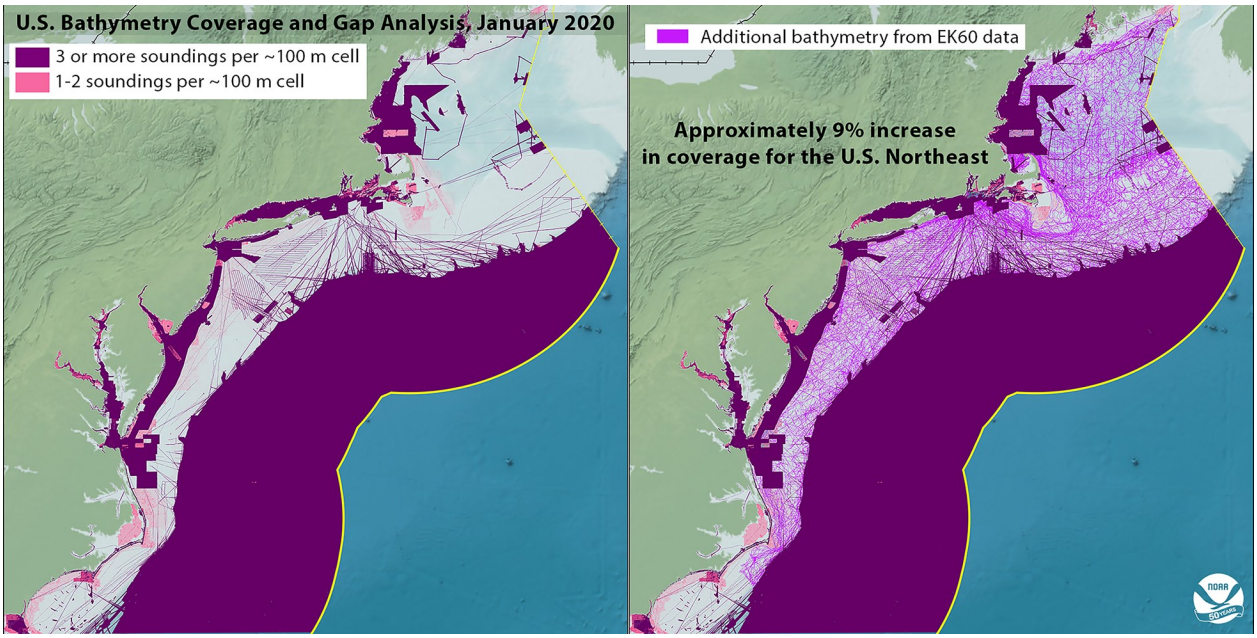

***Figure 3**: Bathymetric data coverage for the Northeast US EEZ (left) and additional NMFS EK60 data coverage for the same region (right). Notice how the EK60 data covers a sizable unmapped area of the United States EEZ. Figure credit: Meredith Westington, NOAA Office of Coast Survey.*

Based on the January 2020 analysis of US bathymetry coverage and gaps, as referenced in the Progress Report of Unmapped US Waters (Office of Coast Survey, 2020), Westington estimates that the EK60 data could increase bathymetric data coverage in the Northeast US EEZ by nine percent, bringing the coverage of the area from 65% to 74% minimally mapped per Seabed 2030 goals (Westington, 2020). The mapped statistic is based on the standard that a mapped area constitutes a density of at least one soundings per 100m grid cell after 1960 (Westington et al., 2019). This large reservoir of single-beam echosounder data has the potential to significantly boost US bathymetric records, especially in light of a recent analysis that estimates it would take around 177 years for a single survey platform running continuously at 7.5 knots to survey the rest of US waters to meet modern survey standards (Greenaway, Batts, and Riley, 2020). Furthermore, a majority of the Northeast US covered by the NOAA Fisheries EK60 data is within depths of 0-200m. This is considered a “high effort” zone because multibeam survey swaths are narrower at these depths than in deeper zones and would require more passes to collect complete coverage.

We implement the following steps to extract bathymetry on chart datum from the EK60 water column: seafloor detection, sound speed application, and water level, heave, and draft adjustments. The Python scripts described in this article are currently housed in Pydro, a public, Microsoft Windows-based software suite developed by HSTB. This suite contains tools, libraries, and information that support the processing and analysis of hydrographic data that aid in refining seafloor detections into depths (Gallagher et al., 2020). Since the main script exists in the Pydro environment, it is able to access tools for estimating harmonic sound speed from historical data in the World Ocean Atlas (WOA) database (Boyer et al., 2013), and tide information from the Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO) auxiliary product: Finite Element Solution (FES) global tide model, 2014 (AVISO+ FES2014b) (NOVELTIS et al., 2014).

Ultimately, the purpose of the described workflow is to enable the automated extraction and adjustment of acoustic data from the EK60 surveys to derive useful bathymetry. As mentioned previously, the geographic expanse of the EK60 surveys makes them valuable for filling current gaps in hydrographic maps. This data also has the potential to contribute to global mapping projects such as Seabed 2030, which aims to map the global ocean by 2030 (Westington et al., 2019). This style of workflow may also have implications with other projects involving large datasets. Additionally, this project highlights the usefulness of the AVISO tide model, which can be used to process other bathymetric datasets and promote hydrographic studies in new areas.

2. Methods

The overall workflow for obtaining and processing EK60 data is broken into several stages. First, EK60 RAW files are queried and downloaded from the NCEI public cloud (National Centers for Environmental Information, 2017). Once the files are local to the processing resources, our code extracts the time, navigation, and water column records from the EK60 RAW files. The seafloor is then extracted from the water column data, and the time and navigation are used to query tides and sound speed to create a best estimate of depth. Seafloor extraction includes identifying prevalent features within the water column, identifying the most likely candidates, and then calculating a two-way travel time (TWTT) for the selected features. A low pass filter is applied to the seafloor to remove heave artifacts, and draft is applied as recorded in the RAW file. After processing all survey files are completed, the data are gridded at eight meter resolution for comparison to existing data. A resolution of eight meters was chosen to match the resolution of existing data at the ENC Band 3 region.

Seafloor Detections

Seafloor detections are based on image processing techniques and the assumption that the seafloor is the largest and strongest target in the water column data. This approach first extracts the water column amplitude time series for each file into a two-dimensional array with dimensions corresponding to the number of samples and the number of pings for each frequency. For each frequency, a Scipy (Virtanen et al., 2020) image edge detection method performs an initial feature detection by applying an eight standard deviation Gaussian filter to remove noise and a Sobel filter in the along-ping (vertical) direction to find significant positive gradients. We defined significant gradients as greater than one standard deviation of the Sobel gradients found within the file, and we selected positive gradients since the seafloor should increase in amplitude from the background noise. A region of interest for the feature is then extended to include the samples after the significant positive gradient to include when the gradient reaches a minimum (maximum negative) gradient since this corresponds to a decrease in power amplitude and the backside of the feature (***Figure 4***).

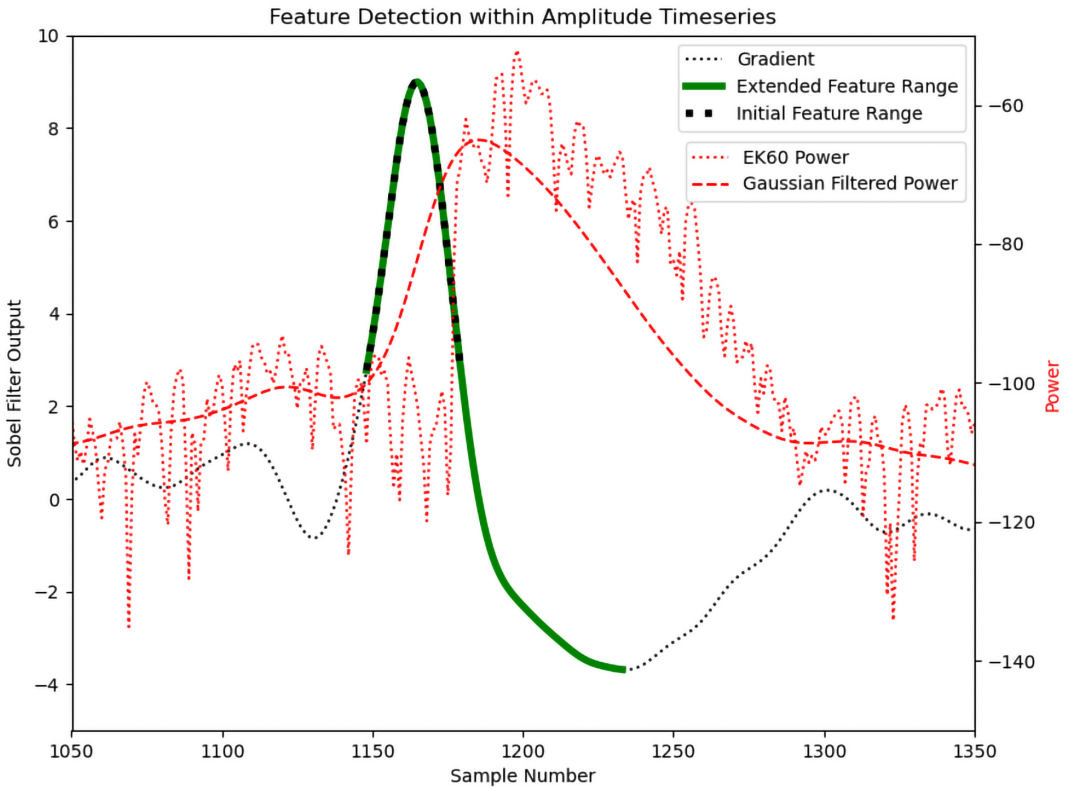

Figure 4: *A subsection of the Sobel gradient and power time series in the area of a detected feature. The raw power and Gaussian filtered power illustrate change relative to the Sobel filter gradient. We demonstrate the detected feature as extended to the minimum gradient, and how this range of samples corresponds to the maximum power amplitude.*

These regions of interest are then grouped by classifying across pings using OpenCV (cv2 as a python library) (Heinisuo, 2020) to create features with metrics. Each feature within the file is tracked with a start and stop ping index, the index of maximum amplitude for each ping within the feature, the average signal to noise computed between a blanking distance and the feature, and the sum of the maximum amplitudes within the features. Features are then sorted by descending sum of the maximum amplitudes for the separate features, and the maximum non-overlapping (in ping index) features are selected. Features with a signal to noise ratio less than 30 dB are discarded. This series of steps is repeated for each transducer/frequency recorded in the RAW file.

Future iterations on detecting the seafloor will likely change how features and seafloor detections are defined. The current method begins with the feature designation at one standard deviation of the amplitude gradient above the average for the file, but the feature may preferably begin at the maximum gradient so as to better exclude water column objects near the seafloor. Also, the end of the feature is probably better defined as when the negative gradient returns to background levels, and the actual seafloor defined as a weighted average of the values within the feature. This would help smooth seafloor detections, and the actual feature range definition would have a negligible impact as the average would be computed in the linear, rather than a logarithmic, domain. Also, rather than the arbitrary 30 dB signal to noise ratio filter for a weak target currently in place, the target strength for features should be estimated and compared to established seafloor target strengths (Weber, 2020). Occasionally, areas with steep slopes appear to have overlapping features, and perhaps this can be accommodated as well.

After the TWTTs are calculated for each transducer, the data is combined into a single numpy array (van der Walt et al., 2011) indexed by time values with missing data removed. The lists are iterated through to consolidate unique time values and remove records with no values for any transducer. Currently, the lowest frequency is considered the most stable detection, but the highest frequency is assumed to have the highest fidelity on the water/seafloor interface, although also prone to misdetection on water column targets. We start by assuming the lowest frequency is correct and then progressively selecting the next highest frequency that is within two pulse lengths of the currently selected detection.

Sound Speed

Sound speed is required to convert TWTT to a distance. A common approximation of sound speed is 1500 m/s, although ocean sound speed can vary by roughly 3% from this value. The use of representative profiles derived from historical data can be used to determine a better estimate of the harmonic sound speed for a particular location and season, although the residual error induced by this estimate is a function of the variability in sound speed for the location. The sound speed is retrieved from the locally downloaded WOA13 database (Boyer et al., 2013) using the latitude, longitude, POSIX timestamp, and a rough depth measurement calculated from the low frequency TWTT (***Figure 5***). Because the variability in sound speed between records is usually very small, a standard harmonic sound speed value for every one hour is calculated and applied to all records within that time frame. That returned sound speed value is then used to calculate the range to the seafloor by multiplying each transducer's TWTT by the sound speed and then dividing by two. While in situ sound speed measurements are ideal, they are not readily available in the raw EK60 files. Using the modeled harmonic WOA sound speed estimates is more accurate than using a static approximation of 1500 m/s, and introduces potential error that is less than one percent of depth based on consultation with SmartMap (HydrOffice, 2020).

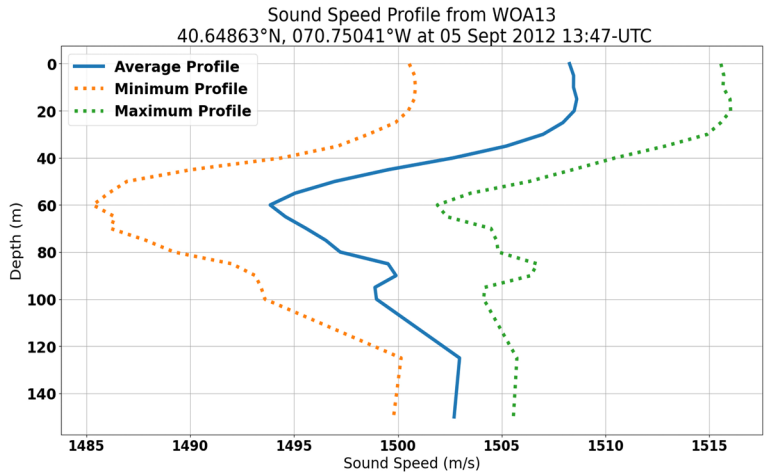

Figure 5: *An example of an average sound speed profile from WOA (Boyer et al., 2013). These profiles were used to calculate a harmonic sound speed used to correct the EK60 two-way travel time.*

Heave

The heave of a ship can significantly influence depth measurements, so we apply a low pass filter designed to determine heave values and remove high-value artifacts from the seafloor detections. A fifth-order Scipy Butterworth filter is applied with a ten second cutoff by resampling the seafloor at one Hz and applying the filter. Heave is then estimated by differencing the original and bandpass data and then resampling the heave to the original timestamps. This provides heave as a separate, though dependent, variable alongside the original detections such that it can be removed and replaced with a better solution if desired. The approach of applying a lowpass filter was inherited from the previous Saildrone work, although that approach did not attempt to separate the heave value. Further work for using a highpass filtered heave from the GPS GGA string will likely be explored in the future.

Tides

Correction for tides requires two separate but related components: realization of the tidal datum and a model for time-dependent water levels. We achieve both through AVISO+ FES2014b database, which includes 34 tidal elevation components defined on a 1/16° grid. The FES2014b hydrodynamic model includes assimilation of long time series satellite altimetry data from Topex/ Poseidon, Jason-1 & -2, TPN-J1N, ERS-1 & 02, and Envisat, as well as the assimilation of global tidal gauge data. The FES software distribution contains a C/Python API that may be used to calculate tidal height time series for any particular point within the global grid. FES2014 was produced by NOVELTIS, LEGOS, CLS Space Oceanography Division, and CNES. It is distributed by AVISO, with support from CNES (NOVELTIS et al., 2014).

Tide corrections in situ to the vessel tracks are computed to a mean lower low water (MLLW) datum to adjust the EK60 observed depths for charting. Interpolated tide predictions were first pre -processed to compute datums on a 1/60° grid, in line with the sampling resolution of the NOAA gravimetric xGEOID products (National Geodetic Survey, 2019). Tidal datums representative of the NOAA 19-year National Tidal Datum Epoch were resolved by averaging select semi-diurnal extrema (higher high waters, high waters, low lower waters), spanning one year of FES2014b computations at each grid node. For each EK60 sonar transmission latitude, longitude and timestamp, FES2014b-predicted tides relative to the local mean sea level (LMSL) are computed. For navigational safety, the LMSL tides are adjusted to MLLW by spatially interpolating separation values from the 1/60° datum grid. The resulting MLLW tide heights are then used to adjust the observed depths obtained from the EK60 seafloor detection processing. In addition to MLLW-LMSL, the datum grid includes the aforementioned mean high water datums and geoid height, as well as (local) mean sea surface ("ellipsoid") height, so that the EK60 data may be referenced to the NAD83 or WGS84 reference frames.

To validate AVISO+ tide predictions, comparisons were made to modeled water levels computed from NOAA CO-OPS Discrete Tide Zones at 67 locations offshore of the Northeast US coast. Differences were computed at the centroid of each tide zone, where verified water level observations from NOAA tide stations were processed using the publicly available model parameters (amplitude and time offsets) attributed to each zone. The comparison time period spanned five days from May 1st to May 5th, 2020, using six-minute tide data available through the CO-OPS tide data API (Center for Operational Oceanographic Products and Services, 2020). We subtracted the NOAA zoned tides from the AVISO+ predictions and found the average difference at the 67 locations ranged from 7cm to 51cm, with standard deviations ranging from 6cm to 17cm (***Figure 6***).

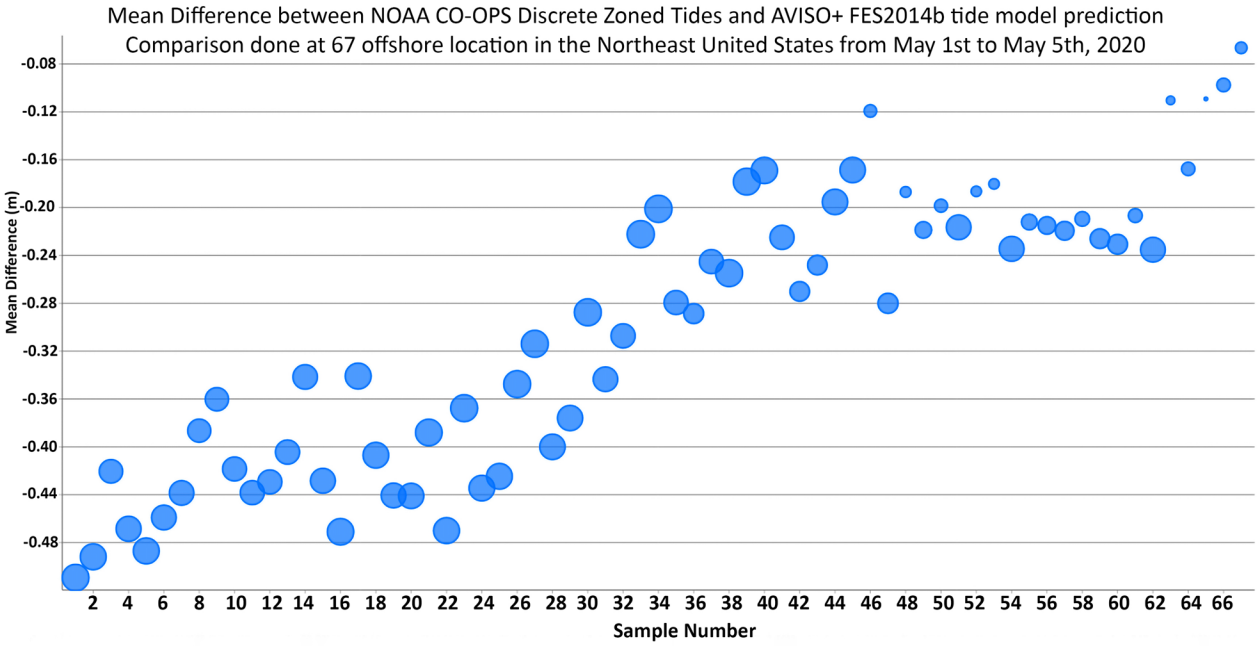

***Figure 6**: Mean difference between AVISO+ FES2014b tide predictions and NOAA CO-OPS discrete zoned tide observations at 67 offshore locations.*

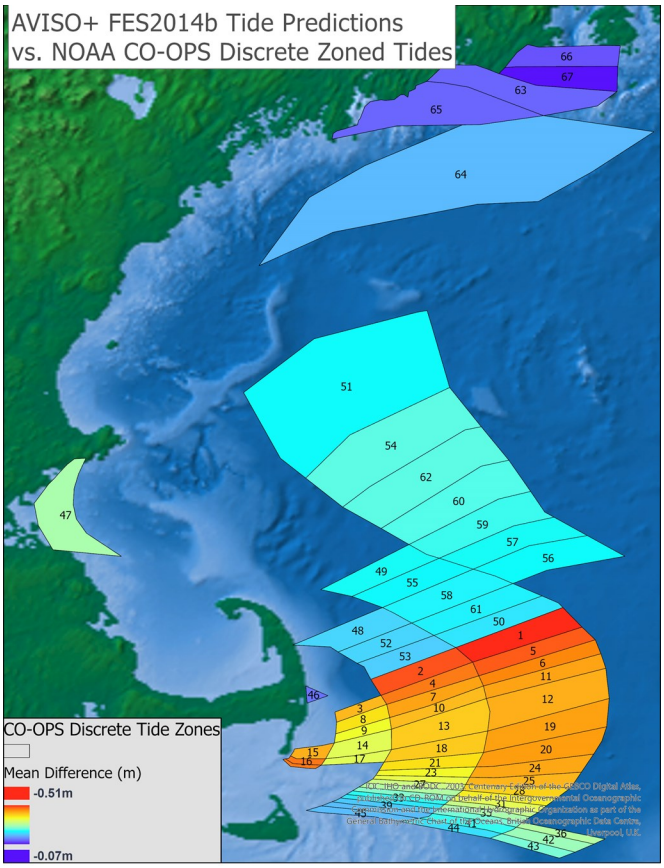

***Figure 7**: CO-OPS Tide Zones used for comparison to the AVISO+ FES2014b tide predictions.*

We observed some correlations between the mean difference and geographic location, especially east of Cape Cod, which raises questions concerning this approach to estimating survey time tides (***Figure 7***). The measured differences were mainly a consequence of variations in tidal magnitude rather than tidal phase (e.g., ***Figure 8***). While meteorological effects could explain some varying geographic biases given the short time frame of the comparison, it is important to note that these comparisons are on datum. Both models (NOAA zoned tides and AVISO+ predictions) include a potential bias in resolving the tidal datum definition relative to the mean sea level away from water level observation points. The AVISO+ FES2014 model includes assimilation of tide gauge observations as well as long-term altimetry measurements of the ocean surface. The amplitude of the aviso model may be superior in terms of a reduced datum bias in the offshore region. More effort to compare these on-datum water level models for a larger range of times and locations would be a valuable contribution to both this project and other projects seeking a solution for a first order tidal height estimate.

Representative tide data from the region used to compare EK60 results with reference bathymetry in Rhode Island Sound is shown below (***Figure 8*** and ***Figure 9***).

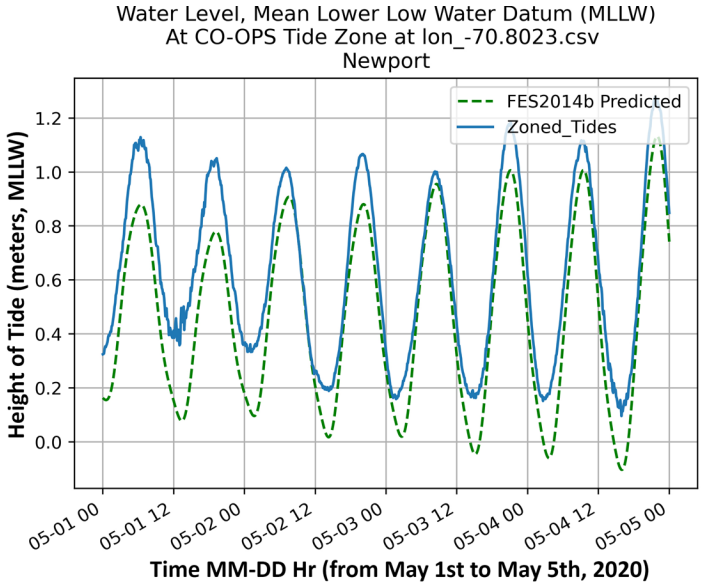

Figure 8*: Comparison of AVISO+ FES2014b predicted tide values and verified tides in Rhode Island Sound.*

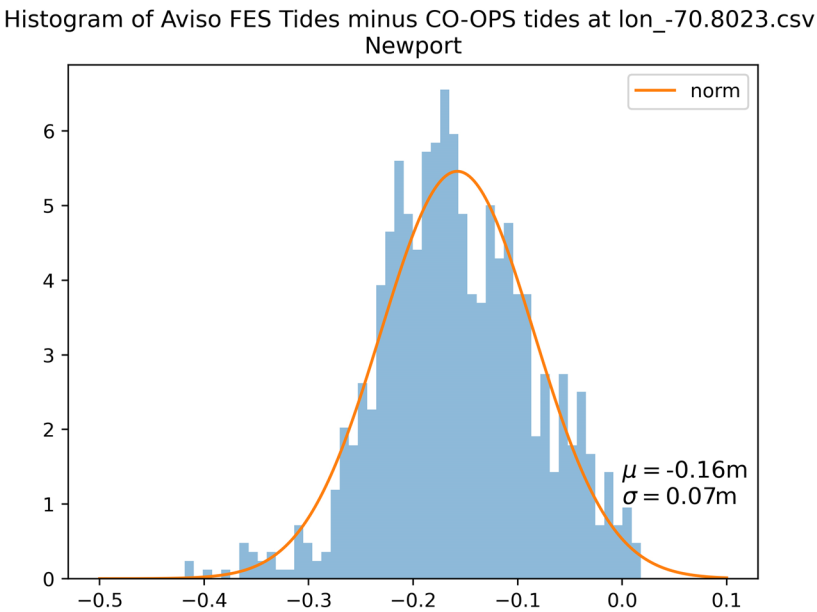

Figure 9: *Histogram showing the distribution of differences between AVISO+ FES2014b predictions and NOAA CO-OPS discrete zoned verified tide-corrected values in Rhode Island Sound.*

We recognize this is a restricted geographical and temporal analysis and does not represent the quality of the tide prediction everywhere or with time dependent events. Local meteorological effects are not well accounted for with this approach, but this can also be true of zoned tide models that propagate shore based measurements over large distances. This comparison demonstrates the AVISO model can be used to improve a final depth estimate to a similar order as traditional tide models and is thus a reasonable solution to apply as a first order solution for offshore fisheries data.

Transducer Draft

Another significant piece of information when deriving depths is accounting for transducer draft. Contemporary NOAA Fisheries Survey Vessels (FSVs) have the EK60 mounted on a drop keel and thus can significantly change the draft of the transducers even during a cruise. Nominally these drafts range from six meters when the drop keel is retracted to the hull and nine meters when fully deployed. We elected to use the draft value provided in the EK60 datagram since other manually logged information was not readily available or necessarily more reliable. If the draft value in the EK60 file is found to be zero, which is assumed to be incorrect, the process defaults to a maximum draft value of nine meters because these vessels are more likely to operate with the drop keel deployed (Walsh, 2020).

The final step of the primary script is to save the georeferenced seafloor detections with meaningful processing information to enable downstream review. The output of the process includes an ascii text file with columns for time, longitude, latitude, sound speed, heave, tide, used draft, depth from each transducer, and the selected detection. Also, a log file is created for each RAW file in the directory with any errors. If the default draft value is applied because a zero draft was found in the file, it is logged here. An overview graph consisting of two subplots, one showing scatterplots for each transducer and the best detection, and the second showing the heave, sound speed, tide, and draft, are also created. This image helps visualize each file's depth measurements at each frequency and the factors that influence them. Finally, an image with the water column data with the detections for each frequency is also produced to support a quality review of the seafloor detection.

Additional scripts were used to download RAW data from the NCEI database as well as to extract navigation values from text files for analysis. One particularly useful script we wrote was gridData.py, a script written to grid point data and export rasters with a given resolution. This code grids the processed output of the seafloor detection and georeferencing script in order to streamline the comparison process to existing NOAA surveys. For each survey, all files from the previous phase of the process are concatenated into a single geodataframe and gridded. The gridded data are broken into tiled GeoTIFFs that have eight meter node spacing with separate layers for the mean, minimum, and maximum values for the detections within the cell footprint.

The resulting statistics are based on the difference between the gridded EK60 seafloor detections and the qualified bathymetry. That is to say that the bathymetry values from collocated NOAA surveys were subtracted from the EK60 bathymetric values to determine overall differences between measurements.

3. Results

Once the previously described methods were tested sufficiently to justify work on a larger scale, the results of the seafloor detection algorithm were analyzed for reliability and accuracy against EK60 data collected from 19 NMFS cruises. In general, these methods show promising results when compared to contemporary NOAA hydrographic surveys from the same regions.

With the successful execution of the script each RAW file is represented by multiple processed results, such as an overview plot and several time-series images (***Figures 10*** and ***11***). The following figures are examples of results from a survey conducted by NOAAS *Henry B. Bigelow,* which provided the basis for the testing data used in this study (National Centers for Environmental Information, 2011)

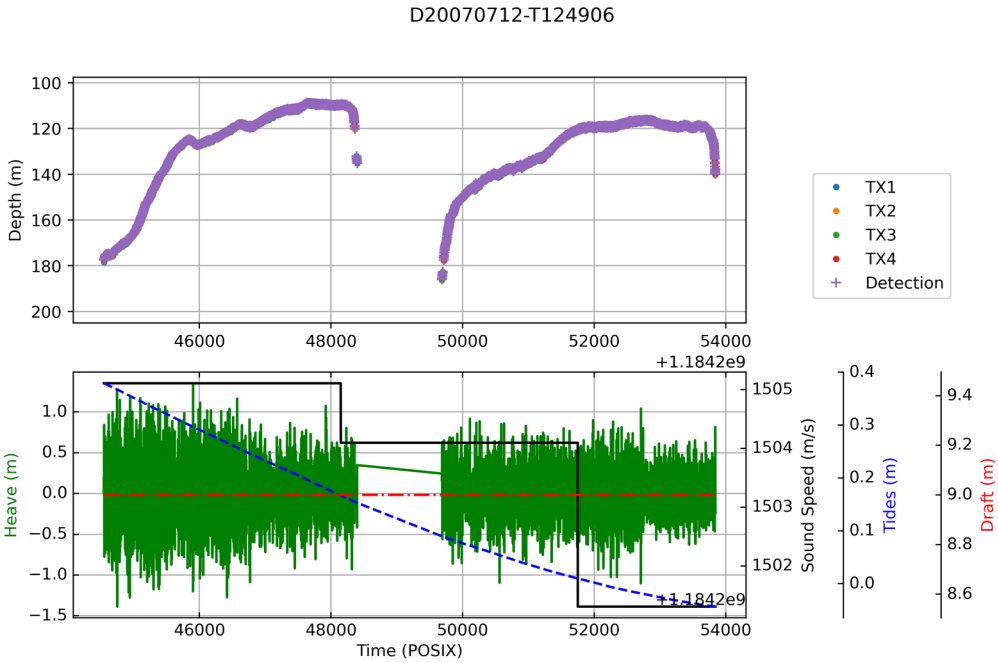

***Figure 10**: Example of overview plot generated by the EK60 script for RAW file D20070712-T124906 of the NOAAS Henry B. Bigelow. The top graph shows seafloor detections for all transducers, which are all colocated in this case, while the bottom shows values for tides, sound speed, heave, and draft.*

The time-series image (***Figure 11***) visualizes the water column for a single RAW file. The red line indicating the seafloor shows a sudden change in depth, most likely from the survey ship passing over a steep drop off. A second return for the seafloor is also noticeable underneath the red line in the top image. Time-series such as this one showcase visible marine features of both the water column and the ocean floor to aid in the processing of bathymetric data.

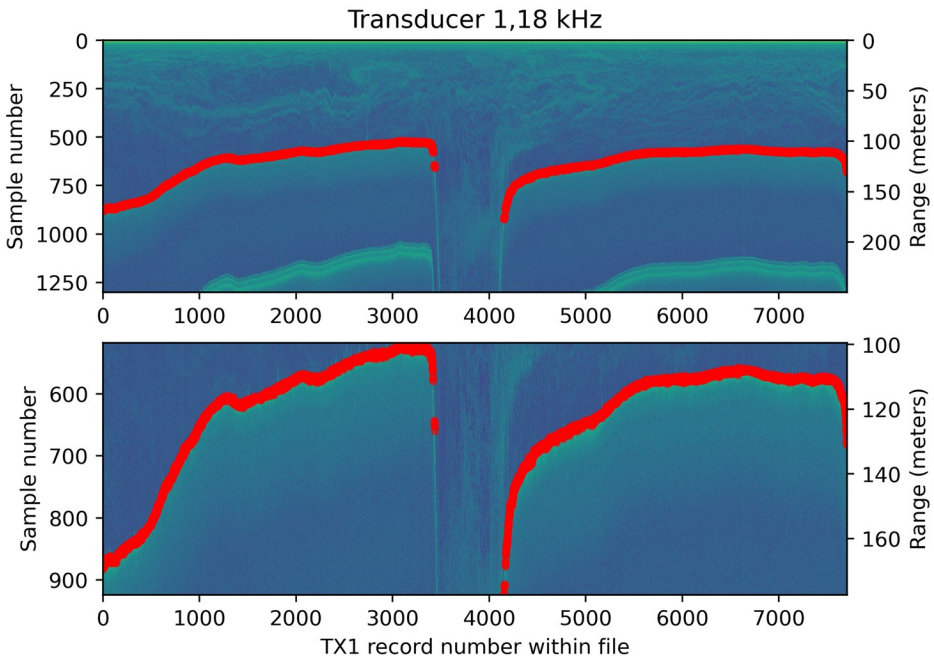

***Figure 11**: Example of time series image for one transducer generated by the EK60 script for RAW file D20070712 -T124906 of the NOAAS Henry B. Bigelow. For each RAW file, an image like this one was produced for each transducer, providing a visual for the water column and seafloor at that location.*

Most importantly, we needed a method for testing the accuracy of the EK60 results compared to existing bathymetry surveys. As mentioned in the methods section, a gridding script was used to test the accuracy of the processed seafloor detections. Existing multibeam surveys were downloaded from the *NOAA Bathymetry Viewer* (National Centers for Environmental Information, 2015) as a Bathymetric Attributed Grid (BAG) and compared to the final product of the derived and gridded EK60 depths. All 19 NMFS cruises were compiled and compared to a combined BAG file which held current bathymetric data (2007 - 2015) for the corresponding locations (***Figure 12***). The combined BAG file was compiled as an eight meter resolution raster so as to match the resulting EK60 grid resolution. The RAW data processed in this study took a cumulative 632 days (2007 - 2019) to collect by fisheries vessels over 87,134 linear nautical miles.

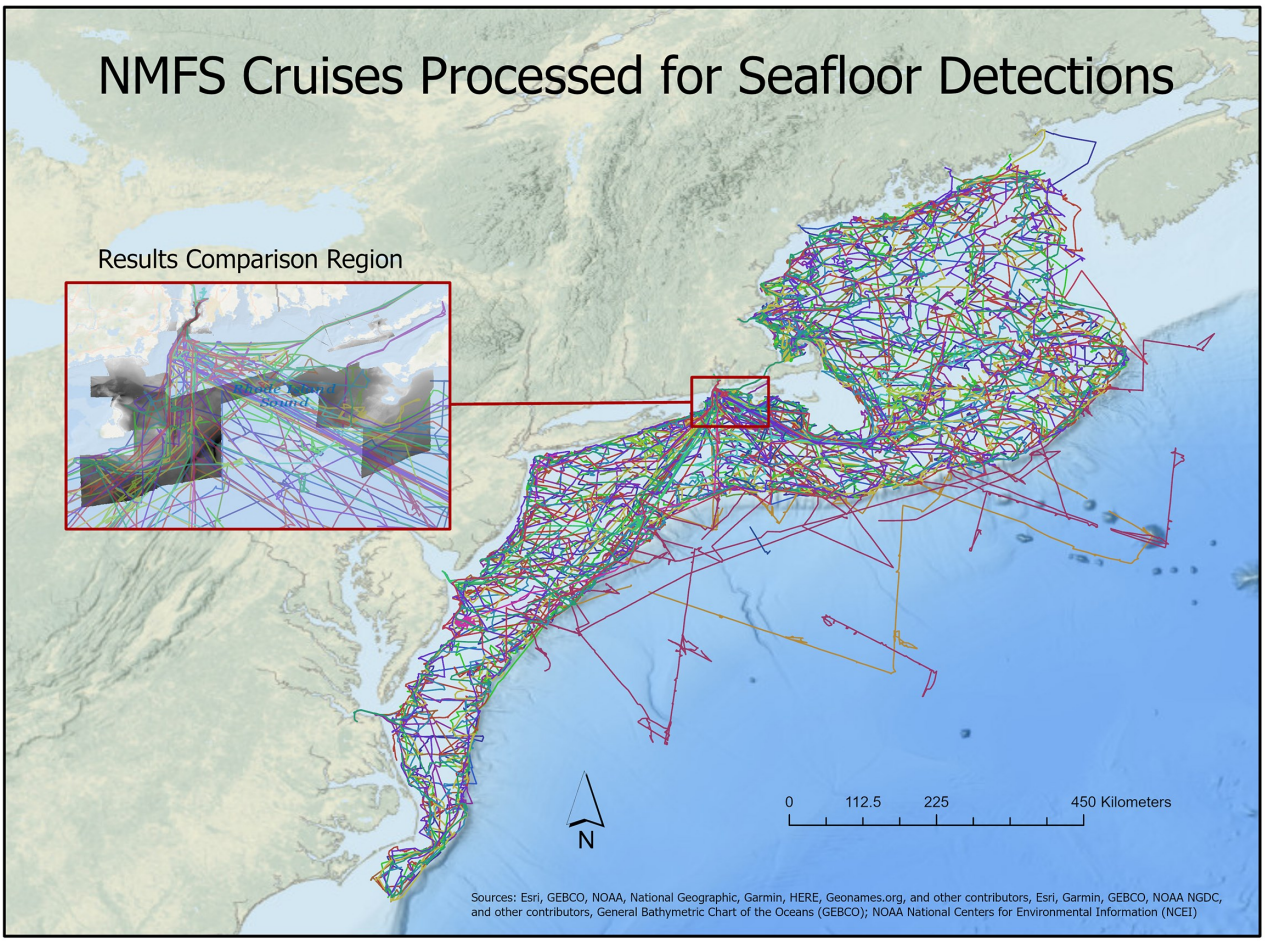

Figure 12*: Cruise tracklines for the 19 NMFS cruises processed for seafloor detections and the results comparison region with survey BAG file used for analysis (National Centers for Environmental Information, 2015; National Centers for Environmental Information, 2011).*

The reference BAG file survey values were subtracted from the eight meter gridded EK60 data using the raster calculator geoprocessing tool in ArcGIS Pro to create difference grids. The eight meter difference grids were then used to generate points for each grid using the raster to point conversion tool in ArcGIS Pro. Once each cruise had difference-points for each eight meter grid, the point feature classes were merged using the ArcGIS merge tool to generate collective results for all 18 of the *Henry B. Bigelow* cruises analyzed, as well as a separate result for the *Pisces 1301* cruise. The following statistics resulted from the analysis.

The EK60-generated seafloor detections from the *Henry B. Bigelow* have a mean difference of 0.68 meters deeper than the seafloor detections of reference surveys (***Figure 13***). After removing outliers that were greater than three standard deviations from the mean, the analysis yields a mean difference of 0.438 meters deeper than the seafloor detections of reference surveys (***Figure 14***). 92.2% of all EK60 results are within two meters of BAG survey values. Also, 83.9% of EK60 seafloor detections have a deeper bias than reference survey values, while 16.1% have a shallower bias. 3.5% of the EK60 results had difference values between 2.5 and 4.5 meters deeper than the BAG survey values and have a mean difference of 3.27 meters deeper than the reference survey values (***Figure 15***). Furthermore, 3.2% of results have differences of 4 meters or greater from reference BAG values. That being said, 82.4% of all detections were within one meter of absolute difference from the BAG survey (***Figure 16***).

We found that sections of cruise HB1304 account for 63.5% of the grid cells with difference values between 2.5 and 4.5 meters deeper than the BAG survey values. While the section of HB1304 values average 3.3 meters deeper than the survey values, the profile of the seafloor detections aligns closely with the profile of the reference survey seafloor detections (***Figure 17***). For this particular cruise section, the draft value in the EK60 files was missing and replaced by the default, centerboard-down value, of nine meters during processing. The three meter offset between seafloor detections and reference survey values is thought to indicate that the centerboard was up for this section of HB1304 with an actual draft of six meters.

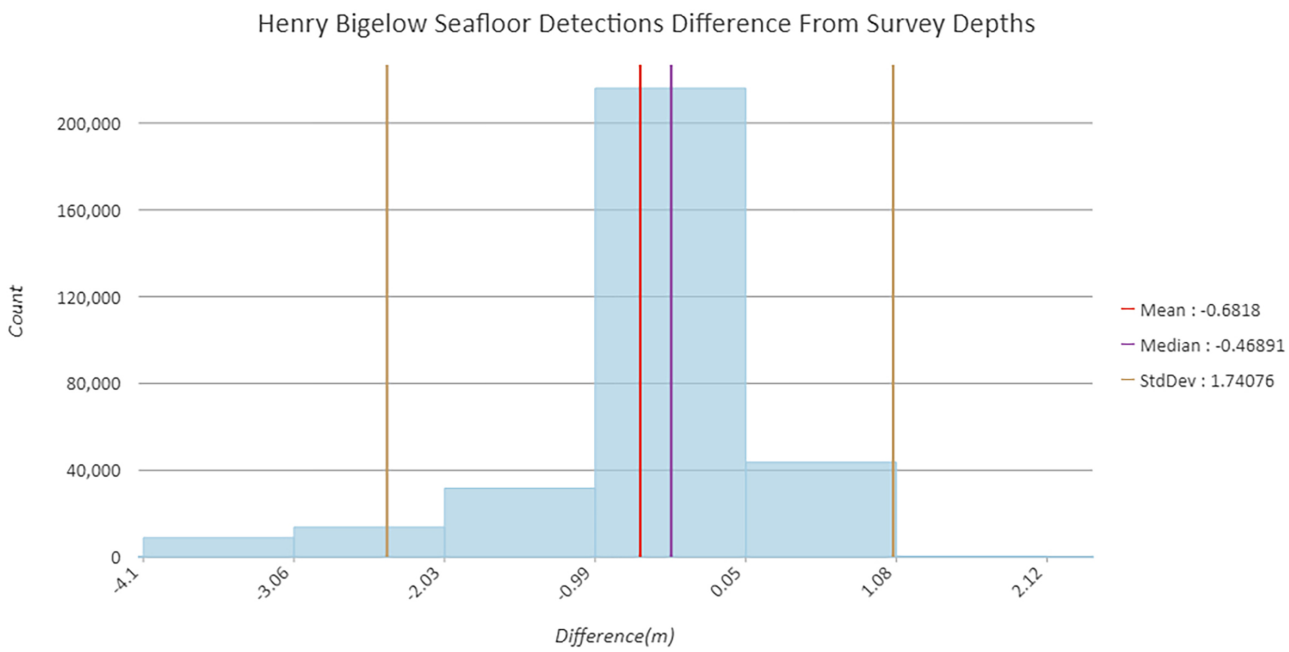

Figure 13:: *Distribution of difference values between Henry B. Bigelow seafloor detections and BAG survey depths.*

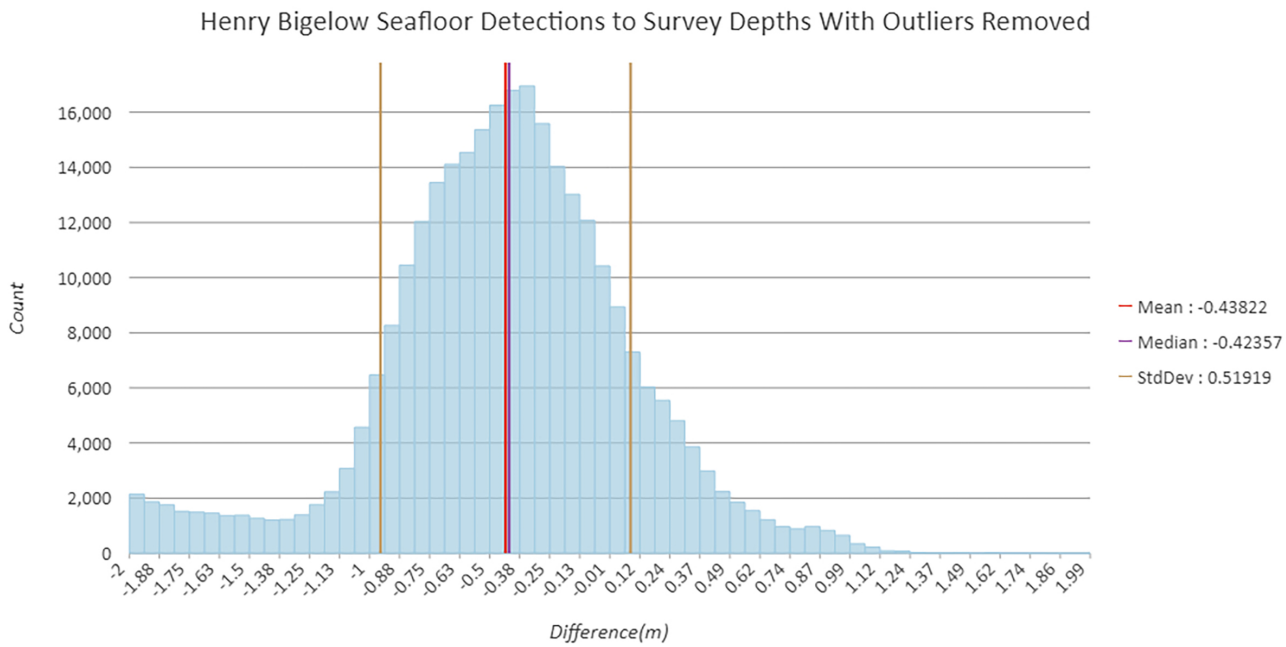

***Figure 14:**: Distribution of difference values between Henry B. Bigelow seafloor detections and BAG survey depths with outliers removed (removed anything greater than two meters absolute difference).*

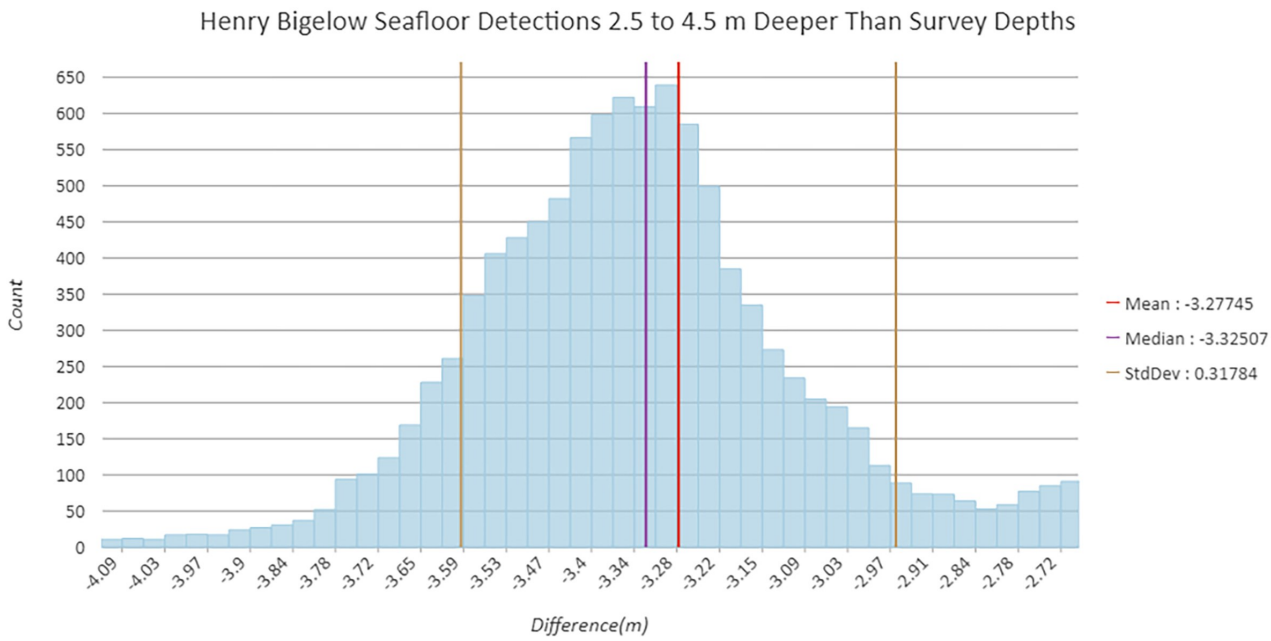

***Figure 15:**: Distribution of Henry B. Bigelow seafloor detections results with difference values between 2.5 and 4.5 meters deeper than reference survey depths. The approximate three meter bias is thought to result from FSV with six meter draft, centerboard-retracted surveys, with missing draft values.*

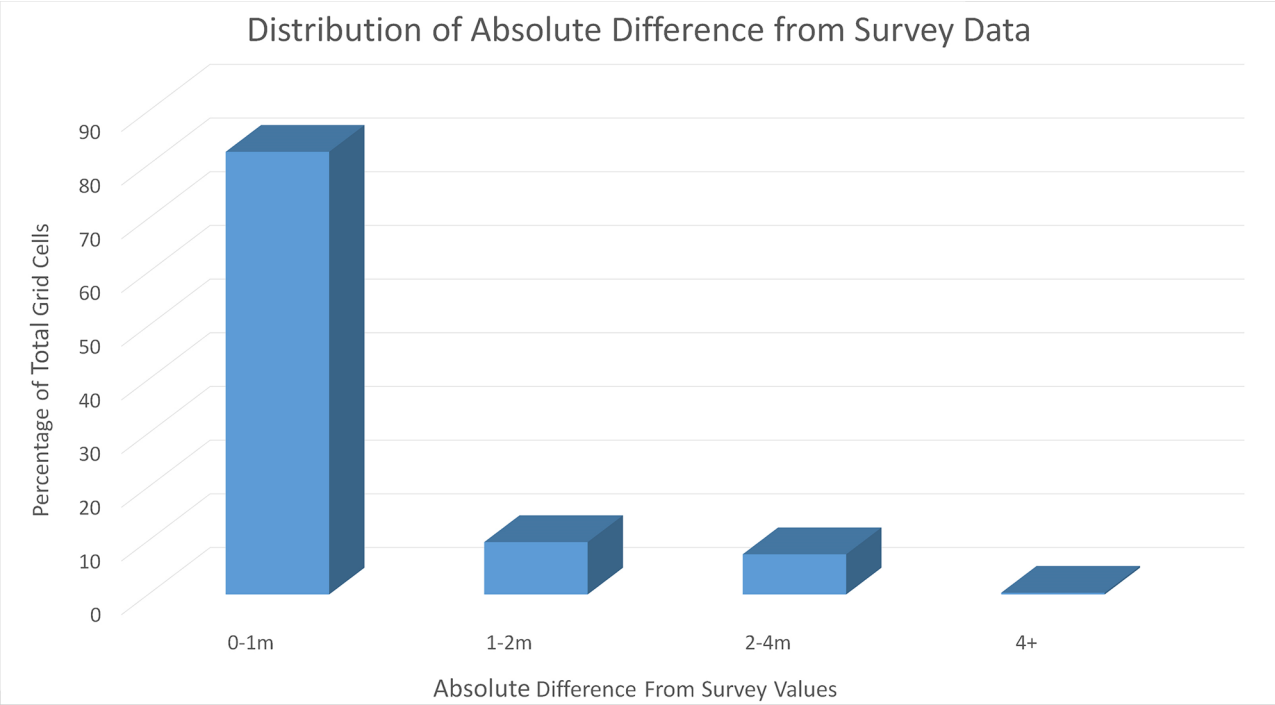

***Figure 16:**: Distribution of absolute difference between seafloor detections and BAG survey depths.*

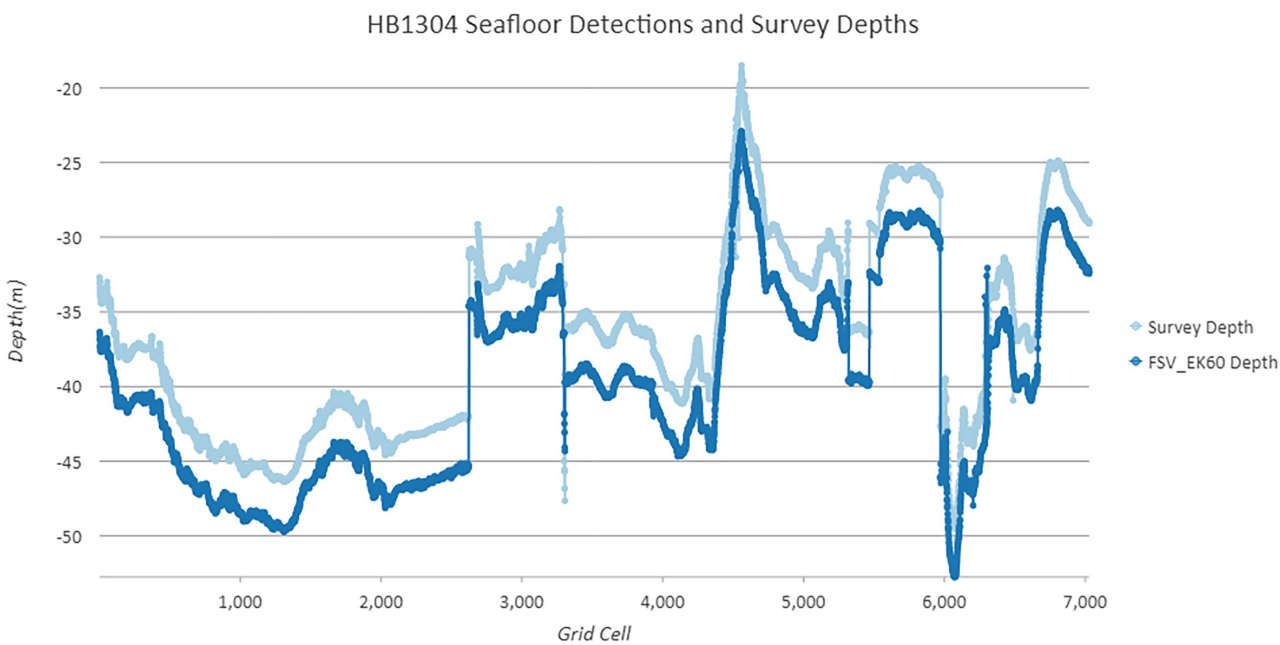

***Figure 17** : HB1304 grid cells with a near-constant difference between 2.5-3.5 meters, indicative of an erroneous draft corrector value.*

In addition to the results mentioned previously, the EK60 script was tested on separate surveys from NOAAS *Pisces* and NOAAS *Nancy Foster.* The resulting files indicate that the script can be transferable to other ship surveys, although some modifications for different NMEA datagrams and default draft values may be required.

The regions of the *Pisces* 1301 cruise that overlapped the reference BAG file had a mean difference of 0.62 meters deeper than BAG file values, and 85.2% of the results were within two meters of the reference survey values (***Figure 18***). With all outliers greater than two meters difference removed, the PC1301 cruise had a mean difference of 0.59 meters deeper than BAG file values (***Figure 19***). Like the *Bigelow* cruise data, the *Pisces* 1301 cruise had an increase in grid regions with difference values between 2.5 to 4.5 meters deeper than survey values. We found that these were also likely the result of missing draft data, which defaults to a nine meter value when processing, assuming that the centerboard is down. Similar to the cause of the three meter deeper bias in the *Henry B. Bigelow* results, the centerboard on the *Pisces* may have actually been in a retracted position at this point, with a draft of six meters, creating the approximate three meter discrepancy. However, unlike the *Henry B. Bigelow* processed data, the *Pisces* 1301 also had an increase in grid regions with a three meter shallower bias from the reference bathymetry, which is indicative of the centerboard being extended, but the draft value in the RAW file was erroneously recorded as retracted.

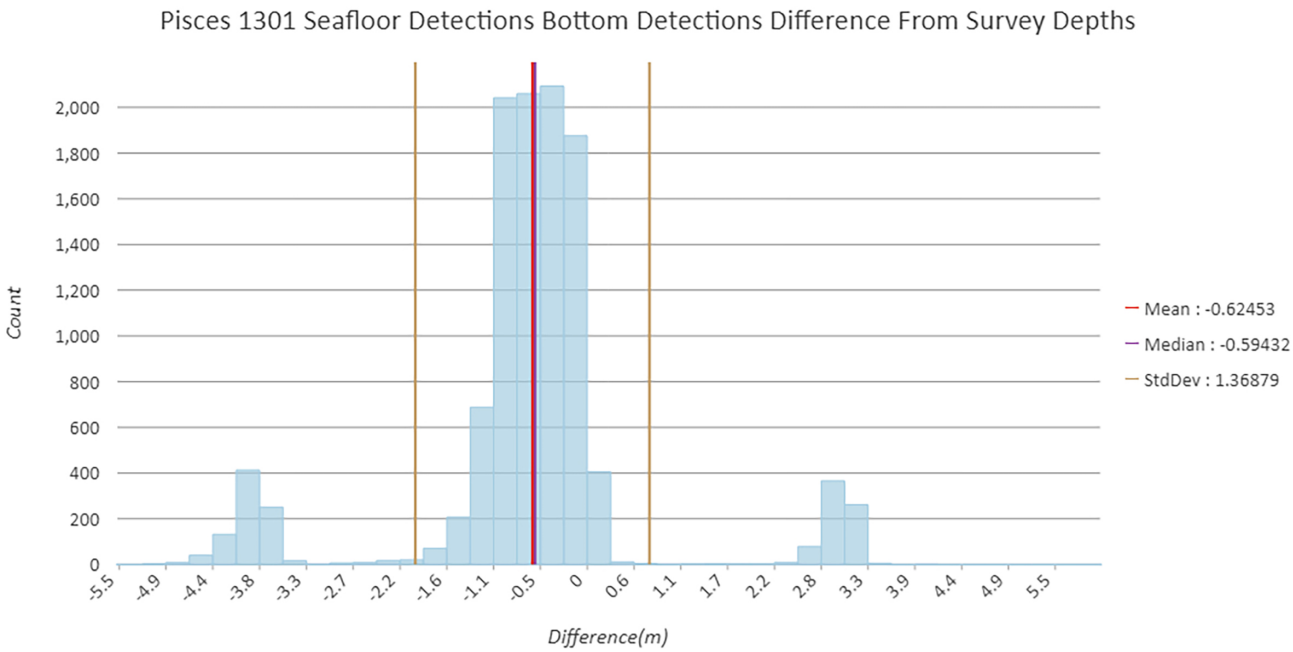

Figure 18 *: Distribution of Pisces 1301 difference values between seafloor detections values and BAG survey depths. The two aggregations around -3 meters and 3 meters difference are likely the result of missing or inaccurate draft measurements.*

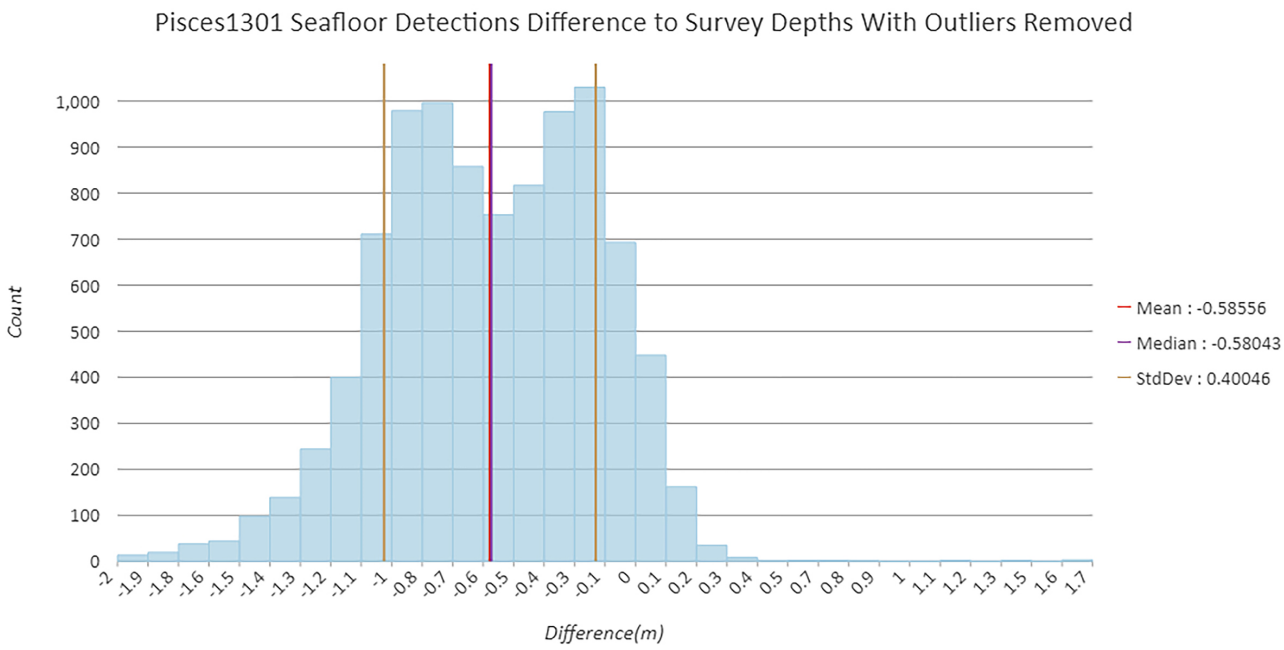

Figure 19 *: Distribution of Pisces1301 difference values between seafloor detections and BAG survey depths with outliers removed (removed anything greater than two meters absolute difference). The bi-Gausian distribution shown by the values in this survey is an area of further analysis we would like to explore.*

4. Discussion

EK60 data from historical fisheries surveys are not the typical systematic and complete coverage surveys preferred by hydrographic offices, but they may be the best available data to improve bathymetric compilations in rarely surveyed regions. As mentioned previously, using EK60 for mapping purposes could increase the overall bathymetric coverage on the order of nine percent in the Northeastern United States. The average difference between the EK60 seafloor detections and the reference NOAA survey values is one meter or less (***Figure 16***), which is comparable to established survey and charting standards. What remains unstated is a quality metric for these data.

Table 1

Large estimates for the uncertainty associated with each stage of the described processing workflow.

Source	Estimate Type	Fixed (meters)	Depth Multiplier
Detection	Random	2	0.01
Sound Speed	Bias	0	0.01
Tides	Bias	0.5	0
Heave	Random	1	0
Draft	Bias	0.5	0
Combined Uncertainties	$\sum_{0}^{m} Bias_m + \sqrt{\sum_{0}^{n} (Random_n)^2}$	3.2	0.02

The various methods proposed for the reduction of EK60 water column data to bathymetry for charting bear further development to improve how they work and properly qualify their uncertainty. We discuss various justifications for why these methods are better than nothing, but significant effort remains to accomplish well qualified uncertainty estimates for each part. By way of rough and ungrounded uncertainty estimates to contextualize the resulting data relevant within typical survey metrics, we propose **Table 1** for consideration.

The uncertainties for hydrographic surveys are sometimes described in terms of two parts describing a linear trend. The depth multiplier acts to vary the uncertainty with depth while the fixed part is not depth dependent. Adding our proposed uncertainties as a root sum square for the random components combined with estimated biases as a crude uncertainty model, we derive the fixed uncertainty to be 3.2 meters and additionally increases as two percent of depth.

In comparison to the S-44 standards set forth by the International Hydrographic Organization (IHO), the EK60 seafloor detections meet the standards for Order 2 surveys when compared to reference surveys. As stated by the IHO, these second-order surveys apply to locations where full seafloor coverage is not required and where unmarked navigational hazards are unlikely. These parameters are the least strict of all survey standards and typically only apply to surveys greater than 100 meters in depth (International Hydrographic Bureau, 2008). When evaluating the IHO S-57 zone of confidence categories (CATZOC), the EK60 data seems to fall between the parameters of B and C category surveys in terms of horizontal and vertical uncertainty, and total seafloor coverage and detection of bathymetric features. CATZOC B states that hazardous navigational features may exist but are not expected, while CATZOC C states that a full area search was not achieved and that depth anomalies may be expected. EK60 data fits squarely within the typical survey characteristics of CATZOC C, as this data is typically collected on an opportunity basis along a passage (Office of Coast Survey, 2016). Furthermore, the rough uncertainty estimates proposed in Table 1 becomes better than CATZOC C in greater than 40 meters, reinforcing the idea that these data are best considered in deep and offshore waters. Regardless, this fisheries data could substantially increase the general understanding of the seafloor beyond the boundaries of current NOAA hydrographic surveys. Additionally, it is worth noting that all EK60 data was collected during routine fisheries surveys, meaning that no extra resources were expended at sea to obtain this bathymetry.

Analyses were conducted to determine the cause of the 3.3 meter discrepancies observed between the EK60 data and the verified surveys (***Figure 17***). One explanation is missing draft information in the RAW file, and another is wrong draft information in the RAW file. With three possible values: six meters - when the centerboard is fully retracted and flush with the hull; nine meters - when the centerboard is fully extended; and 7.5 meters - an intermediate position of the centerboard, it would seem the intermediate position is either never used or always reported accurately since a bias of 1.5 meters is not prevalent. Our process defaults to a nine meter value when no draft information is available, so the periodic bias in either a positive or negative direction (***Figure 18***) would suggest that occasionally the draft value is not updated in the RAW EK60 data. A nine meter default draft value would only bias in one direction, so the other bias is likely a six meter value in the EK60 when the centerboard is fully deployed at nine meters. Unfortunately, it was clear that the default draft value is not accurate in all cases. For example, in sections of HB1304, a near-constant 3.3 meter deep bias was observed when comparing it to the reference BAG data (***Figure 17***), and our process reported using the default value. Given the differences between the EK60 survey HB1304 and the corresponding BAG survey, it is suggested that certain attributes such as draft be diligently recorded in EK60 files. We recommend that fisheries vessels collecting EK60 data have some automated way of recording draft over time in a machine-reading manner so that the values can be accurately maintained when performing seafloor detections.

Along with the comparisons and statistics mentioned previously, it is important to acknowledge uncertainties in the corrections used for seafloor detections in the described workflow. Further refinement to this algorithm should include uncertainty calculations for tides, harmonic sound speed, heave, draft, and other vertical and horizontal components. The largest single source of vertical uncertainty is the estimation of draft since the position of the centerboard on NOAA FSVs is not always accurately and timely recorded in a machine-readable format within the RAW file. Estimating the vertical uncertainty component from the AVISO+ tide model is an area of an ongoing study, as there is interest in applying the tide correction model to other sources of

bathymetric data in US waters. Since frequent sound speed casts are not available during the fisheries cruises, this project estimated the likely sound speed profile for the survey locations and times based on past measurements available in the WOA. This estimate introduces some error, likely less than one percent of depth, but would be captured in any comparisons with reference datasets. Uncertainties for ship heave corrections have not been explored but should be included during the refinement of this algorithm.

5. Conclusion (Applications)

In conclusion, although these surveys are not systematic in terms of coverage, the EK60 bathymetric datasets can contribute to the overall mapped area statistic for the US EEZ. Based on the results of this paper, this data has the potential to be classified between IHO CATZOC B and C (Office of Coast Survey, 2016). The recent timeline of the EK60 surveys may offer some updated bathymetric information in terms of accuracy and detail. This wealth of bathymetric data can be used to increase overall bathymetric coverage by up to nine percent (***Figure 3***) and aid initiatives such as Seabed 2030 (Westington et al., 2019). A key development in automating the processing of RAW EK60 data for multiple datasets was incorporating a global tide model (AVISO+ FES2014b) into the EK60 script. The AVISO+ tide model (NOVELTIS et al., 2014) has potential for many other applications such as crowdsourced bathymetry (CSB) projects. By automating the process of converting RAW EK60 readings into a digital elevation model (DEM) raster format readily ingested by the national bathymetry pipeline, the manual effort to use these data is significantly reduced. The workflow is designed to easily accommodate unique EK60 datasets and desired export parameters. The versatility of Python allows users to easily adjust the script to match survey specifications, making it possible for this workflow to be utilized in different projects and potentially improving other archived datasets that could benefit and improve our global bathymetric understanding. These specifications may include but are not limited to ship draft and tidal calculations. With further development, this script can iterate through downloading and processing multiple surveys worth of fisheries bathymetry data making it a useful tool for deriving information about the ocean floor from existing but previously untapped bathymetric data.

6. Acknowledgments

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Articles

EVALUATION OF THE PRECISION OF PHASE-MEASURING BATHYMETRIC SIDE SCAN SONAR RELATIVE TO MULTIBEAM ECHOSOUNDERS

By LCDR V. B. Pimentel[1,2], LCDR C. Florentino[1,2], A. A. Neto[2]

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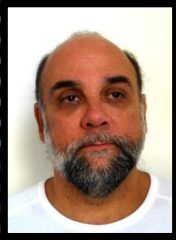

Abstract

The International Hydrographic Organization (IHO) and the Directorate of Hydrography and Navigation (DHN) consider that where the under-keel clearance is critical, bathymetric surveys should provide full seafloor coverage. Multibeam Echosounders (MBES) and Phase-Measuring Bathymetric Side Scan (PMBS) are capable sensors to achieve this coverage, however, they have different technologies. The MBES is widely accepted by the international community and considered the standard system in surveys that require the highest IHO accuracy. The aim of this paper is to assess whether the PMBS can achieve comparable results with the MBES, focusing on Nautical Chart production. Despite “noisy” data and some effects, this research suggests that PMBS can be used to meet IHO requirements, under some special conditions.

Résumé

L'Organisation Hydrographique Internationale (OHI) et la Direction de l’hydrographie et de la navigation (DHN) considèrent que les levés bathymétriques devraient fournir une couverture complète du fond marin pour mettre à jour les cartes marines où le dégagement sous la quille est critique. Les capteurs bathymétriques capables d'atteindre une telle marque sont les sondeurs multifaisceaux et le balayage bathymétrique à mesure de phase. Cependant, la technologie d'acquisition est différente dans chaque capteur. L'échosondeur multifaisceaux est déjà largement accepté par la communauté internationale et considéré comme le système standard dans les enquêtes qui nécessitent la plus grande précision de l'OHI. Par conséquent, cet article évalue si le côté bathymétrique à mesure de phase atteint un résultat compatible avec l'échosondeur multifaisceaux, en se concentrant sur la production de cartes marines. Malgré les données bruyantes et certains effets, cette recherche suggère qu'il peut être utilisé dans certaines conditions.

Resumen

La Organización Hidrográfica Internacional (OHI) y la Dirección de Hidrografía y Navegación (DHN) consideran que cuando la sonda bajo quilla es crítica, los levantamientos batimétricos deberían proporcionar una cobertura completa del fondo marino. Las Ecosondas Multihaz (MBES) y el Sonar de Barrido lateral batimétrico de medición de fase (PMBS) son sensores capaces de lograr esta cobertura. Sin embargo, tienen tecnologías diferentes. El MBES es ampliamente aceptado por la comunidad internacional y se considera el sistema estándar en los levantamientos que requieran la mayor precisión de la OHI. El objetivo de este documento es evaluar si el PMBS puede lograr resultados comparables al MBES, centrándose en la producción de Cartas Náuticas. A pesar de los datos «ruidosos» y algunos efectos,

1. Introduction

An important component of a hydrographic survey is the bathymetric measurements. Currently, Multibeam Echosounder (MBES) systems are the most used sensor for morphological investigation and seafloor mapping. It fulfills the International Hydrographic Organization specifications (IHO, 2008) and the Brazilian Hydrographic Service requirements, due to its swath and low uncertainty.

However, the Phase-Measuring Bathymetric Sidescan (PMBS) has been presented as an alternative technology to the MBES. Some studies were presented by Gostnell (2005), Gostnell, Yoos and Brodet (2006), Madricarlo, Foglini and Tonielli (2011), Dodd (2013), Brisson, Wolfe and Staley (2014), Ai, Armstrong and Fleury (2015), Jerram and Schmidt (2015a), Ma, Xu and Xu (2016) and Bongiovanni and Schmidt (2016), where issues regarding data acquisition, processing methodologies and potential uses of this equipment were discussed.

Even after positive results, the PMBS technology remains under discussion. The equipment is applied by some hydrographic services (e.g. USACE – USA) and not fully adhered to by others (NOAA – USA). In Canada, regulations are provided to be followed, but no specific equipment is mentioned to achieve them. In Brazil, the present standard procedures do not define the acceptance of any equipment, but several requirements are usually achieved by MBES (DHN, 2017). The use of PMBS is, therefore, very incipient in the country, owing to both the existing world controversy and the lack of national studies with methodical hydrographic rigor focusing on regional scenarios (oceans, rivers, lakes and seas).

This work adds to previous efforts in the analysis of PMBS performance, seeking to improve consistency to the evaluation of the PMBS suitability for Special Order hydrographic surveys. To accomplish this, the IHO and the Brazilian Hydrographic Service specifications (defined by the Directorate of Hydrography and Navigation) were strictly observed.

2. Theoretical concepts

MBES are sonars capable of providing bathymetric data by crossing the acoustic waves through a transmitting and a receiving sensor, which are arranged orthogonally, in a technique known as mills cross (Bjørnø, 2011; L-3 COMMUNICATIONS SEABEAM INSTRUMENTS, 2000; Simmons et al., 2017). In this arrangement, the beams are formed at the intersections between the transmitting and the receiving wavefronts (L-3 COMMUNICATIONS SEABEAM INSTRUMENTS, 2000). These beams, after the two-way travel time, provide the seafloor signal detection that is used to calculate the depth, which is done by amplitude or phase detection (IHO, 2005).

The PMBS is a sensor capable of simultaneously providing backscatter and bathymetric information (Jerram and Schmidt, 2015a). It consists of a transmitter and more than one receiver spaced at a distance multiple of the signal wavelength "λ" (KONGSBERG MARITIME, 2014; Lurton, 2000; Wilby, 1999). Georeferenced depth information is provided by measuring the echo's phase difference at the receiver transducers (IHO, 2005).

In a quick comparison, the PMBS has a lower cost (Ai and Parent, 2011); has a greater swath capability in shallow water (Brisson; Wolfe; Staley, 2014; Gostnell, 2005; Jerram and Schmidt, 2015b); provides a faster survey with better visualization at the edges of the swath (Brisson; Wolfe; Staley , 2014); has a higher data density (USACE, 2013), leading to a larger across-track resolution (1-10 mm) (Jerram and Schmidt, 2015a; Jerram and Schmidt, 2015b; Ma; Xu; Xu, 2016); has the same backscatter view of a sidescan sonar (Brisson; Wolfe; Staley, 2014; Jerram and Schmidt, 2015b); and uses the principle of interferometry, which is also used in MBES phase detection of the outer beams.

Despite these characteristics, the PMBS is not yet fully accepted by the international hydrographic community (Brazil included). This is due to a number of factors such as low detection capacity in nadir (Dodd, 2013, Ma, Xu, Xu, 2016); very noisy data (Dodd, 2013; Jerram and Schmidt, 2015b); depth ambiguity (layover); large volume of data, which requires better computing capability (Jerram and Schmidt, 2015b; Ma; Xu; Xu, 2016); and strong vertical uncertainty (Brisson; Wolfe; Staley, 2014; Jerram and Schmidt, 2015b; NOAA, 2017).

3. Methodology

3.1 TESTS AND AREAS

In order to evaluate the acceptance of PMBS by the Brazilian Hydrographic Service, tests were developed to assess certain critical capacities, while comparing the results with a simultaneously acquired MBES survey. To perform this experiment, a vessel-pole-mounted PMBS and vessel-organic hull-mounted MBES were used.

Five test sites were chosen within the Guanabara Bay (***Figure 1***). The Guanabara Bay has an area nearly 384km^2, with a central channel approximately 30 meters deep. The seafloor has an average depth is 5.7 meters and consists of quartz sand at the entrance to the Atlantic Ocean, associated to the effects of waves and tides. The remainder of the seafloor, is mostly mud, resulting from Holocene transgression and river sedimentation (Kjerfve et al., 1997).

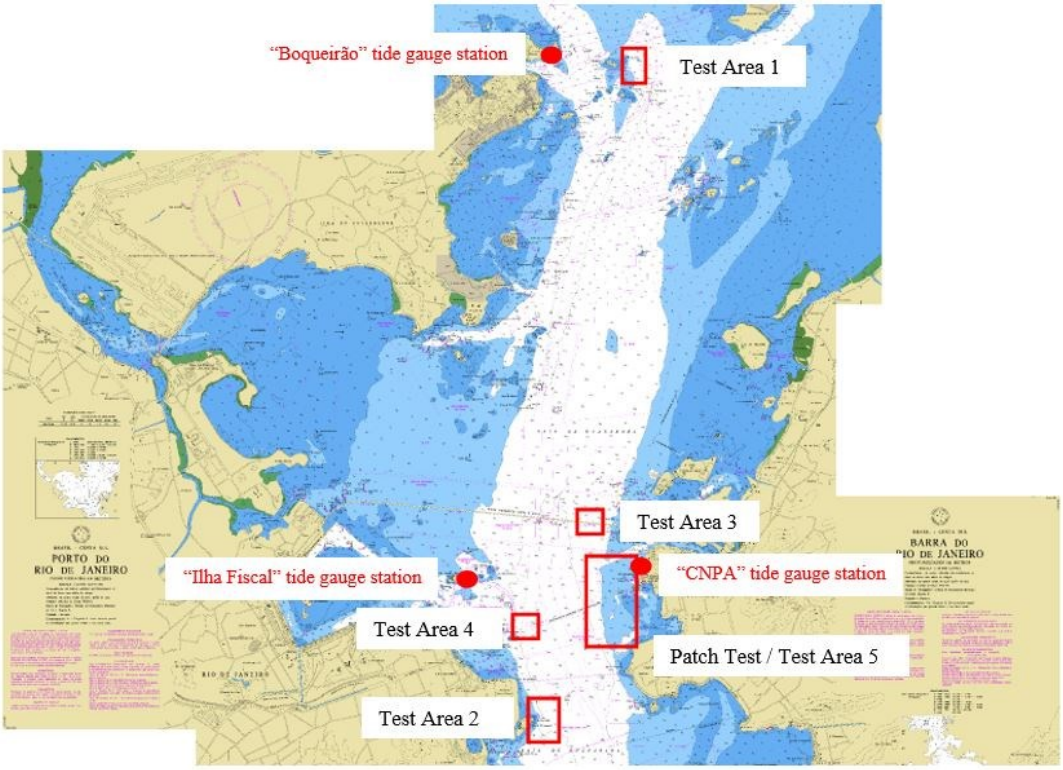

Figure 1 *– Location of the test areas and the tide gauge stations. Source: Adapted by authors.*

Test Area 1 aims to verify the ability of PBMS to precisely detect and delineate bathymetric features. The area is about 13 meters deep and approximately 0.375km^2 wide (750m x 500m), with numerous rock outcrops with varied sizes and shapes.

Test Area 2 is designed to check the ability of PBMS to resolve slopes with shallow to steep gradients. The chosen area covers around 0.350km^2 (550m x 700m) in the vicinity of Villegagnon

Island, with varied gradients and depths ranging from 1.5m to 39m. In this way, several slope gradients (approximately 4 to 10 degrees) were covered, providing data for different analyses.

Test Area 3 aims to observe the maximum distance the PMBS can detect objects that are pronouncedly off the seafloor and estimate their height. The detection of objects with substantial vertical relief is a fundamental factor for safety of navigation. For this purpose, an area of 0.1Km^2 (250m x 400m) and with an average depth of 15 meters was selected. The area comprises 5 pillars of the Presidente Costa e Silva Bridge which rise above the water. This allows simulation of targets that the survey vessels cannot approach due to the risks involved.

Test Area 4 seeks to detect the shoalest depths of pronounced vertical features that do not reach the water surface. Thus, a wreck area of 0.330Km^2 (600m x 550m) was chosen, with an average depth around the object of 30 meters, with a minimum known depth of 20.8 meters.

Test Area 5 aims to verify the efficiency of the PMBS compared to MBES. The survey line spacing was chosen according to interferometric parameters. It is known from the literature that the PMBS has a maximum swath width of approximately 10-12 times the water depth, while the MBES has 5-6 times the water depth (Jerram and Schmidt, 2015b). The purpose was to verify the useful coverage efficiency of the PMBS. For this test, we choose an essentially flat area of approximately 1.4km^2 (1,750m x 800m) with depths varying from 3 to 20 meters.

Test Areas 3 and 4 were also used for the resolution tests; verifying bathymetric resolution and data density.

3.2 EQUIPMENTS

The survey was performed on August 02nd and 03rd of 2017. The equipment used were:

A blister-mounted *Kongsberg EM2040* multibeam echosounder, operating at 400KHz central frequency; INS *Kongsberg Seapath 300* with *MRU5* and 2.582m spaced heading antenna; GPS positioning with *Fugro DGNSS 3710* correction; *AML Micro X* sound velocity sensor; and *Kongsberg SIS* navigation and acquisition software.

A pole-mounted Kongsberg Geoacoustics Geoswath 4R phase-measuring bathymetric sidescan, operating at 250KHz central frequency; INS *Applanix POS MV WAVE MASTER* 2 and 1.9m spaced heading antenna; GPS positioning with *RTK Marinestar Fugro* correction; *Valeport Mini SVS 25mm* sound velocity sensor; and *Geoswath Plus* acquisition software.

The Sound Velocity (SV) Profile information was acquired using the *AML Minos X* sensor at 10cm resolution. SV data was processed into the SIS software and uploaded into the data during acquisition in MBES and during the post-processing in PMBS. The profiles were acquired before commencing the survey in each area and in every time the SV varied more than 2 m/s at the face-of-transductor sound velocity sensor.

The tide information was collected at tide gauge stations of Boqueirão, Fiscal Island and the Ponta da Armação Naval Complex (CNPA, in Portuguese) (***Figure 1***).

Throughout the survey, the weather was fine, with low wind speeds (0-3 on the Beaufort scale).

3.3 PROCESSING DATA

MBES data were processed in CARIS HIPS & SIPS 10.2. The PMBS data were processed in the GEOSWATH PLUS software. Both data were then exported to CARIS HIPS & SIPS 10.2 for the CUBE surface generation at different resolutions.

3.4 QUALITY CONTROL

The quality control was performed by measuring the precision and accuracy of each surface node.

3.4.1 Precision

The precision was verified by two methods: 1 - calculating the CUBE hypothesis TPU (Calder and Mayer, 2013); 2 - calculating the sample uncertainty of each node.

In the first method, if 95% of the nodes had a TPU within the recommended range for a given IHO Order, the surface would be accepted for that Order. In the second method, the node sample uncertainty was calculated from the standard deviation multiplied by 1.96 (in order to have 95% confidence, considering a Normal distribution) of all the considered valid depth information that is contained within a node (Pereira, 2016). In practical terms, it represents the dispersion of the data and is equivalent to the first one. If 95% of the nodes show sample uncertainty within the range recommended for a particular IHO Order, the surface will be considered in that Order.

While the first method takes into account the uncertainties that give rise to depth information, the second is based on the coherence of the bathymetric data.

3.4.2 Accuracy

The accuracy of PMBS surfaces was evaluated in three ways: (1) observing the dispersion of the MBES data (here considered as the reference surface) relative to the PMBS depth surface (here called layer $Depth_{PMBS}$); (2) by calculating the depth difference surface between the MBES ($Depth_{MBES}$) and the PMBS ($Depth_{PMBS}$) surfaces; (3) by calculating the surfaces that contain the difference of the shallowest depth information, hereinafter referred to as Shoal layers ($Shoal_{MBES}$ and $Shoal_{PMBS}$).

The multibeam data dispersion from the $Depth_{PMBS}$ layer was done using the "QC Report" tool of the CARIS HIPS & SIPS software (CARIS, 2017). The program checks the statistics of some standard lines (MBES lines) against the surface that will be evaluated ($Depth_{PMBS}$). Based on the surface depth values, another two above-and-below parallels surfaces are virtually created, ranging the TVU IHO Orders. If, the percentage of pings of each line that lies within this range is higher than or equal to 95%, the surface can be considered representative of the order it was evaluated against (Pereira, 2016).

The difference surface is calculated by subtracting the values of the MBES and PMBS depth layer ($Depth_{MBES}$ - $Depth_{PMBS}$). Such procedure provides a qualitative comparison opportunity.

The layer containing the difference of the shallowest depth is very useful for hydrographic services. In Brazil, to ensure navigation safety, the surface layer used to create the nautical chart is the one that contains the shoalest depths found at each node. Although this surface may not be the most accurate or suitable when it comes to the real seafloor identification, it is useful to guarantee there will be no obstacles shallower than those selected and reported during the data processing.

4. Results

Table 1 gives an integrated perspective of the results. It is possible to observe that the analysed criteria from all areas have very similar statistical results.

Table 1 – Statistical Results for all surveyed areas. Organized by the authors.

	Area 1		Area 2		Area 3		Area 4	
	MBES	PMBS	MBES	PMBS	MBES	PMBS	MBES	PMBS
Mean of the hypothesis uncertainty (m)	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.2
Special Order (assessing the TPU)	100%	100%	100%	100%	100%	100%	100%	100%
Node standard deviation (m)	0	0.2	0	0.2	0	0.2	0	0.2
Special Order (assessing the node sample uncertainty)	99.5%	36.8%	99.8%	21.9%	99.1%	54%	99.3%	21.8%
1a Order (assessing the node sample uncertainty)	N/A	98.8%	N/A	96.8%	N/A	97.1%	N/A	97.9%
Density	51.5	227.6	48	268.5	49.2	120.1	35.2	157.7
QC Report		Special Order		Special Order		Special Order		Special Order
***Depth*$_{MBES}$ - *Depth*$_{PMBS}$(m)**		μ = 0.1		μ = 0.1		μ = 0		μ = 0
***Shoal*$_{MBES}$ - *Shoal*$_{PMBS}$ (m)**		μ = 0.6		μ = 0.7		μ = 0.5		μ = 0.6

Regarding the accuracy of each test site, it is possible to observe that the mean hypothesis uncertainty calculated by the CUBE algorithm was lower than the one recommended for Special Order for both methods, so that all surface nodes satisfy this requirement. Regarding the node standard deviation, the MBES showed a considerably smaller deviation (***Figure 2b***) than the PMBS (***Figure 2c***)., meaning that the valid data from the second sensor (PMBS) are more scattered. Due to the small dispersion of the node standard deviation, the MBES data was classified as Special Order, while the PMBS data can only be classified as Order 1A. Another aspect to be observed is that the average density of the pings per node was 2.4 to 5.6 times greater for the PMBS than that of the MBES.

When the accuracy is analyzed, it is observed the PMBS surface reached Special Order. The difference between the depth surfaces (Depth layers) ranged from 0 to 0.1m, with the MBES surface being shallower. This indicates that the two sensors estimated the depths in a remarkably similar way. The situation changes when we consider the difference between the Shoal layers. In this case, the difference varies between 0.5m and 0.7m proving again the dispersion of the PMBS data. If the data considered valid from the PMBS had cohesion like the MBES, the range of depth difference between the Shoal layers would be equivalent to the differences observed for the Depth layers.

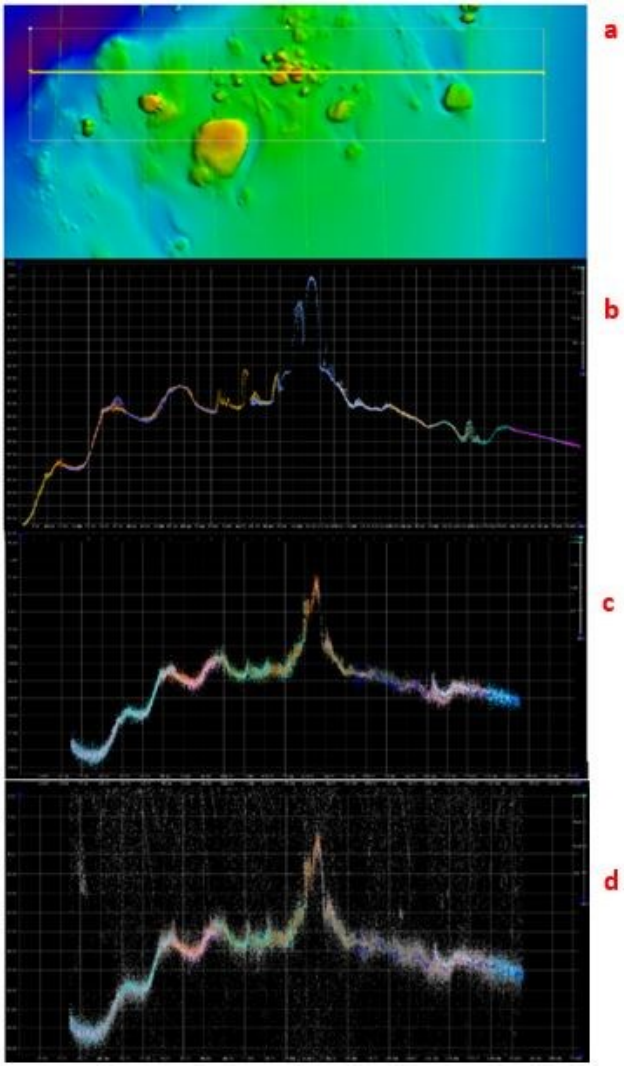

Figure 2 *– **a)** Rock outcrops in Test Area 1. The yellow line marks the profiles shown in the frames bellow; **b)** a MBES data profile; **c)** a PMBS data profile; **d)** a PMBS data profile with the reject data*

4.1 AREA 1 AND 2 – LAYOVER EFFECT STUDY CASE

A layover effect occurs when two different echoes arrive at the same time at the transducer. As there are no sectoral angles of reception, as in the multibeam, the sensor processes the two signals as noise. Sometimes, this ambiguity also happens when the sonar beam reaches the top of a tall feature before it reaches the base of it and is more critical in nadir and steep gradient regions. From ***Figure 3***, one can better visualize how this effect occurs in sloping features. In this figure, the seafloor is represented in blue, an imaginary seafloor with higher slope represented by the dotted green line, the sensor by the yellow dot and the wavefront in orange. It is possible to notice that, in the case of the blue seafloor whose slope is smaller than the opening angle θ, the "echo B" will have traveled a greater distance than the "echo A". If the green seafloor is considered, we have the opposite situation and "path B" would be shorter than "path A", arriving at the sensor at the same time as some other echo reflected by the seafloor, creating ambiguity and, therefore, noise. Thus, it can be concluded that if the distance travelled "B" ≤ "A", there will be information ambiguity, and that if the slope of some seabed feature is greater than the complement of the grazing angle α, the layover effect of will occur.

The PMBS useful swath is 10 to 12 times the water depth, so there are incident angles ranging from approximately 90° to 5.7° to 4.3°. Thus, it is known that features with slopes approximately greater than 85.7° will always be subject to layover effect.

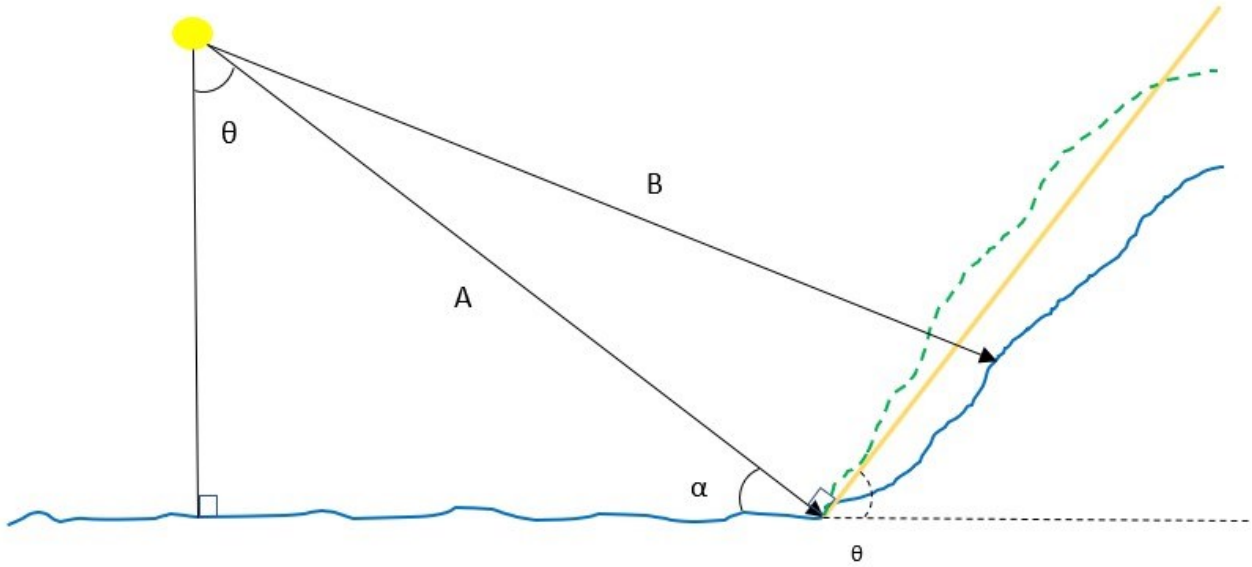

Figure 3 *– Layover Effect principle*

However, adjacent survey lines tend to reduce the layover effect if the gradient is not so abrupt. In a 200% coverage situation, the terrain will be ensonified at least by two swaths that will have points with different aperture angles, so that while one of the swaths may show layover effect, the other may not. When the seafloor or target has a slope greater than the maximum incident angle (around 5°), this effect cannot be remedied. Therefore, this effect was not seen in Area 2, where the seafloor slope is very low, but can be seen in the rock outcrops of Area 1 where the slopes of the rock edges are larger than the PMBS maximum transmission opening angle. An interesting example is the rock shown in ***Figure 4a*** (inside the red circle). On the softer gradient side, there is no layover effect, while in the most abrupt side it was evident.

It can be observed in the Shoal Depth surfaces difference (***Figure 4a)*** that the shape of the rocks does not get very well defined in the PBMS data compared to the MBES data (***Figure 4b***), resulting in depth misestimation. The largest ones lie exactly at the steep edge of the rocks (***Figure 4a***). Because these areas are very steep, they are susceptible to the layover effect. In Test Area 2, due to the softer gradients (less than 15 degrees of slope), the differences between the Depth layers are not so noticeable.

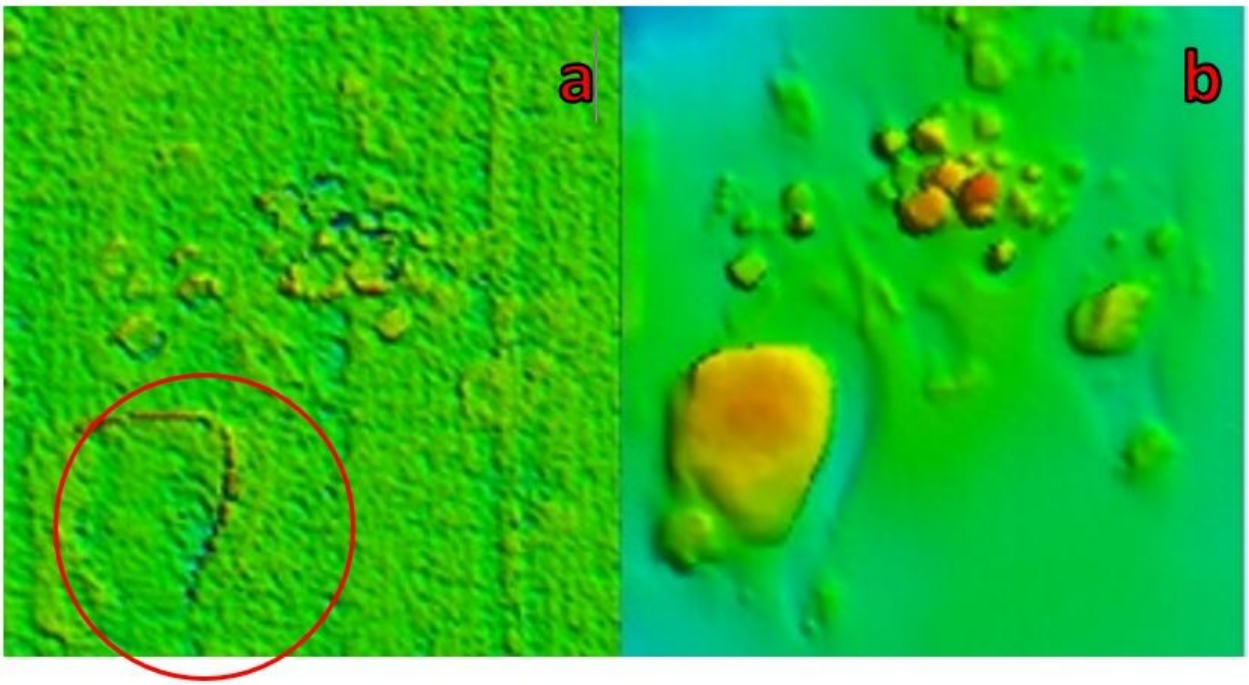

Figure 4 *– **a)** Shoal Difference Surface Layer with the rock's edges highlighted; and **b)** MBES Depth Layer showing the analyzed rocky field in the Test Area 1.*

Probably the layover occurred in both areas, but due to the overlapping of the survey lines, it was not noticed in Area 2. In Area 1 (***Figure 4b***), despite the overlapping of different swaths, the slope of the stone edges is beyond the grazing angle, a situation in which the layover will always appear, independent of overlaps.

4.2 AREA 3

Area 3 stands out for the existence of the bridge pillars (***Figures 1, 5a*** and ***5b***). These features simulate targets with a vertical projection that reaches the water surface, making it impossible for the survey vessel to approach to the abutments.

The detection of these objects by the PMBS is more pronounced than in the MBES, as can be seen through the of comparative bathymetric profiles (***Figure 5c***) between the surfaces generated by both sensors. The Shoal layer in the PMBS shows that this sensor could image and quantify the height of bridge pillars almost to the water surface, although they were not totally identified in the Depth layer. This is the result of different acquisition technology and data processing technique. Automatic processing was not able to detect the abutments, requiring manual operator intervention. However, once this parameter is adjusted, it is observed that the PMBS was able to detect the targets to approximately 0.5m below the sea surface. The MBES Shoal layer depicts the targets to approximately 10m water depth, while the Depth layer recorded only a small elevation.

Due to the proximity between the pillars of the bridge, another situation that can be simulated is the survey of a narrow channel or river, with no space to run adjacent lines. In the lines with no swath overlapping, the nadir gap is visible (extreme left and right of ***Figure 5b***). In these cases, the area immediately below the sonar has a lack of bathymetric information, which is a disadvantage of the PMBS system relative to MBES.

It is also noticeable the PMBS swath is larger. This makes it easier to survey in the vicinity of targets or features that pose risks to the vessel and in places very close to river banks or to the coast. In these cases, the PMBS imaging will cover a larger area thus posing less risk to the equipment and survey team.

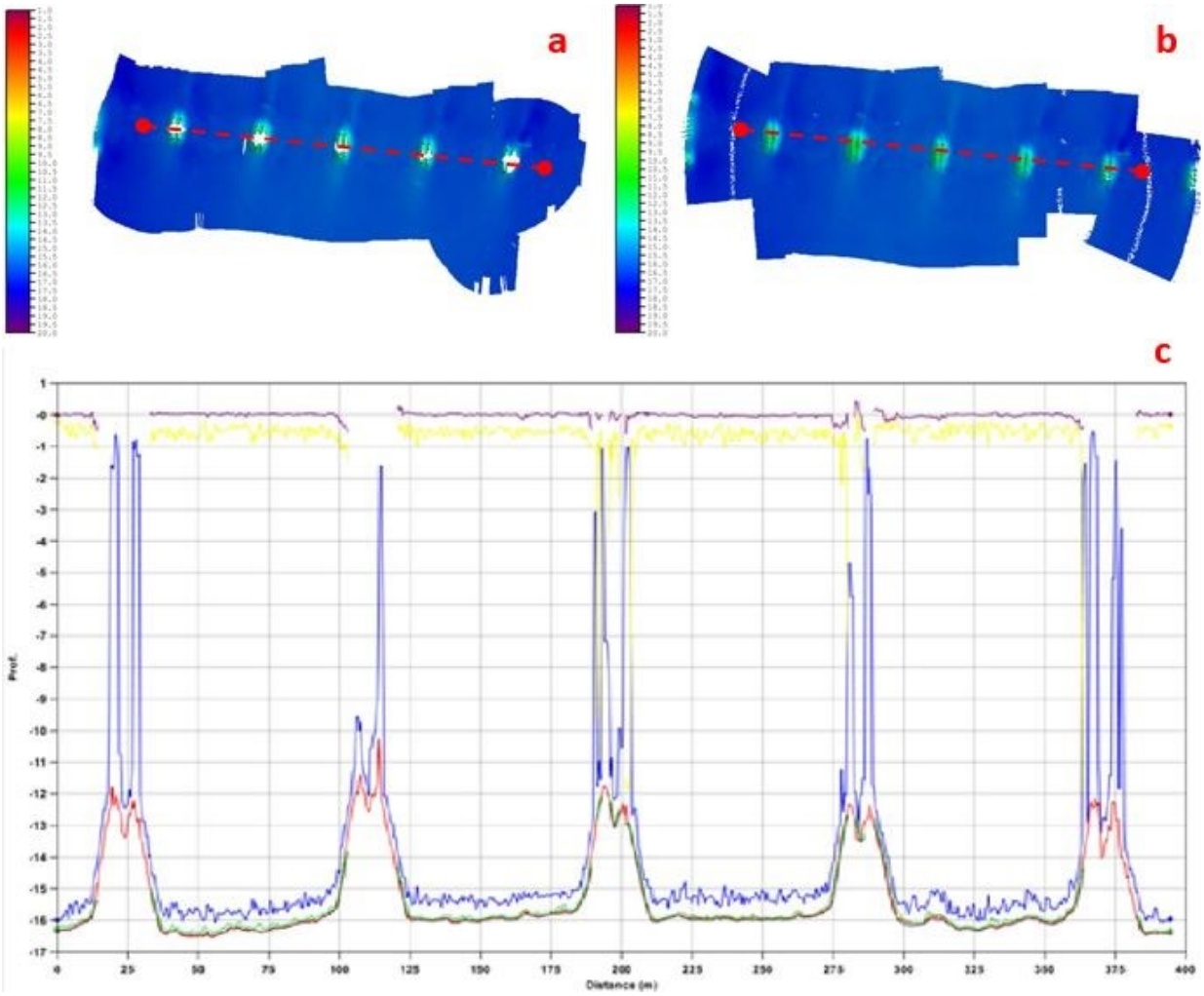

Figure 5 – a) *The MBES Depth layer surface;* ***b)*** *The PMBS Depth layer surface. In the a) and b) frames, the depths are ranging from 1m – dark red – until 20m – violet. The red dashed line indicates the profile in frame c; and* ***c)*** *A comparative frame showing the profiles. There are six different profiles: MBES Depth layer (black), MBES Shoal layer (green), PMBS Depth layer (red), PMBS Shoal layer (blue), Depth difference layer (purple) and Shoal difference layer (yellow).*

4.3 AREA 4

This area is characterized by the presence of a shipwreck (***Figures 1, 6a*** and ***6b***). The multibeam shoal layer is slightly shallower than the corresponding PMBS shoal layer (***Figure 6c***), reflecting the amount of noise captured by the PMBS system during acquisition. Although the target has been fully ensonified, the true depth information was neither properly quantified nor transformed into a real bathymetric information. The masking of true depth information is quite common on such situations when the data is rejected as noise due to inconsistencies in the depth determination in a way similar to the layover effect.

In flat or low gradient areas over the wreck, on both layers (Depth and Shoal), the bathymetry acquired with PMBS is shallower than that acquired with MBES, as observed in the other areas.

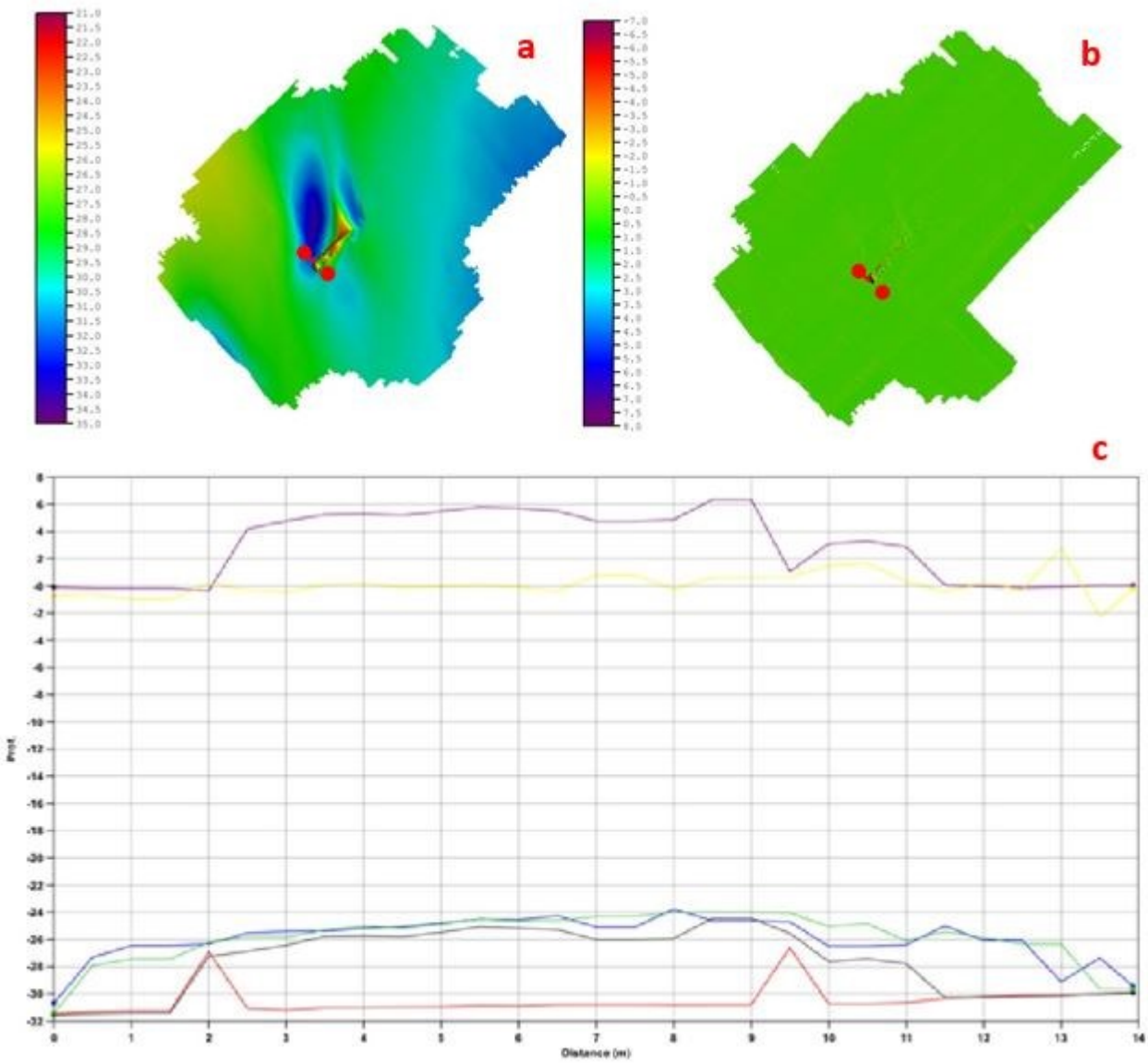

Figure 6 *– The stern of the wreck.* ***a)*** *The MBES Depth layer surface;* ***b)*** *Shoal Difference layer surface. The red line indicates the profile in frame c; and* ***c)*** *A comparative frame showing six different bathymetric profiles: MBES Depth layer (black), MBES Shoal layer (green), PMBS Depth layer (red), PMBS Shoal layer (blue), Depth difference layer (purple) and Shoal difference layer (yellow).*

4.4 AREA 5

The efficiency test has the objective of comparing the time to survey a given area or the size of a surveyed area in a given time. In this work, we used the second approach.

It is known the PMBS and the MBES swath may be different for a given water depth. ***Figure 7*** shows that the PMBS was able to practically achieve full coverage using the same swath width. For a better analysis of the results, the area was divided into 3 sectors: from 25.2m to 15m (***Figure 8a***), from 15m to 5m (***Figure 8b***), from 5m to 2m (***Figure 8c***). ***Figure 8a*** shows the

PMBS was able to easily cover 100% of the area with no need to change the swath. Meanwhile, it is clear the MBES would need more survey lines and, therefore, more time, to totally cover the same area. ***Figure 8b*** shows that MBES leaves huge gaps between the survey lines, whereas the PMBS shows only small nadir gap. In ***Figure 8c*** the gaps between the MBES lines are much more pronounced, while the gap between PMBS lines is practically non-existent.

Figure 7 *– In the left, the MBES depth layer surface and in the right, the PMBS depth layer surface. The colours are related to depths ranging. From 25.2m until 15m in blue, from 15m until 5m in green and from 5m until 2m in purple.*

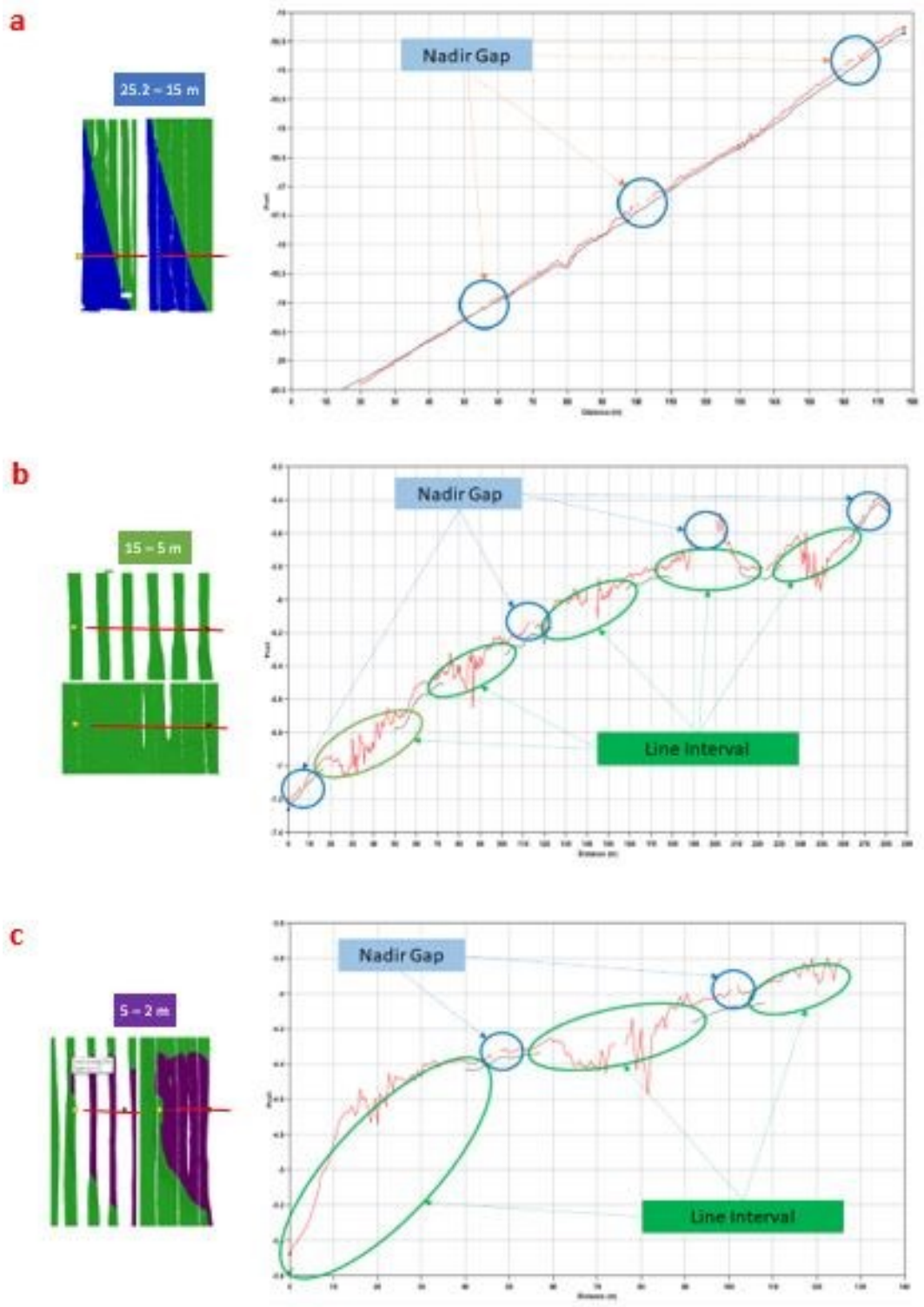

Figure 8 – a) *Test Area 5 field, where the depths vary from 25.2 to 15m;* ***b)*** *Test Area 5 field, where the depths vary from 15 to 5m; and* ***c)*** *Test Area 5 field, where the depths vary from 15 to 5m. In frames a), b) and c), the red line indicates the where the profile was taken. In the profiles graphic, there are two different lines: MBES Depth layer (black) and PMBS Depth layer (red).*

While the MBES had a constant swath of approximately 3 times the water depth for the whole area, the PMBS achieved swaths of approximately 3.4 times the water depth in areas 20m deep, 6.7 times the water depth in areas 9m deep and 12 times the water depth in areas 3.5m deep. Therefore, the test showed that PMBS is more efficient when the water depth is 15 meters or shallower. When the whole area is considered, the PMBS efficiency was 37.4% higher than the MBES.

4.5 RESOLUTION TEST

For the resolution test, it is interesting that the areas have noticeable bathymetric features. Thus, we will only address different resolutions in the Areas 1 and 4.

Table 2 correlates resolution and ping density per node for both areas. In a first analysis, we used a quantitative approach to evaluate the surfaces considering that, according to Calder and Mayer (2003), in the CUBE interpolator, the minimum desirable number of pings to compose a cell is 11. According to this criterion, resolutions of 0.1m on both sensors and 0.2m on MBES are discouraged.

Table 2 *– Data density per node for different resolutions. Organized by the authors.*

Resolution	Density per node – Area 1		Density per node – Area 4	
	MBES	PDBS	MBES	PDBS
0.1 m	2.1	9.7	1.9	7.4
0.2 m	8.3	36.6	5.7	25.5
0.3 m	18.6	82.2	12.7	57.1
0.5 m	51.6	227.6	35.2	157.7
1.0 m	98.9	448.7	139.9	625.9

Nevertheless, surfaces must also have their resolutions assessed qualitatively through visual analysis by observing how the morphological features behave in each image shown in ***Figure 9***. As the resolution improves, there is an increase in the number of blanked areas and noise. In contrast, it is possible to have a better notion of the seafloor features, as well their details and texture.

Another aspect to be explored in the image visualization is the difference in the target's size. Bigger targets (such as seen in Area 4) tend to be noisier, masking some target details (***Figure 9***, Test Area 4, PMBS frames). In general, despite the greater number of pings per node the PMBS data provided greater statistical robustness, the data is more scattered, generating noise. If we degrade the resolution to suppress the noise, details are also be smoothed.

Achieving a trade-off between the size of blanked areas, amount of noise and the visualization of target details is what will provide the optimal resolution for each case. Factors such as target size, depth, survey purpose should also be considered when defining the resolution to be used during the survey. Although the PMBS can produce a much larger number of pings per node than MBES, it presented a much noisier data, making it difficult to work with resolutions better than 30cm.

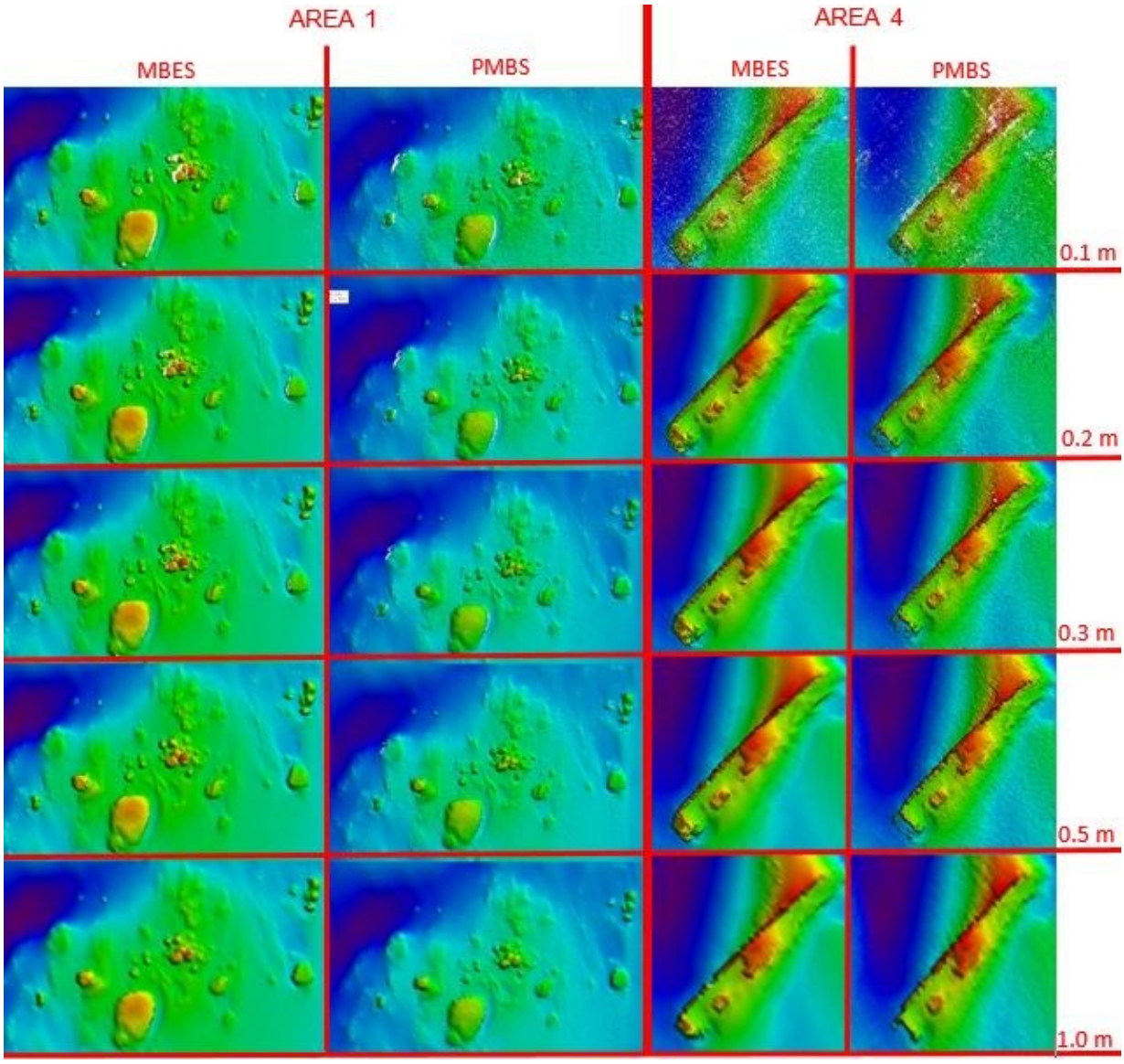

Figure 9 *– Different depth layers resolutions for Test Areas 1 and 4. The rocky images are from Test Area 1 and the wreck images are from Test Area 4. The resolutions are in the right side.*

5. Discussion

The sensors were evaluated for their relative precision in different conditions. The assessment was done in two different ways: with respect to the hypothesis and the node sample uncertainties. The first was meant to verify how the TVU was propagated, while the second was focused on the evaluation of the data dispersion. The results showed that MBES data was able to achieve Special Order on both criteria. The PMBS hypothesis uncertainty also matched Special Order since all the information that supported the bathymetric information had low uncertainty. However, its data showed high dispersion level, making the node sample uncertainty not able to reach Special Order standard, but only Order 1A. To better understand this issue, ***Figure 10*** depict the MBES and PMBS hypothesis and node sample uncertainty for Area 1.

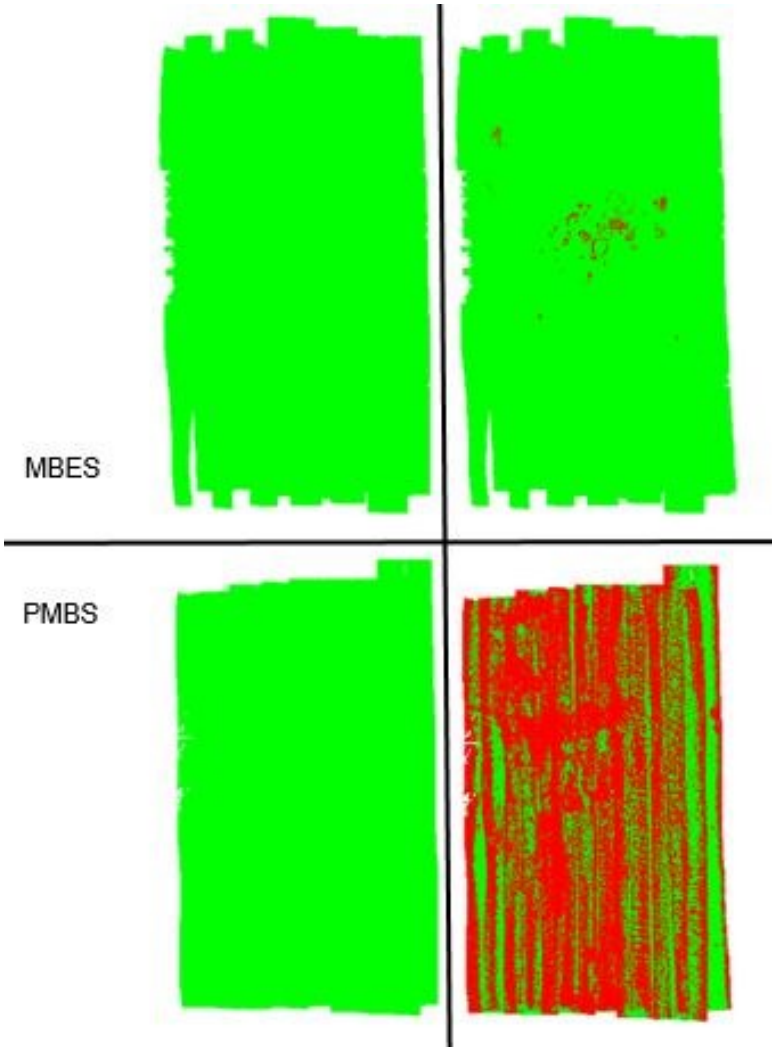

Figure 10 *– MBES and PMBS surface assessed for Special Order. Left column is the result for hypothesis uncertainty. Right column shows the results for node sample uncertainty. The nodes that achieved Special Order in each criteria are in green. The ones that did not are in red.*

It was expected to see the nodes related to a very steep seafloor in red in all situations and for both systems, as seen for the existing rock outcrops in this area. The relevant fact here is that PMBS surface achieve Special Order in the hypothesis uncertainty criteria, but did not for the node sample uncertainty, even under flat seafloor condition. This shows that not only is the PMBS data dispersion is to high, as demonstrated by Brisson; Wolfe; Staley (2014); Jerram and Schmidt (2015b) and NOAA (2017), but also how careful one must be when evaluating a bathymetric surface. ***Figure 11*** shows, on the other hand, that PMBS data matched Order 1A of the IHO standard, indicating that these systems may be used if the demands for the survey are not so rigorous (***Table 1***).

Figure 11 *– PMBS surface assessed for Order 1a in the node sample uncertainty criteria. The nodes that achieved Order 1a are in green. The ones that did not are in red.*

The **accuracy** was analyzed in 3 ways (***Table 1***). First, using CARIS HIPS & SIPS QC Report tool, it is observed that all areas surveyed with the PMBS were within the Special Order. The second way was to compare the Depth layers surface generated with MBES and PMBS data. This showed that the depth difference ranged between 0 and 10cm, with the PMBS layer always representing shallower depths. The third way was by comparing the layers representing the shallowest depths (shoal layers), since this is the preferential data exported to the nautical charts. In this case the depth difference ranged among 0.5m to 0.7m for all study areas. This results from the data dispersion level, which is high for the PMBS Shoal layer. The problem here is that exporting the PMBS Shoal layer to the nautical chart would decrease the risks to navigation safety, but would have an impact by decreasing the navigable draft of a channel

Another important aspect is the amount of noise in the raw data. The whole PMBS data shows a large amount of noise (see ***Figure 2d***), as already demonstrated in Dodd (2013) and Jerram and Schmidt (2015b). This noise can be generated by several factors: ambient noise, the vessel and the equipment itself (Lurton, 2000); multipath (mainly in shallow and targeted locations) (Denbigh,

1989); shifting footprint effect, baseline decorrelation effect (Lurton, 2000); and layover effect (Ărăcin and Calin, 2000; Saucan et al., 2015; Woock and Frey, 2010). In our research the layover effect was mainly observed in the edges of very steep morphological features, while noise is mostly widespread in the data

In this work, it was considered that a good resolution for the PMBS would be 0.3m. Despite delivering a higher data density than the multibeam (USACE, 2013; Jerram and Schmidt, 2015a; Jerram and Schmidt, 2015b; Ma; Xu; Xu, 2016), the PMBS has a very large amount of spurious data, which became more evident in surfaces with higher resolutions. This fact limits the resolution improvement, restricting the PMBS to the MBES surface resolution level. The resolutions of 0.1m and 0.2m did not provide the minimum amount of pings (***Table 2***) to ensure the node's statistical robustness according to Calder and Mayer (2003). At the same time, these resolution levels enhance the noise in the data, giving the surface a very "rough texture". On the other hand, surface resolution of 0.4m or higher decrease the ability of the data to show the targets details resulting in a "out-of-focus" surface (***Figure 9***).

The PMBS efficiency was greater than the MBES especially at depths shallower than 15 meters. This is essentially due to its larger swaths in shallower regions (Brisson; Wolfe; Staley, 2014; Gostnell, (2005); Jerram and Schmidt, (2015b)). When tested in a flat area, the nadir gaps observed in the PMBS data, makes the need for 100% overlapping mandatory as stated by Dodd (2013) and Ma, Xu, Xu (2016).

Due to the amount of bad data in the PMBS (***Figure 2a***), manual processing is practically impossible. Automatic and statistical processing, despite being strongly recommended, can still exhibit flaws. We suggest that data processing shall be done statistically, to have most of the noisy data rapidly cleaned, and manually, to further clean the data and better delineate the bathymetric features. The development of a better automatic technique for PMBS data cleaning is a challenge that must be addressed in order to reduce the processing time needed to generate the final bathymetric surface.

Thus, based on the results of the present study and considering the PMBS characteristics presented above, it is possible to conclude that PMBS is mostly recommended for restricted areas, with relative low gradients, shallower than 15 meters, which have been already mapped, since small features or structures edges can be masked by the noisiness or layover effect.

In an area where the dangers to navigation are already known, the PMBS can be used, since the uncertainties related to the target's shape can be diluted in the sounding selection or absorbed by the scale of the nautical chart. As an example, in this survey, the edge's uncertainty (when compared to the MBES surface) of the rock outcrops seen in Area 1 was around 1m. Considering the graphic reduction value in Brazil is 0.28mm, the scales that can address such uncertainty would be the ones smaller than 1:3,571 (1/0.00028). If the edge uncertainty cannot be properly estimated, one can use the THU (Total Horizontal Uncertainty) as the value for graphic reduction. Considering the maximum recommended THU for the order 1A (5m + 5% of the depth), the scale would be even more restrictive. In this case scales approximately ≤ 1: 25000 would be accepted. However, this parameter must be based on the analyst's experience and the purpose of the survey. ***Table 3*** summarizes all the conclusions of the present work.

Table 3 – PMBS surveying area suggestion. Organized by the authors.

Sensor	Area			IHO Order	Observation
	Depth	Scale	Seafloor Morphology		
MBES	Any	Depends on THU	Any	Special	XXX
PMBS	≤ 15 meters	≤ 1:3,571	Avoid steep areas or targets	1a	Already surveyed area

It should also be noted that countries that accept bathymetric sidescan sonars have more specific standards which are more restrictive in their criteria and requirements than the IHO S-44 itself. Despite accepting PMBS surveys, the United States (NOAA, 2017), Canada (CHS, 2013) and New Zealand (LINZ, 2010) are examples of countries that are in the situation above. Brazilian hydrographic standards, especially NORMAM-25 (Rev. 2), mostly replicate the specifications and the Orders recommended in S-44 (5th Edition) (IHO, 2008), being more lenient than the standards of the aforementioned countries. The adoption of PMBS systems for Special Order surveys in Brazil must be followed by more systematic tests with methodical hydrographic rigor.

6. Conclusion

A hydrographic survey is a complex process of obtaining information about the environment. The bathymetric measurement, as an integral part of any hydrographic survey, stands out in its complexity, due to the different variables involved and the high level of precision and accuracy required. In turn, end users are continuously demanding more reliable, accurate and less expensive surveys, since the financial and administrative consequences are high.

In this context, the PMBS arises as an option to the existing traditional MBES method. It intends to provide greater efficiency and cost reduction. However, a closer analysis reveals that one technology is not capable to simply replace the other, at least for now.

The PMBS technology has advantages and disadvantages compared to the MBES. We concluded that it is possible to operate and perform bathymetric surveys using PMBS systems, but under less restrictive conditions.

There are other factors that may drive to different results: changes in the bottom type and operating frequency may affect the bottom detection level; survey platform - using PMBS systems on an AUV would deliver very different results, especially due to the its acoustic positioning; rougher sea state and weather conditions demand more sophisticated attitude sensors affecting depth accuracy. It is important that users and equipment technicians be aware of the PMBS limitations and potentialities, exploiting its advantages to the maximum and minimizing its disadvantages. Some drawbacks, like the amount of noise and consequently the dispersion of valid data, can be mitigated by processing (filters or other algorithms) and remain an issue for future investigations.

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Articles




ELLIPSOIDALLY REFERENCED SURVEYING TECHNIQUE

A Review of the Current Status and Development of Ellipsoidally Referenced Surveying Technique in the Coastal and Offshore Zones for Hydrographic Survey Practice

By M. R. Mahmud, M. H. Hamden, A. H. M. Din and A. H. Omar

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Abstract

Technologies sophistication in addition to the Industry 4.0 trend has contributed to the high-accuracy ellipsoidal height from the Global Navigation Satellite System (GNSS) to be used in hydrography for vertical positioning. The method known as Ellipsoidally Referenced Surveying (ERS) provides direct measurement of sea floor to the ellipsoid and a translation of the reference from the ellipsoid to the precise geoid or chart datum. This article is an attempt to review the nations which have adopted ERS technique for hydrographic survey practice. A few case studies on practicing ERS technique are summarised to determine the ability of this technique. Future outlooks are also discussed on realising the ERS technique in Malaysia and the role of agencies in supporting the ERS realisation. In conclusion, adopting this technique will modernise and indirectly challenge the new norm in hydrographic surveying practice in Malaysia.

Keywords: Ellipsoidally Referenced Surveying, Vertical Separation Model, Hydrographic Survey, GNSS Positioning, Satellite Altimetry, Tidal Modelling

Résumé

La sophistication des technologies, en plus de la tendance Industry 4.0, a contribué à ce que la hauteur ellipsoïdale de haute précision issue du système mondial de navigation par satellite (GNSS) soit utilisée en hydrographie pour le positionnement vertical. La méthode connue sous le nom de levés référencés à l'ellipsoïde (ERS) fournit des mesures directes du fond marin à l'ellipsoïde et une translation précise de la référence de l'ellipsoïde par rapport au géoïde ou au zéro des cartes. Le présent article décrit une tentative de passer en revue les nations qui ont adopté la technique ERS pour la pratique des levés hydrographiques. Quelques cas d'étude sur la pratique des levés ERS sont résumés afin de déterminer les capacités de cette technique. De futures perspectives font également l'objet de discussions quant à la réalisation de la technique ERS en Malaisie, ainsi qu'au rôle des agences à l'appui de la réalisation de l'ERS. En conclusion, l'adoption de cette technique modernisera et défiera indirectement la nouvelle norme en matière de pratique hydrographique en Malaisie.

Mots clés : Levés référencés à l'ellipsoïde, modèle de séparation verticale, levés hydrographiques, positionnement à l'aide du système mondiale de navigation par satellite (GNSS), altimétrie par satellite, modélisation des marées.

Resumen

La sofisticación de las tecnologías*, además de la tendencia de la Industria 4.0, han contribuido a que la altura elipsoidal de alta precisión del Sistema Mundial de Navegación por Satélite (GNSS) sea utilizada en la hidrografía para el posicionamiento vertical. El método conocido como Levantamientos referenciados elipsoidalmente (ERS) proporciona una medición directa del fondo marino al elipsoide y una traducción de la referencia a partir del elipsoide al geoide preciso o al datum de cartas. Este artículo es un intento de revisar las naciones que han adoptado la técnica ERS para la práctica de los levantamientos hidrográficos. Se resumen algunos estudios de casos sobre la práctica de la técnica ERS para determinar la capacidad de esta técnica. También se examinan las perspectivas futuras de la realización de la técnica ERS en Malasia y el rol de las agencias en el apoyo a la realización de la ERS. En conclusión, la adopción de esta técnica modernizará y desafiará indirectamente a la nueva norma en la práctica de los levantamientos hidrográficos en Malasia.

Palabras clave: Levantamiento referenciado elipsoidalmente, Modelo de Separación Vertical, Levantamiento Hidrográfico, Posicionamiento GNSS, Altimetría Satelital, Modelización de las Mareas

1. Introduction

Hydrographic surveying deals with depth determination at particular known areas normally for the purpose of creating bathymetry maps of water bodies. Historically, the mandate of soundings has come from the need to chart hazards for navigation (Smith and Sandwell, 2004). The first hydrographic technique used in determination of water depth was the sounding line which was replaced by acoustic sounding techniques (Elhassan, 2015). Also, in the past, locations of sounding depth were determined using shore-based surveying or conventional navigation technique (Berber and Wright, 2016). With the advancement of technology, the development of accurate satellite-based survey methods uses the Global Navigation Satellite System (GNSS) methodology to provide depth measurement positions.

In recent years, GNSS has been used in hydrographic surveying over horizontal positioning. However, it is believed that International Federation of Surveyors (FIG) Publication Number 62 was designed to assist in the grasping of the Ellipsoidally Referenced Surveying (ERS) technology. Mills and Dodd (2014) stated that it is primary concern that the whole phases of ERS to be understood comprehensively. In the case for vertical positioning, high accuracy GNSS processing techniques should be used as the benefit of this vertical positioning, in which the sea surface, water column and sea floor are referenced directly to a mathematically derived reference ellipsoid. High accuracy GNSS positioning techniques for vertical positioning of hydrographic survey works known as Ellipsoidally Referenced Surveying (ERS) has been utilised by the hydrographic survey community. This technique works as the features are referenced directly to a mathematical surface (ellipsoid) established from high accuracy GNSS observations and provide a translation of reference from the ellipsoid to the geoid or chart datum. Most of the organisations utilising ERS methods have established their own Standard Operating Procedures (SOPs) through in-house practice as well as trial and error research. The abundance of knowledge that is being utilised by the organisations can assist to promote a series of desirable practices for hydrographic industry. Few concerns need to be taken into account in executing ERS technique such as data acquisition from high accuracy GNSS, high accuracy GNSS data processing, vertical separation model (VSEP) development and application, quality assurance / quality control (QA/QC) of vertical offsets, high accuracy GNSS, motion and VSEP as well as their uncertainties. Last but not least is the data archive reference. Nevertheless, FIG Publication 62 has explained the concerns on the aforementioned. This publication also extended and updated the discussion conferred in FIG Publication 37.

While hydrographic organisations are looking forward to the use of ERS technique, the creation and verification of VSEP is a major challenge. The discovery of models to link the ellipsoid to the geoid is fairly unambiguous. The predominant issue is converting the data from geoid to the chart datum (CD). Creating an ellipsoidal height at the tidal point of the reference is the simplest approach that would create precisely observed separation (SEP) between the reference ellipsoid and chart datum. This article summarised the case studies from the countries that have adopted ERS technique. To this end, further discussion on realising the ERS technique in Malaysia will be explained and the role of agencies that support the realisation.

2. Nations that Create ERS and Case Studies

The entire ERS process must be understood comprehensively in order to enhance the potential of ERS technique for realisation in each country. Adaptation to the future employment of ERS technique in hydrographic society had caused many researchers to look more specifically at this concept. Many countries have started to look into implementing ERS technique. Here, a summary of a few organisations that have created the ERS technique are discussed.

2.1 National Oceanic and Atmospheric Administration Vertical Datum (NOAA VDatum)

In order to enhance the efficiency, precision and adaptability of survey activities, NOAA hydrographic field units have been collecting bathymetry utilising an ellipsoid reference since 2016. Subsequently, bathymetry referred to the ellipsoid may be translated either to other ellipsoids, orthometric or tidal datums provided by NOAA's Vertical Datum Transformation (VDatum) method, saving the hydrographer from depending concurrently on coastal tide gauge. A contemporary vertical datum transformation tool (VDatum) was developed by the NOAA to resolve the inconsistent datum issues.

VDatum translates geospatial data across 36 various vertical reference systems and eliminates the most important barriers to data exchange that enable simple translation of elevation data from one vertical datum to another. Generally, VDatum is constructed to vertically translate geospatial data from a range of tidal, orthometric and ellipsoid datums which enable the users to transform their data from specific horizontal or vertical references into a common system. This could also allow the fusion of various geospatial data in desired reference levels (NOAA, 2020a). VDatum models are created on a regional basis, with the objectives of seamless coverage for all-near waters in the United States. Conforming to FIG publication 62, three or four measures are required to translate the hydrographic survey data depending on which vertical datum is the data referenced during data acquisition. The measures are as follows:

i. The data must be referenced to the NAD83 primary ellipsoid.

ii. Transformation of the NAD83 ellipsoid to the NAVD88 primary orthometric datum.

iii. Transformation between NAVD88 and the Mean Sea Level (MSL)

iv. Transformation between MSL and Mean Lower Low Water (MLLW).

Successful development and implementation of the VDatum in a given geographical region is useful for a number of coastal applications (NOAA, 2020b). Existing bathymetric and topographic data can be transformed into a seamless digital elevation model (DEM) by first using VDatum to link the data to a specific vertical datum. It is also beneficial to the applications dependent on a seamless land-water DEM, such as storm surge and tsunami modelling, habitat restoration, sea level rise effect and ecosystem studies. VDatum also provides advantages on supporting the surveying on the ellipsoid which can reduce the vertical uncertainty from heave and dynamic draft as well as decouple tide measurement from survey.

2.2 Continuous Vertical Datum Separations for Canadian Waters

Canada is one of the countries involved in developing national continuous vertical datum separation models (SEPs) between GRS80 reference ellipsoid tied to the NAD83 Canadian Spatial Reference System (CSRS) geodetic frame and chart datum. The Continuous Vertical Datum for Canadian Waters (CVDCW) project was originated by the Canadian Hydrographic Service (CHS) to develop hydrographic-quality ellipsoid to CD surfaces in supporting the ellipsoid bathymetric reduction.

The main aim of CVDCW's SEP, known as Hydrographic Vertical Separation Surfaces (HySEPs), is to capture the spatial variability between stations and offshore by integrating ocean models, tidal data, sea level trends, satellite altimetry and geoid model. According to Robin et al. (2014), HySEPs will enable the use of GNSS for hydrographers and navigators as well as it is effective for oceanographers, environmental researchers, surveyors and engineers. The achievement is accomplished through selective combination of both sets of model and observational data. The sources needed include:

i. Geoid Model (CGG2013), which is utilised to determine the variation of the geoid with respect to the NAD83 ellipsoid.

ii. Dynamic ocean topography (DOT) used to bridge MSL to the geoid model.

iii. Hydrodynamic models utilised to examine variations in tidal regimes which provide an initial estimation of the difference between lower low water large tide (LLWLT) or other datum.

iv. Tidal stations (water level and GNSS observations) utilised for validating and modifying ocean model results.

v. Satellite altimetry used to provide measurement of the separation between the ellipsoid and MSL as well as to verify the geoid, DOT and SEP.

Figure 1 shows the schematic diagram of HyVSEP components and data sources. Approaches used to fill, control and modify each HyVSEP surface are dependent on three aspects, namely an underlying grid's resolution and synchronisation, a Laplacian interpolator and a smoother finite element (FE).

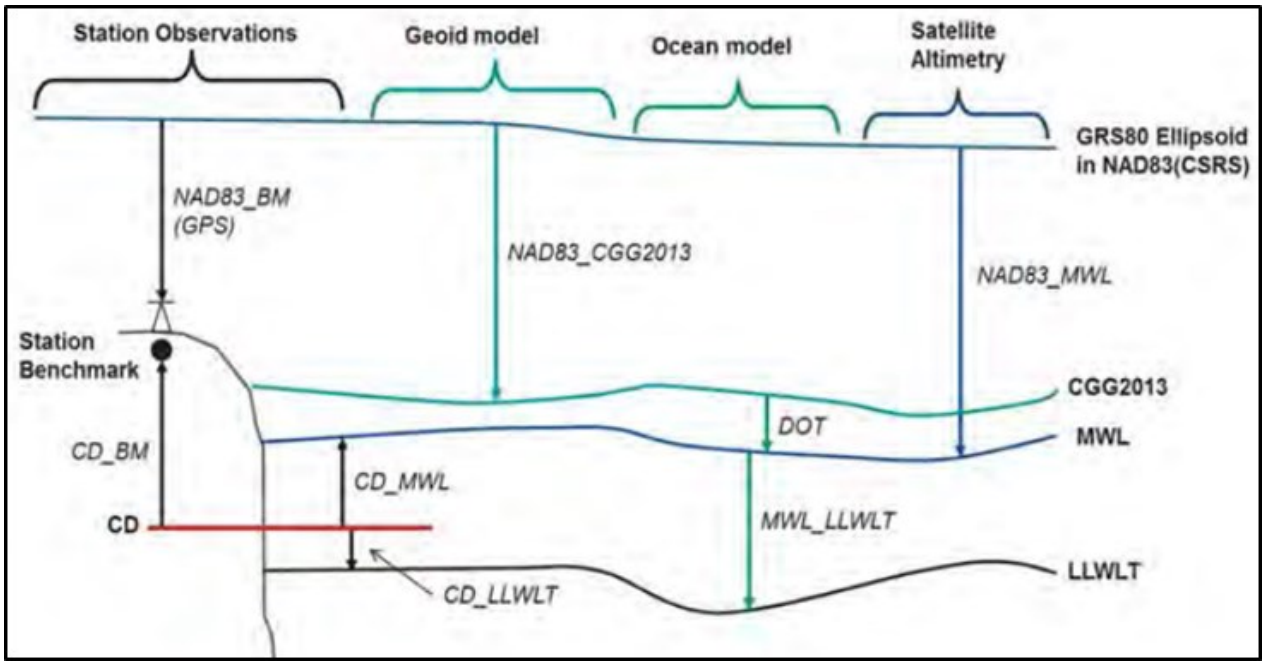

Figure 1 *Schematic diagram of HyVSEP and data sources (Robin et al., 2016)*

To this end, Robin et al. (2014) stated that HyVSEP is a modern vertical reference 3D model for the CHS. HyVSEP, especially CD surface, would enable the use of GNSS technology in data collection and increase the accuracy of nautical chart's bathymetric data. Last but not least, HyVSEP would help to link bathymetry with topography data and act as a tool to address climate change and adaptation.

2.3 Vertical Offshore Reference Frame (VORF) by United Kingdom Hydrographic Office (UKHO)

The Vertical Offshore Reference Frame (VORF) is a research project developed by collaboration between University College London (UCL) and United Kingdom Hydrographic Office (UKHO). This project started in 2005 and conveyed as a revolutionary model in 2008 for UK and Ireland. The goal of the VORF was to derive a set of models representing the locations of vertical datum surfaces with respect to a common base (GRS80 ellipsoid in ETRF89) thus enabling data to be translated from one datum to another. The vertical height information being derived in VORF model are, namely, chart datum (the reference level for nautical charts), MSL, lowest astronomical tide (LAT), highest astronomical tide (HAT), mean low water springs (MLWS), mean high water springs (MHWS), European Terrestrial Reference Frame (ETRF89), Newlyn Ordnance Datum, Poolbeg Ordnance Datum and other vertical land datum that affect the coastlines of the area concerned. Each reference frame shall be represented as a seamless surface within ETRF89 with a gridded spatial resolution of approximately 1 km. ***Figure 2*** illustrates the VORF surfaces in which land and sea datums are related to each other.

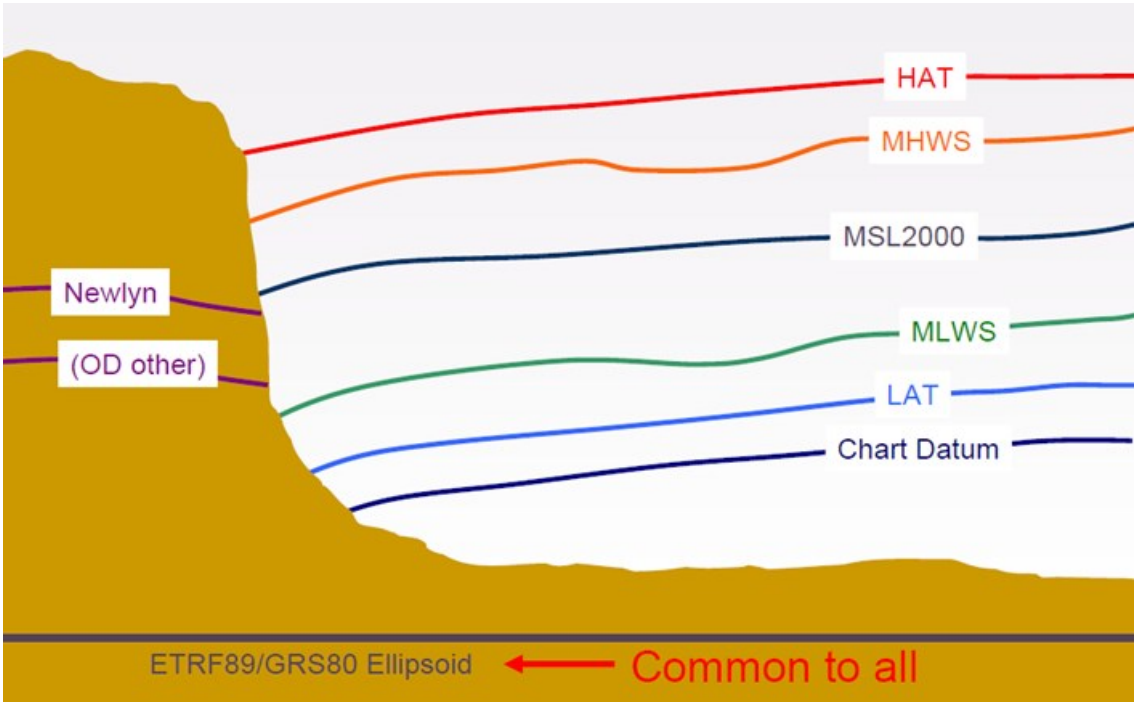

Figure 2 *VORF surface of land and sea (Ziebart & Iliffe, 2009)*

Until recently, hydrographic surveys were usually kept isolated from land surveys, and surveys at sea often used such inadequate data sets that changes in the datum were not readily possible. With the introduction of technology such as GNSS and LiDAR as well as growing interest in coastal zone areas, there is an urgent need for a system that will transform seamlessly between various reference surfaces. There are many applications which could potentially make use of the system. For instance, every vessel installed with a high precision GNSS and utilising the VORF transformation program can essentially become its own tide gauge without depending on the tide gauge observation at remote areas. It is expected to not only have a major influence in maritime safety but also important impacts of activities on operations such as hydrographic surveys.

There are several advantages in performing bathymetry data processing with VORF and GNSS.

This can increase speed of deployment where no reliance on tide gauge or requirement to transfer the chart datum. Besides, it provides rapid turnaround of surveys and rapid response to emergencies. ***Figure 3*** shows the schematic bathymetry data processing with VORF and GNSS.

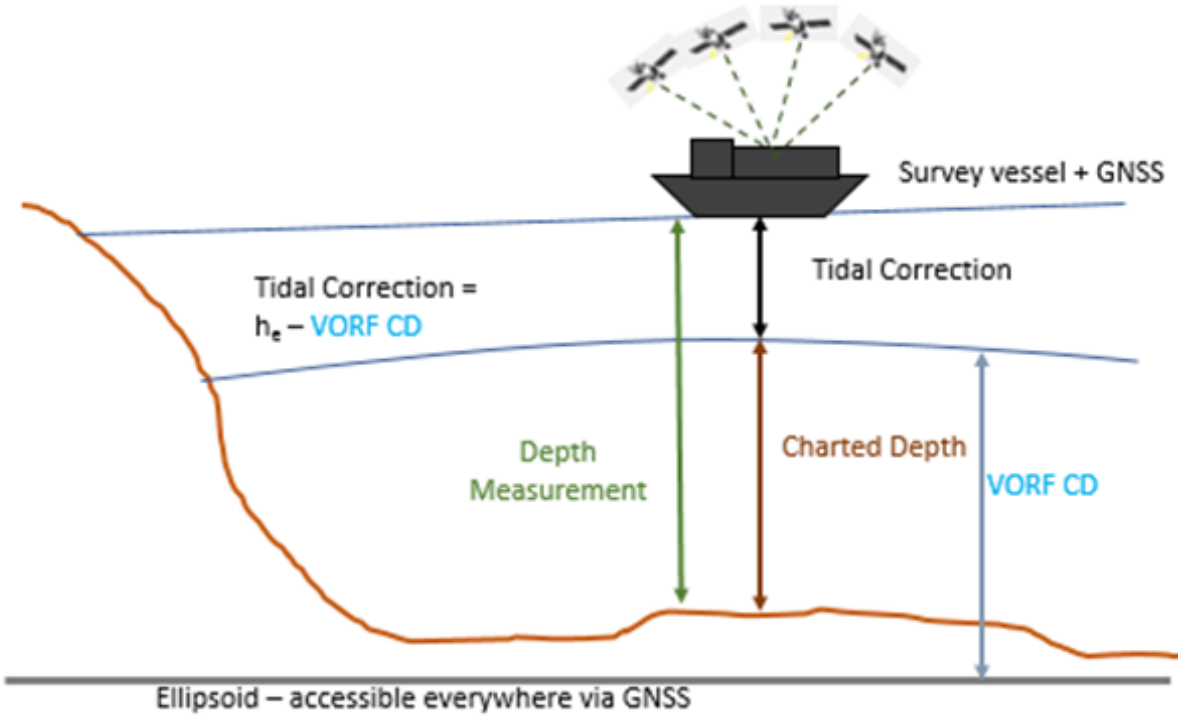

Figure 3 Bathymetry data processing with VORF and GNSS solution (adapted from Howlett, 2009)

2.4 Australian Coastal Vertical Datum Transformation (AusCoastVDT)

Australian Coastal Vertical Datum Transformation is a research project focussing on adopting an ellipsoidal based method for vertical datum transformation (VDTs). In 2004, there had been some VDT projects handled namely AUSHYDROID model. This model is supposed to assist ellipsoidal surveying at nearshore, coastal and offshore within the Australian region. AUSHYDROID would allow hydrographic surveyors and other end users to translate the geospatial data between LAT and GRS80 ellipsoid vertical datum. AUSHYDROID would also contribute several benefits to Australia's blue economy including the following:

i. Integrating bathymetry and land-based observations using a specific reference frame;

ii. Allowing regional description of coastlines and intertidal zones;

iii. Aid in the identification of territorial baselines, marine cadastre and jurisdiction claims; and

iv. To establish a benchmark for forecasts of sea level rise and climate change approach for coastal infrastructure.

According to Keysers et al. (2015), the surfaces developed in AUSHYDROID were only for the Queensland coast and serve limited datum transformation options, whereas AusCoastVDT approach employs hydrodynamic modelling and it is a national approach which allows transformation in either direction between a broad range of vertical datum. The primary aim of AusCoastVDT is to promote the development of continuous elevation data sets around the

Australian coastal region with an emphasis on the specific Australian challenges. ***Figure 4*** shows the significant vertical datums and the relationship between them. The related marine datums for AusCoastVDT are LAT, which is chart datum in Australia, MSL, MHWS and HAT. The ellipsoid based transformation approach selected uses a series of gridded surfaces, where each surface determines the separation of one vertical datum from GRS80 ellipsoid. It blends MSS and other tidal surfaces to ease and speed up the computation in implementing the vertical transformations. GRS80-AHD, GRS80-MSL, GRS80-LAT, GRS80-MHWS and GRS80-HAT are the five gridded separation surfaces produced in this project.

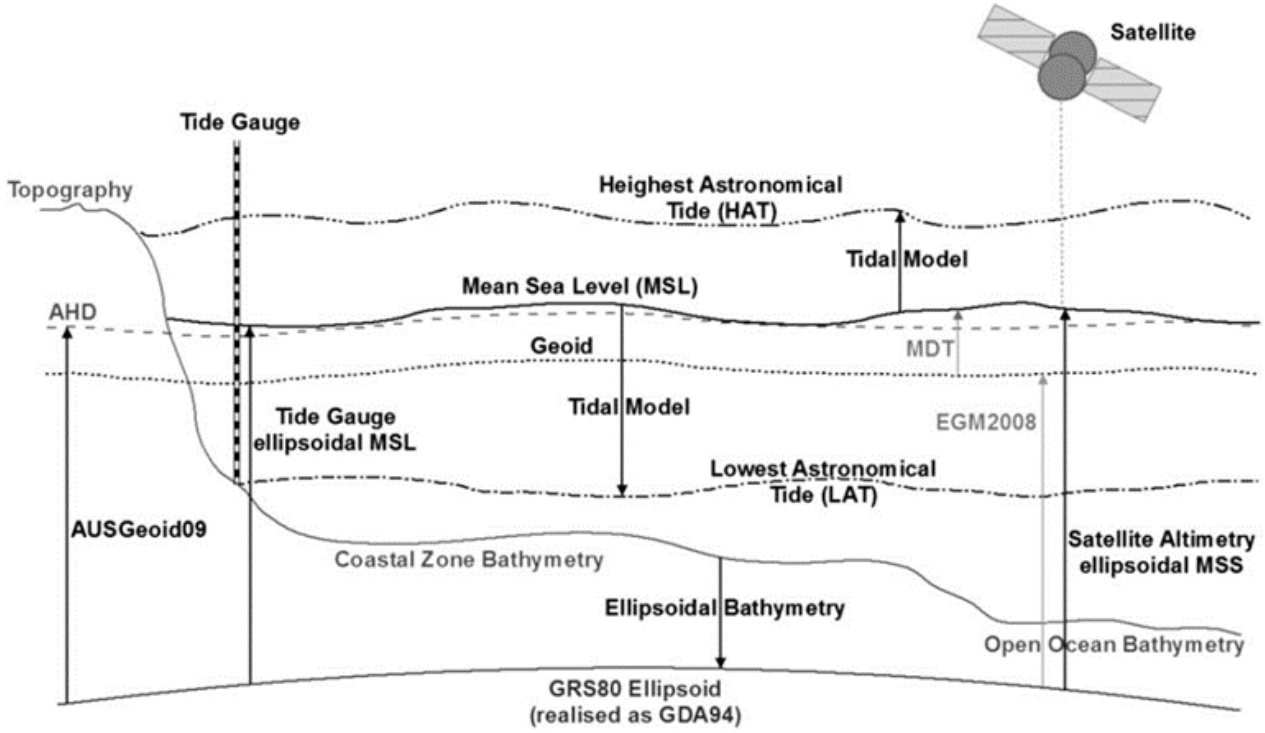

Figure 4 *Schematic depiction of ellipsoid based vertical datum transformation approach (Keysers et al. 2015)*

2.5 Miscellaneous

Substantially, more researchers have looked into the implementation of ERS technique besides the ones described earlier. Most of the Europe countries have looked into ERS practice and recommended best practices that the hydrographic surveying community use in ERS work as described in FIG publication No. 62. According to the authors' knowledge, besides Australia, several countries in East Asia region such as Japan, China, South Korea (Lee et al., 2017), Taiwan (Lin, 2016), Indonesia (Poerbandono, 2019) including Malaysia (Hamden et al., 2018) are intensifying the studies towards practicing ERS technique in the field of hydrography. For instance, Lee et al. (2017) had done research on ERS concept by analysing the feasible accuracy assessment of GNSS-derived height from carrier phase-based positioning. Two techniques were employed (Precise Point Positioning, PPP and Post Processed Kinematic, PPK), which infers that PPP-derived vertical solutions are more robust than PPK. This is because the comparison in Lee et al. (2017) was between PPP and medium range PPK in which the length of baselines was within the range 150 km to 260 km. These baseline lengths are far greater than the usual acceptable for single baseline PPK since single baseline PPK method is highly dependent on the distance between rover and its reference station. Thus, PPK is typically considered to be more robust than PPP for baselines length within approximately 20 km to 30 km depending on the

weather conditions. In addition, Lin (2016) found that the ellipsoidal related bathymetric survey can prevent interference from various tidal zones and it is expected to replace the traditional bathymetry survey with ellipsoidally reference bathymetric survey in the future. Ligteringen et al. (2013) reported in their work that vertically, the height solution was less reliable than the horizontal solution, but that it was reasonably accurate to achieve the consistency of the tidal reduction solutions and to conform with the IHO S-44 standard.

3. Malaysia towards Implementing ERS

Malaysia is not left behind in attempting to realise ERS technique. Malaysia is essentially a maritime country, spanning approximately 4,700 kilometres of coastline and bordering on four main water bodies, namely Malacca Straits, South China Sea, Sulu Sea and Celebes Sea. The implementation of ERS project in Malaysia corresponds with its strategic location where most of the land area is surrounded by the sea. Furthermore, Malaysia is among the busiest maritime countries in terms of sea trade activities, especially in the Malacca Straits and South China Sea. Planning on implementing ERS technique as well as developing national seamless vertical separation model in Malaysia should be supported by several important agencies. Three main agencies involved in implementing and supporting ERS technique are academic institutions, Department of Survey and Mapping Malaysia (DSMM) and National Hydrographic Centre (NHC).

3.1 Role of Academic Institution

Universiti Teknologi Malaysia (UTM) is one of the academic institutions conducting on-going research in developing seamless vertical separation model (VSEP) for bathymetry derivation using ellipsoidally referenced surveying technique. This research is the first initiative in which the main idea is to realise ERS-derived bathymetry technique in Malaysia. VSEP model will be developed by modelling the assimilation of multi-mission satellite altimetry and tidal data to produce a series of stable reference surfaces. Bathymetry can be derived by integrating the seamless VSEP model with high-accuracy ellipsoidal height from GNSS data. Therefore, bathymetry referenced to the ellipsoid can subsequently be transformed to any derived surfaces. Vertical surfaces that needed to be included in VSEP model are:

i. Geoid model (MyGeoid), used to demonstrate the variation of the geoid with respect to the ellipsoid.

ii. Mean Sea Surface (MSS) produced from an average of multi-mission satellite altimetry derived sea surface height (SSH) over a period of time which covers the offshore area. Meanwhile, Mean Sea Level (MSL) produced an average level of the surfaces over 18.6 years at selected tide gauge stations that covers nearshore area.

iii. Mean Dynamic Topography (MDT) used to connect MSL or MSS to the geoid model.

iv. Lowest astronomical tide (LAT) and highest astronomical tide (HAT) produced from tidal datum modelling at selected tide gauge stations and satellite altimetry tracks.

GNSS derived bathymetry will be deployed at the study area when the VSEP model is well developed. The equations of depth determination as explained by Hamden and Din (2018) are still being adopted continuously in this research project. ***Figure 5*** depicts the pictorial representation on the migration of hydrographic surveying technique from the current practice towards implementing the ERS technique. To this end, if the research project is successfully developed, the academic institution such UTM can play a role to inculcate and provide awareness to the local practitioner in hydrography community to adopt this technique in hydrographic survey practice.

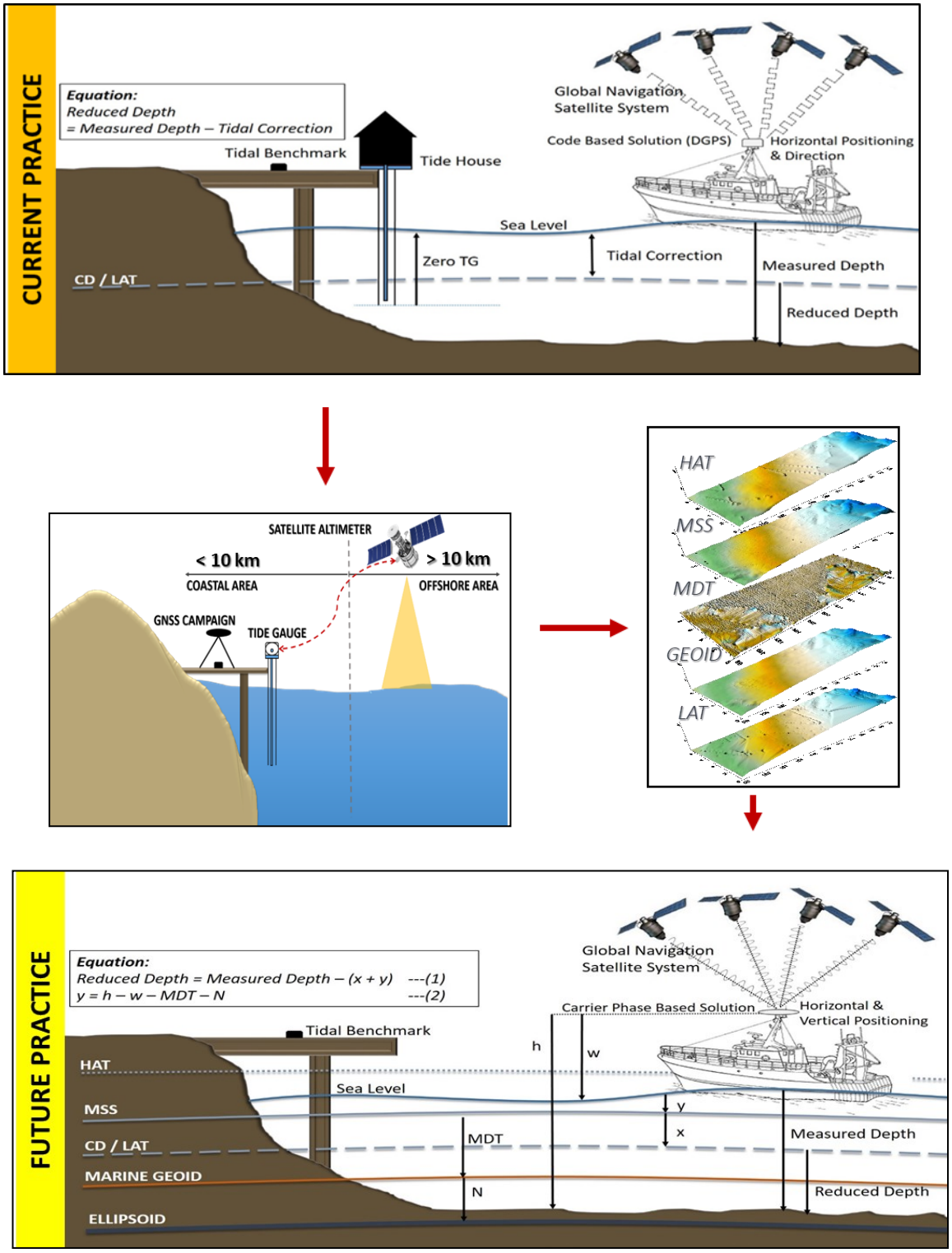

Figure 5 *Migration of hydrographic surveying technique from current practice towards implementing the ERS technique*

3.2 Role of Department of Survey and Mapping Malaysia (DSMM)

The Department of Survey and Mapping Malaysia (DSMM) is the most important agency in supporting the realisation of ERS technique. DSMM is the competent Malaysian Government authority in maintaining the National Spatial Reference System. This is achieved by the establishment of geodetic infrastructures including horizontal and vertical survey controls throughout the country for the purpose of national development, security and defence. DSMM has been developing geodetic infrastructures which indirectly would support the implementation of the ERS technique for future practice. The geodetic infrastructures are, namely, Continuously Operating Reference Station (CORS), also known as Malaysian Real Time Kinematic Network (MyRTKnet), Marine Geodetic Infrastructure (MAGIC) project and Tidal Observation Network.

i. Malaysian Real-Time Kinematic Network (MyRTKnet)

MyRTKnet is an infrastructure that has been formed by the GNSS network reference stations and control centre. It is also one of telecommunication systems which provide the GNSS data in order to deliver the position in real time. MyRTKnet service, which was established in 2003, consists of only 27 GNSS reference stations throughout the country. In an attempt to provide improved service to the users, the DSMM has now developed a total of 96 GNSS reference stations, of which 65 stations are located in Peninsular Malaysia and 31 stations in Sabah and Sarawak. Most of the stations are established at 30 km to 100 km intervals. The reference stations track and transmit GNSS signal through dedicated data lines to the control centre server at DSMM Geodesy section. Here, it manages and distributes the GNSS correction to the users in real time. Currently, all users will achieve centimetre precision. The distributions of MyRTKnet stations as shown in ***Figure 6*** can be retrieved in the website (http://www.rtknet3.gov.my/).

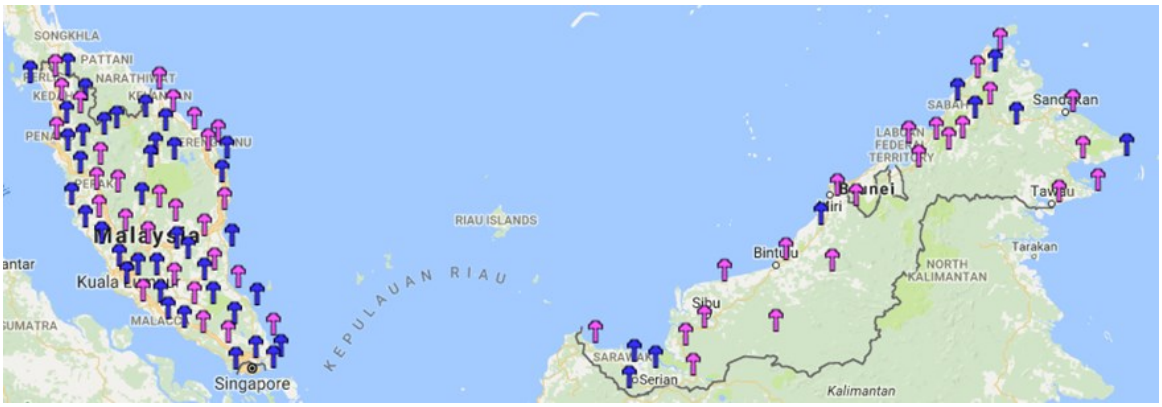

Figure 6 *Distribution of MyRTKnet stations in Malaysia (DSMM, 2018)*

Generally, the services provided by MyRTKnet are in form of data supply as shown in **Table 1.** The data supplied to the user consists of either real time data or post-processed data depends on the objective of the measurement itself. In the meantime, users need to comply with current measurement specifications conduct work to obtain good measurement results.

Table 1 Types of data provided by the Control Center (DSMM, 2005)

No.	Type of Data	Data Characteristics	Description
1	Virtual Reference Station (VRS) Correction	Real Time	• An integrated system which links and utilizes data from permanent reference stations to model errors throughout the coverage area. • This model is used to synthesize virtual reference stations near the user's location which then provide a localized set of standard format correction messages to the roving receiver.
2	Single Base Correction	Real Time	• Correction is provided for areas within 30 km from any MyRTKnet single permanent reference station. • Required through cellular phone connection and the corresponding differential data will be transmitted from the control centre to the rover.
3	Network Base Differential Global Positioning System (DGPS) Correction	Real Time	• Correction is provided for the whole of Peninsular Malaysia and areas within 150 km radius from Kota Kinabalu and Kuching. • This could be utilized in applications such as sub-meter mapping and navigation. Data availability upon request.
4	Virtual RINEX Data	Post Processed	• Virtual RINEX data are GNSS RINEX format data generated by MyRTKnet system based on approximate coordinates provided by users. • These data are the virtual reference station data that will be used as a reference by users for baseline computation.
5	RINEX Data	Post Processed	• The observed permanent reference station data in RINEX format are available through the website. • Data can be obtained at any interval ranging from 1s to 60s for post processing application.

This MyRTKnet provides reference station information for RTK or Post Processed Kinematic (PPK) technique during deployment of GNSS observation in ERS technique. The network RTK solutions are only applicable on the land areas due to the dense distribution of continuously operating reference stations (CORS). It is undeniable that a virtual base station solution established from network RTK allows much greater distances between base stations than single baseline solutions. Nevertheless, the deployment of

GNSS observation in ERS technique are focussing in the coastal and open seas. It is impossible to implement network RTK solution since the GNSS positions on the particular area are located outside of the network boundary. Therefore, for ERS applications, MyRTKnet system in regard to the single baseline solution is considered for coastal regions which baselines length restricted to 10-30 km. Beyond the coastal (open seas), PPP solution is considered since it is more robust than PPK technique as aforementioned.

ii. Marine Geodetic Infrastructure (MAGIC)

The MAGIC project intends to establish and maintain modern marine geodetic infrastructures for Malaysian waters with the primary objective to protect national sovereignty over marine area under its jurisdiction. Other objectives of this project are to strengthen geodetic ties in Malaysia waters development, scientific research and control of water security purposes as well as to enhance the nation's geodetic and geospatial data supply (Azhari et al., 2017). There are five project components of MAGIC, which are as follows:

a. Marine Geodetic Network (MGN) of Islands near the international maritime boundary. Establishing MGN is to connect the land and marine areas under the Geocentric Datum of Malaysia 2000 (GDM2000).

b. Establishment and upgrading of Permanent Active Marine Geodetic GNSS Stations with the primary purpose of strengthening the existing GDM2000 in the marine areas.

c. Marine Geodetic Height System over Malaysian waters which is to provide seamless spatial data across land and sea interface. This is because Malaysia does not have a consistent vertical datum across land and sea interface.

d. Seabed Topography Survey for Malaysian waters with the main objective of creating a continuous land to sea large scale base map to support DSMM's marine cadastre project.

e. Upgrading a Central Processing and Database Centre for the Marine Geodetic Infrastructure. Marine Geodetic Database (MGDB) has been established using ArcGIS Database System. This MGDB will act as a base for the implementation of a robust Marine Spatial Information Infrastructure (Marine SDI) for Malaysia.

iii. Tidal Observation Network

The key purpose in installing tide gauge stations is to determine a continuous time series of sea level for the purpose of establishing a vertical datum for the nation. DSMM is one of the few organisations responsible for the general management of data collection, validation, analysis and dissemination of sea level data. ***Figure 7*** shows the distribution of DSMM tide gauge stations in Malaysia.

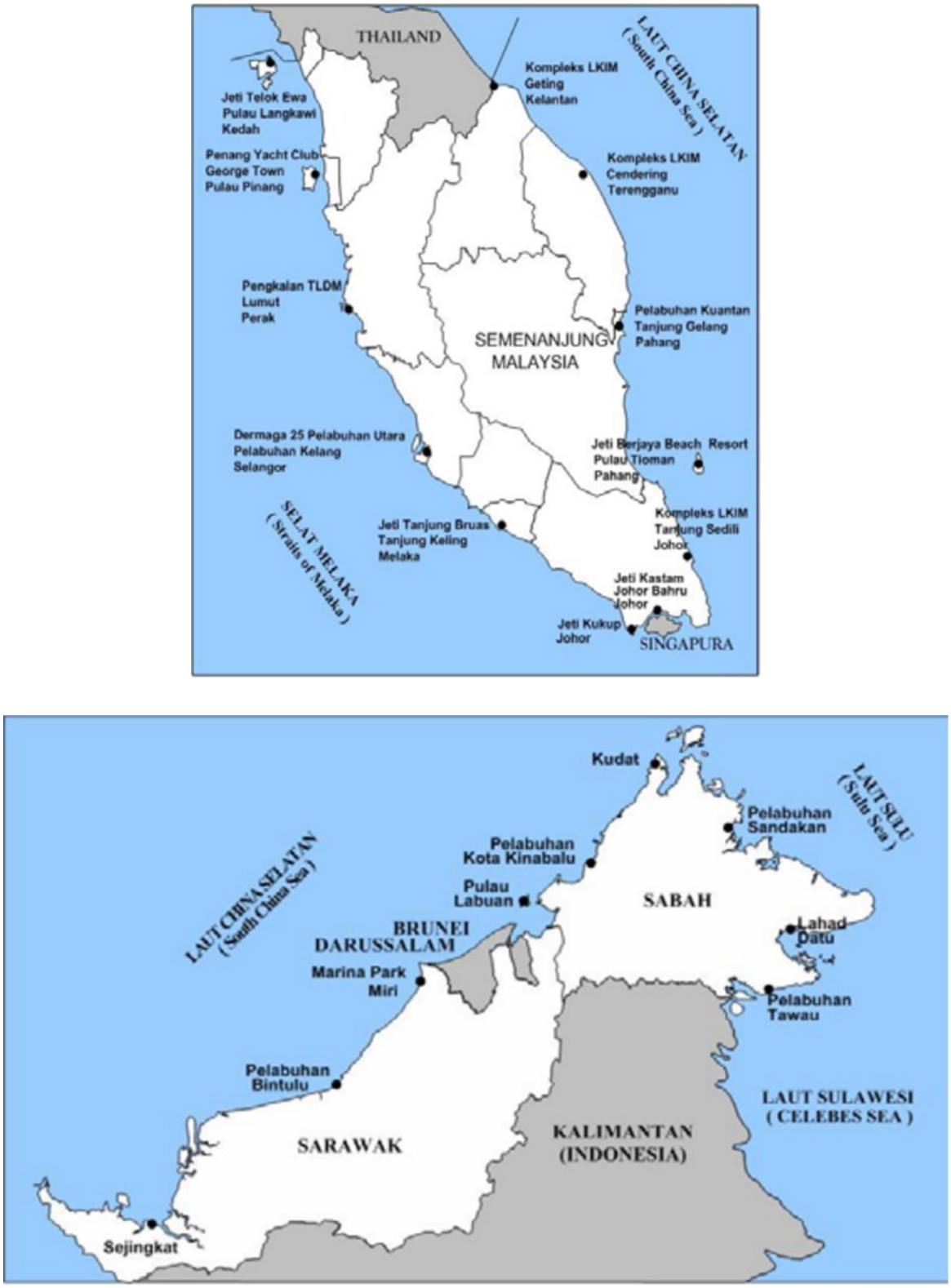

Figure 7 *Distribution of DSMM tide gauge stations (DSMM, 2012)*

DSMM handles the Tidal Observation Network (TON) of 21 continuously operating tide gauge stations along the coast of Malaysia. Nevertheless, two stations have ceased operation, which are Johor Bahru in 2014 and Sejingkat in 2010. DSMM also took an initiative to connect some of the tide gauge stations in the national TON with telemetry connections such that the data of sea level can be transmitted automatically to the central facility in Kuala Lumpur. To this end, the tidal data from tide gauges are important in developing VSEP model as this data will be utilised to derive various vertical datum such as MSL, LAT, HAT and MDT that represents nearshore areas.

3.3 Role of National Hydrographic Centre (NHC)

Apart from DSMM, the National Hydrographic Centre (NHC) is also one of the agencies that can be considered important in realising ERS technique in Malaysia. This is because NHC is responsible for carrying out the regional hydrographic survey of Malaysia. The NHC is an agency that represents the government in addressing more global issues such as technical issues of maritime demarcation. In relation to the research project, the academic institution could collaborate with NHC in terms of testing the reliability of the developed VSEP model during deployment of ERS technique. Since NHC produced nautical charts for Malaysia, comparison between ERS-derived bathymetry and the depth from nautical chart can be analysed.

4. Conclusion

This paper has summarised and reviewed the nations that have successfully implemented ERS technique in which developing and validating the vertical separation model are the greatest challenge. A number of organisations have developed or are in the process of developing vertical separation model. Their projects have been commenced either for hydrographic purposes in permitting the utilisation of GNSS for referencing depth measurements or to empower the creation of seamless coastal datasets. Thus, the vertical datum transformation projects that have been conducted, such as VORF by UKHO, VDatum by NOAA, AusCoastVDT and AUSHYDROID by Australia, for example, can be used as a handbook or reference sources in implementing ERS technique in Malaysia. As Malaysia is looking forward to implement this technique, a proper guideline as well as work process must be designed in detail. As such, there is a need for coordination, support and participation among the various government agencies or stakeholders affected, for instance, DSMM and NHC including academic institutions in realising ERS technique for hydrography survey practice in Malaysia. In the event that this ERS practice is favourable or acceptable, it could become a game changer towards the current practice of hydrographic surveying. This would also be a new norm for the hydrographic community especially for Malaysian Hydrographic Society (MyHS) in carrying out their hydrographic works in the future.

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Articles

ACCELERATING THE USAGE OF EARTH AND OCEANS OBSERVATION DATA IN HYDROGRAPHIC APPLICATIONS

The Canadian Hydrographic Service
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Abstract

Accessing accurate, up-to-date data to support chart production in Canada's vast and complex waterways can be challenging. In order to improve efficiency in charting these navigable waters, The Canadian Hydrographic Service (CHS) has developed new techniques that leverage Satellite Based Earth Observation (EO) data. The main applications developed by CHS include: Satellite Derived Bathymetry (SDB), intertidal zone mapping, extraction of accurate coastlines, change detection/rate of change of coastal features and virtual tidal gauges. The results obtained demonstrate that EO data is a reliable source of Hydrospatial information that can meet the CHS and International Hydrographic Organization (IHO) charting requirements.

Keywords : Optical Imagery, Radar, Canadian Hydrographic Service, Satellite Derived Bathymetry, Coastline Extraction, Change Detection, InSAR, Polarimetry, Nautical Charts.

Résumé

Accéder à des données exactes et à jour en vue de soutenir la production de cartes dans les vastes et complexes voies navigables du Canada peut représenter un défi. Afin d'améliorer l'efficacité dans la cartographie de ces eaux navigables, le Service hydrographique canadien (SHC) a développé de nouvelles techniques qui exploitent les données d'observation de la Terre (EO) par satellite. Les principales applications développées par le SHC comprennent : la bathymétrie par satellite (SDB), la cartographie de la zone intertidale, l'extraction de lignes de côte précises, la détection des changements/le taux de changement des caractéristiques côtières et les marégraphes virtuels. Les résultats obtenus montrent que les données EO sont une source fiable d'informations hydrospatiales qui peuvent répondre aux exigences en matière de cartographie du SHC et de l'Organisation hydrographique internationale (OHI).

Mots clés : Imagerie optique, radar, Service hydrographique canadien, bathymétrie par satellite, extraction de lignes de côte, détection des changements, InSAR, polarimétrie, cartes marines.

Resumen

El acceso a datos precisos y actualizados para apoyar la producción de cartas de las vastas y complejas vías fluviales de Canadá puede ser un desafío. Para mejorar la eficacia al cartografiar estas aguas navegables, el Servicio Hidrográfico Canadiense (CHS) ha desarrollado nuevas técnicas que utilizan datos de la Observación de la Tierra (EO) por satélite. Las principales aplicaciones desarrolladas por el CHS incluyen: Batimetría satelital (SDB), cartografía de zonas inter-mareales, extracción de líneas de costa precisas, detección de cambios/nivel de cambios de características costeras y mareógrafos virtuales. Los resultados obtenidos demuestran que los datos de OE son una fuente fidedigna de información hidroespacial que puede cumplir los costeras y mareógrafos virtuales. Los resultados obtenidos demuestran que los datos de OE son una fuente fidedigna de información hidroespacial que puede cumplir los requisitos cartográficos del CHS y de la Organización Hidrográfica Internacional (OHI).

Palabras clave : Imágenes ópticas, Radar, Servicio Hidrográfico Canadiense, Batimetría satelital, Extracción de líneas de costa, Detección de cambios, InSAR, Polarimetría, Cartas náuticas.

1. Introduction

The Canadian Hydrographic Service (CHS) is the national Hydrographic Office (HO) which is responsible for aiding mariners with safe navigation through Canadian waters. This mandate is supported through the provision of nearly one thousand nautical charts and hundreds of publications which identify risks to navigation in Canada's vast coastal regions, as well as many of its inland waterways. Like all HO's, CHS relies upon traditional hydrographic techniques for the maintenance of its charts, such as multibeam bathymetric surveys, as well as airborne and ground-based Light Detection and Ranging (LiDAR) surveys. While these techniques provide accurate and reliable measurements, their high-cost and limited geographic coverage restrict the ability for wide area application within reasonable periods of time. As Canada contains the longest coastline in the world, significant resources are required to ensure that all navigable waters are charted appropriately and to modern standards. These efforts are amplified in the Arctic as the remoteness and climatic conditions of this region increase the cost of hydrographic surveys and prevent most activities from taking place for the majority of the year.

The Government of Canada has utilized several initiatives to address the challenges of charting to modern standards. Under the World-Class Tanker Safety System Initiative (WCTSS), (Government of Canada, World-Class Tanker Safety System, 2015), and in collaboration with Transport Canada (TC); Fisheries and Oceans Canada (DFO), through the Canadian Coast Guard (CCG) and CHS were responsible for developing the Northern Low Impact Shipping Corridors initiative (Chénier et al., 2016). The work on defining navigational corridors i**s** now continuing under the Oceans Protection Plan (OPP) (Government of Canada, Oceans Protection Plan, 2017). For CHS, this framework helps prioritize its survey and charting efforts in the key navigational areas of the country. This is done with the help of a Geographic Information System (GIS) called the CHS Priority Planning Tool (CPPT), which uses the corridors as one of the primary GIS layers to define CHS surveying and charting priorities (Chénier et al., 2018). Under WCTSS and OPP, new investments were made to increase the safety to navigation in Canadian waters. These investments not only supported an increase in hydrographic survey collection and production of navigational products, but also included the installation of multibeam sonar on CCG vessels for future surveying capabilities. Despite these latest efforts, important gaps still remain to complete coverage of all Canadian waterways. The Canadian Arctic is the region of the country with the most gaps, where only 14% of the waters are adequately surveyed.

To help further develop the safety to navigation and improve survey mission planning, CHS has also been exploring new technologies and modern Hydrospatial tools (Hains, 2020) within remote sensing. Under the Government Related Initiatives Program (GRIP) of the Canadian Space Agency (CSA), CHS has been investigating the potential of Space Based Earth Observation (EO) for various hydrographic applications. This paper will focus on the development of the approaches that were developed by CHS to accelerate and optimize the usage of SBEO. The approaches developed include: (1) Satellite Derived Bathymetry (SDB), (2) Coastline extraction, (3) Evaluation of rates of change, (4) Intertidal zone mapping, and (5) Virtual tidal gauges. These approaches used hybrid solutions that leveraged the advantages of both optical and radar EO sensors while using medium to high resolution imagery. The primary goals of developing these techniques were: (1) evaluate how the different remote sensing techniques could help CHS better meet its mandate and objectives; (2) test these techniques in Canadian waters to get a realistic assessment of their accuracy; and (3) integrate into CHS operations the SBEO techniques that show an adequate level of reliability based on International Hydrographic Organization (IHO) standards.

2. EO Dataset

This paper outlines a resume of all SBEO hydrographic applications that were implemented by CHS. Since varying requirements were needed for each application, a multitude of EO sensors were used. For some applications, a hybrid solution that used both optical and radar imagery was implemented. The sensors varied from medium to high resolution. ***Table 1***. provides an overview of the sensors used in this research. The sensor type, spatial resolution, spectral resolution, swath and the revisit period are the main factors that influenced the choice of the best sensor to use for each application.

Table 1: List of the main EO sensors used in CHS hydrographic applications

Sensor	Type	Resolution				
		Spatial	Spectral Bands	Radiometric	Swath	Temporal
Worldview	Optical	0.5m-High	8 Multispectral (2.5m) 1 Panchromatic (0.5m)	16 bits	16.4 km	1.1 days
Pléiades	Optical	0.5m-High	4 Multispectral (2.8m) 1 Panchromatic (0.5m)	16 bits	20km	26 days
SPOT 6 & 7	Optical	1.5m-High	4 Multispectral (6m) 1 Panchromatic (1.5m)	16 bits	60km	6 tasking plans per day
Plan-etScope	Optical	3.6m-High	4 Multispectral	16 bits	24x8km	Daily
RapidEye	Optical	5m-Medium	5 Multispectral	12 bits	77km	Daily (off nadir) 5.5 days (at nadir)
GeoEye-1	Optical	0.5m-High	4 Multispectral (1.65m) 1 Panchromatic (0.41m)	16 bits	15.2km	Sun Synchronous
Sentinel-2	Optical	10m Medium	13 Multispectral (4 bands at 10m)	12 bits	100km	2-3 days (mid latitude)
Landsat	Optical	30m Medium	8 Multispectral (30m) 1 Panchromatic (15m)	16 bits	185x180km	16 days
Radarsat-2	Radar	6m High	Full Polarimetric	SLC	50 km	23 days
		1m High	Spotlight	SLC	18 km	23 days
RCM	Radar	5m	Compact Polarimetry	SLC	30 km	4 times /day
Sentinel-1	Radar	10m	TOPS Dual VV-VH	SLC	250 km	4 days
ALOS	Radar	5m	Dual HH-HV	SLC	70 lm	14 days
TerraSar	Radar	3m	HH	SLC	30 km	11 days

The selection of an adequate sensor is dependent on many factors based on the application. For shoreline mapping, the scale of the chart is a good indicator for the image resolution that will be required. ***Table 2*** shows the Electronic Navigational Charts (ENC) scales based on Navigational Purpose (IHO , S-66, January 2018). Since the mapping standard is approximately half a millimeter at chart scale, the EO requirement for a berthing scale chart at 1:4000 would be 2 m, which would illustrate the need for high resolution data. For harbor scale charts, high resolution data would also be preferable, whereas medium resolution data would be acceptable for approach and coastal charts. The main reason for not using high resolution imagery for all the six navigational purposes is not only the cost, but also the processing time. For example, to cover the full extent of a coastal chart at the scale 1:150 000, it would require around 100 high resolution images, but only one or two medium resolution images. Based on the mapping requirements, the medium

resolution (Sentinel-2 and Landsat) imagery also exceeds what is needed to meet mapping standards for coastal scale. Since the data from these sensors is free of charge, and the large swath size of one image is often enough to cover the full chart, it is preferred to use the medium resolution data over the lower resolution data. The medium resolution imagery also provides a suitable level of positional accuracy. For these reasons CHS does not use low resolution data for shoreline mapping.

Table 2 : Electronic Navigational Charts (ENC) scales based on Navigational Purpose (IHO , S-66, 2018)

Navigational Purpose	Name	Scale Range	Required Image Resolution
1	Overview	<1:1 499 999	Low
2	General	1:350 000 – 1:1 499 999	Low
3	Coastal	1:90 000 – 1:349 999	Medium
4	Approach	1:22 000 – 1:89 999	Medium
5	Harbor	1:4 000 – 1:21 999	High
6	Berthing	> 1:4 000	High

The use of optical imagery requires cloud-free data. Alternatively, microwave remote sensing using Synthetic Aperture Radar (SAR) overcomes these limitations by offering valuable geophysical parameters with a high frequency revisit in all-weather and daylight-independent conditions. The acquisition in ascending and descending orbits also helps in targeting acquisition times that correspond with the low and high water lines.

3. Methods

3.1 Optical Satellite derived Bathymetry (SDB)

One of the main study sites used to develop the CHS SDB approach was Cambridge Bay (69°07' N, 105°02' W), a hamlet located on Victoria Island, Nunavut (***Figure 1***). Water in Cambridge Bay is generally clear with a depth visibility of around 15 m. The bottom is mostly composed of sand and rock, but the benthic environment is more heterogeneous with numerous patches of vegetation, making the site somewhat complex for SDB.

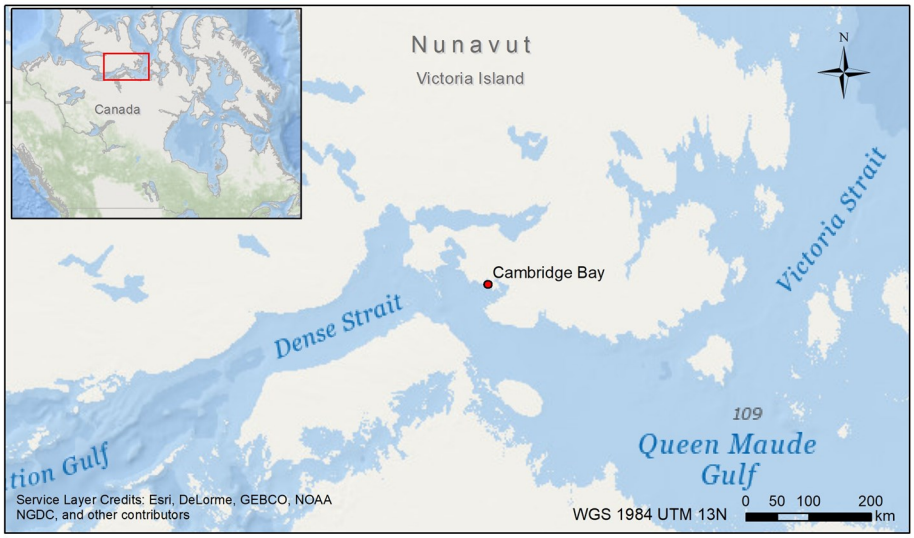

Figure 1. Location of the Cambridge Bay study site on Victoria Island, Nunavut.

3.1.1 Sensors

Prior to defining the best approach to use for the study, a major step was to evaluate the impact of the EO datatypes on the accuracy of SDB (Ahola et al. 2018). CHS follows the guidelines (***table 3***) based on the International Hydrographic Organization (IHO) CATegory of Zones Of Confidence (CATZOC) levels to define the acceptable standard of data (International Hydrographic Organization , S-57 Supplement, 2014).

Table 3 : Required depth accuracies for IHO CATZOC levels (IHO, 2014).

CATZOC Level	Depth Range (m)	Required Depth Accuracy (± m)
A1	0-10	0.6
	10-30	0.8
A2 & B	0-10	1.2
	10-30	1.6
C	0-10	2.5
	10-30	3.5

The sensors that were tested to evaluate the best option for use in optical SDB were: WorldView-2, Pléiades, PlanetScope, SPOT, Sentinel-2, and Landsat-8. Table 4 provides an overview of the specifications of the imagery provided by each sensor. To simplify the analysis of sensor impacts on SDB, the Lyzenga's empirical linear multi-band SDB technique (Lyzenga, 1985) was selected as the only approach used to extract the SDB.

Table 4 : Specifications for satellite imagery examined for this work.

Sensor	Acquisition Date	Acquisition Time (UTC)	Sun Azimuth Angle (°)	Sun Elevation Angle (°)	Spatial Resolution (m)
WorldView-2	20 September 2015	18:37	176	22	2
Pléiades	12 July 2016	18:52	175	43	2
PlanetScope	10 July 2017	17:56	159	42	3
SPOT	1 August 2015	18:35	170	39	6
Sentinel-2	11 August 2017	18:59	179	36	10
Landsat-8	28 August 2015	18:37	173	31	30

The SDB results that each sensor produced were compared with the IHO CATZOC requirements (***Table 3***). In this study, we did not consider the S-44 (S-44 is one of the IHO series of hydrographic standards) as the data was already available to be used for chart production. The SDB results demonstrate that the spatial resolution has an impact on the SDB accuracy as seen by the correlation in ***Figure 2***, with higher resolution data generally outperforming low resolution sensors for overall accuracy. PlanetScope presents an exception to this trend, as it achieved worse

results than lower resolution SPOT data. This may be due to reduced positional accuracy (relative to the other sensors) and reduced calibration potential with the microsatellite format. Based on these results, the low-resolution Landsat-8 and Sentinel-2 datasets should not be used as the main sensors for charting purposes but could be useful tools for mission planning. The PlanetScope data also did not achieve adequate results in the deep water and was outside the CATZOC B requirement for the 0-10m range. The two high resolution sensors (WorldView-2 and Pléiades) provided the best results and therefore are the main sensors used by CHS for SDB chart updates. Even if the study clearly demonstrates a link between the sensors spatial resolution and the SDB accuracy, it is important to note that the different acquisition dates of each image limit our understanding of spatial resolution impact on the SDB accuracy. The suitability of the best image to use for SDB also depends on other factors such as sun glint effect, water turbidity, sun angle, waves and cloud coverage.

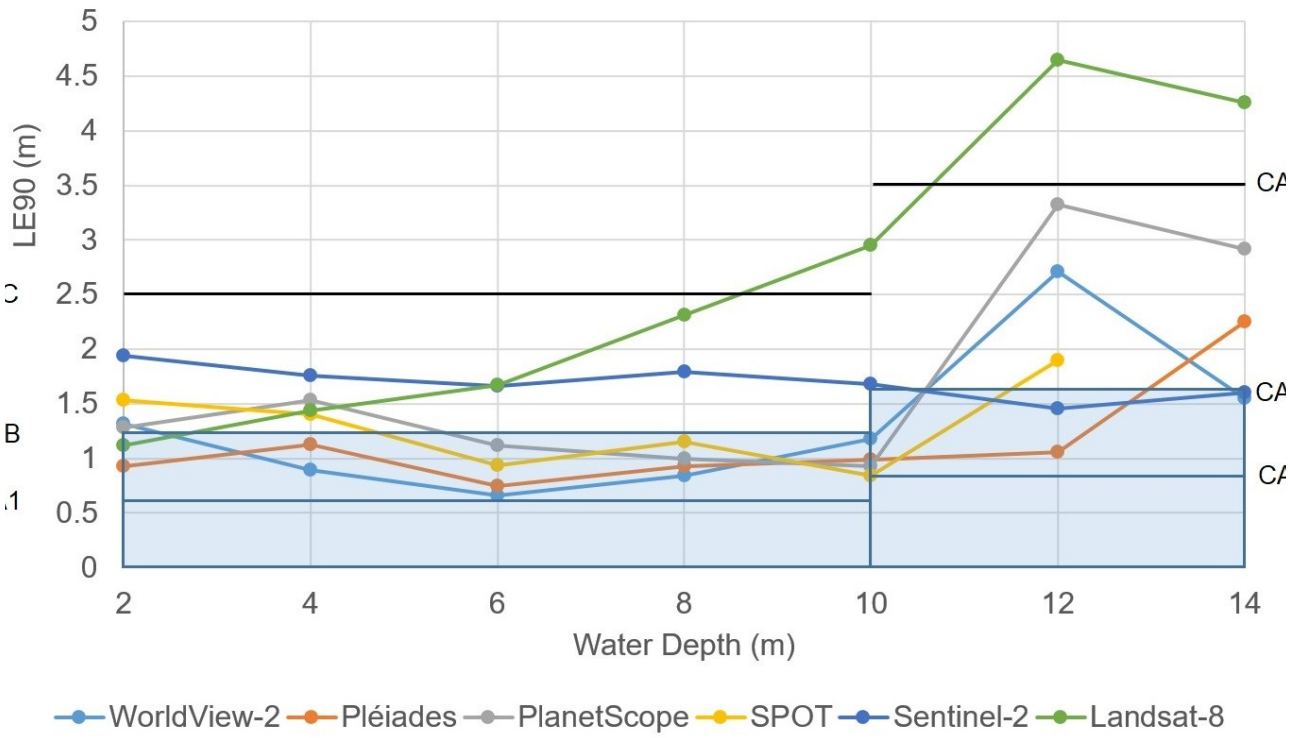

Figure 2.: *SDB accuracy based on sensor type, and IHO requirements based on water depth. The shaded blue boxes represent the IHO CATZOC A/B requirement based on water depth.*

3.1.2 Spectral bands

Besides the spatial resolution, there are other important factors to consider when selecting the best image to use. Another study by CHS (Chénier et al. 2018) demonstrated that the radiometric resolution of a sensor also has an impact on the SDB accuracy. The lower frequency wave-lengths such as the yellow and red bands of WorldView 2 and 3 help improve the SDB accuracy in shallow waters (0-4 m). Therefore, the technique used should utilize the advantage of different bands offered by multispectral sensors. The results in Chénier et al 2018, demonstrated that in the two empirical approaches tested ; the Multi-Band Model (Lyzenga,1985) and the band ratio model (Stumpf et al. 2003), the multi-band approach generally exceeded the performance of the band ratio technique with the traditional blue and green (**ln(B)/ln(G**))band ratio. By adapting the band ratio approach with different band ratio combinations (Chenier et al. 2018) based on water

depths, the results achieved were almost identical to that of the multi-band technique. The blue and green band ratio is very effective for sites that have clear, deep waters, but for shallow environments with higher sediment levels, the blue and yellow band ratio provided better results. Thus by adapting the band ratio combination approach to the site conditions and water depths, the accuracy of the SDB will increase.

3.1.3 SDB approaches

After determining the optimal sensor to use, CHS evaluated different SDB approaches that would provide the best results in Canadian waters. During this work, CHS was the first to propose looking at photogrammetric approaches to extract SDB (Chénier et al., 2016). Two photogrammetric approaches were evaluated: an automatic approach (Hodul et al., 2018) and the traditional 3D manual approach (Chénier et al., 2018). Other techniques like classification and empirical approaches were also tested. Since all the approaches provided different advantages and disadvantages, optimal results were obtained by developing a hybrid model that leverages the advantages of the different approaches and also meets the level of confidence in the SDB. Using a level of confidence approach (Chénier et al., 2019a), CHS was the first HO to obtain the CATegory of Zones Of Confidence (CATZOC) A2/B requirement for SDB. The proposed level of confidence method operates through understanding the level of agreement between each of the applied SDB techniques. It aims to develop a final SDB estimate where the highest number of techniques agree within 1 meter. ***Table 5*** provides the results obtained by using the level of confidence approach. The area where at least three of the four techniques agreed represent 81% of the SDB coverage. These results not only provide confidence to the results, but also match the CATZOC A2/B requirements (***Table 3***), and therefore could be used as a tool to update nautical charts.

Table 5. Accuracy assessment results for the multi-approach technique.

Number of Techniques Agreeing within 1 m		LE90 (m)							
			Depth Range						
	Coverage %	Bias	0-10	0-2	2-4	4-6	6-8	8-10	10-14
4	31	-0.10	1.01	1.21	0.85	0.85	0.98	1.27	1.00
3	50	-0.19	1.26	1.23	0.90	1.14	1.28	1.25	1.24
2	19	0.05	1.28	1.30	1.21	1.25	1.24	1.07	1.90
4 & 3	81	-0.16	1.21	1.26	0.87	1.08	1.24	1.28	1.20
All	100	-0.12	1.24	1.30	0.95	1.15	1.24	1.18	1.78

3.2 SAR Bathymetry

As demonstrated above, the optical SDB bathymetric measurements of shallow water are hampered by the water clarity. The accuracy tends to decrease with water depth and in Canadian waters, visible depth range is limited to around 20 m. SAR bathymetry can provide estimates based on the influence of underwater structures on hydrodynamic processes by taking advantage of the high sensitivity of radar backscatter of rough surfaces. In the following section, we present a review of results obtained based on investigating and developing SAR applications.

The ocean's surface, gravity, waves and water depth are related by the linear dispersion relationship in shallow water (Brusch et al. 2011; Mishra et al. 2014). This relationship is used to estimate the bathymetry in near coastal waters. Particularly when approaching the coast, waves and

seabed change rapidly in a coordinated manner (Wiehle and Pleskachevsky 2018). The waves tend to align parallel to the shoreline and manifest by an increase in both height and frequency as a response to changes in the underwater topography (Brusch et al. 2011). SAR wavelengths of the observable long gravity wave changes can be extracted using Fast Fourier Transform (FFT) and Wavelet transform methods on high-resolution SAR imagery (Mishra et al. 2014). Limitations of these methods stem from finding adequate SAR data with discernable wave features, and the quality and accuracy of these methods remain largely unconstrained as the studies investigating them are limited to very high-resolution imagery. CHS, in collaboration with C-CORE tested the SAR bathymetry approach using a study site on the north shore of Haida Gwaii Island, British Columbia (BC). In this study, four Sentinel-1 images with visible waves were selected and used to generate the SAR SDB. The acquired images are Ground Range Detected (GRD) products with Interferometric Wide Swath modes and have a nominal 10 m resolution in VV polarization (***Figure 3***).

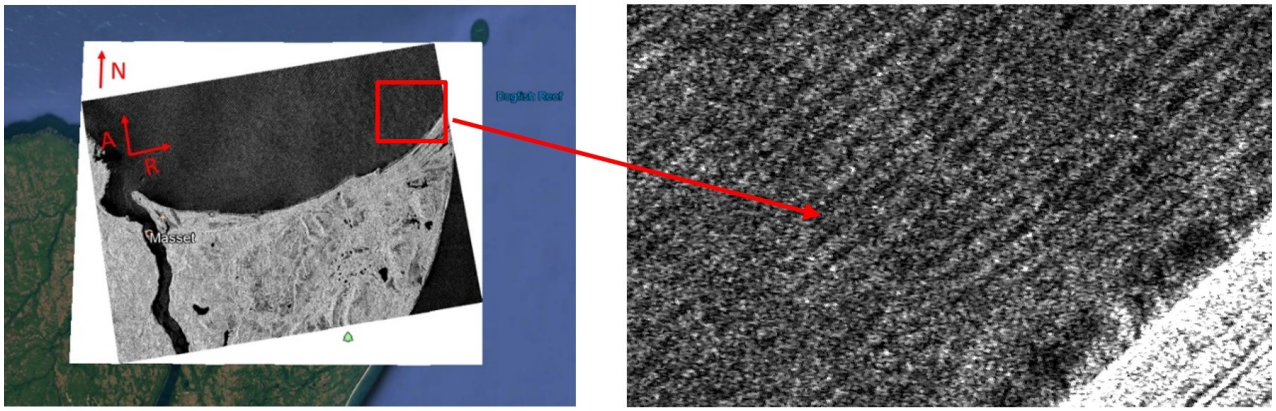

Figure 3 : *Sentinel-1 scene of Haida Gwaii with a zoomed in view of waves visible in the image (C-CORE, 2019).*

The retrieval process performance assessment was performed using CHS surveys (C-CORE, 2019). ***Figure 4b*** shows a relative agreement of estimated SAR bathymetric values against single beam CATZOC B survey data 4a. With a combined RMSE of 4.49 m which indicates that the SAR bathymetry does not meet the IHO CATZOC requirement for charting purposes (***Table 3***). By investigating the different water depth classes (Table 6), we noticed that as with optical SDB there is a correlation with water depth an accuracy, with accuracy tending to decrease as depth increases. These results demonstrate that SAR SDB can meet the CATZOC C requirement for water depth from 10 to 40 m. Even if the main goal of this study was to demonstrate that SAR SDB could be used for mission planning and shoal detection, the accuracy obtained in the 10-40 m also demonstrated potential for chart update. There are also several other factors that can impact SAR bathymetry results. We can cite the quality of surveys data, the spatial resolution and the frequency of the SAR system used, the difference of water height to the sea level during the acquisition and the quality of the wave features present in imagery. However this technique offers other advantages to CHS. Water depths of 40 m could be extracted in the Haida Gwaii site where optical SDB could only reach depths of up to 10 m. The main limitation of this technique is that the user must have suitable imagery. The approach requires one or more SAR images capturing discernable wave features on sea surface. As the measured SAR backscatter from surface water is dependent on surface roughness. Changes in surface wave properties are induced by changes in the topography of the sea bottom. Therefore, the latter can be sensed through its effects on sea surface. Throughout the study, 58 images were investigated with only four of those images being usable to extract the SAR SDB. Due to this limitation, no images were available for the Cambridge Bay site. Further investigations are also needed to

assess the approach using Radarsat-2 and RADARSAT Constellation Mission (RCM) data acquired in higher spatial resolution modes, as better resolution data could help improve the accuracy of the SAR SD

a) b)

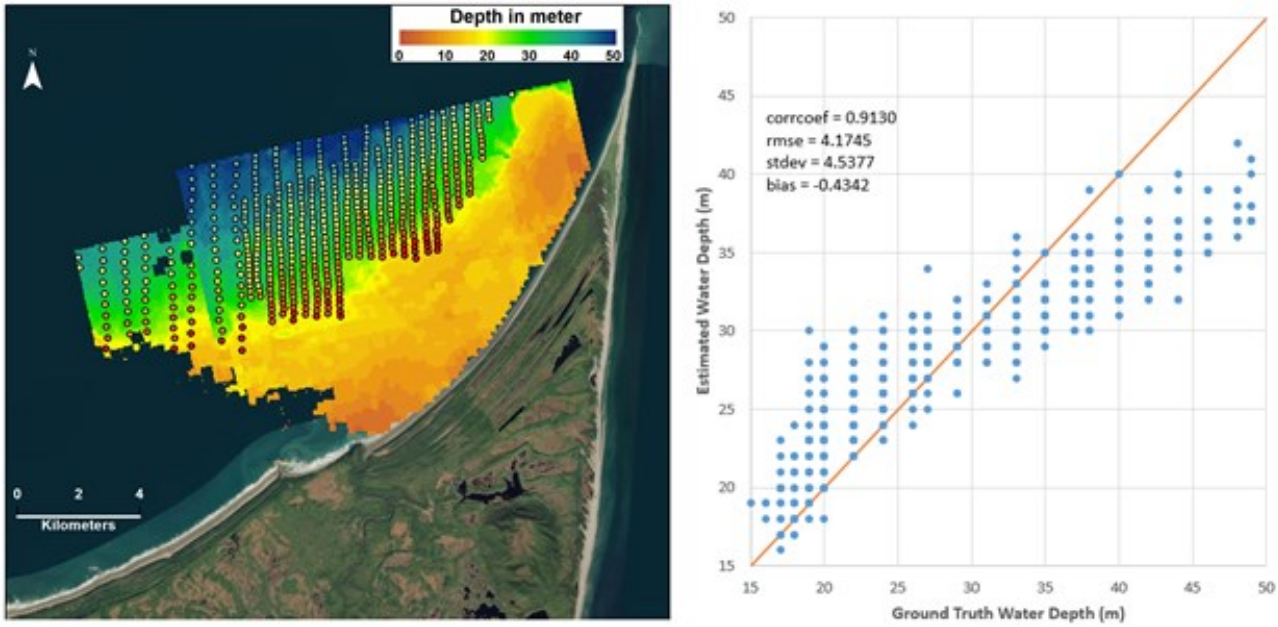

Figure 4 a) & b) : *Bathymetry results from the combined average of four Sentinel-1 scenes acquired on 14 Dec. 2018, 19 Dec. 2017, 12 Nov. 2017, and 8 Oct. 2017, respectively. In (a), single beam CATZOC B survey data dispalyed on the top of estimated bathymetry and in (b), the chart of estimated water depth against survey data. ©ESRI Imagery Basemap*

Table 6 below breaks down the RMSE values by depth class for each image as well as the combined average of all images. Results indicate that depths up to 40 m output predicted depths with RMSE values ranging from 3 to 5 m. However, above 40 m in depth the error significantly increases to more than 8 m. This suggests that SAR bathymetry can only be used in intermmediate depths as seen in ***Figure 4*** as well.

Table 6 : RMSE values by range depth of the four Sentinel-1 scenes as well as a combined average of all four images.

Depth Range (m)	Average		Image 1		Image 2		Image 3		Image 4	
	No. of Points	RMSE (m)	No. of Points	RMSE (m)	No. of Points	RMSE (m)	No. of Points	RMSE (m)	No. of Points	RMSE (m)
10-20	99	3.40	87	4.61	80	3.31	85	3.98	90	5.24
20-30	266	3.25	237	4.58	193	3.41	217	3.40	245	5.05
30-40	146	3.67	118	3.11	68	5.18	104	3.66	132	3.03
40-50	94	8.39	65	7.99	9	8.78	43	9.27	87	7.62
0-50	**605**	**4.17**	**507**	**4.68**	**350**	**3.87**	**449**	**4.13**	**554**	**5.00**

3.3 InSAR technique for VIRTUAL Tidal GAUGES

Making accurate and up to date predictions of water levels is critical to ensure safe navigation. Currently the Canadian Hydrographic Service (CHS) is relying on traditional physical water level gauges to create tidal predictions. While some regions have an even distribution of water gauges,

other areas like the Canadian Arctic suffer from limited spatial coverage. There are only 5 permanent water gauges in the Arctic to cover an area close to 4 million km². The aim of this study is exploring the potential of Interferometric Synthetic Aperture Radar (InSAR) to extract water level information and help charting coastal areas (Chénier et al., 2020a).

To test the approach, a study site with large tidal variations (up to 12 m) and shallow slopes was selected in the Canadian Arctic. The study site is located in Hopes Advance Bay on Ungava Bay, QC (***Figure 5***). Five datasets were acquired for this region: Two co-registered Bistatic TanDEM-X/ TerraSAR-x single look slant range complex SAR images (CoSSC), collected on September 22, 2012, were used for the creation of the InSAR DEM. The images were acquired with a right-looking ascending pass in HH polarization. For the low water line, a Worldview-3 image was acquired on October 2, 2017. For the medium water line, a PlanetScope image acquired on July 25, 2015 was used. To extract the high water line, a RADARSAT-2 image in fine mode was used with an acquisition date of September 8, 2015. The validation data were from tidal gauge observations obtained from existing station number 4325 (***Figure 5***) located at Hopes Advance Bay.

Figure 5 *: Hopes Advance Bay Site, Ungava Bay , Northern Québec, Canada. Image © Service Layer Credits: ESRI, Garmin, GEBCO, NOAA NGDC, and other contributors.*

The InSAR processing of the Bistatic TanDEM-X/TerraSAR-x images was performed using the GAMMA software, and the DEM was generated with a 4 m pixel grid. Before comparing with the tidal gauge information, the model is adjusted to the Chart Datum (CD). ***Figure 6*** represents the InSAR DEM generated from the TanDEM-X/TerraSAR-X images overlapped with the coastline extracted from the imagery at the varying water levels (low, medium and high). Since the water line is very close to a level line, a mode technique was used to extract the most common values from each of the lines. This technique removes the errors generated in the InSAR model. Before comparing the tidal gauge information and InSAR DEM values at the water lines, the values need to be corrected to the CD. The most commonly used CD by CHS for tidal waters is the lowest low water at large tide (LLWLT). The LLWLT values are calculated by averaging the lowest water level from each year for 19 years (Fisheries and Oceans Canada). ***Figure 7*** represents the formula used to transfer the value from the InSAR DEM to the CD at the LLWLT.

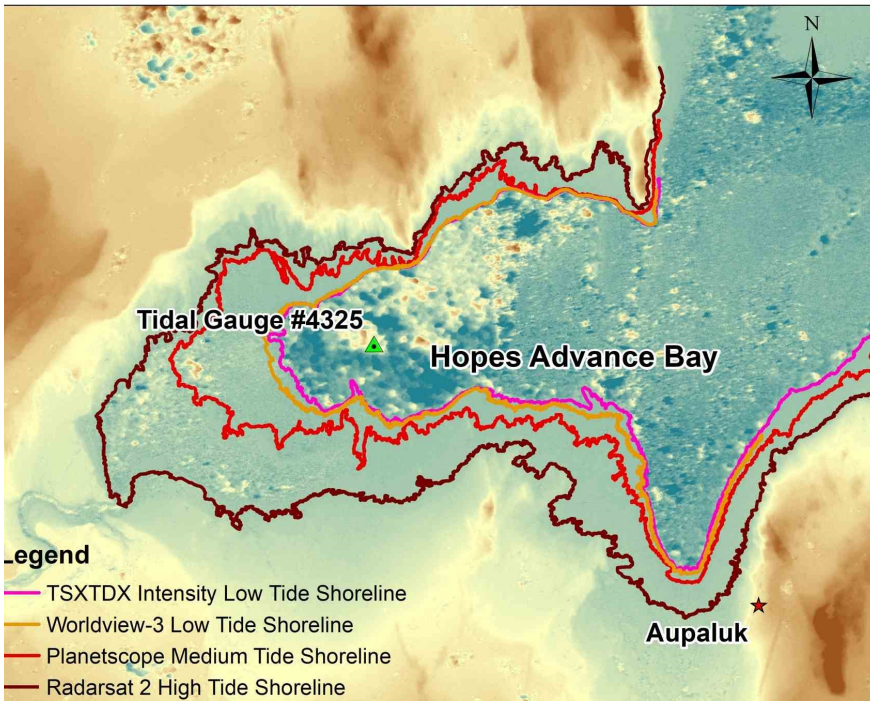

Figure 6 : *Shorelines extracted from the satellite imagery at high (orange), medium (green), and low (yellow and red) tidal conditions are displayed on In-SAR DEM generated with Bistatic Tandem-X/TerraSAR-X Single-Look images.*

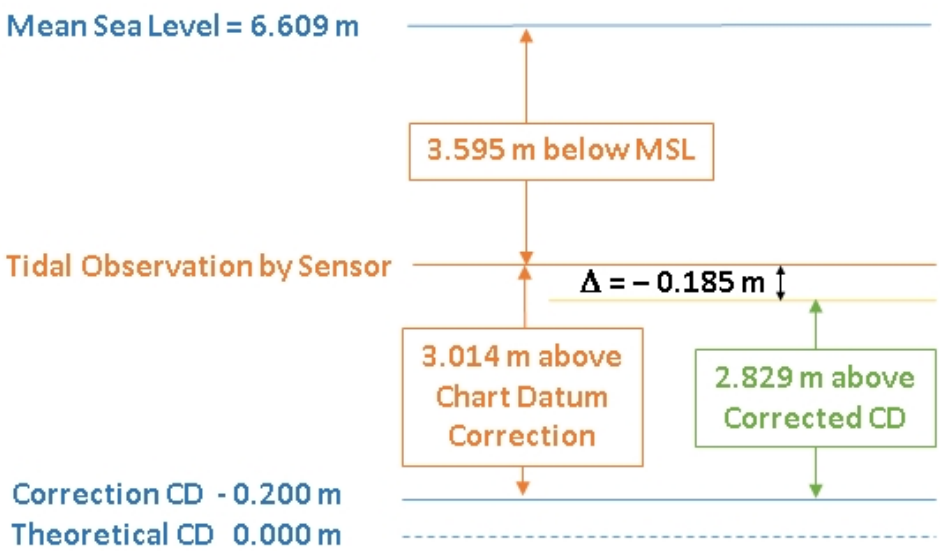

Figure 7 : *Formula used to correct the InSAR values to the CD. Example for the TSX/TDX Intensity image.*

Table 7 provides the results obtained by taking the mode of the InSAR DEM values along the shoreline and subtracting it from the tide station values corresponding to the dates and times of the satellite image acquisitions. The accuracy of the tidal gauge is around 20 cm, therefore the results obtained (27 cm) are within the range of the tidal gauge error. This suggests that the InSAR technique with the coastline extracted from different high-resolution satellite images could

be used as virtual tidal gauges. The results demonstrate a correlation with the errors and tidal conditions, where the best and worst accuracies are seen in low and high tide conditions respectively. Further studies will be required to better understand the source of these correlations, but they could be related to the uncertainty of the tidal gauge which is amplified with large tides. For the InSAR DEM, the reasons explaining this correlation are unknown as there are no large variations in slope or phase coherence. Some of those error could be explained by the different sensor being used to capture the different water lines. More testing will be done to better understand the impact of each sensor on the results. Since there is uncertainty in the tidal gauge and correction of the InSAR to the CD, a relative accuracy assessment was done between each tidal condition (***Table 8).*** Even if the results are in the range of the tidal accuracy, the relative accuracy is a good indicator to better understand the error propagation. Besides the low tides of the TerraSAR water line, all of the other results are around 10 cm. This is caused by the overestimation of the water level in the InSAR model, where all the other values at the different tide conditions are lower than the water gauge. This larger error of 47 cm can be caused by the fact that the low water from the InSAR DEM is at the at the limit of water on land and therefore has a lower phase coherence.

Table 7 : RMSE of the InSAR DEM at different tidal conditions based on shorelines extracted from satellite imagery.

Sensor	Tidal Condition	Tide Station obs (m)	InSAR DEM Mode (m)	Δ difference Tide Gauge InSAR DEM Elevations (absolute Value)
TSX/TDX Intensity	Low	2.829	3.014	0.185
Worldview -3	Low	4.386	4.164	0.222
Planetscope	Medium	5.592	5.254	0.338
Radarsat-2	High	7.352	6.990	0.366

Table 8 : Relative accuracy between different tidal condition.

Tidal Condition	Tidal Condition	Relative difference Tidal Station	Relative difference from InSAR	Δ difference
Low TerraSAR	Low WV-3	1.55	1.15	0.47
Low WV-3	Med Planet	1.20	1.09	0.11
Med Planet	High Radarsat	1.76	1.74	0.02
High Radarsat	Low WV-3	2.96	0.36	0.14

Virtual tidal gauges (VTG) are also created by extrapolating the data collected from existing tidal gauges using regression models (Xu, 2015a,b). The advantages of the regression models are that they can predict water level at all hours, whereas temporal data collection is the main limitation of the InSAR approach. The primary advantage of the InSAR VTG however is that it is based on up-to-date data, which is especially important in areas that have significant coastal erosion. By combining the InSAR approach with a prediction model, the InSAR VTG could help validate the data that are extrapolated from the regression model. There are other hydrographic applications that could also benefit from the output used to create those VTGs. For example, The

InSAR model, combined with the various contour lines could be used to create dynamic navigational products in the S-100 standards. The up-to-date coastal water line could also be used to support the work on the Continuous Vertical Datum for Canadian Waters (CVDCW).

The introduction into the current workflow of the Ice, Cloud and land Elevation Satellite-2 (ICE sat-2) data in order to assist in the estimation of tidal height levels in remote areas has also been considered for future InSAR derived DEM data validation purposes. The Icesat-2 satellite provides along-track heights above the ellipsoid data covering ground and vegetation canopy surfaces and also ice, sea ice, ocean surface height surfaces as well. The ATL08-ATLAS/ICESat-2 L3A Land and Vegetation Height dataset products are acquired by the Advanced Topographic Laser Altimeter System (ATLAS) instrument on board of the ICESat-2 and are processed in fixed 100 meter segments with a temporal resolution of 91 days and variable spatial resolution.

Figure 8 below shows a swath containing ICEsat-2 data compared with the InSAR derived Digital Elevation Model. A height difference of 76 cm is observed at the ICESat-2 point location validating the accuracy of the InSAR derived DEM when compared with the Geodetic data points as a first reference. The drawback of ICESat-2 data is that it only covers a narrow swath of points.

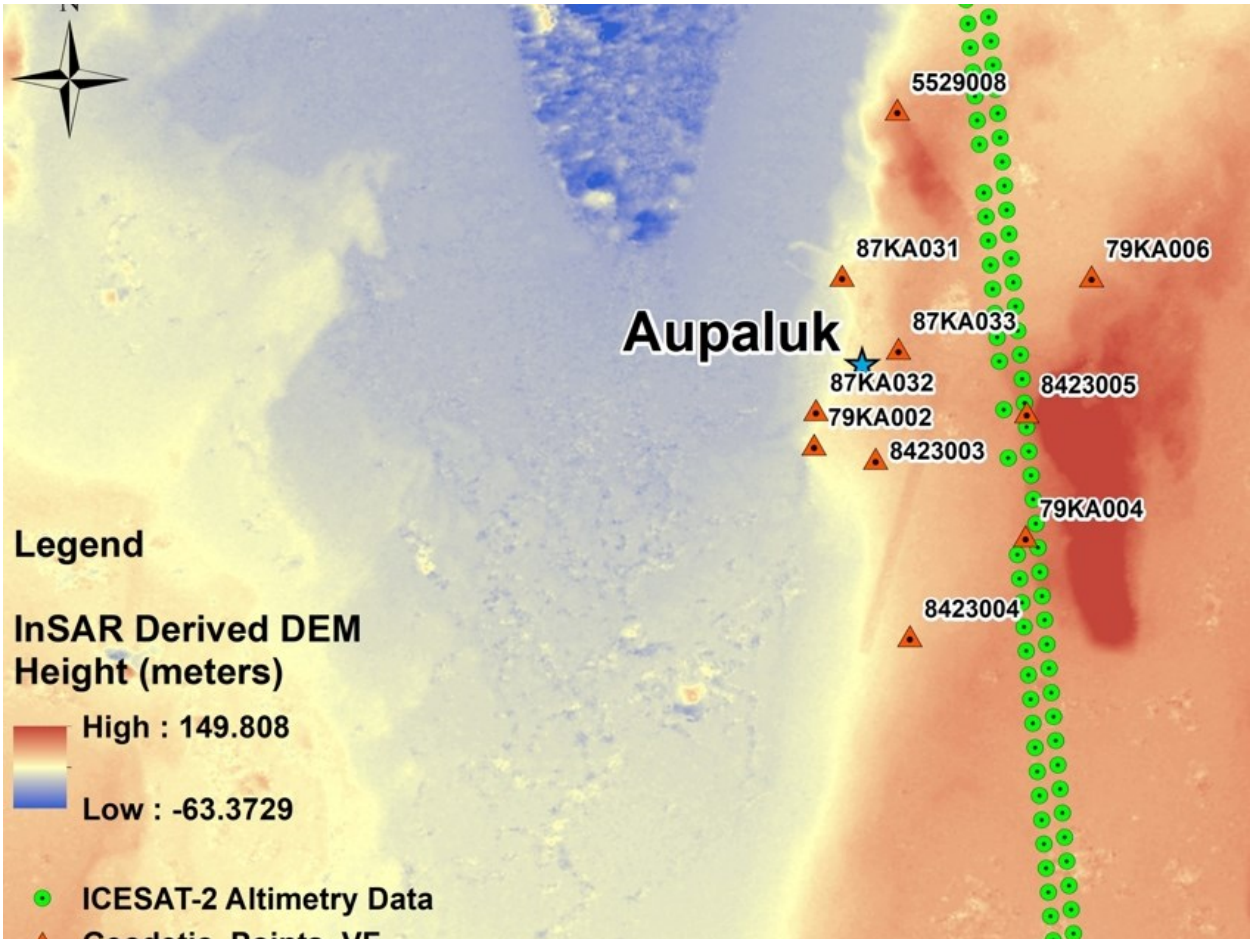

Figure 8 : *Swath covered by ICESat-2 L3A Land and Vegetation Height data*

3.4 Shoreline detection

One of CHS's main operational hydrographic applications using EO data is the production of new shorelines for chart updates. In order to best capture the advantages offered by different sensors, CHS developed a hybrid approach that combines radar and optical EO data (Chénier et al., 2019b). For areas with intertidal zones, CHS has developed an approach where the EO data acquisitions are synchronized with the low water levels from CHS's tidal predictions (Chénier et al., 2016). In fresh water systems, the low and high water lines are extracted using monthly averages (Chénier et al. 2019b). The usage of radar data like RADARSAT-2 and RCM is beneficial for capturing low water conditions during periods of high cloud cover (predominantly October to December), thus ensuring that shorelines representing the lowest water level possible are mapped.

3.4.1 Automatic Approach

In order to make the shoreline extraction as automated as possible, the extraction was accomplished through an object-based image segmentation process using eCognition software. Both radar and optical images were used for image segmentation and classification. ***Figure 9*** represents an area of the Mackenzie River where significant changes were noticed with EO data. The arrow seen in ***Figure 9*** highlights an area of change in the river's channel, where the full width of the river currently passes through an area of land indicated on the chart.

(a) (b)

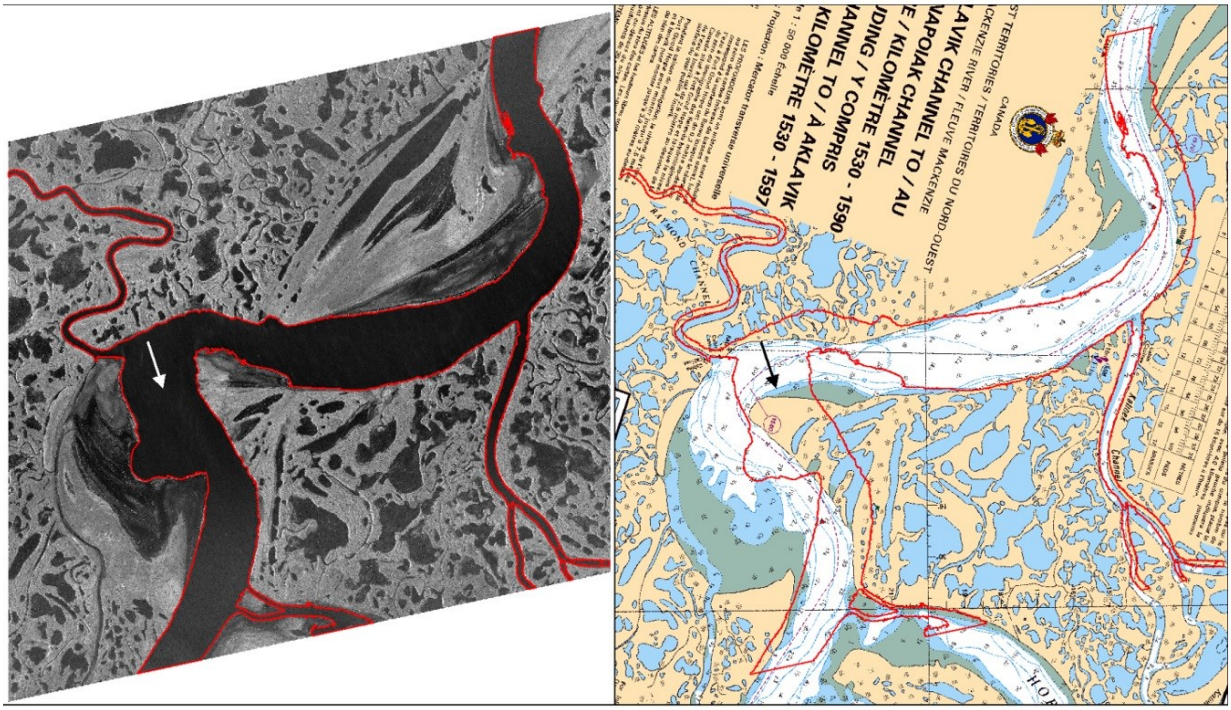

Figure 9 *: Shoreline extracted from EO data over the Mackenzie River. New shoreline overlapped on the RADARSAT-2 Spotlight image (**a**) and chart 6428 (**b**). Note the arrow on both maps: on map (a), the arrow is situated near the current centre of the main Mackenzie River channel. In (b), chart 6428 indicates an area of land at the same location. The charted land area spans nearly the entire width of the current river's location at this point. These graphics highlight significant changes in the position of the river since the creation of chart 6428. RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd. (2014/2016) – All Rights Reserved. RADARSAT is an official mark of the Canadian Space Agency.*

CHS is also exploring automatic methods for shoal detection using artificial intelligence (AI) (Chénier et al., 2020b). Currently, there are large gaps in survey data where potential hazards to navigation are uncharted on CHS products. Using SBEO data, machine learning and deep learning techniques can be applied to identify shoals which may present a hazard to navigation. CHS conducted a test using a random forest (RF) classification which is a machine learning approach, and a convolutional neural network (CNN) classification which is a deep learning approach, over two sites in the Canadian Arctic. The techniques were also tested using both WorldView-2 (2m resolution) and Sentinel-2 (10m resolution) imagery to understand if spatial resolution plays a significant role in classification accuracy. Across the two sites, overall accuracies ranged between 79-85% for both techniques and sensors. These results indicate that neither method is superior. The RF classification is much faster and more user-friendly, but the model cannot be applied to just any image. The CNN classification requires a large training dataset and requires more time and computing power to train the model and classify the image, but it can be built to identify shoals in any image of the same sensor which would be beneficial for CHS in the long-term.

3.4.2 Rate of change

A second aspect of the project is to evaluate the rate of change on the river to better understand the frequency at which the chart would need to be updated. As illustrated in ***Figure 10***, by using archived Landsat data ranging from 1972 to 2011 and a Sentinel-2 image from 2018, a rate of change of approximately 220 m per decade was determined in the most dynamic areas within chart 6428. The rate of change was calculated by measuring the maximum distance from the vectors of the shoreline extracted from the 1972 and 2018 images. For this 46-year period, the maximum distance between the two vectors is approximately 1 km, which represents close to 22 m of change per year. To better predict future changes in the-river, data for every decade (1972 to 2018) were also estimated. This approach is needed to ensure that the shoreline changes were not introduced by one major event, such as a landslide, and progress consistently. Based on the extracted shorelines, we can see in ***Figure 10*** that although some decades, 1982 to 1992 for example, exhibit more change, there is a gradual shift in the river shoreline throughout each decade. Therefore, we can deduce that this general trend will continue to occur in the future and thus special attention will be required in those areas of the river to ensure that the charts are up to date. The detail at which a cartographer can update a map/chart is half a millimeter at chart scale. The scale of chart 6428 is 1:50,000; as such, 0.5 mm on the chart represents 25 m on the ground. With a rate of change of approximately 22 m/year, this chart would need to be revaluated at least every 2 years.

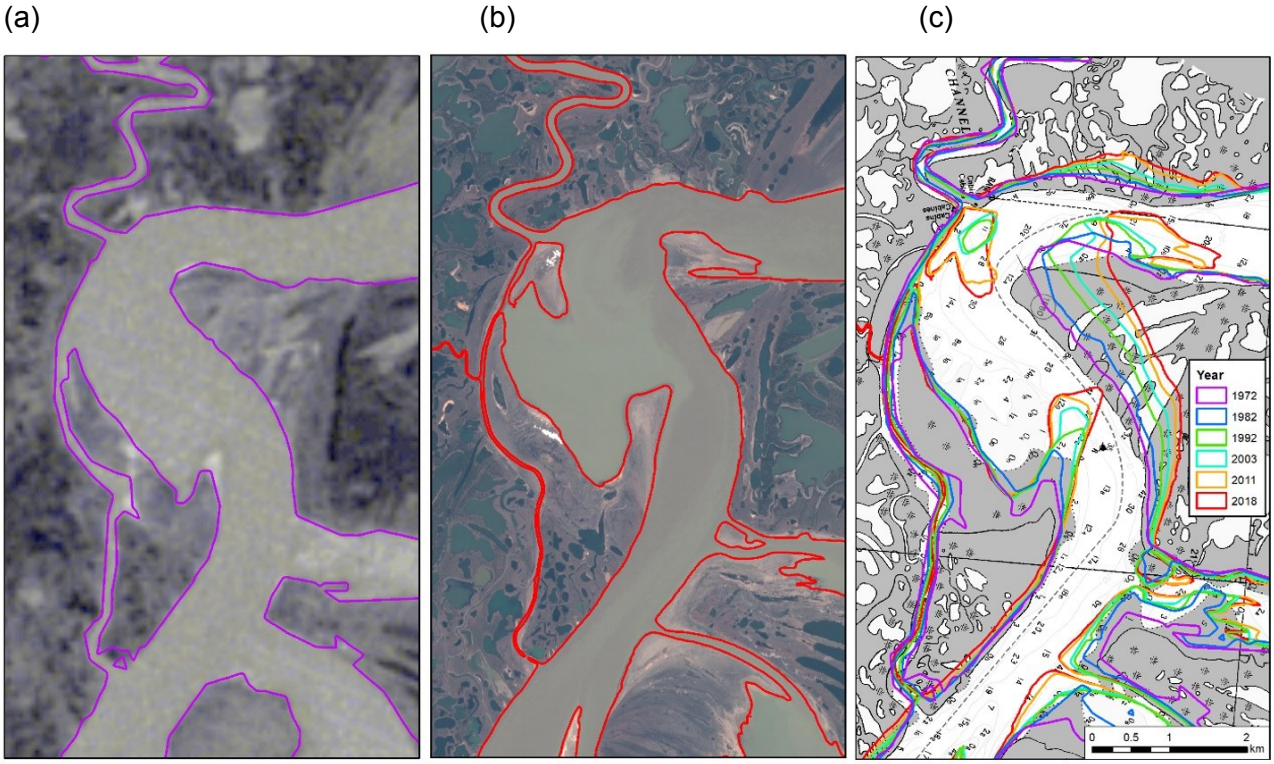

Figure 10 : *Segmentation results showing extracted main Mackenzie River channel and tributaries over a Landsat image from 1972 (a), a Sentinel-2 image from 2018 (b) and over chart 6428 (c). Imagery © 1972, U.S. Geological Survey and © 2018, Copenicus.*

3.5 Polarimetry for intertidal zone mapping

Radar EO data can offer many advantages such as collecting data in conditions of full cloud cover. The polarimetric capabilities of SAR can help in identifying intertidal zones, which are important to CHS since variations in water level can have impacts on the safety of navigation, and therefore the intertidal zones must be mapped on CHS charts.

In intertidal zones, the contrast between target elements is based on their differences in dielectric properties, and the structure of both soil (e.g. soil moisture and roughness, sediment size and shape) and vegetation (e.g. size, orientation and shape) can be used as a contrasting mean for an enhanced sediment classification (Gade et al., 2008). Polarimetric SAR data has been investigated for surface roughness characterization and mapping intertidal zones (Park et al., 2009; Souza-Filho et al., 2011; Lee et al., 2012; Geng et al., 2016; Gade et al., 2018). In contrast to single or dual-polarizations, the use of polarimetric parameters enhance the discrimination of different types of target objects based on their scattering responses (Lee et al., 2012, 2009; Boener et al., 1998; Touzi et al., 2020).

Recent studies investigate the use of polarimetric parameters generated from Quad-pol Radarsat-2 data and the potential of Compact Polarization (CP) of the RCM mission from simulated parameters (Omari et al., 2020). ***Figure 11*** shows an example of these parameters and their equivalent classification results using a Random Forest (RF) approach over a study area located near the village of Tasiujaq (58○42’ N–69○56’ W) along the banks of the Baie aux Feuilles at the mouth of the Bérard river on the west side of Ungava Bay.

In the upper three figures, (a) presents the Freeman-Durden (FD) decomposition, (b) the Touzi discriminators using the Quad-pol images and (c) the Raney m-delta classification derived using the CP. In ***Figure 11(a),*** the double-bounce is shown in red, volume scattering in green, and surface scattering in blue. The vegetation (green area) is dominant over land (FD_volume) whereas in intertidal areas (pink), a mixture of FD_volume and FD_double-bounce. ***Figure 11(b),*** displays a color composite of Touzi extrema represented by a combination of maximum and minimum values of the degree of polarization and the scattered wave intensity (pmin in red, pmax in green and R0max in blue). Land vegetation is highlighted with the blue color where R0max is dominant, exposed rocks represented in white color and intertidal zones in yellow (contribution of both pmin and pmax). The m-delta presentation on the other hand, shows the potential ability to discriminate exposed rocks and open water. Difficulties of discriminating the latter in both FP presentations rise in localized areas where the water surface is affected by wind and wave conditions (surface water is rougher).

Classification results of polarimetric parameters are also shown in ***Figure 11 (bottom three images).*** The Random Forest classification output of FP Freeman-Durden (FD) parameters, Touzi discriminators (pmin, pmax, R0max) extrema of the DoP), and m-delta parameters show an overall accuracy ranging between 61% to 71% (Omari et al., 2020). The polarimetric parameters (information) tend to provide a better description of geophysical properties of the surface and account for roughness, biomass and soil moisture variables. The obtained results from the Omari et al., (2020) study demonstrated that the use of only one polarimetric decomposition as a sole source of information to feed the classification process can provide acceptable results. The authors suggested that to further enhance the accuracy, the polarimetric decomposition must be complemented with another type of data such as optical imagery. This approach is challenging as both data types have to be acquired simultaneously to illustrate identical tidal conditions. This can prove to be quite complicated as the changes in tidal water content of the study site (wet vs dry) and its winding channels are controlled mainly by tidal elevation in intertidal areas. Moreover, the reported results in Omari et al., 2020, showed that fully polarimetric parameters provide the best accuracy due to their high sensitivity to varying surface types. The classification using simulated RCM CP parameters appears slightly less accurate. Still, the CP m-delta obtained results are reasonable when taking the complex and challenging environment into account. The large swath of the CP can encompass the relatively small decrease of classification accuracy compared to FP results, and potentially be used for large scale mapping and monitoring purposes. This may be true for current missions such as ALOS-2 and RCM but a new generation of upcoming satellite SAR missions will be equipped with digital antenna beams offering fully polarimetric capabilities with high resolution and larger swaths.

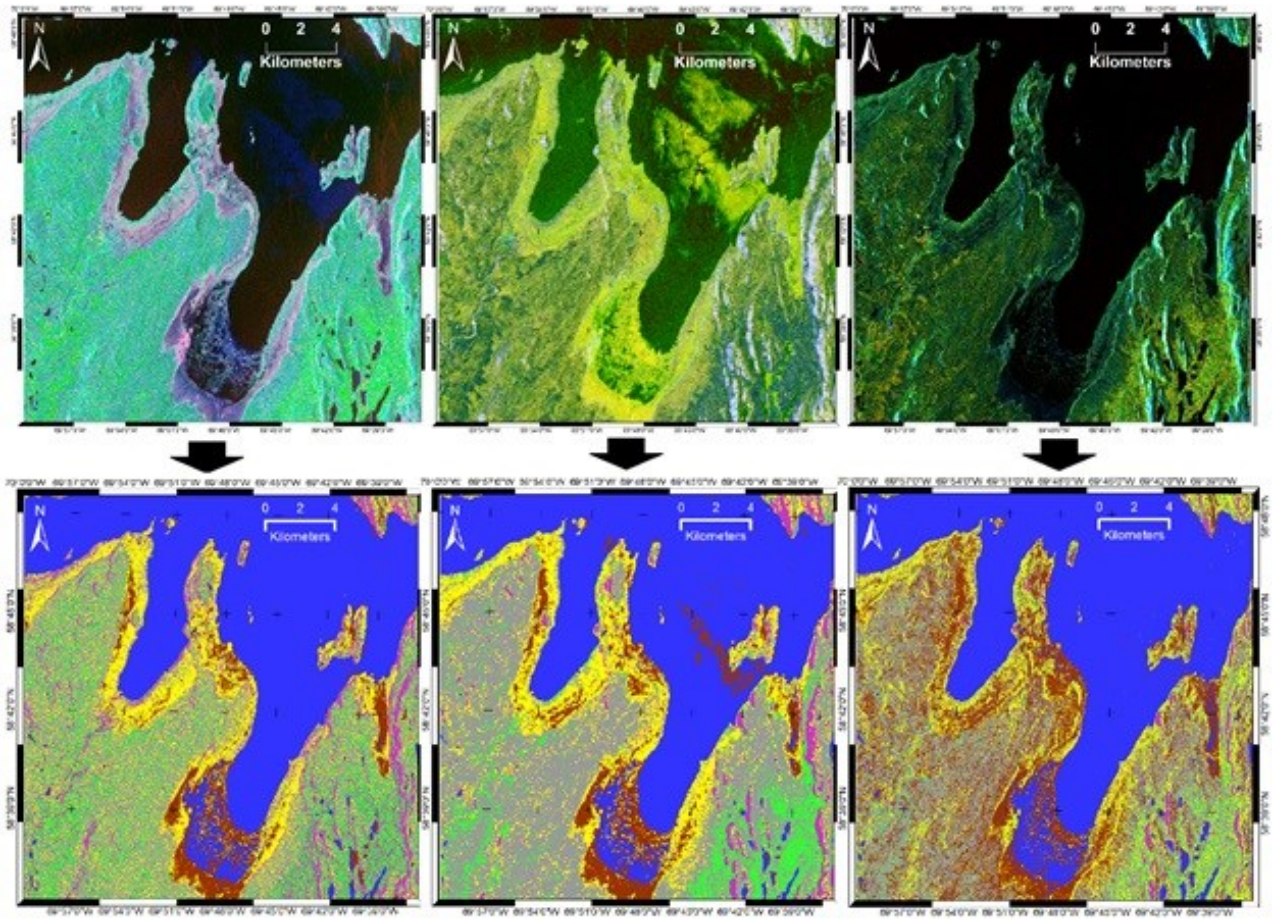

***Figure 11**: Radarsat-2 scene and equivalent Classification results using Random Forest approach over a study area located near the village of Tasiujaq. (a) FP polarimetric Freeman-Durden decomposition (red: double bounce, green: volume scattering and blue: surface scattering), (b) RGB composite of Touzi extrema parameters (red: Pmin, green: Pmax and blue) and (c) is the CP Raney m-delta classification*

4. Discussion

Some recently developed techniques, such as polarimetry for intertidal zone mapping will be integrated in the techniques already in operation like the automatic shoreline detection procedure. This will help reduce the physical component of shoreline extraction and will improve the overall accuracy by reducing human error.

Other EO applications that leverage pre-existing data products have also been developed at CHS. An example of these applications assess water clarity for the planning of LiDAR and imagery acquisitions. Determining the best time of the year to plan LiDAR survey and imagery acquisition is critical to ensure a high level of quality in the data. Avoiding critical dates for alga bloom and sediment deposits will optimize the quality of the data and will reduce the cost of the survey. One of the datasets used by CHS to help plan data acquisition is the MODIS Diffuse Attenuation coefficient for downwelling irradiance at 490 nm (Kd 490) Level 3 data. The Modis Kd 490 products have a 4km resolution but they provide a good indication of the best time of the year to collect data. Research and development is underway to improve mission planning and develop better accuracy in coastal areas. The Kd 489 can be calculated from high resolution data like Sentinel-3A OLCI (300 m resolution) and Sentnel-2 (60 m resolution). In this top-down approach, the lower resolution data are used to target the key dates for the data acquisitions and afterward, the higher resolution data are used to calculate the water clarity in the key periods identified by the

KD 490 obtained from the MODIS data. For the validation of our products, CHS mainly uses multibeam and LiDAR data, but in areas where data is limited, CHS has been looking at other alternatives for validation such as data from the Advanced Topographic Laser Altimeter System (ATLAS) onboard the Ice, Cloud, and Land Elevation Satellite (ICESat-2).

Some applications developed at CHS can also benefit DFO. For example, the InSAR technique can also be used to predict landslides. In June 2019, a landslide along the Fraser River north of Lillooet BC, took place causing big pieces of rock to fall into the river, obstructing the passage of salmon migrating upstream. To prove the suitability of InSAR data processing to monitor the stability of slopes along navigable streams for predicting potential disasters, an interferometric stack of SAR images was used. Upon completion of the InSAR time series analysis, the detection in the progression of displacements over time was analyzed, leading to the identification of the precise location of the landslide incident as shown in ***Figure 12(a). Figure 12(b)*** shows the InSAR Temporal progression displacement. The displacements (in cm) are displayed on the Y-axis while the temporal line is shown on the X-axis (days). The InSAR temporal chart shows that minor displacements started to appear 60 days into the time series analysis, beginning on March 08, 2019. As further InSAR datasets were ingested and processed, an increasing deformation trend was observed until the final collapse of the rock cliff on day 116 when the incident took place (June 23rd, 2019).

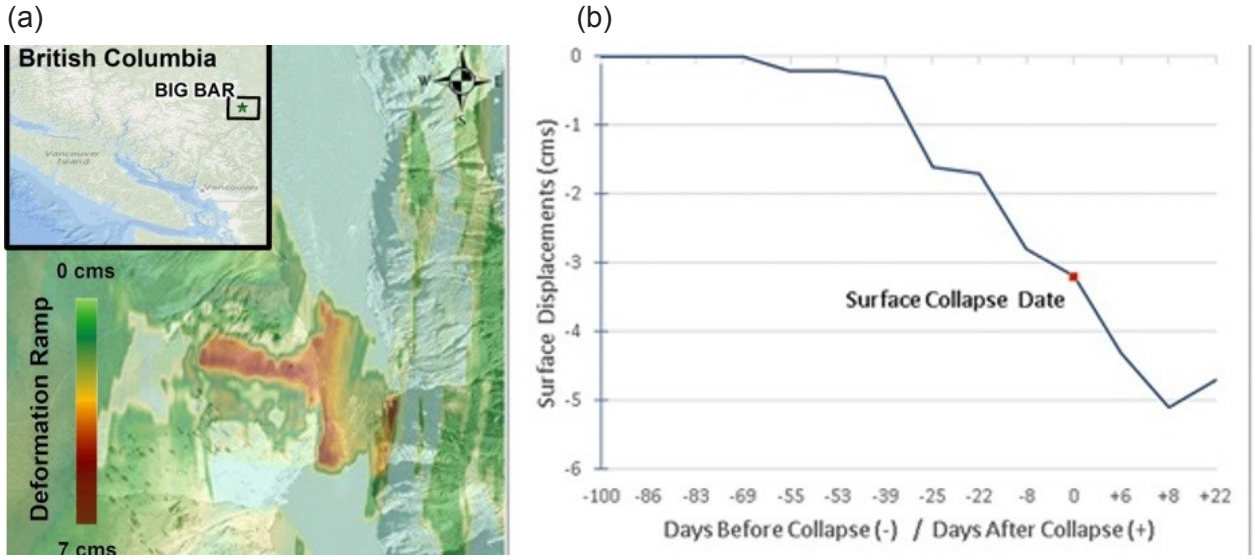

***Figure 12**. (a) Cliff Collapse Location and Deformation Progression Ramp (b) diagram of the collapse in day before and after the collapse day of June 23rd 2019.*

5. Conclusion

As demonstrated in this paper, although different EO techniques can offer many advantages to hydrographic applications, these technologies are still not being utilized at their full potential by HOs. In its specifications of standards, the IHO recognizes the usage of EO in hydrography, however more efforts are still needed to better incorporate EO data. Currently the usage of EO data in official nautical products has been limited. Much of the limited use can be attributed to the lack of qualified expertise in effectively implementing the techniques derived from EO data, as well as the level of confidence which HOs are comfortable in utilizing EO products for hydrographic applications. In order to help accelerate this science, with the support of the IHO, CHS in collaboration with Service Hydrographique et Océanographique de la Marine (SHOM) and the National Oceanic and Atmospheric Administration (NOAA), organized the first International Hydrographic Remote

Sensing workshop (18 to 20 September 2018, Ottawa, Ontario, Canada). At this workshop, 11 HOs were represented and presentations on the different EO applications in hydrography were presented by the HOs, government agencies, members of the private sector as well as representatives from universities. To help the progression of the usage of EO data, a report was presented at the 2nd IHO Council meeting (IHO Council, 2018).

"I*t was felt that regional hydrographic commissions should encourage the use of hydrographic remote sensing (HRS) and satellite-derived bathymetry (SDB) imagery should be used daily by Hydrographic Offices to improve chart information and assist in making cartographic decisions".*

" The Secretary-General pointed out the interrelationship between SDB and S-44 and the compelling need to open categories beyond nautical charting surveys, using a metrics approach. The Chair of HSSC gave assurance that HSPT was working on the metrics in liaison with other working groups, especially with respect to data quality. Participants welcomed the excellent report and the use of SDB/HRS, highlighting its value for planning purposes and with respect to highly changeable areas, including in areas with high tectonic activity and islands that were not easily accessible"

In order to further implement the use of EO data throughout CHS and to help recruit the expertise needed within the organization, a Remote Sensing Center of Expertise (CHSRSCoE) was created in 2017 to apply the EO techniques developed. As previously mentioned, the most common requests are for the creation of new shorelines, but in June of 2018, CHS updated its first chart that has been updated using SDB data (Havre-aux-Maisons, CHS chart 4955, New Edition: 06/15/2018). CHS has also developed processes to include SDB data in future chart production. The RSCoE at CHS will continue developing new approaches that can help leverage the advantages offered by EO data and adapt the developed techniques to the large variety of new sensors and EO products that will become available in the future.

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7. Authors Biography

René Chénier is a manager at the Canadian Hydrographic service (CHS) where he is managing the Geodesic, Geomatics and Remote Sensing groups. René has been working at CHS for the last 10 years here he has established the CHS Remote Sensing centre of expertise. His fields of expertise include Satellite Derived Bathymetry (SDB), Interferometric synthetic aperture radar (InSAR) , Polarimetry, Geometric modeling , Photogrammetry , Radargrammetry, Digital Elevation Model, Classification using artificial intelligence, ship detection and Monitoring, Hydrography , cartography , costal erosion and habitat mapping.

Khalid Omari received the PhD and MSc degrees in remote sensing from the Ottawa-Carleton Geoscience Center, University of Ottawa in 2009 and 2002 respectively. After 14 years as remote Sensing scientist at the Canada Centre for Remote Sensing (CCRS)/Canada Centre for Mapping and Earth Observation (CCMEO), he joined the Canadian Hydrographic Service (CHS) at Fisheries and Oceans Canada (DFO) where he is currently remote sensing scientist developing applying methodologies and approaches of Earth observation generated product related CHS applications. His prior research at CCRS was related to EO applications using SAR polarimetry, Interferometry and optical multispectral/hyperspectral related techniques. His Ph.D. dissertation focused on radiative transfer modeling in vegetation canopies and the extraction of biophysical and biochemical parameters of vegetation canopies from hyperspectral data.

Enrique Blondel is a Researcher at the Canadian Hydrographic Service, Fisheries and Oceans department. He graduated as a civil engineer at the Universidad de los Andes (Venezuela) and further studied at l'Université du Québec à Montréal in Geographic Information Systems (GIS). He has 25 years of experience in photogrammetry and remote sensing analyzing and processing synthetic aperture radar imagery for radargrammetry and interferometry applications to generate digital elevation and surficial temporal displacement/deformation models covering natural resources, mining, oil & gas, urban and coastal environments within the Canadian context since 2005; and in the oil and gas field, in the Venezuelan oil industry during the period 1995-2002 in the construction of oil and gas facilities. He has worked for the past 9 years in the research and development of methods with a focus on processing and validation of synthetic aperture radar imagery related to the monitoring and early detection of surficial deformations using interferometric SAR and the generation of InSAR derived digital elevation models in Canada and other countries. Mr. Blondel is furthermore an active landscape photographer enthusiast and deep-sky astrophotography hobbyist.

Adam Jirovec has been working at the Canadian Hydrographic Service since 2017, in both the Geomatics and Remote Sensing groups. Adam has over 10 years of GIS and Remote Sensing experience in both a professional and academic setting. He graduated from the University of Ottawa in 2011 with a Bachelor of Arts with a Specialization in Geography, and also holds a post graduate certificate in the Geographic Information Systems program at Algonquin College. His work at the Canadian Hydrographic Service has focused on utilizing Remote Sensing data for charting applications such as coastal mapping, shoal detection and satellite derived bathymetry.

Mesha Sagram has been working in the remote sensing group at the Canadian Hydrographic Service (CHS) since 2018 where she has gained much of her experience in remote sensing. Prior to this position, Mesha completed a wide variety of GIS projects through educational and work experience. She has attained a Bachelor of Science degree with Honours in Environmental Science, an Advanced Diploma in GIS Applications, and an Ecosystem

Restoration Graduate Certificate. In the past year, Mesha finished her Master of GIS Applications degree which was focused on improving satellite-derived bathymetry (SDB). Currently, her role at CHS includes research in SDB and deep learning, as well as coastal mapping and shoal detection.

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Articles

THIRTY YEARS OF SATELLITE DERIVED BATHYMETRY
The charting tool that Hydrographers can no longer ignore.

By J. Laporte[1], H. Dolou[1], J. Avis[1], O. Arino[2]

1. ARGANS Ltd
2. European Space Agency

Abstract

Thirty years after being introduced into national chart series, Satellite Derived Bathymetry (SDB) charts are still struggling to be recognised as valid navigation documents, capable of meeting the level of confidence required by the S-44 IHO standards for hydrographic surveys.

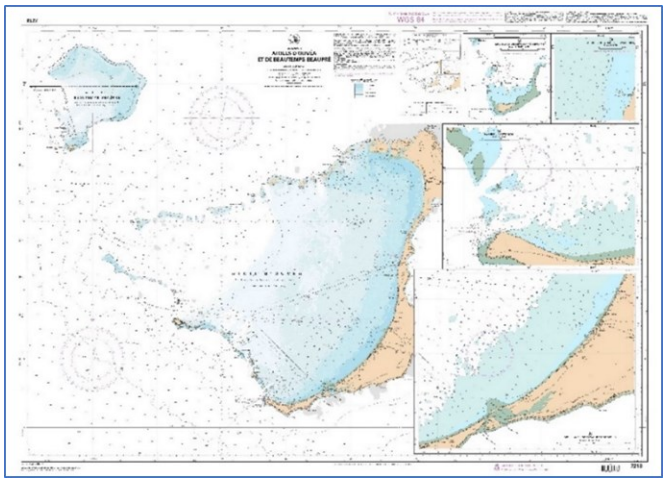

Figure 1 *: The first SDB official chart, © 2010 SHOM (Publication 1990 based on a 1988 Spot image)*

The advent of new generation satellite constellations, such as Sentinel-2[3], provide improved geolocation and, thanks to higher revisit frequency, an almost unlimited capacity to detect natural dangers visible from space within the limits of the sensing instruments. Thus, this negative vision of SDB must change.

Written by Hydrographers, this article aims to provide a scientific background adapted to practical Hydrography; introduce the notion of "Perfect Image", first mentioned at the International Hydrographic Remote Sensing workshop (Ottawa, September 2018); and rehabilitate older concepts such as Depth of Penetration (DOP), which make SDB an incomparable instrument to chart the World's shallow waters (***Figure 1***). Here, "incomparable" does not mean "perfect", as there are limits to SDB capacity to detect and quantify bottom structures that will be detailed later.

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[3] *The frequent mention of Sentinel-2 should not lead the reader to believe that the authors are focussing on this constellation. The intention is to show how satellite hydrography has evolved naturally from exploiting unique images to processing large collections that provide ever-improved information, the latest example happening to be Sentinel-2.*

Résumé

Trente ans après leur introduction dans les portefeuilles nationaux, les cartes issues de la bathymétrie par satellite (SDB) rencontrent toujours des difficultés à s'imposer en tant que documents satisfaisant aux exigences de sécurité de la navigation, requises notamment par la publication S-44 (Normes de l'OHI pour les levés hydrographiques).

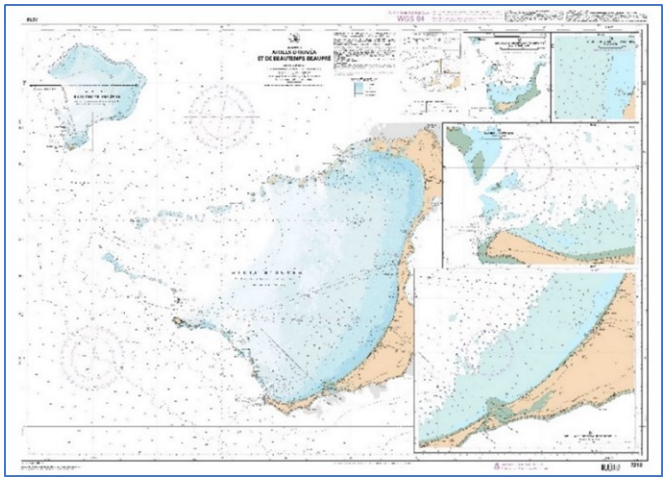

Illustration 1: La première carte SDB officielle, © 2010 SHOM
(Publication 1990 basée sur une image Spot de 1988)

Or, l'avènement d'une nouvelle génération de constellations satellitaires telles que Sentinel -2 [3], offre une géolocalisation améliorée et, grâce à leur haute fréquence de répétitivité, une capacité presque illimitée de détection des dangers naturels visibles depuis l'espace dans les limites des performances des capteurs embarqués. Aussi, cette vision négative de la SDB doit-elle changer.

Écrit par des hydrographes, cet article vise à fournir un contexte scientifique adapté à la pratique de l'hydrographie, à introduire la notion de «*Perfect Image*», mentionnée pour la première fois lors de l'atelier télédétection hydrographique, Canada 2018, et à réhabiliter des concepts plus anciens comme la profondeur de pénétration (DOP), qui fait de la SDB un instrument incomparable pour cartographier les eaux peu profondes du monde (***cf. illustration 1***). Ici, «incomparable» ne signifie pas «parfait», puisqu'il y a des limites à la capacité de la SDB à détecter et à quantifier les détails du fond. Ces limites sont argumentées dans l'article.

[3] *La mention fréquente de Sentinel-2 ne devrait pas amener le lecteur à penser que les auteurs se concentrent sur cette constellation. L'intention est de montrer comment l'hydrographie par satellite est naturellement passée de l'exploitation d'images uniques au traitement de grandes séries qui fournissent des informations toujours meilleures, le dernier exemple étant Sentinel-2.*

Resumen

Treinta años después de haber sido introducidas en las series de cartas nacionales, las cartas de Batimetría satelital (SDB) siguen luchando por ser reconocidas como documentos de navegación válidos, capaces de cumplir con el nivel de confianza requerido por la norma S-44 de la OHI para levantamientos hidrográficos.

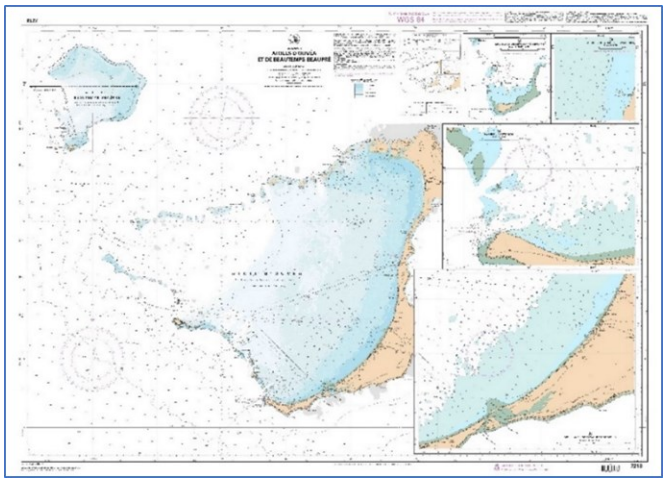

Figura 1 : La primera carta oficial SDB, © 2010 SHOM
(Publicación de 1990 basada en Spot image 1988)

La llegada de las constelaciones de satélites de nueva generación, como Sentinel -2[3], proporcionan una mejor geolocalización y, gracias a una mayor frecuencia de revisiones, una capacidad casi ilimitada de detección de peligros naturales visibles desde el espacio dentro en los límites de los instrumentos de detección. Por lo tanto, esta visión negativa del SDB debe cambiar.

Escrito por Hidrógrafos, este artículo tiene por objeto proporcionar antecedentes científicos adaptados a la Hidrografía práctica; introducir la noción de «Imagen Perfecta», mencionada por primera vez en el Taller Internacional de Teledetección Hidrográfica (Ottawa, septiembre del 2018); y rehabilitar conceptos más antiguos como la Profundidad de Penetración (DOP), que hacen de la SDB un instrumento incomparable para cartografiar las aguas poco profundas del mundo (***Figura 1***). Aquí, «incomparable» no significa «perfecto», ya que hay límites a la capacidad de la SDB para detectar y cuantificar las estructuras del fondo que se detallarán más adelante.

[3] La frecuente mención de Sentinel-2 no debería hacer creer al lector que los autores se centran en esta constelación. La intención es mostrar cómo la hidrografía satelital ha evolucionado naturalmente de la explotación de imágenes únicas al procesado de grandes colecciones que proporcionan información cada vez mejor, siendo el último ejemplo Sentinel-2.

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1. Background

Since the beginning of seafaring, careful visual watching of dangers has been the Navigator's best asset for survival in shallow waters. During his search for traces of the unfortunate Lapérouse expedition, Beautemps-Beaupré, who would become Napoleon's Hydrographer, had refined Captain Cook's geometrical method of determining South Pacific reefed coastlines from a safe distance by taking sights with a sextant from the ship crow's nest. Replace the lookout with an optical sensor, human appreciation of shoals' glow by stricter measurements of reflectance, and rule of thumb by bathymetric modelling, and you have all the ingredients of today's Satellite Derived Bathymetry.

The main drivers for the use of SDB are the need to achieve full bottom coverage, ability to provide horizontal precision comparable with the ship's positioning systems, and provision of a reliable image-based alert system when shallow dangers are suspected in the absence of traditional field surveys, irrespective of vertical measurement that SDB is unable to yield with the precision required by the IHO S-44 Standards. None of these can be achieved unless the environment conditions are adequate, i.e. clear skies and waters transparent enough to see the bottom, which were also Captain Cook's preconditions and are now remote sensing's major constraints, somewhat attenuated by the availability of larger collections of images.

If one waits long enough to meet these requirements with ever improving satellite constellations, sustained by practical scientific considerations, all based on empiric observations, there is no reason not to be able to chart most of the World's coastal areas, which up to the present time have remained 99% unsurveyed according to the GEBCO database. Funding such a major undertaking has always been, and shall remain, an issue however, compared to traditional methods that would take hundreds of years and require massive resources, SDB images and processing are affordable, easy to use and accessible to all. Provided they have been cleared of cloud cover and impenetrable turbid patches, and given enough images, a SDB time series can theoretically track everything within the DOP, extricate permanent bottom structures from transient background, and yield validated, although vertically imprecise, bathymetric information. No costly classical survey methods limited to one single swath could deliver the same. When validated by professional hydrographers, SDB seems good enough to fill the World's empty coastal databases and fulfill developing countries' mapping requirements. Further, if regulated by sworn Hydrographers sanctioned by the IHO, SDB can lend added confidence to the qualitative information needed by Mariners for safer navigation.

2. C-13 Manual on Hydrography update

Although broached superficially by the C-13 Manual on Hydrography, last updated in 2011, satellite imagery has been used since the 1980's by Hydrographic Offices, mainly for topography updates and survey planning. Since then, Space Agencies have significantly improved Earth Observation (EO) sensors, spatiotemporal resolution and image quality, whilst laboratories developed their own requirements for habitat classification and environmental monitoring. Despite non-existent IHO procedures, SDB products also started to be promoted and delivered by private service providers for large environmental projects such as a survey of the Great Barrier Reef. With the exception of the International Hydrographic Remote Sensing workshop organised in 2018 by the Canadian Hydrographic Service, the Hydrography community remained conspicuously absent during these developments, which seems indicative of a lukewarm interest despite early support from IHO leaders.

However, by making use of the latest EO satellite improvements, notably revisit time and sensor spectral performances, hydrographic research and development entities, mainly supported by the European Space Agency and few advanced HOs, have developed new tools and gathered

sufficient evidence to confirm the benefits SDB can offer toward improving coastal water cartography, i.e:

- Near absolute capability to detect natural bottom structures in shallow waters up to depths of about 20 metres, providing the bottom is unambiguously visible from space;
- 11 metres or even better absolute horizontal precision without further ground control;
- spectrally calibrated composite images free of corrupted pixels. To designate these spatiotemporal objects, the term “Perfect Images” was introduced incidentally at the 2018 Remote Sensing workshop mentioned earlier;
- the potential to develop Depth of light Penetration statistics applicable to optical remote sensing worldwide;
- and, thanks to the elimination of corrupted pixels, improved depth assessment, in spite of being generally outside S-44 standards except in small areas endowed with a well-controlled environment.

2.1 Methodology

2.1.1 SDB Theory

Before plunging headfirst into abstract formulae, the Hydrographer must bear in mind that SDB is not a pure mathematical science, but is the art of rigorously interpreting natural phenomena characterised by an almost infinite quantity of unknowns. Achieving the true water depth from multi-spectral imagery depends on the analyst but, their interpretation, supported by physics-based equations governing the propagation of photons from the source of energy to the sea bottom and back to the satellite (***Figure 2***), categorises SDB as an applied science.

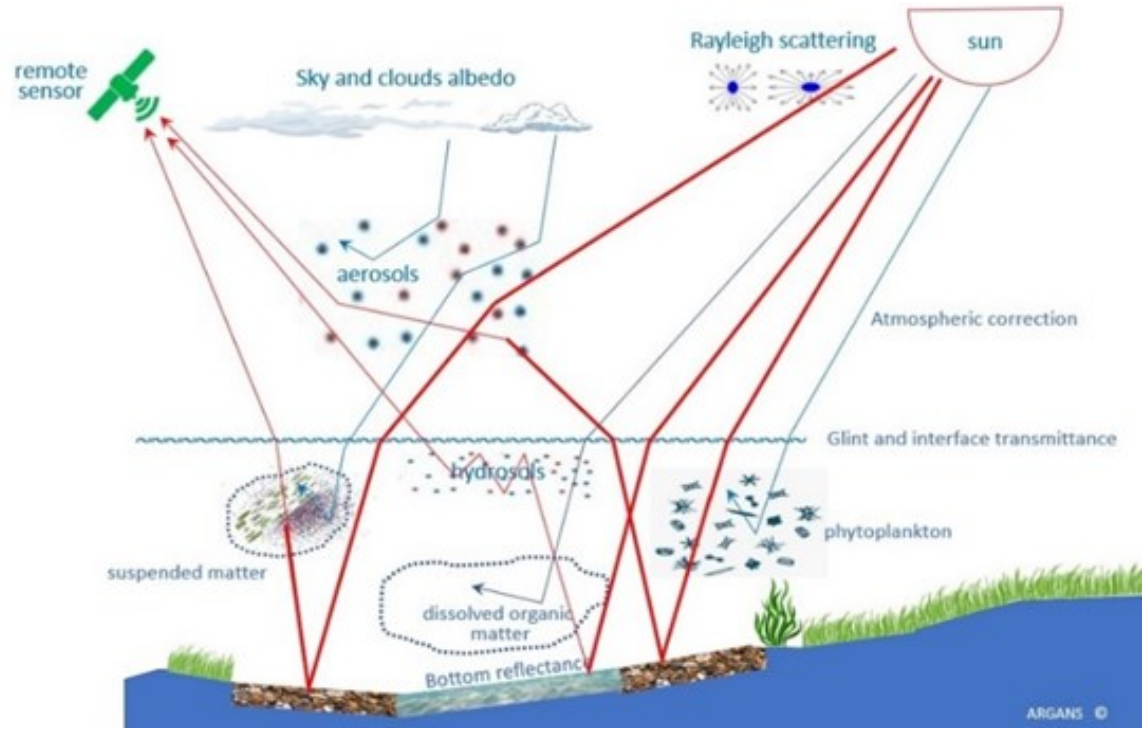

Figure 2 *: SDB fundamentals: only red paths may contain attenuated depth information.*

To solve the simple depth equality: (Z = a function of an almost infinite quantity of unknowns), the analyst disposes of a limited set of equations provided by the sensor's spectral bands, five at the most: blue and/or coastal blue, green, yellow and two near infrareds. This system can't be resolved unless the number of unknowns is reduced drastically by selecting small areas characterised by similar environmental conditions, leaving only those unknowns necessary to find a solution to the basic equation of radiative transfer, which extracts the bottom signal; i.e. the Remote Sensing Reflectance R_{rs}[7] observed by the satellite after travelling though the water column, across the surface, and through the atmosphere.

For the record, the remote sensing reflectance R_{rs} above the surface, which is provided by satellite missions' L2A products [8], is linked to the reflectance [9] in the water by :

$R_{rs}\left(0^{+},\theta_{obs}^{air},\theta_{sun}^{air},\phi\right)=\frac{t}{n^{2}}\frac{E_{0}\left(0^{-}\right)}{E_{0}\left(0^{+}\right)}r_{\infty}\left(0^{-},\theta_{obs}^{w},\theta_{sun}^{w},\phi\right)$, where t is the transmittance of radiance from water to air, and n is the index of refraction of water: $t \cong 0.96$, $n \cong 1.34$ and the ratio of irradiances $\frac{E_0(0^-)}{E_0(0^+)}$ is close to 1 when the sun is vertically overhead.

In short, calculating Reflectance is all about counting bottom-reflected photons reaching the sensor against a noisy background. Optimising the Signal to Noise Ratio (SNR) depends on increasing the number of photons comprised in the signal, using a performing sensor, and filtering noises. This in turn calls attention to the pixel size and the image spectral resolution, which cannot be extended indefinitely at the expense of SNR.

A last point, possibly the most important, is the paramount predominance of human supervision over models. SDB techniques process the colour of each pixel individually and are incapable of establishing a correlation with the next pixel and surrounding environment. Only an experienced analyst can form an intelligent judgement and decide between two solutions (***Figure 3***) which is the most plausible. With the advent of Landsat-8 and Sentinel-2 time series, this supervised approach can be substantially simplified by machine learning methods, such as Random Forest[10], trained to generate optimal solutions amongst numerical models.

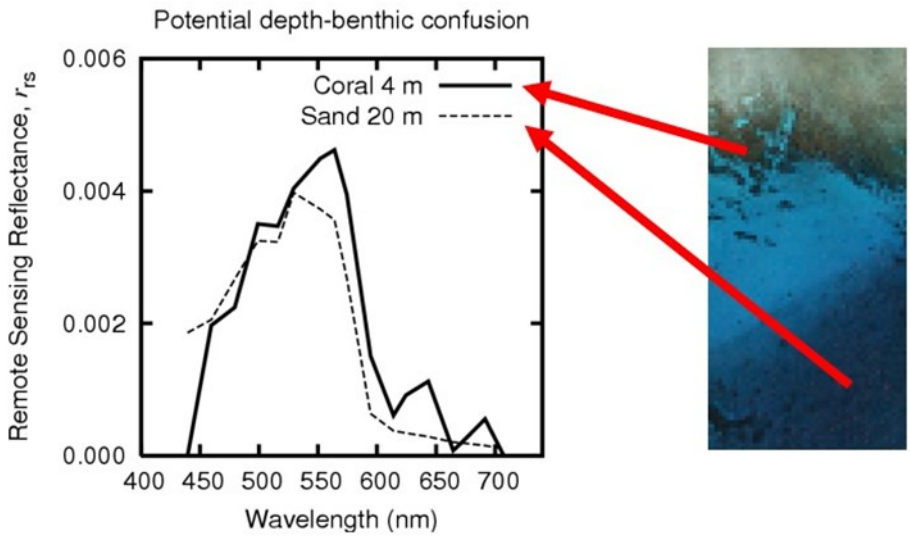

Figure 3 *– SDB Fundamental Uncertainty. (source: Dr Hedley's IDA tutorial 2019)] Only the analyst can decide whether the same dark pixel corresponds to a deep sandy bottom or a shallow dark bedrock.*

[7] *The reflectance R(z,λ) of the surface of a material is the fraction of incident radiant flux reflected by that surface*
[8] *Sentinel-2 L2A: Bottom-Of-Atmosphere (BOA) reflectances in cartographic geometry.*
[9] *E_0 = scalar irradiance; R = irradiance reflectance; 0^+, 0^- = altitudes 0 above and under the surface; θ = direction; Φ = power. These are further developed at Table 1.*
[10] *Breiman, L. Random Forests. Machine Learning 45, 5–32 (2001).*

2.1.2 Equations, Notations, Models and Software

Rather than going through the mathematical developments needed to describe the laws of radiative transfer, we shall review the ingredients used in the SDB cooking recipe, i.e. the light propagation basic principle, the Radiative Transfer Equation, the variables at play and their mathematical notations, the unknowns, and finally the software.

⇒ **Maximum depth achievable in coastal waters**

Considering that photons must travel a round-trip, 25 metres is the maximum depth achievable in Case-2 shallow waters as shown by the NOAA light absorption diagram. (***Figure 4***)

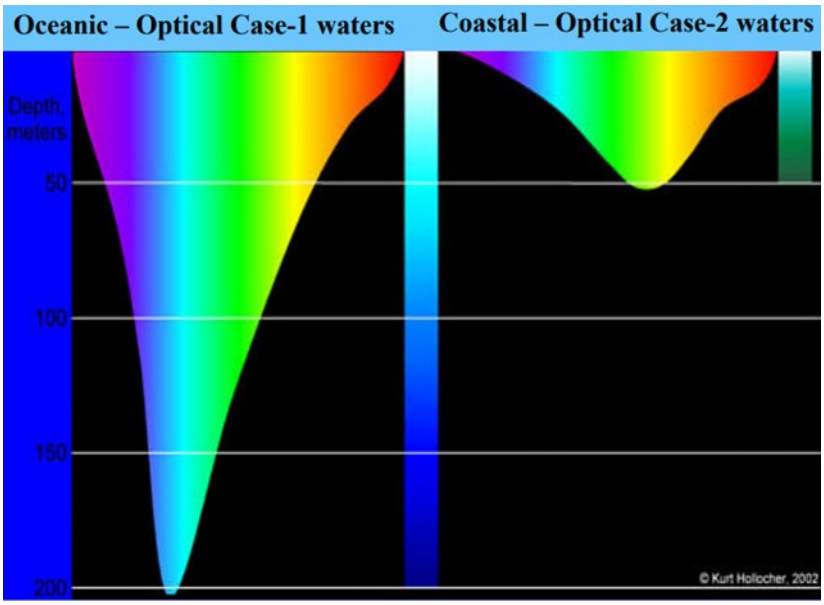

Figure 4 *:SDB fundamentals: Light penetration in Case 1 and 2 waters (Image courtesy of Kyle Carothers, NOAA-OE)*

⇒ **The Radiative Transfer Equation (RTE)**

The useful depth information has to be extracted from the radiance components received by the satellite detector. Presuming that data have already been corrected for atmospheric and air/water interface effects, the relationship between the water Intrinsic Optical Properties (IOPs) and the radiance can be described by the formula that Curtis Mobley calls ***the formidable integro-differential Radiative Transfer Equation[11].***

$$cos\theta \frac{dL(z,\theta,\varphi,\lambda)}{dz} = -c(z,\lambda)\, L\,(z,\theta,\varphi,\lambda) + \int_{4\pi} L(z,\theta',\varphi',\lambda) \times \beta(z;\theta',\varphi'$$

$$\rightarrow \theta,\Phi;\lambda)d\Omega' + S(z,\theta,\varphi,\lambda)$$

[11] *Radiative Transfer in the Ocean, C.D. Mobley, Copyright © 2001 Academic Press, p.23252321 - 2329 .*

Rather than discussing the RTE in detail, we shall give an idea of the variables at play by displaying Mobley's notations, familiar to environment scientists who normally prefer focusing on practical software applications than cross-questioning already established fundamentals.

⇒ Mobley's notations

The table below gives a rough idea of the variables at play and the symbols most commonly used by Mobley and the RTE.

Table 1 – A selection of common RTE symbols and abbreviations[11]

AOP	Water Apparent Optical Properties, related to IOP through the RTE
DOP	Depth of Penetration. Depends on IOP, air/sea interface, sky radiance, sun viewing angle and irradiance.
IOP	Water Inherent Optical Properties, i.e. concentrations in Chlorophyll, CDOM, etc.
OAC	Optically Active Components
RTE	Radiative Transfer Equation
E_d^{0+} (S_{ky}, Θ_s)	Irradiance measured on the sea-surface, combining skylight (S_{ky}) and sunlight (Θ_s)
E_d (z,λ)	Downwelling irradiance
K_d (z,λ)	Diffuse attenuation coefficient, i.e. decrease with depth of the ambient downwelling irradiance
ϕ_v	Viewing azimuth angle from the solar plane
L_w	Water leaving radiance. This measures light intensity of light, i.e. the luminance emitted from a surface per unit area (solid angle)
λ	A wavelength in the Ω_{VNIR} region
O^+	a position of observation just above the sea-surface
O^-	a position of observation just below the sea-surface
$R_{rs}(\theta,\phi,\lambda)$	Spectral Remote Sensing Reflectance of the ocean
$R(z,\lambda)$	Irradiance Ratio (E_u/E_d), a measure of how much of the radiance E_d traveling in all downward directions is reflected upward into any direction E_u
$S(z,\theta,\phi,\lambda)$	Source light term
S_{ky}	Skylight with sources (light diffusion on molecules and aerosols) and sinks (clouds, attenuation on molecules and aerosols) in the whole semi-hemisphere
ρ	Light reflectance (ratio of radiances) on sea bottom
Θ', ϕ'	Incident direction
Θ, ϕ	Scattered direction
Θ_v	Viewing angle from nadir
Θ_s	Subsurface solar viewing angle from zenith
Ω_{VNIR}	Visible and near infrared spectral band, between 400 and 1100 nm
z	Depth z at position *Lat, Long*

⇒ RTE basic function and algorithms

To retrieve depths in shallow-waters, remote sensing must simultaneously combine the effects of bottom reflectance, water-intrinsic optical properties, atmospheric corrections, interface transmittance (characterised by surface glint) and the various scattering and absorption properties depicted in ***Figure 2***.

SDB basic assessment is that all power fluxes, i.e. the various radiances and irradiances, decrease exponentially with depth in homogenous water, free of local boundaries effects.

We are still struggling with the boundary effects that bring about additional components in the simplified spectral irradiance, caused by multireflection under the surface or by suspended particles. These boundaries effects were correctly identified by Mobley, but intentionally ignored in his Hydrolight model that our most qualified Scientist, Martin-Lauzer[12], tries to improve. Using Mobley's notation, the relation between depth and radiant energy due to this exponential decrease can be written conveniently as:

$$E_d(z,\lambda) \equiv E_d(0,\lambda) \exp\left[-\int_0^z K_d(z',\lambda)\, dz'\right]$$

in which appears the SDB's most important function K_d (z, λ), e.g. the diffuse attenuation for spectral irradiance. K functions depend mainly on water properties (IOPs), and marginally on environmental conditions such as sun incident light and sea state. K functions are computed using Mobley's Hydrolight radiative transfer numerical model that gives analysts the ability to simulate different environmental conditions and adjust their parameters.

A detection occurs when the optical sensor sees a fluctuation due to a photon hit. The fluctuation might be on one pixel $\delta L_b(\vec{x}_0)$ or a few pixels $\left\{\delta L_b(\vec{x}) \middle| \vec{x} \in V(\vec{x}_0)\right\}$ where $V(\vec{x}_0)$ is a vicinity of $\vec{x}_0$

Bottom detection occurs when $\mathrm{mes}\left\{\delta L_b(\vec{x})\right\} \geq \Delta^{\mathrm{trh}}_{\mathrm{mes(L)}}$ where mes is a measure of the water leaving radiance L_w, and $\Delta^{\mathrm{trh}}_{\mathrm{mes(L)}}$ is a threshold.

⇒ Unknowns and the obligation to restrain analysis to small areas

As said earlier, there is almost infinite unknowns at play to characterise the layers that photons have to pass through during their transit from the sun and sky to the sea bottom and back to the satellite sensor. Most SDB parameters are determined by field observations and plotted on spectral diagrams, found in scientific papers, where they can be retrieved and be fed into SDB models.

These parameters include absorption, scattering in the water column and Rayleigh scattering in the upper atmosphere, reflection from the bottom and the surface, emissivity from the sun and the sky above, transmissivity across the air/water boundary, glint corrections depending of the force & direction of the wind and swell, water organic and inorganic constituents, types of aerosols, ad *libitum*.

To find a solution to such a large system, the ocean has to be subdivided into small homogeneous areas of similar composition, each of which can be described by a simple forward model of the form:

$$r_{rs}(\lambda) \approx f\,(P, G, X, H, E, m)\,(\lambda),$$

where $r_{rs}(\lambda)$ is the remote sensing reflectance of the ocean as seen from space, P is the concentration of phytoplankton, G is the inorganic *Gelbsdorf* absorption, X is the particle backscattering, H is the depth, E is an endmember characterising the types of bottom (sand, mud, rocks, algae; etc.) and m is their mixing ratio.

It might be tempting to use n-bands hyperspectral instead of m-bands multispectral sensors to augment the number of equations (n > m) but this is an illusion[13] as the signal to noise ratio would

[12] *SHOM's most capable Physicist, Martin-Lauzer*

[13] *e.g. see Remote Sensing of Coastal Aquatic Environments pp. 77 & 78, edited by Richard Miller et al. ©Springer 2005 .*

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then become indistinct and unable to provide exploitable solutions. Satellite hyperspectral sensors, with their well-known ability to classify bottom structures, have very narrow bands (1:10th to 1:100th those of multispectral captors such as Sentinel MSI or Landsat OLI) and receive less photons, making them comparable to VHR satellites that deliver less depth information due to their lower SNR.

⇒ **The two Empiric and Physics-based approaches**

All SDB models must be able to match convincingly the solutions they have provided with the observed reality. Unfortunately, due to the quasi-infinity of unknowns and the limited availability of observations, there can't be any solution unless carefully thought simplifications are introduced. These in turn entail differences between the model's results and the field observations that define an uncertainty interval characterised as best as possible by error bars.

There are traditionally two types of SDB models based on spectrum-matching; the first, called **"Empiric"** or data-based, after Lyzenga (1978) and upgraded by Stumpf et al. (2003), requests establishing, by Monte-Carlo experiments, a linear regression between observed points and modelized pixels of known radiance and assumes that the behaviour law thus defined can be applied across the whole image; the second, called **"Physics-based"** after Lee, Mobley et al. (1999) relies on direct radiative transfer models simplified by the use of semi-analytic formulae.

In fact, both approaches are empiric and physics-based. Both assume that the light attenuation with depth is approximately exponential, require some preliminary knowledge of the water column constituents and spectral behaviour of the substrate, and both are of the form:

$$R_{rs}(\lambda) \approx B + A \exp(-k \text{ x depth})$$

where the coefficient A, B and the k function are deduced by regression to empirical data for the whole image by Lyzenga and constrained within every pixel by what is physically possible in physics-based methods.

⇒ **Software**

Software methodologies leave aside the problem of atmospheric correction and focus on analysing the separation between the signals from the water column and seabed.

There are two groups of methods depending whether radiances are measured (e.g., absorption and scattering coefficients), or pre-defined.

The table below[14] quotes twenty known models referred to in the list of publications *in fine*, but there seems to be no limit to the number of candidates.

Reference	Approach	Resolution	Output	Applicability
Lyzenga	Band combination	Multispectral	Combination of bands	First "empiric" model (1978) applicable in high transparency waters and homogeneous bottoms. Poor in shallow waters.
Spitzer & Dirks	Band combination	Multispectral	Composition of 2 to 3 bands	Developed for SPOT and Landsat. Same as Lyzenga.
Tassan	Band combination	Multispectral	Combination of bands	Sequential application to turbidity gradients.
Sagawa et al.	Band combination	Multi and Hyperspectral	ρ index	Suitable to poor transparent waters but needs good map references.

[14] *Source of information: ARGANS internal R&D and Water and Remote Sensing publication: Column Correction for Coral Reef Studies by, by Maria Laura Zoffoli, Robert Frouin and Milton Kampel - Sensors 2014, 14, 16881-16931.*

Conger et al.	Band combi-nation	Multi and Hyperspectral	Pseudo-colour bands	Assumes homogeneous environment. Ineffective in red band.
Gordon & Brown	Algebraic	Multi and Hyperspectral	ρ index	Assumes homogeneous environment and empirical determination of parameters.
Maritorena et al.	Algebraic	Multi and Hyperspectral	ρ index	Assumes homogeneous environment and high transparency.
Bierwirth et al.	Algebraic	Multi and hyperspectral	ρ derivation	Needs clear waters. Yields composite maps of depths structure and bottom re-flectance.
Purkis & Pasterkamp	Algebraic	Multispectral	ρ index	Assumes high transparency and needs good map references.
Lee et al.	Algebraic	Multispectral	ρ index	Semi-analytical. Uses detailed IOP and assumes homogeneous environment.
Yang et al.	Algebraic	Multispectral	ρ index	Analytical. Suitable to multi layered water column.
Louchard et al.	Optimized matching	Hyperspectral	Bottom types, Z and OAC	Requires careful preparation of spectral library.
CRISTAL	Optimized matching	Hyperspectral	Bottom types, Z and OAC	Requires careful preparation of spectral library.
BRUCE	Optimized matching	Hyperspectral	Bottom types, Z and OAC	Requires careful preparation of spectral library. Useful in low diversity areas.
SAMBUCA	Algebraic	Hyperspectral	Bottom types, Z and OAC	Assumes that bottom is a linear combina-tion of two substrates. Derived adaptation of Lee et al inversion scheme to optimise depth retrieval.
SWAM	Algebraic	Hyperspectral	Bottom types, Z and OAC	Adaptation of SAMBUCA developed for integration into SNAP/Sentinel-2 toolbox. This still needs software optimisation to make it performing and user-friendly.
BOMBER	Algebraic	Hyperspectral	Bottom types, Z and OAC	Derived adaptation of Lee et al inversion scheme to optimise bio-optical outputs.
Hedley's Image Data Analysis (IDA, ex-ALUT)	Optimized matching	Hyperspectral	Bottom types, Z and OAC	Derived adaptation of Lee et al inversion scheme. A user-friendly workhorse that optimizes computing time by subdividing parameters space.
PIF	Multitemporal analysis	Multi and hy-perspectral	Normalised time series	Pseudo Invariant Features using DNs (digital numbers) of co-registered time series of same satellite.
Bertels et al.	Geo-morphologic	Multi and hy-perspectral	Maps of bot-tom types	Suitable to reefs of consistent bottoms and environment.

2.1.3 Satellite Images

⇒ **Image selection**

There cannot be good SDB modelling without excellent images.

Twenty years ago, good images were so rare that it could take up to five years to select, at great cost, a reasonably exploitable scene (***Figure 5***), but things have changed for the better. EO

analysts now have access to a large supply of images of various resolutions and performances.

Further, the advent of high-resolution, high-revisit, free-access constellations, such as the Sentinel family of the Copernicus programme, have considerably changed the traditional approach by offering calibrated time series that can be merged into co-registered and spectrally normalised "Perfect Images", free of clouds and transient artefacts.

Although not as simple as it looks, downloading large numbers of images can be realised from ESA or NASA open-access hubs, but is best achieved by non-commercial applications such as CODE-DE (https://code-de.org/) that offers more than 15 PB of Sentinel and Landsat data, or at cost through commercial service providers, such as Amazon, Sinergise and others, who offer additional facilities such as full visualisation of scenes allowing for a preliminary selection according to cloud cover, glint and water turbidity.

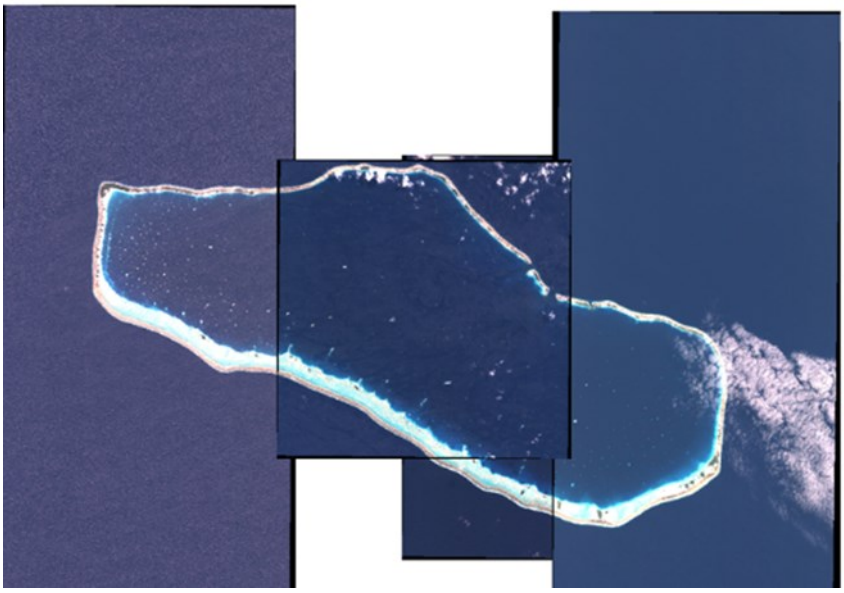

Figure 5 *: A Pleiades 4-images mosaic]*
In spite of appearances, the two left scenes are worthless because of glint

⇒ HR or VHR imagery?

Until very recently, it was assumed that best results could only be obtained with expensive, very high-resolution (VHR) imagery, rather than using free HR satellites such as Landsat 8 or Sentinel 2. This changed dramatically after extensive tests, covering a large number of sites, mages and constellations carefully selected by a Hydrographic Office, established that better results were in fact obtained with time series of lesser resolution, and not occasionally but systematically. Although results are generally protected by Intellectual Property Rights, the test results obtained in 2019 under the aegis of the European Space Agency can be made available to the public.

This can be explained in simple terms by considering how an HR 10 x 10 metre pixel receives more photons than a VHR 0.5 x 0.5 metre's, resulting in a better Signal to Noise Ratio. But this is not all as better captors such as Sentinel-2 MSI endowed with more spectral bands and band shift control have been developed. And further, one may speculate whether a 0.5 x 0.5 metre resolution is really necessary when natural microstructures eventually detected by VHR images are included in the same generalised contour, stretched for security reasons at scales < 1: 50 000 sufficient to fill

adequately the World's poorly surveyed areas. This might be objected by surveyors mainly concerned by large scales needed for harbours and berthing usage bands for which SDB, even at VHR resolution, is unlikely to comply. However, the risk of giving undue precedence to vertical precision over broader portrayal is intentionally to leave blanks on the charts while a wealth of satellite information useful to Safety of Navigation is available. The need to achieve a fair compromise between these two apparently conflicting priorities points at the importance of applying informed hydrographic judgement in conjunction with Safety of Navigation common goals. The SDB cartographer's guideline will be to comply with the CATZOC requirements, a composite criterion that comprises horizontal position accuracy, vertical accuracy and seafloor coverage. Considering the mediocrity of SDB vertical performances against the two other criteria, the analyst will apply conservative judgment to isolate potential dangers by stretching depth contours so as to discourage navigation in potentially shallow areas.

The advantages of HR time series over single VHR images have been listed and commented in the following table.

Assets	HR (Sen-2)	VHR (WV, Pleiades…	Comments
Sensor performance	√	√	CNES would advocate rightly that Pleiades and S-2 MSI performances are similar, but then, the use of HR time series confers an advantage over single VHR images in SDB applications.
Band shift control	√		
Photons count	√		HR pixels contain at least 100 times more information than VHR's
Interpixel Signal to Noise ratio	Low	High	
SDB usable Spectral bands	5	3 to 5	
Revisit time at Equator	5 days		
Suppression of clouds and transients	√		Time series can yield "Perfect Images"
Deglinting		√	HR cannot correct glint effect for waves < pixel size ≈10 m
Absolute horizontal precision without ground control points	11 m		VHR can achieve far better precision but this needs geodetic control
Performance on same computer	15 minutes	8 hours	HR Computing time 30 times faster
SDB Value-for-money	√		VHR minimum charge ≈ € 20/sq. km

Whilst HR images, thanks to time series, are sufficient and comparatively more efficient for most hydrographic surveys at scales < 1: 50 000, one must not dismiss lightly the specific advantages of VHR, be they for large scale surveys or co-registration to improve HR mosaics' horizontal precision, when phenomena such as coastal erosion have to be observed. Setting aside the prohibitive computation time due to the number of pixels, if there were no limit to the amount of VHR images that could be viewed and merged, there is no doubt that marginally better results could be achieved. However, these would unfortunately come at a cost and remain unaffordable to most users, making the HR time series a unique opportunity for Hydrographic Offices and for meeting developing countries coastal charting essential requirements.

2.1.4 SDB novel performances

⇒ **A New paradigm…**

Hydrographers, so far, have been focussing on SDB poor vertical precision falling short of the S-44 Total Vertical Uncertainty (TVU) standards and being unlikely to improve when processing large areas. However, this vision, driven by the need to achieve high precision at large scales > 1: 50 000, has to change as SDB's main asset is not TVU, rather its aptitude to provide an advanced capability to detect shoals in large areas, assuming the sea bottom is visible from space. By offering 100% coverage and very precise determination of visible structures, satellite "Perfect Images" can contribute decisively to safety of navigation by detecting dangers that can be depicted on charts and thus avoided by Navigators.

⇒ **…characterised by a near 100% guarantee of shoal detection…**

Thanks to sufficiently extended time series, the need to achieve total coverage, even in Arctic waters and, if one waits long enough, in frequently cloud-covered coasts, can now be met over large areas and avoids confusion with transient artefacts. SDB provides a guarantee, dubbed provisionally "Optical Wire Sweep", combining full surface coverage and quasi-unlimited horizontal precision of relatively large natural features, but somewhat imprecise depth assessment and inability to detect small man-made structures. (***Figure 6***).

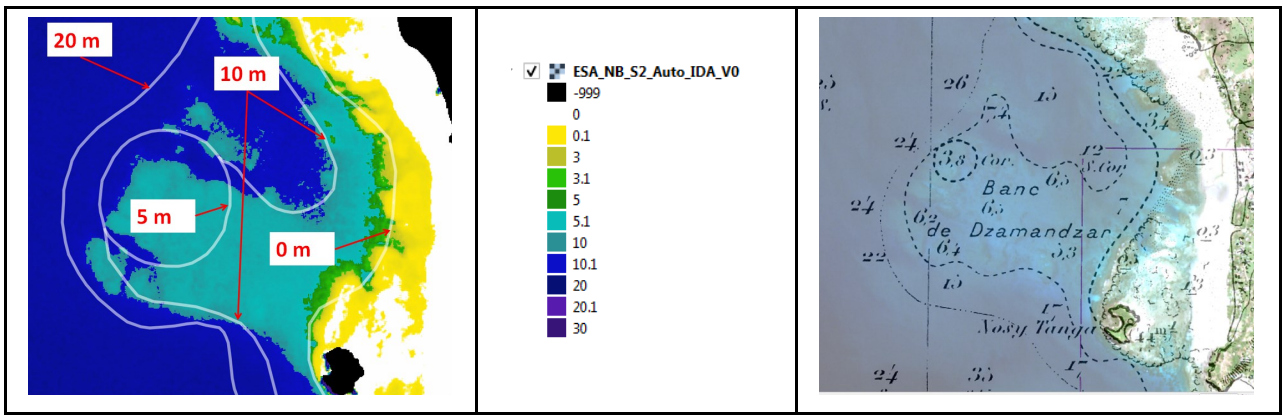

Figure 6 : Rehabilitation of a vintage chart
The "Perfect Image" on the left confirms and completes the ancient chart on the right with an almost 100% guarantee of shoal detection and surface coverage.

The key to detecting features is being able to see the sea floor from space, which led to the development of a DOP algorithm that will be detailed later.

⇒ **…unfortunately associated with a relatively poor vertical precision…**

TVU varies with the size of the area of interest (AOI). If the AOI is small enough and environment conditions and parameters are properly appraised, then S-44 TVU standards can be met, as shown in a recent Japanese study[15] using Landsat-8 time series in exceptionally clear waters. But this cannot be extended indefinitely to larger zones. Based on time considerations, a compromise has to be found between S-44 compliant micro-processing and blurry over-simplification (***Figure 7***) consisting of merging areas characterised by different environments.

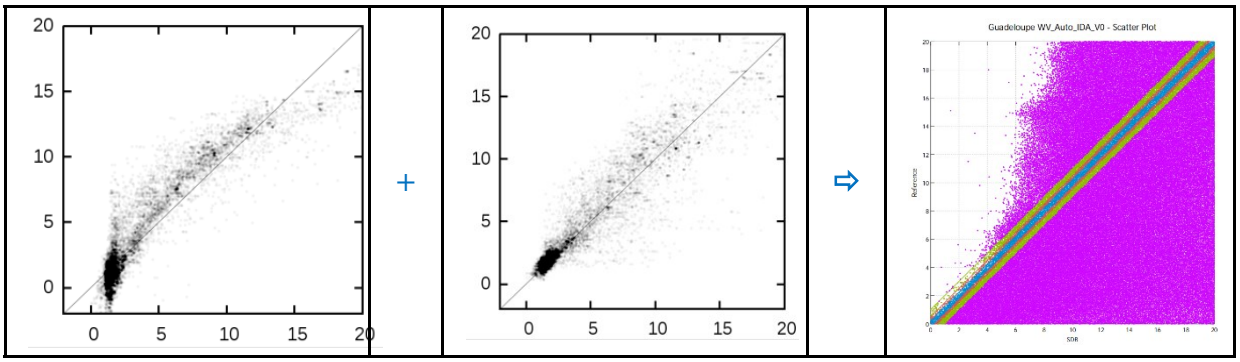

Figure 7 *: SDB depths TVU Scatter plot]*
Merging too many S-44 compliant areas usually ends-up with a larger non-compliant zone

⇒ **…but a better control of uncertainties…**

Effective SDB applications, such as Dr. Hedley's Image Data Analysis model, depict uncertainties as error bars, but it has been determined these have been simplified for the users' convenience and could be slightly improved for better depth control. For instance, increased turbidity makes the bottom look deeper while spectral errors affect the apparent reflectance. Failing to take into account minor sources of radiated energy, such as those generated by boundaries effects, impacts depth retrieval. All these adverse consequences necessitate exploring the models' parameters in detail and going back to Mobley's formidable RTE. Non-Gaussian processes might elicit several solutions that cannot be averaged but could be submitted with their range of uncertainties to the analyst who would then make an informed final choice.

Uncertainties sustained by an arduous examination of probability laws have been studied with the intention to qualify SDB results with improved percentages of errors. This gave rise to complex mathematical developments compiled in a number of internal research notes that can be communicated to those interested. As a principle, uncertainties distributions calculated for one image and one pixel only have to be extended to a whole batch in order to determine possible solutions, which cannot be approximated by simple arithmetic averages.

⇒ **….at an affordable cost.**

The financial criteria will likely limit the use of expensive VHR systems to specific large-scale applications despite their merits. In a global ocean bordered by coastal waters that have hardly been properly surveyed according to GEBCO records (***Figure 8***), only satellites that can extract stable information from a large collection of swaths may be considered to fill the World's charting gaps systematically.

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[15] Satellite Derived Bathymetry Using Machine Learning and Multi-Temporal Satellite Images- Sagawa et al. - Japan RESTEC - Published in Remote Sens. Issue 2019, 11(10), 1155 of 14 May 2019

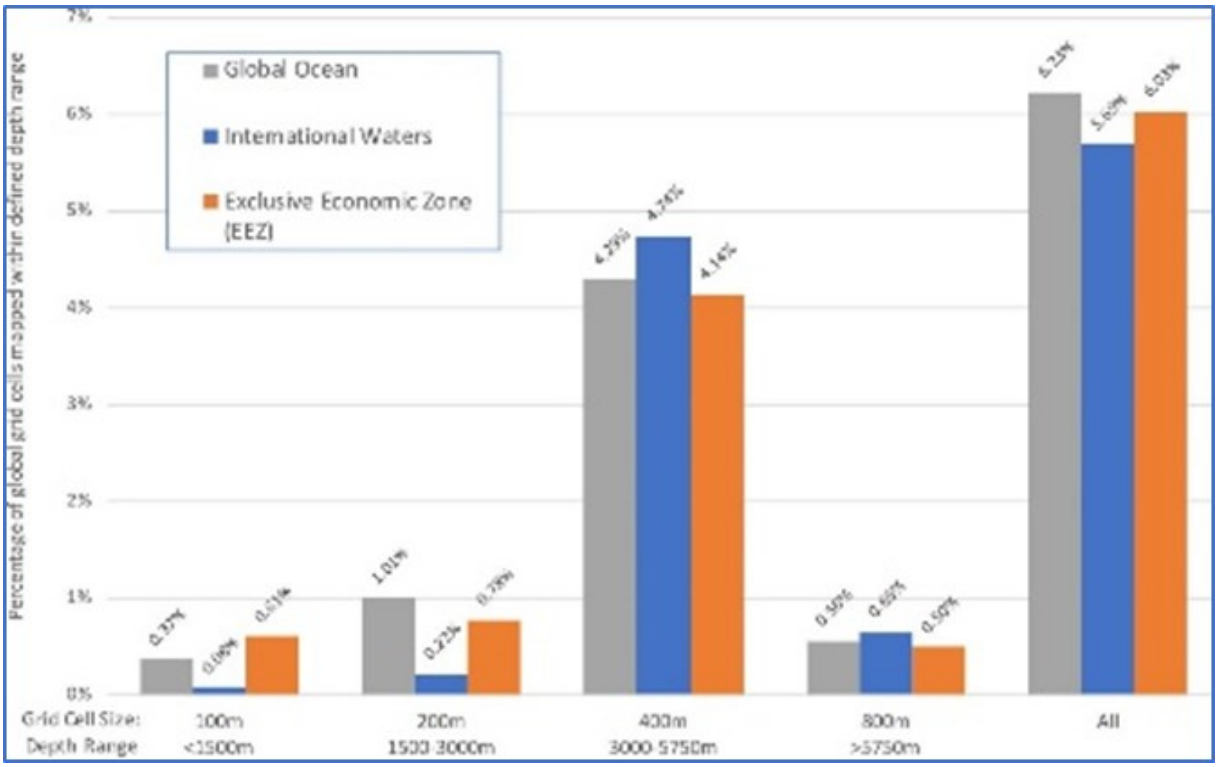

Figure 8 *: GEBCO Histogram of the World ocean percentage covered*

Not only do HR time series have the potential to deliver a first answer, but they can deliver it quickly, as long as the sea floor is visible from space. Looking forward, once validated and standardised, SDB methodology, which is more reliable than traditional reconnaissance survey techniques, could easily and affordably provide the required information to replace the ancient charts that still clutter our official chart series. Further, the methodology could easily be disseminated worldwide through Capacity Building initiatives and help developing countries to fulfil, with minimum help, their own cartographic needs.

2.2 Applications

2.2.1 Present-day

With the exception of the French Hydrographic Office, who has been adding SDB-enhanced charts into the national chart series for thirty years and has developed its own procedures in the absence of IHO standards, hydrographic offices have deemed SDB to be reliable only for survey planning and topography complements to traditional charting. However, SDB is now starting to be used by the United Kingdom Hydrographic Office Admiralty charts and the United States National Oceanic and Atmospheric Administration, and is regularly tested by the Canadian Hydrographic Service with a goal to document safe navigation channels in the Northwest Passage with proper navigational charts.

In parallel, non IHO-compliant mapping services have been offered by private companies with various success, ranging from an impressive geomorphologic survey of the whole Great Barrier Reef in support of Australian Universities[16] to the exploration of future Marine Highways in uncharted waters[17] and determination of precise UNCLOS baselines[18].

Very recently, SDB time series have been successfully employed to reduce risk in the deployment of towed arrays in shallow waters, and tested in their ability to rehabilitate ancient charts (based on lead-line surveys) in order to turn them, at minimum cost, into up-to-date navigational documents.

2.2.2 In future

In the near future, it is envisaged to test the ability of Sentinel-2 time-series to reduce the considerable lack of coastal material in the GEBCO database. If successful, this test could be extended to the World database and online mapping websites would be approached to disseminate the information globally.

Sentinel-2 revisit time has been harnessed to the task of monitoring coastal erosion. To this end, time series have been combined with VHR satellites to obtain a sub-metric horizontal precision. Sentinel-2 provides 5 days revisit time and broader coverage, while WorldView or Pleiades bring the precision required to observe small coastal changes, almost in real time.

Lack of funding notwithstanding, nothing at this juncture should prevent developing countries to improve their cartographic schemes by rehabilitating older charts and filling in the blanks along their coasts with new satellite navigational charts on which the infamous label, “NOT TO BE USED FOR NAVIGATION,” would be removed and replaced by a less conspicuous and more subtle warning.

3. Latest SDB breakthroughs

3.1 Circumstances Latest SDB breakthroughs

SDB breakthroughs were initiated by the launching of Sentinel missions (2014) and the rapid accumulation of a large collection of satellite images demonstrating the benefits of revisit time sensed earlier by Landsat-8. It took time to fill the Sentinel database, which now occupies on the order of ten petabytes of data, and for research and development hydrographers to take advantage of newly available “Perfect Images”. Testing of this concept has just been completed thanks to ESA initial funding through projects such as Sen2Coral and Sentinel Coastal Charting Worldwide tutored by knowledgeable technical officers.

Sentinel-2 was originally focussed on land but Sen2Coral, the first maritime project consisting of observing coral bleaching, demonstrated that coastal applications such as environmental mapping and nautical charting were possible and could be just as important.

In parallel, the IHO has initiated a revision of its S-44 publication on Standards for Hydrographic Surveys, offering the opportunity to introduce Earth Observation satellites as an additional instrument to the Hydrographers’ and Nautical Cartographers’ toolbox.

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[16] *Hamylton, S.M.; Hedley, J.D.; Beaman, R.J. (About the Great Barrier Reef): Derivation of High-Resolution Bathymetry from Multispectral Satellite Imagery: A Comparison of Empirical and Optimisation Methods through Geographical Error Analysis. Remote Sens. 2015, 7, 16257-16273.*

[17] *GEF Concept Note: WESTERN INDIAN OCEAN Marine Electronic Highway Development and Coastal and Marine Contamination Prevention Project Phase II (2011)*

[18] *Benin, the Republic of Congo, Cote d’Ivoire and Togo submissions to the UN Division for Ocean Affairs and the Law of the Sea (DOALOS) – 2015 - 2019*

Table 4 : Excerpt of tentative SDB standards (ongoing contribution to the S-44 HSPT Proposal)]
The critical point is to make sure that no validation can be pronounced without sworn Hydrographers' approval.

Parameter / Data Type	3	5	6	8
EARTH OBSERVATION AND REMOTE SENSING				
Capability of system to measure Depth [range in m]	20	10	5	
DOP (Depth of Light Penetration) [m]	Optional	10	5	1
Resolution (e.g. pixel size) [m]	20	10	5	1
Revisit period [days, hours]	> 15 d	5 to 9 d	1 to 4 d	< 12 h
Overall validation and professional expertise [FIG/IHO category, other credentials]	Cat B	Cat B	Cat A	Cat A

3.2 Time Series

By introducing Sentinels' short revisit time, ESA has revolutionised a way of thinking shaped by centuries, not days. To quote two examples, in Western Europe, the chart of Northern Britany first surveyed by Napoleonic Hydrographers -and actually amazingly precise- has only been replaced recently by a modern survey using multibeam echosounders, while in West Africa the International chart series are still using coastal data collected under sail by Georgian Royal Navy Hydrographers.

The main advantage of revisit time is that, by stacking scenes of the same spot, it allows to identify and suppress transient details such as clouds, sediment plumes and other artefacts that obscure the observation of plain bottom, making it possible to merge layers of georeferenced and radiometrically normalised pixels to obtain "Perfect Images".

Two recent tests, the ESA "Sentinel Coastal Charting Worldwide" and a simultaneous extensive "Bathysat" project conducted on about ten different sites and using VHR and HR images have established that depths calculated with SDB software fed with "Perfect Images" combining up to fifty Sentinel-2 scenes are better than those derived from single VHR images (***Figure 9***) selected with care.

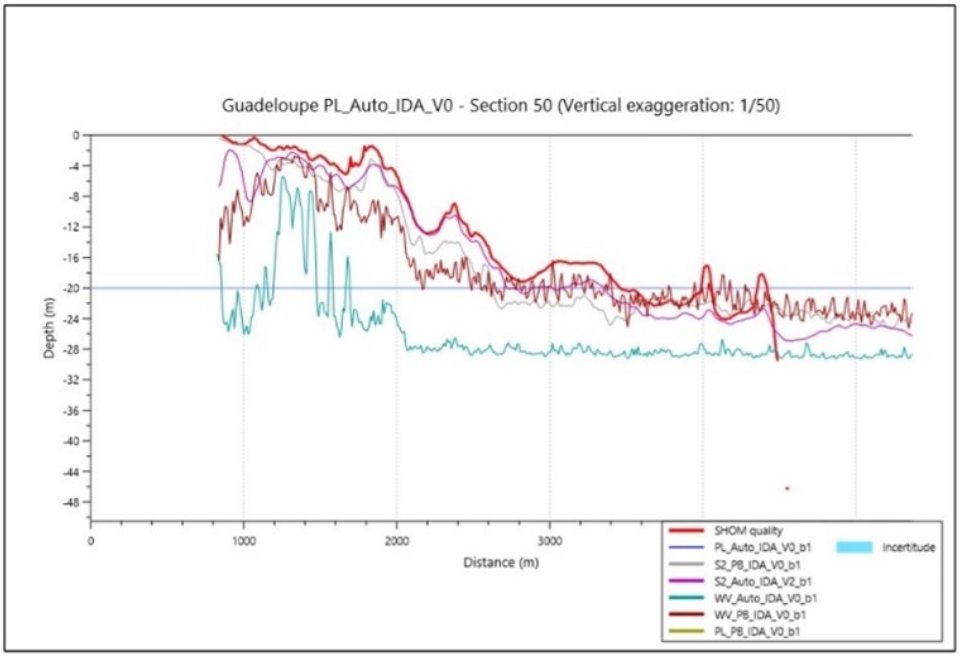


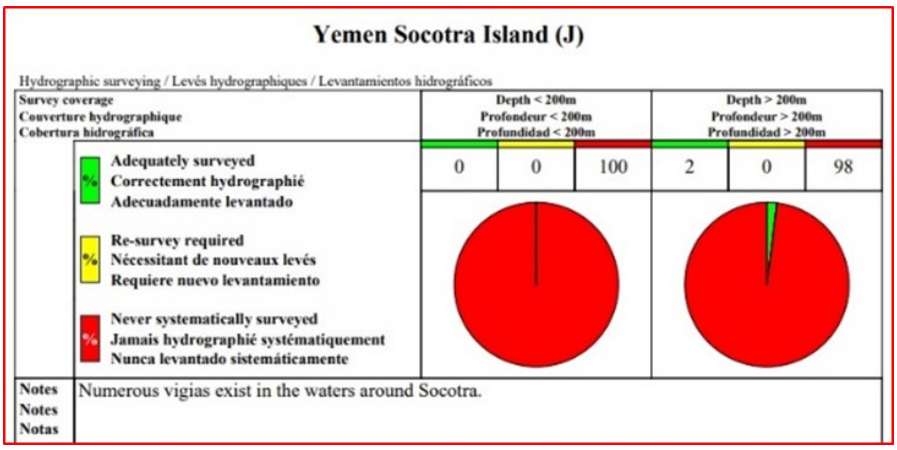
Figure 9 : Comparison of a Sentinel-2 "Perfect Image", with Ground Truth, Pleiades, and World View cross sections

The purple trace (S2_Auto_IDA_V2_b1) follows better the red sonar profile than single VHR images WW_Auto and PL_PB

3.3 Depth of Penetration (DOP)

In order to process "Perfect Images" with their bathymetric models, Hydrographers must make sure they will be able to see the sea floor with passive EO satellites or reach it with active LiDAR.

By assessing the depth of penetration of light in a water column characterised by its intrinsic optical properties, a DOP software[19] adapted from earlier water transparency modules has been developed to determine, at a given time and for a given satellite, if the bottom is visible from above and thence, whether optical methods can be applied. To this end, before deciding to start an SDB or LiDAR survey, analysts should be able to consult the reference IHO document, the C-55 *Status of Hydrographic Surveying and Charting Worldwide* completed with DOP statistics (***Figure 10***).



Yemen Socotra Island (J)

Hydrographic surveying / Levés hydrographiques / Levantamientos hidrográficos

Survey coverage Couverture hydrographique Cobertura hidrográfica	Depth < 200m Profondeur < 200m Profundidad < 200m			Depth > 200m Profondeur > 200m Profundidad > 200m		
% Adequately surveyed Correctement hydrographié Adecuadamente levantado	0	0	100	2	0	98
% Re-survey required Nécessitant de nouveaux levés Requiere nuevo levantamiento						
% Never systematically surveyed Jamais hydrographié systématiquement Nunca levantado sistemáticamente						
Notes Notes Notas	Numerous vigias exist in the waters around Socotra.					

[19] *This software is an output of the "Sentinel Coastal Charting Worldwide" project mentioned earlier. It has been delivered to ESA under the name "Impact of field-proven SDB on the world uncharted waters (DOP)".*

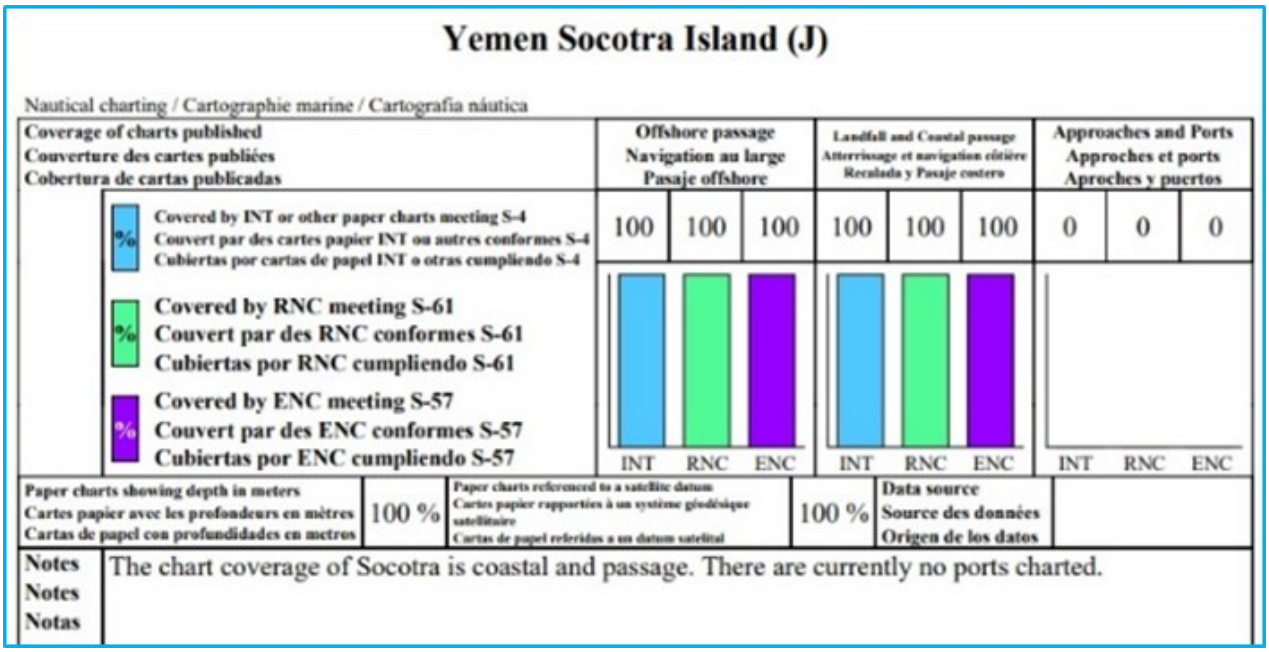


Figure 10 *: One of the two hundred and sixty-three C-55 world areas displaying the state of surveys (top) and charting (bottom)*

By using the colour of the ocean to determine the Intrinsic Optical Properties of any water body and applying the classical logarithmic absorption curve across the light spectre, DOP can calculate the light penetration and determine the cut-off threshold beyond which the reflected bottom signal is lesser than the noise. DOP can be used to confirm whether optical bathymetry is feasible in coastal regions inaccessible to boats equipped with multibeam echosounders.

Depending on the precision required; DOP can use colour of the ocean data retrieved from MERIS, Sentinel-3/OLCI or Sentinel-2/MSI.

3.4 Confirmation of visible shoals by making use of revisit time

Revisit time confers an entirely new detection capability to satellites, making them a survey tool on their own and not just a complement to sonar surveys. Until recently, disproving doubtful shoals depicted on charts would have required a new hydrographic survey whilst now, provided that the bottom is visible and analyst have access to large collection of images, SDB detection can provide a remote sensing confirmation of existence (***Figure 11***). Indeed, identical pixels observed in the same place at different times categorises them as belonging to a permanent feature, however, analysts must be certain that the bottom is visible, hence the importance of evaluating DOP in all optical control methods. DOP is becoming the key criteria to validate optical detection.

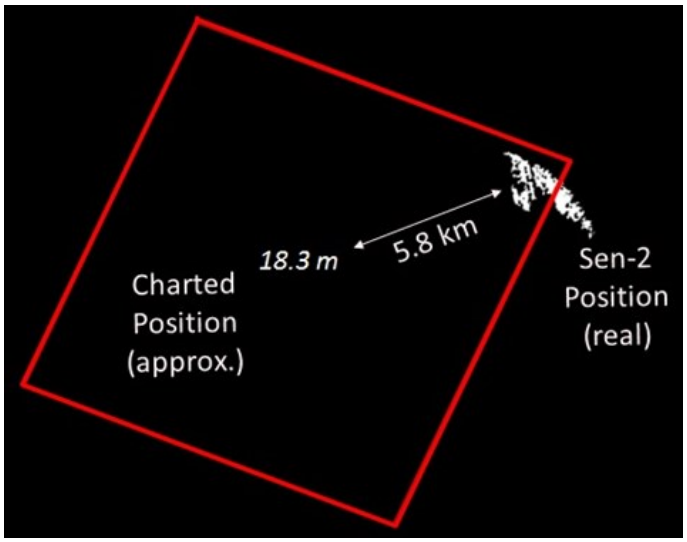


Figure 11 *: Sentinel-2 conformation of a misplaced shoal*

By peering at blue spectral bands, this shoal was found on three out of five Sentinel-2 images carefully selected from a large time series of over 50 scenes spread over several months.

3.5 SDB costs considerations

Be they powerful oil & gas companies or impoverished coastal States, cost considerations are important for potential users of SDB. Reducing risk in its geophysics surveys to support deployment of very large towed arrays mentioned earlier, a supermajor classified SDB exploration along "Best achievable" and "Good enough" criteria, using commercial VHR images in the first case and free HR time series in the latter. Much to the buyer's surprise, there was no significant differences between results and a better detection capacity in favour of time series. "Good enough" surveys were in fact cheaper and faster to process while "Best achievable" led to never ending developments. As a result, this dual approach was finally abandoned.

4. Conclusions: HR Time series Pros & Cons

Based on 2019 extensive tests results following dozens previous satellite surveys conducted with less performing constellations, the HR time series pros and cons, best represented by Sentinel-2, can be listed as follows in ***Table 5*** *:*

Table 5 : Sentinel-2 Pros & Cons

Pros	Cons	Comments
Value-for money[20]		Sentinel-2 offers an open and free access to its imagery compared to an average € 20 per sq. km for VHR commercial images.

[20] With regards to value-for-money, one has to be aware that there are hidden costs to Sentinel-2 open-access images supported by ESA's 22 Member States.

"The vision of ESA is to enable the maximum benefit of Earth observation for science, society and economic growth in Europe, served by European industry. ESA will implement this vision through its Earth observation programmes, working in close cooperation with Member States, the EU, EUMETSAT and European industry within the widest international framework."

Radiometric calibration		Control of spectral shift is essential to be able to compile images shot at different times.
5 days Revisit time at Equator		
Suppression of transients		Production of "Perfect Images" by compilation of large collections of images
11 metres absolute horizontal precision		No more topographic surveys for scales < ≈ 1: 50 000 for sufficiently clear shallow waters properly assessed by DOP analysis.
	Mediocre vertical precision	SDB weak point, somewhat improved by the introduction of "Perfect Images" and/or the calculation of averages over large collections of normalised images.
10 m resolution pixels	Insufficient for demanding applications such as erosion monitoring, ports and berthing.	Better adapted to most bottom natural structures. Reduced calculation time compared to VHR processing
Signal to Noise ratio		Better photons count and less interpixel noise.
Calculation performance with standard computer		15 minutes per scene instead of 8 hours for the same area with VHR images, allowing for multiple replays and improved real-time processing.

Although slightly less performing due to their earlier entry in service (2013), these conclusions are valid for Landsat-8, as observed in the ESA Sen2Coral earlier project[21]. With the advent of performing new generation satellites offering global revisit time such as Landsat-8 and Sentinel-2, SDB has moved from being an exploratory methodology, usable with great circumspection, to becoming an indispensable method for improving safety of navigation in shallow waters, provided that the sea floor can be observed unambiguously from space. This prerequisite can be met with the emerging concepts of "Perfect Images" and Depth of Penetration.

SDB awareness shared by too few Hydrographic Offices is now spreading globally thanks to the support offered by authoritative voices such as IHO and the European Space Agency.

All that is left is for Hydrographers to rigorously develop and standardise a method, already widely used by Biologist and Environment Scientists, that has the potential to extend sufficiently precise coastal mapping to the World's uncharted waters.

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[21] *John Hedley; Chris Roelfsema; Vittorio Brando; Claudia Giardino; Tiit Kutser; Stuart Phinn; Peter Mumby; Omar Barrilero; Jean Laporte; Ben Koetz. Coral reef applications of Sentinel-2: Coverage, characteristics, bathymetry and benthic mapping with comparison to Landsat 8. Remote Sens. Environment; 2018.*

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6. Authors Biography

Jean Laporte – Senior Hydrographer – ARGANS Ltd. a former Naval Aviator and senior Cat A Hydrographer, Jean Laporte is *ingénieur général* (Flag Officer, Reserve Service) of the Armament Corps. He has spent most of his career as Charge Hydrographer in the French Hydrographic Office and is currently Chairman of the IHO Hydrographic Dictionary Working Group and ARGANS Managing Director.

His scope of expertise encompasses hydrography, charting, air and shipborne surveys, satellite bathymetry (SDB) and remote sensing, International laws of the sea (UNCLOS & SOLAS), EEZ border agreements, bilateral co-operation agreements, Marine Electronic Highways, Capacity Building and finally, Chinese history and culture.

Henri Dolou – Senior Hydrographer & Cartographer - ARGANS Ltd. a FIG/IHO/Cat A Hydrographer, Henri spent 30 years as Engineer and Charge Hydrographer in the French Hydrographic Office where he was involved in surveys covering the world's oceans and seas. He remains an IHO Advisor in African Capacity Building and Professor on hydrography and oceanography in various French institutions.

His scope of expertise encompasses hydrography, data Quality Control, charting, satellite bathymetry & remote sensing, spatial oceanography, International laws of the sea (UNCLOS & SOLAS), EEZ border agreements, Capacity Building, Risk management & Auditing.

Joseph Avis MSc – EO Scientist – ARGANS Ltd received his BSc in Physical Geography before completing his MSc in Remote Sensing and GIS at Aberystwyth University, Wales, UK. His MSc thesis was researching the impact of suspended sediment on mangrove forests through remote sensing data.

Olivier Arino PhD – ESA Senior Advisor received his PhD in Remote Sensing with maximum honours from the *Institut National Polytechnique de Toulouse* in 1990.

After a postdoc at CNES/CNRS focussed on the International Geosphere Biosphere Programme of the European Commission, he joined the European Space Agency in 1991, where he worked as ENVISAT product engineer for the next seven years, then Head of Project section and Application section.

He initiated the GlobSeries projects that led to ESA's Climate Change Initiative and authored more than 100 Scientific papers in different fields such as Albedo, Vegetation, Land Cover, Active Fire Detection and recently, Coastal Charting

Articles

MORPHOGRAVIMETRIC CHARACTERIZATION OF THE EASTERN AND SOUTHEASTERN REGIONS OF THE BRAZILIAN CONTINENTAL SHELF

By F. Pereira Batista; G.L. Galvão Teixeira and L. C. Torres

Abstract

The use of satellites in the acquisition of geophysical variables has allowed the advancement of joint analysis of bathymetry and gravimetry fields in marine regions where these data are scarce or insufficient, which allows a detailed description of the geomorphology and mass distribution of different provinces of a continental margin. In Brazil, although there is a great effort in the execution of marine geophysical surveys by ships, there is a great difficulty in filling some gaps, due to the size of its continental margin. Therefore, this article aims to analyse the joint spatial data of the bathymetric and gravimetric fields (Free-air and Bouguer) of the eastern and southeastern Brazilian marine region from the TOPEX database, using the tools developed in Python computer language. The results obtained were integrated gravimetric and bathymetric profiles, maps correlating such geophysical fields and diagrams that allowed the combined application of quantitative and qualitative statistical methods on the Bathymetric and gravimetric data. Anomalies of 100 mGal were observed along the Brazilian continental margin, with the largest variations recorded along the Vitoria-Trinity Ridge in the order of 200 mGal, and the remarkable correlation between free-air gravity and bathymetry profiles could also be observed.

Keywords: Brazilian Continental Margin ; Gravimetric anomalies.

Résumé

L'utilisation des satellites dans l'acquisition de variables géophysiques a permis de faire progresser l'analyse conjointe des champs bathymétriques et gravimétriques dans les zones maritimes où ces données sont rares ou insuffisantes, ce qui permet une description détaillée de la géomorphologie et de la répartition des masses des différentes provinces d'une marge continentale. Au Brésil, bien que de nombreux efforts soient déployés pour l'exécution de levés géophysiques maritimes par les bâtiments, il est très difficile de combler certaines lacunes, en raison de la taille de la marge continentale du pays. Cet article vise donc à analyser les données spatiales communes des champs bathymétriques et gravimétriques (Free-air et Bouguer) de la zone maritime de l'est et du sud-est du Brésil provenant de la base de données TOPEX, en utilisant les outils développés en langage informatique Python. Les résultats obtenus ont été des profils gravimétriques et bathymétriques intégrés, des cartes corrélant ces champs géophysiques et des diagrammes qui ont permis l'application combinée de méthodes statistiques quantitatives et qualitatives sur les données bathymétriques et gravimétriques. Des anomalies de 100 mGal ont été observées le long de la marge continentale brésilienne, les variations les plus importantes étant enregistrées le long de la dorsale Vitoria-Trinité, de l'ordre de 200 mGal, et la corrélation remarquable entre la gravité à l'air libre et les profils bathymétriques a également pu être observée.

Mots clés : marge continentale brésilienne ; anomalies de gravité.

Resumen

El uso de satélites en la adquisición de variables geofísicas ha permitido avanzar en el análisis conjunto de campos de batimetría y gravimetría en regiones marinas, en las que estos datos son escasos o insuficientes, lo que permite una descripción detallada de la geomorfología y la distribución de masas de diferentes provincias de un margen continental. En Brasil, aunque los buques hacen un gran esfuerzo en la ejecución de levantamientos geofísicos marinos, existe una gran dificultad para llenar algunos vacíos, debido al tamaño de su margen continental. Por lo tanto, este artículo tiene por objeto analizar los datos espaciales conjuntos de los campos batimétricos y gravimétricos (Aire libre y Bouguer) de la región marina del Brasil oriental y sudoriental a partir de la base de datos TOPEX, utilizando las herramientas desarrolladas en el lenguaje informático Python. Los resultados obtenidos son perfiles gravimétricos y batimétricos integrados, mapas que correlacionan esos campos geofísicos y diagramas, que han permitido la aplicación combinada de métodos estadísticos cuantitativos y cualitativos sobre los datos batimétricos y gravimétricos. Se observaron anomalías de 100 mGal a lo largo del margen continental de Brasil, registrándose las mayores variaciones a lo largo de la cresta Vitoria-Trinity del orden de 200 mGal, y también se pudo observar la notable correlación entre la gravedad al aire libre y los perfiles batimétricos.

Palabras clave: Margen continental brasileño ; anomalías gravimétricas.

1. Introduction

The importance of studying the surface and subsurface of the marine floor is directly related to the planning of human activities, regarding mainly economic and strategic factors, such as the exploration of mineral sea bed resources, the development of coastal and oceanographic engineering projects related to offshore activities, the exploration of living resources, and the various research activities that occur in these regions (SOUZA, 2006 and NADIM *et al*., 2006).

The effective study of gravimetry is characterized as a potential geophysical method of great applicability for the identification of many distinct geological formations, for the exploration of minerals, oil and gas, as well as in a great number of geodetic applications (LUIZ & SILVA, 1995 ; KEAREY, et al*.,* 2009). In this context, major scientific advances in the field of geophysics since the 1970s (GIBSON & MILLEGAN, 1998), along with the advent of the space age and high-precision satellite positioning, have enabled the development of airborne geophysics, enabling data acquisition by using global mapping from space.

The delineation of the many diverse marine floor features can be obtained by means of bathymetry and the identification of gravimetric anomalies. This is accomplished by combining satellite-based altimetry with the implementation of various filtering techniques and parameter corrections, for example, the adjustment of radar space track densification and the correction of "non-geological" noise in the gravimetric field, in order to increase the accuracy and precision of this field, so allowing an estimate of the topographic data in a given region of interest (SANDWELL & SMITH, 2009; SANDWELL *et.al*, 2013 ; SANDWELL *et al*, 2014).

The importance of gravimetric field research to the various sectors of exploration activities is widely known, but there are still few completed studies on the Brazilian marine extension. This fact is directly related to the high operational efforts involved to mobilize and execute such task using research ships. In this context, the motivation for this work includes the study and spatial analysis of the morphogravimetric variability present in the Brazilian Continental Shelf (BCS).

The present study expects to contribute to the integrated spatial analysis of bathymetric fields and gravimetric anomalies (free-air and Bouguer) related to the Brazilian East and Southeast oceanic regions, with emphasis on the continental shelf. The bathymetric data have been used to reproduce the seabed morphology surface and the gravimetric data have been used to identify the subsurface depth caused by the differences in the region's density distribution. This analysis, carried out after processing geophysical data from satellites, allows the profiling of the physiographic characterization of the seafloor of this region, as well as the statistical qualitative evaluation among geophysical parameters. For this purpose, bathymetric and gravimetric data from a public domain database have been used, and a computing routine has been developed to process these data, using the Python programming language, a technique that is widely used in the academic environment. The use of such tool in support of geophysical information acquisition activities becomes a reliable reference, given the projected purposes, for future studies in this area.

2. Area of study

The present work will pay attention to the description and characterization of the Eastern and Southeastern extensions of the coast, whereas the selected study area has been delimited between the 5º S and 25º S parallels and the 026ºW and 049ºW meridians, off the oceanic region of this area.

The Brazilian continental margin is classified as Atlantic type, comprising an area around 5.003,397 Km^2, that represents to 59% of the Brazilian emerged territory (COUTINHO, 2005). This characteristic is noteworthy when observing the extension of its continental shelf, mainly in

areas that present great sedimentary contribution, as the mouth of the Amazon River, for example (COUTINHO, 2005). Remobilization and sedimentary deposit are dynamic processes, which, considered on a global scale, are consequences of the ocean transgression-regression process, and it is characterized by the shallower strip of the surrounding continental rim existing in most continents. The formation of the continental shelf is generally based on the processes of weathering and erosion that take place along the continental margin, as well as the deposit of minerals in coastal regions (MARINO, 2006). The morphological study of the coastal area is of vital importance for understanding the morphology of the underwater relief, as will be observed in the current paper.

According to Coutinho (2005), the maximum extension of the continental shelf, off the Caravelas region (in the state of Bahia), stands out, followed by its size decrease due to the presence of volcanic intrusions that favour the formation of reefs, protecting the Regencia region coast (in the state of Espírito Santo). From this region on, the shelf gradually widens again due to the sedimentary contribution increased by the Rio Doce river delta, between the Vitória and the Cabo Frio regions.

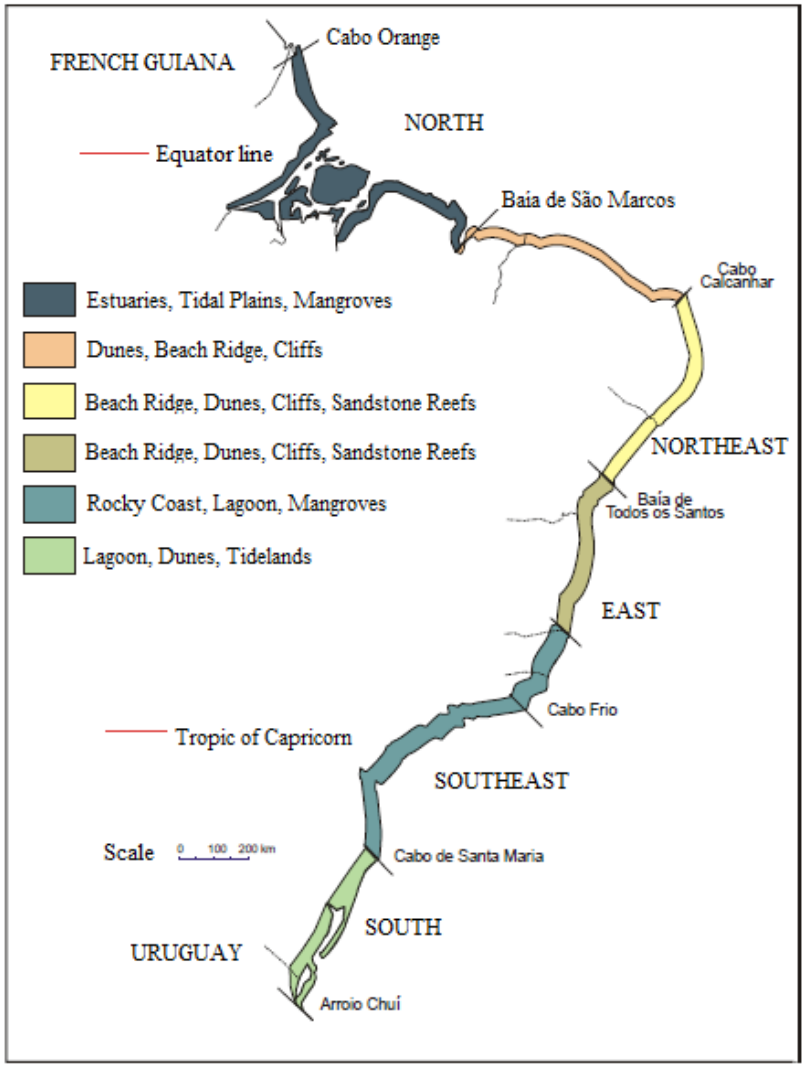


Figure 1 *: Subdivision of the Brazilian continental margin into sectors proposed by Silveira (1964) modified by Villwock (1994). Only the oceanic regions adjacent to the Eastern and Southeastern sectors will be used in this paper. Source: Modified version by Coutinho (2005).*

The Southeast sector is characterized by the widening of its continental shelf, with maximum width near the Santos region and minimum width between Cabo de São Tomé and Cabo Frio regions nearby area (COUTINHO, 2005).

In general, the great diversification observed on the Brazilian Continental Shelf morphology can be noticed, mainly in terms of its longitudinal extension, as it is narrower in the Central and Northeast quadrants, and wider in the North and South sectors, with width values ranging from 90 to 320 km. Such diversification can be observed around the shelf gradient, as it also varies in the different sectors, with shelf break depths ranging from 40m to 200m (GOES & FERREIRA JR., 2017).

3. Methods

In an integrated way, this work aims to explore the joint analysis of the bathymetric and gravimetric fields of the southeastern and eastern sectors of the Brazilian continental margin. As consequence, it was necessary to adopt a method that allows to infer the correlations between these fields in terms of space and through normal profiles taken from the coastline to the deep sea.

The method adopted throughout this study has at its core the characterization of the gravimetric data related to the acquisition of bathymetry and free-air gravimetry data extracted from the TOPEX database webpage located at http://topex.ucsd.edu/cgi-bin/get_data.cgi. The data used are freely accessible and made available in ASCII format, and they are characterized by the geographical positioning and parameter magnitude to be analyzed in those coordinates, and they have been interpolated for a one-minute degree spatial resolution and 1 mGal accuracy. In order to effectively compile and interpret the data, it was necessary to use several tools and libraries available in the semi-interpreted Python programming language, and then to reorganize the bathymetry and gravimetry data vectors referenced to a matrix field, which allowed correlation of the data and production, as results, integrated gravimetric and bathymetric profiles and maps, as listed in ***Table 1***. For the effective study of the spatial distribution of these geophysical fields, statistical methods such as dispersion diagrams and determination of correlation coefficients were used, in order to relate both the bathymetric and gravimetric fields obtained.

Table 1 - Representation of results and parameters generated.

FIGURE	GEOPHYSICAL REPRESENTATION
Figure 3	Altimetric field and Gravimetric free-air field
Figure 4	Gravimetric free-air field of the study area
Figure 5	Bathymetric field of the study area
Figure 6	Transverse bathymetric profile near LAT 24ºS
Figure 7	Overlap of free-air gravity anomaly fields on isobaths
Figure 8	Free-air anomaly and bathymetry data cross profile at LAT 20ºS
Figure 9	Dispersion diagram *free-air* gravitational anomalies x Bathymetry at LAT 20ºS
Figure 10	Overlap of the bouguer gravity anomaly fields over the isobaths.
Figure 11	Transverse profile integrating free-air anomaly data, Bouguer anomaly and Bathymetry at LAT 20ºS
Figure 12	Dispersion diagram Bouguer x Bathymetry at LAT 20ºS
Figure 13	Spatial dispersion diagram free-air x Bouguer gravitational anomaly at LAT 20ºS

In many different applications of gravimetric prospection, the measured gravity (g) values are subject to different types of reduction, according to their purpose. Thus, the gravity anomaly is adopted as the value of "g" on the surface of the geoid, where the gravity reduction at sea level can be obtained (GEMAEL, 2002). The generic definition of the gravity anomaly may be seen as:

Equ 3.1 $$\Delta g = g_0 - \gamma$$

Where g_o would be the reduced gravity to the geoid, and γ the representation of theoretical gravity on normal Earth related to the reference ellipsoid. In order to bring the observed gravity down to the "mean sea level", and to compensate the effects of the altitude difference from the geoid, we have applied the free-air correction C_f (also known as Faye reduction) and the anomaly obtained from such a correction receives the same name (GEMAEL, 2002).

Equ 3.2 $$\Delta g_f = g - \gamma + C_f$$

The general free-air correction (C_f) for a known orthometric altitude gravimetric station (h) is given by the equation 3.3, where the value of the correction equals the product between the vertical gradient and the orthometric altitude. In Geodesy and Geophysics studies the mean gradient of normal gravity for the WGS84 reference ellipsoid is used as the value of 0.3086 (GEMAEL, 2002; CARREIRA, 2015)

Equ 3.3 $$C_f = \frac{\delta g}{\delta h} h \quad \therefore C_f = 0{,}3086h$$

The gravimetric data from satellite radar observations are already compensated for the free air correction but have to be corrected for the excess or deficiency of mass of the observation points located at elevations higher or lower than the elevation datum (sea level or the geoid); and for variations in the observed gravitational acceleration caused by variations in topography near each observation point. The type of correction, which is characterized by the suppression of the external masses to the geoid or removal of topographic masses, is called the Bouguer correction (C_b), where the Bouguer anomaly is obtained from the free-air correction by adding the C_b factor, and where the resulting anomaly is expressed by:

Equ 3.4 $$\Delta g_b = g - \gamma + C_f + C_b$$

To determine the general simplified Bouguer correction, according to Carreira (2015), it should be considered that the external masses to the geoid are distributed on a hypothetical horizontal plateau of infinite length and thickness equal to the height of the point to be observed, with homogeneous density and approached to a curved plateau called Bouguer plateau. The Bouguer correction will have an alternating signal dependent on the location of a given point in relation to the reference surface – the geoid in this case. As the study area is in the marine domain, the Bouguer correction will have a positive signal and usually includes the topographic correction because the Bouguer plate is assumed to have density of the water and the thickness of the water depth. The Bouguer gravimetric anomaly can be described by equation 3.5, where $\Delta\rho$ represents the density contrast between the water and substituted material, "G" the universal gravitation constant and "h" the water depth in meters:

Equ 3.5 $$\Delta g_b = \Delta g_f + C_b \quad \therefore \Delta g_b = \Delta g_f + 2\pi\rho G h$$

4. Results and discussion

The information was processed using the Python computer language, that produced, on the spatial domain, profiles and integrated gravimetric and bathymetric maps, enabling the correlation and spatial analysis of these fields for the study region (***Figure 2***).

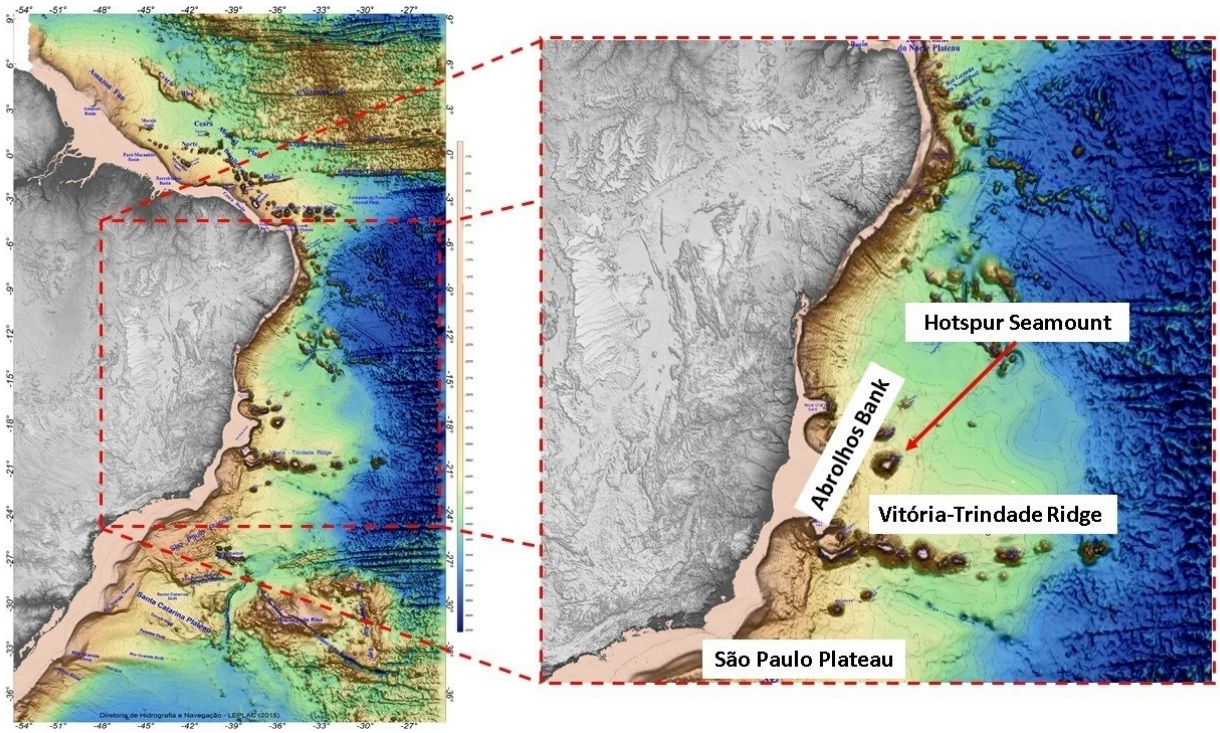


Figure 2 *– Physiographic map of the Brazilian continental margin showing the study area outlined in red in the left image and in higher detail in the right image. Source: Directorate of Hydrography and Navigation (DHN, 2019).*

In the eastern and southeastern ocean regions of Brazil, complex geomorphologies can be observed, represented by Figure 2, where the continental shelf is characterized by large longitudinal spatial variations, where it is also observed the great variability of the sea floor physiographic features, which are of great importance for the understanding and study of the local geology, as well as the morphodynamical processes acting on a large scale. Among such features, the Vitória -Trindade Ridge, the São Paulo Plateau and the Abrolhos Bank stand out in spatial terms.

The altimetry field is shown in the Figure 3a and the free-air field of gravimetric anomalies is illustrated in Figure 3b. Such images display a pixel-matrix composition of the fields in question, from the available data. It should be noted that the representations are not georeferenced, and it is difficult to interpret them in terms of discrimination of the effective continental area of the oceanic region. In the field of altimetry, the brown coloration expresses both the continental area and its extension over the coastal region up to the continental shelf. Secondly, it should be noted that in the scope of both representations, geophysical parameter magnitudes of each field are not directly expressed, and the most accentuated values have been inferred from different digital values based on a color palette.

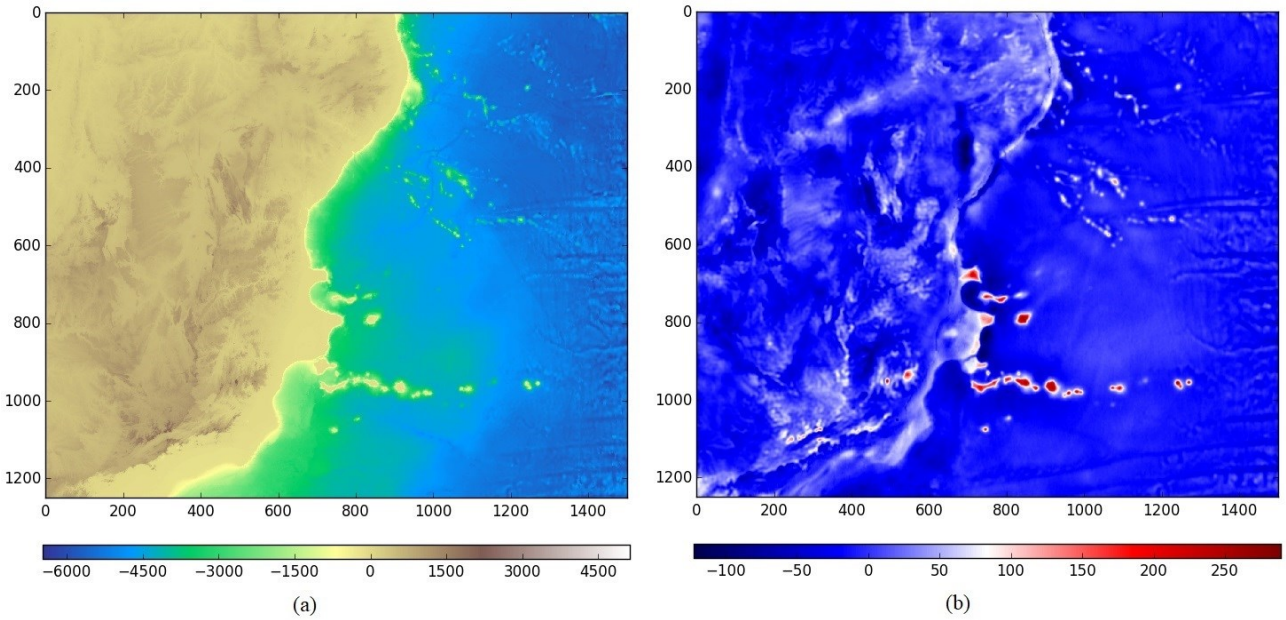


Figure 3 *: Altimetric field (3a) and Free-air Gravimetric field (3b); only the data acquired in digital levels are shown. The vertical and horizontal axes are expressed in pixels*.

After the spatial arrangement of the information at the digital level, it was necessary to obtain georeferenced matrices in order to promote a better visualization and analysis of these fields, as illustrated by ***Figures 4*** and ***5.*** Such representations allow production of the geophysical values associated with each point of the geographical coordinate grid. Additionally, the masking of the continental region has been done, so that the study can focus on the marine portion only. In both figures, the horizontal and vertical axes represent the latitude and longitude values for the geographic grid, with the meridians and parallels equally spaced on a regular grid of 2º; in order to make for easier visualization and interpretation of the location of the physiographic provinces along the marine region in question.

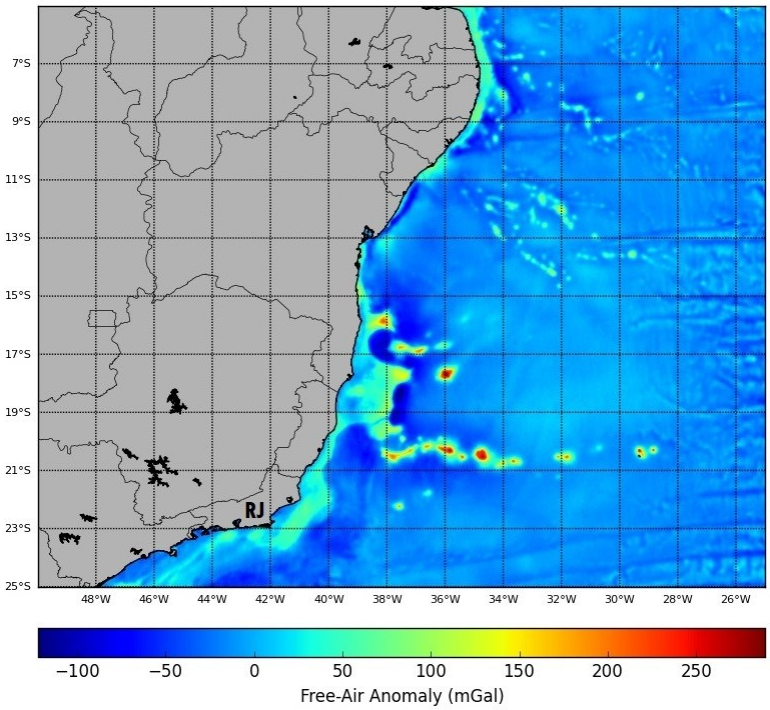


Figure 4 **;** Marine physiographic plotting and gravitational anomaly, with gravimetric values ranging between -100 and 250 mGal, with depths ranging from 0 to 5000m. The Figure was georeferenced in order to present the geophysical parameters inserted in a grid of geographic coordinates. A filter has been used in order to mask the gravimetric anomalies on the continental domain.

In the marine portion, one notices variations of free-air gravitational anomalies in the order of -100 to 250 mGal. The lowest values, in blue color, are associated with the scope of the ocean basin in general, with more pronounced values related to the fracture zones and seamounts present in the eastern and northeastern quadrants of the study region. The values observed between -20 and 80mGal are distributed along the continental shelf, and there is also some uniformity in the distribution of the anomaly values observed in this region, due to the plain structure of the continental shelf, mainly in the southeastern quadrant (***Figure 5***). On the other hand, in the eastern quadrant, one can notice a narrowing of the shelf that is associated with the bathymetric gradient towards the deep-sea basin, which consequently will be related to a greater variation in the observed free-air gravimetry values.

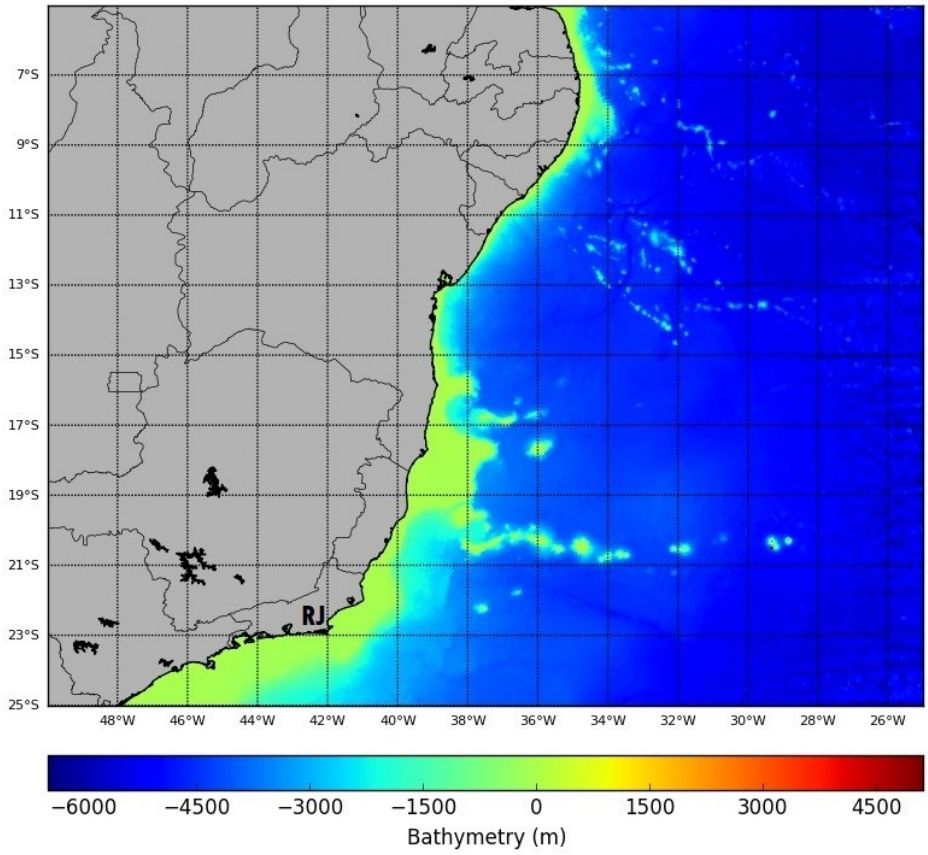


Figure 5 **:** Representation of the bathymetric field of the study area. The smallest depths are represented along the continental shelf, growing progressively up to the ocean basin.

When analysing the free-air gravimetry and bathymetry gradient profiles, represented by ***Figures 4*** and ***5***, respectively, typical features of an "Atlantic" margin can be identified, mainly between the latitudes of 16ºS and 25ºS, with the “wider shelf (represented by greenish tones), strong bathymetric gradient between the shelf break slope and the base of continental slope, continental rise and finally, the deep sea basin. Such fragmentation of the physiographic provinces that represent a typically passive margin can also be observed in the transverse bathymetric profile extract from the southern portion of the Rio de Janeiro (RJ) that is represented in ***Figure 6***, near the latitude of 24ºS and extends between the longitudes of 33ºW and 39ºW.

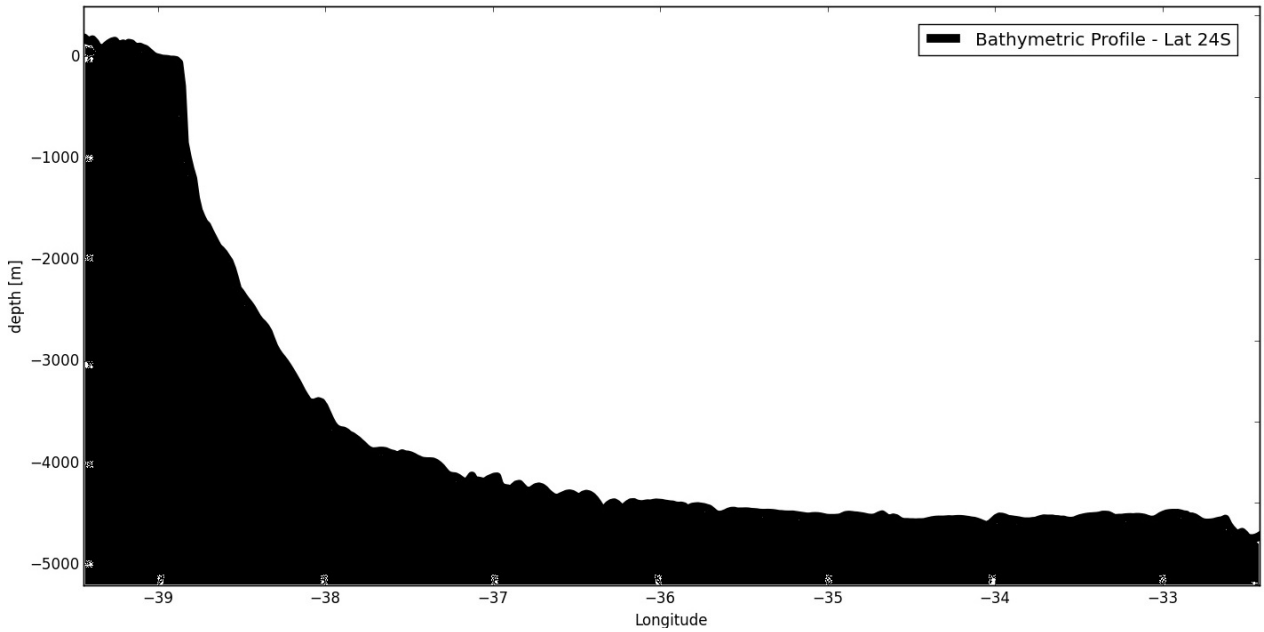


Figure 6 *: Transversal bathymetric profile on the Brazilian continental margin in the latitude of 24ºS extended between the longitudes 33ºW and 39ºW. The profile was extracted from the bathymetric map represented by* ***Figure 5.***

In the bathymetric field, close to latitude of 21ºS, the Vitória-Trindade Ridge can be seen, represented by smaller bathymetries, with estimated depths varying between -2500 to -20m. Between latitudes 16ºS and 19ºS extending between longitudes 35ºW and 38ºW, the Abrolhos Bank and the Bahia Plateau near the Abrolhos Marine National Park are apparent, with deptsh ranging from -50m to -1500m.

In the field of gravimetric anomaly free-air (***Figure 4***), large variations are observed across the continental margin, this fact is justified by the complexity of the region's physiographic features. Peaks of anomalies, 0 and 80 mGal, are noted mainly in the continental shelf region where the São Paulo Plateau and the Abrolhos Bank stand out. The most accentuated peaks of gravimetric field are observed mainly in the Vitória-Trindade Ridge and in the Hotspur seamount, with anomalies ranging from 150 to 250 mGal.

Data processing and analysis of the isobath overlapping of gravimetric anomalies free-air, illustrated by the ***Figure 7***, generated an integrated map of these parameters. This map allows the correlation of the peaks of anomalies found with the geomorphology of the region. There is a strong relation between these parameters, where accentuated peaks of anomalies are directly related to intense topographic gradients. In this analysis, only the morphology of the submarine relief is considered, without simultaneously analysing the fields of mineralogy, constitution/ thickness of sedimentary layers, and rock compositions.

This analysis highlights the gradient of the bathymetric field around the continental shelf, followed by the slope and rise, presenting a correlation with the gradual free-air gravimetric anomaly present throughout the east and southeast marine regions. In addition, the presence of the Abrolhos Bank, the Hotspur Seamount, and the Vitória-Trindade Ridge, stands out, once again, with their respective anomalies also associated with the topographic gradient. Such physiographic provinces are illustrated in a very expressive way from the representative observation of free-air gravimetric variations through a colour palette, which makes the interpretation of the image simpler and more elucidative.

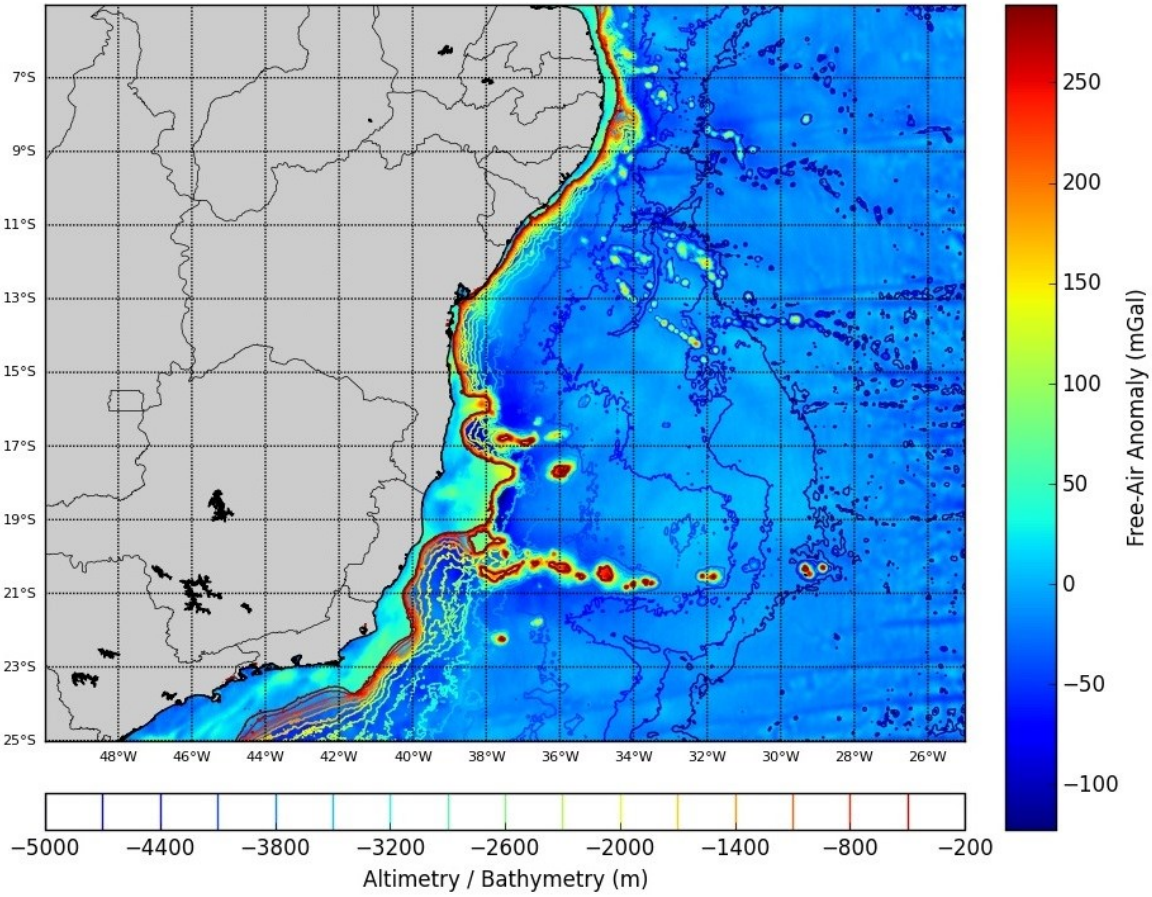


Figure 7 *: Plotting of isobaths over the gravimetric anomalies free-air field. The map allows the analysis of the simultaneous correlation between the parameters, showing the direct correlation between both variables.*

The correlation between the profiles of free-air gravimetry and bathymetry gradients, represented by ***Figure 7***, can also be observed from a transversal view of the parameters, by the longitudinal mass distribution of the Vitória-Trindade Ridge, represented by the graphic of ***Figure 8***, where this profile was traced near to the 20ºS latitude extending between the 29ºW and 40ºW longitudes. In this representation, the direct relationship between the topography and the free-air anomaly is clearly observed. In the vicinity of the 35ºW longitude, an inversion can be observed between the lines of the gravimetric and bathymetric profiles, further SE are observed greater depths with greater anomalies and further NE it is possible to observe shallower bathymetry depth with smaller gravimetric anomalies. Such free-air anomalies can be explained by the inhomogeneity of the crust, varying in thickness and composition, with the continental region presenting an average thickness of 35km and granitic composition (ρ_m= 2,65 g/cm^3), and the oceanic crustal region having a basaltic nature (ρ_m= 3,0 g/cm^3) and thickness ranging from 5 to 8 km. (GUERRA & CUNHA, 2013)

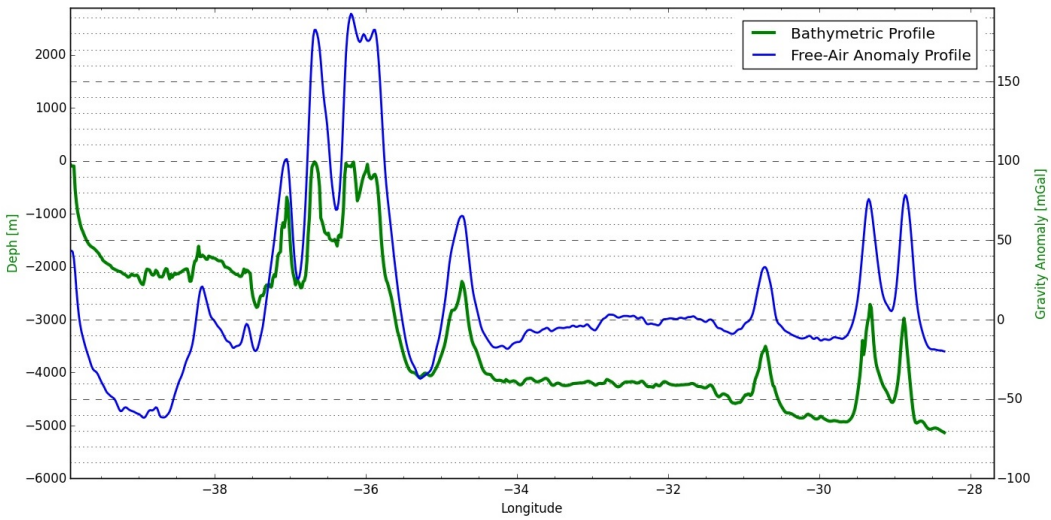
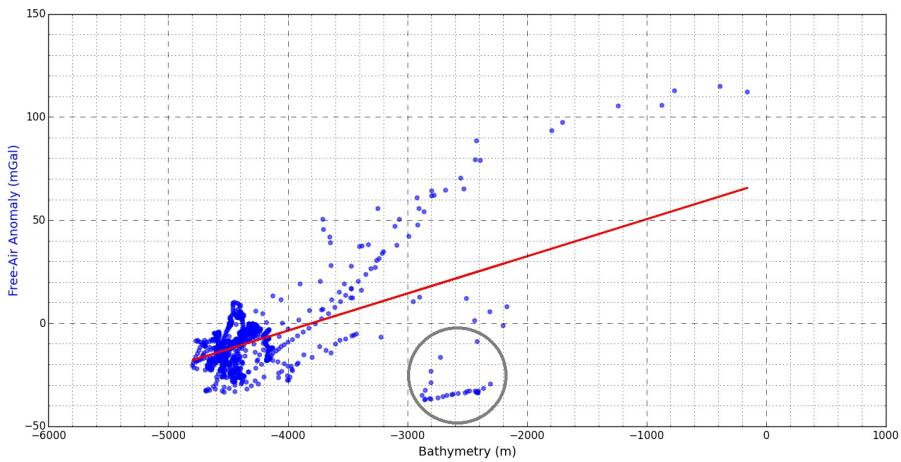


Figure 8 *– Transversal profile integrating free-air gravimetric anomaly and bathymetry data at approximately 20ºS latitude, demonstrating the strong correlation in the spatial field between the bathymetric and gravimetric parameters.*

In order to validate the direct spatial relation between bathymetry and free-air gravimetry, under a statistical perspective, a dispersion/correlation diagram was traced between these variables, utilizing as reference the data present in the vicinity of 20ºS latitude (***Figure 9***). According to Moore (2003), a dispersion diagram presents the shape, direction and measures the degree of relation between two quantitative variables.

The simultaneous graphical representation of the ordered pairs of bathymetric and gravimetric values were investigated, using Pearson's linear correlation coefficient (r), in order to estimate the standard and the intensity of association between the variables. The following "r" values are used as references: Between 0.10≤ r ≤ 0.29 as considered a weak correlation; 0.30≤ r ≤ 0.49 as moderate correlation; and 0.50 ≤ r ≤ 1 can be interpreted as strong correlation (COHEN, 1988). For this evaluation, the correlation coefficient was calculated with its magnitude equal to 0.5473, characterizing a moderate correlation between the variables. It can be seen in Figure 9 the intensification of the points sampled in the geographic grid, and the positive linear correlation, where the same trend, of growth or decay, is expected between the values of bathymetry and gravity free-air. Such visualization is presented by the orientation of the line obtained from the linear regression processing of the sampled points, characterized by the following equation y= 0,01802x + 68,42.

Figure 9 *: Dispersion diagram representing the spatial variations of the free-air gravitational anomaly with the bathymetry in the vicinity of Latitude 20ºS. The positive correlation between the variables stands out and observed from the linear regression of the sampled points allowing to trace a line that summarize the general trend.*



For the Bouguer correction, listed by equation 3.5, the simplified Bouguer correction was implemented, where “h” would be the bathymetry obtained from a certain point over the geographic mesh, or also designated as orthometric height, and “ρ” would be an average of the variation density of water in the oceans, with a adopted value of 1.046 g / cm3 as a reference for the reduction of the Bouguer plateau. The value used for the water density was obtained from the average between the water density on the surface as similar to the presented by PICKARD & EMERY (1990). From these adjustments, the spatial overlap of the field of gravimetric anomalies was performed with the Bouguer correction over the field of isobaths, represented by ***Figure 10***. Such a map, as well as the one listed in Figure 8, allows the spatial correlation of anomalies found with the submarine relief. The representation of the Bouguer anomaly map allows one to analyze the information of the gravimetric field in a deeper way, allowing evaluation of the oceanic and continental interface crust depth, disregarding the influence of the underlying topographic masses.

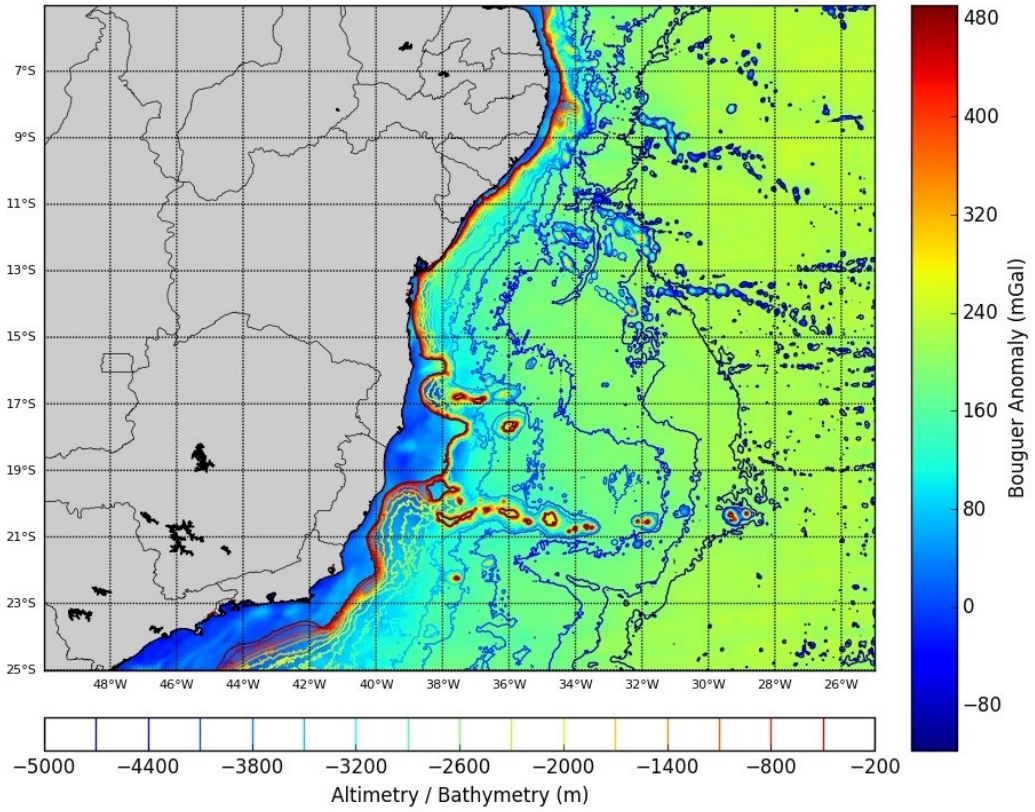


Figure 10 - *Overlapping the fields of gravity anomalies corrected of the Bouguer anomaly over the isobath, allowing to analyse the relation between the variables.*

The greatest changes observed between the free-air and Bouguer anomalies are analysed throughout the ocean basin, and they are more significant according to the distal advance in the direction to greater depths. Under this assessment, when comparing the maps in ***Figures 7 and 10***, it is noted that, at depths around -4000m, where anomalies were previously observed in the range of -100 to 50 mGal (***Figure 7***), variations are now observed between 160 and 260 mGal (***Figure 10***). This difference between values of Bouguer and free-air anomalies is due to the fact that the latter anomaly has a significant and positive correlation with topographic variations, as shown by the dispersion diagram ***(Figure 9***). In general, the gravimetric profiles related to the Bouguer anomaly show a marked increase in its magnitude as the coastline towards the ocean basin is observed, with greater depths. Such analysis can be interpreted based on the transversal

spatial profile, the parameters of bathymetry, free-air gravimetry anomaly and gravimetry with Bouguer correction for the proximity of latitude 20ºS (***Figure 11***).

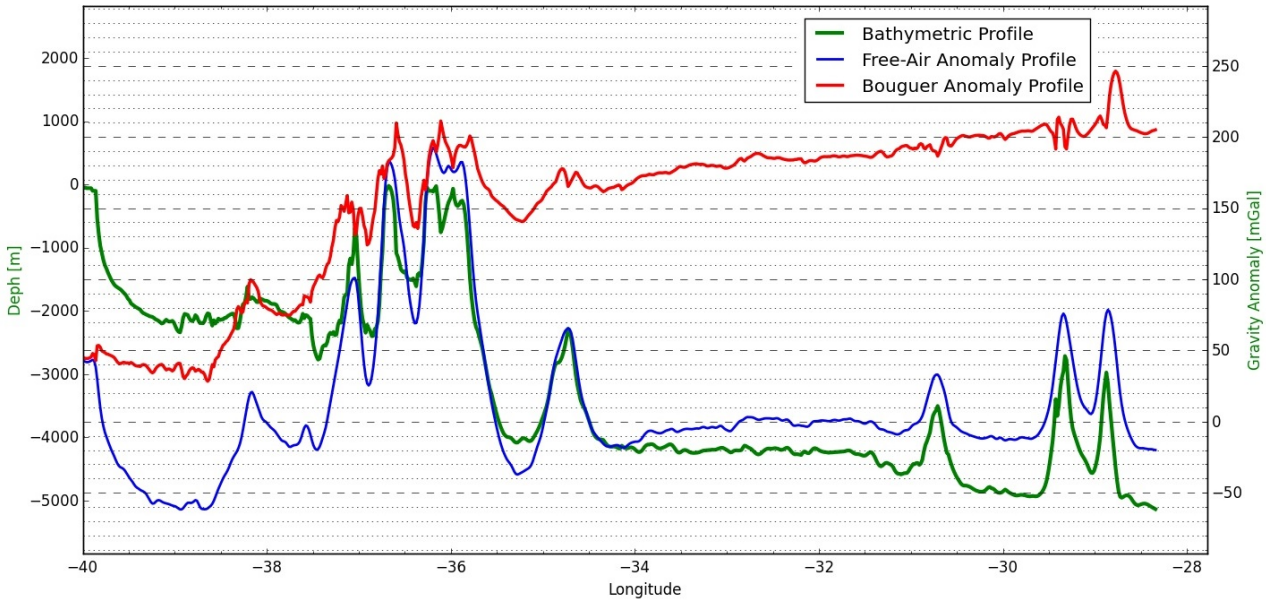


Figure 11 : Transverse profile integrating data on free-air gravimetric anomaly, Bouguer anomaly and bathymetry at approximately 20ºS latitude, demonstrating the strong correlation in the existing spatial field between bathymetry and free-air gravimetry, and the inverse trend of the Bouguer anomaly in relation to bathymetry with the distal advance of the continental margin.

Another interpretation of this profile would be the observation of the progressive increase in the magnitude of the Bouguer anomaly related to the thinning of the oceanic crust in relation to the continental crust (GUERRA & CUNHA, 2013). In order to verify the spatial relation between Bouguer anomalies and bathymetry, under a statistical perspective, a dispersion diagram between these variables was also traced, utilizing as reference the data present in the proximity of 20ºS latitude (***Figure 12***). For this evaluation, the correlation coefficient (r) was determined, with its magnitude equal to -.6838, thus showing a strong negative correlation between the fields, which shows the inverse behaviour, of growth or decay, between the values of Bouguer anomaly and bathymetry. Such interpretation can be made by analysing the behaviour of the line obtained from the linear regression, where y = -0.0258x + 68.42. It is important to note that the coefficient obtained between bathymetry and Bouguer anomaly is greater than that related to free-air anomaly and bathymetry.

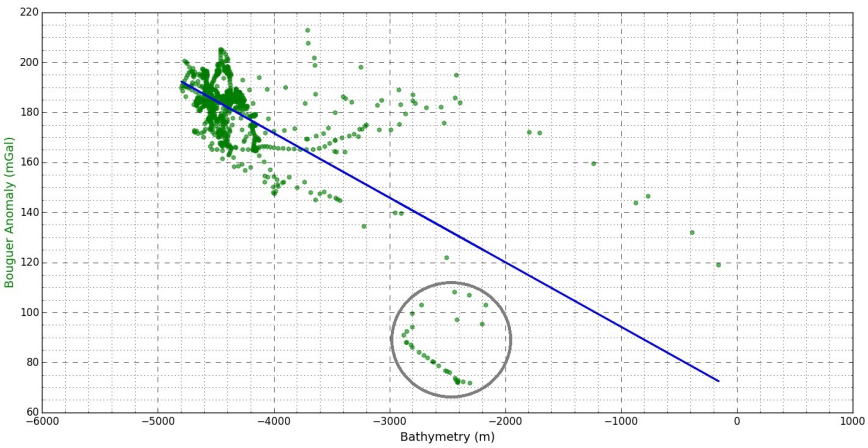


Figure 12 : *Dispersion diagram representing the spatial variations of the Bouguer gravitational anomaly with the bathymetry in the proximity of latitude 20ºS. The negative correlation between the variables stands out, interpreted based on the linear regression of the sampled points allowing to trace a line and analyse its behavior.*

Following the same line of reasoning as to the implementation of a qualitative statistical analysis, the dispersion diagram was traced between the gravimetric parameters of Bouguer anomaly and free-air anomaly, represented by the ***Figure 13***, for the region near 20ºS latitude. The correlation coefficient was calculated with a value of 0.2365, which characterizes a weak correlation between the variables, despite the intensification of the points sampled in the geographic grid. From the linear regression processing of the sampled data, it was possible to obtain the line that would characterize the concomitant trend of the variables, and this line is expressed by: y = 0.2713x + 181.21. Based on the weak correlation verified between these variables, it is concluded that the correction implemented was satisfactory, effectively removing the influence of the relief on the gravimetric Bouguer anomaly values.

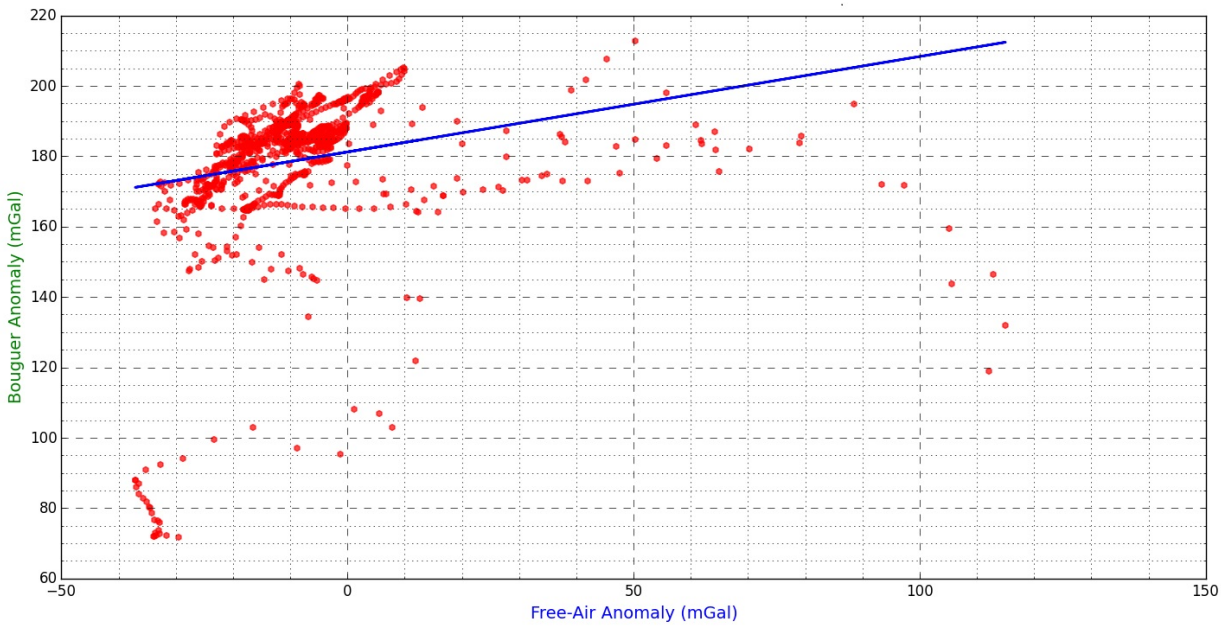


Figure 13 : *Dispersion diagram representing the spatial variations of the free-air and Bouguer gravitational anomaly in the vicinity of latitude 20ºS. The weak correlation between the variables is highlighted, characterized by the low inclination of the line obtained through the linear regression of the sampled points.*

Finally, regarding the correlations between the Free-air and Bouguer gravimetric anomalies present in ***Figures 9 and 12***, one is able to determine the presence of a set of data that significantly influences the inclination of the line. These set of data, delimited by the gray circle, are located at depths between -2000 and -3000m. In the correlation of gravitational anomaly free-air and bathymetry (***Figure 9***), it was possible to verify that these data are responsible for reducing the correlation and decreasing the inclination of the line. In the Bouguer gravitational anomaly and bathymetry correlation (***Figure 12***), it was verified that these data are responsible for increasing the inclination of the line and contributing to the increase in the correlation. Thus, it is verified that the variation of these correlations is caused by these data located in the region of the continental slope and its adjacencies.

5. Conclusion and final considerations

The development of this work proposed the integrated spatial analysis of the bathymetry fields and gravimetric anomalies related to the Brazilian east and southeast marine regions. This allowed a trace of a profile on the physiographic characterization of the region's sea floor, as well

as the qualitative statistical evaluation between geophysical parameters. The importance of using the Python computer programming language is highlighted, as a facilitating agent in the processing and presentation of data, since it offers several free tools and libraries that allowed an interface for the treatment of gridded data and the production of analysis and results such as: graphics, interactive profiles, maps and diagrams. The altimetry and gravimetry data from the TOPEX database were presented as viable for qualitative use, and the parameters were interpolated for a resolution of 1 minute of degree and accuracy of 1 mGal. With regard to quantification in the geophysical scope, it is noted the complexity of the arrangement of gravimetric anomalies in the studied region, where in the field of free-air anomalies, it values in the order of 100 mGal were found to distributed along the continental shelf, and largest peaks, on the order of 250 mGal, were associated with the Vitória-Trindade Ridge, the Abrolhos Bank, and the Hotspur Seamount. In this same field, the lowest values, around -100 to 60 mGal, were found in the ocean basin, with smaller values in the fracture zones and seamounts present in the east and northeast quadrants.

In the field of Bouguer gravimetric anomalies, the modification of the geophysical parameter in question is notable, with the greatest changes observed with the distance of the continent towards the greater depths of the oceans, in which anomalies at depths of -4000m, which previously varied from - 100 to 50mGal (free-air), can now be observed between 160 and 260 mGal (Bouguer). Such changes in geophysical parameters would be associated with the crustal "thinning" of the oceanic part in relation to the continental crust.

The spatial analysis of the fields of free-air gravimetry, Bouguer gravimetry and bathymetry through statistical parameters was presented in a satisfactory and significant way, where, with the analysis of the dispersion diagrams in the bathymetric and free-air gravimetry fields, it is possible to observe a moderate positive linear correlation (r = 0.5473) between the variables. For the Bouguer bathymetry and gravimetry fields, a strong negative linear correlation (r = -0.6838) can be observed between the parameters. When analysing the dispersion fields of Bouguer and free-air gravimetry, a weak linear correlation (r = 0.2365) is observed for the region in the proximity of 20ºS latitude, and this relation is best seen from the observation of the trend of the line that supports the correlated variables.

For future work, it is recommended to reduce the geographic mesh to support analysis at much higher spatial resolution. Another suggestion would be to carry out the analysis of geophysical parameters from different data acquisition platforms, whether acquired *in loco* or remotely, in order to compare the information with a goal to increase the accuracy of the data and allow the determination of necessary adjustments.

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Notes

THE CANADIAN OCEAN MAPPING RESEARCH AND EDUCATION NETWORK (COMREN)

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Abstract

In Canada, ocean, river, lake and coastal mapping knowledge, capacity building and know-how are strengthened through a network of members from academic institutions and one nonprofit organization. This note highlights the Canadian Ocean Mapping Research and Education Network (COMREN), its purpose and its membership.

1. Introduction

To ensure the continued flourishing of humankind, it is essential to develop the global ocean economy sustainably. This will require intelligent decisions based upon comprehensive and accurate information – especially that obtained from the analysis of ocean mapping data. Global warming, climate change, sustainable development, and an innovative blue economy are critical affairs for the world's coastal nations. For instance, marine shipping is the backbone of transnational material trade, and its classification as an essential service throughout the COVID-19 pandemic has been vital to maintaining the societal order of nations during the crisis.

Hydrographic surveying and marine geospatial science being much more than nautical charting for safe and efficient navigation – alternatively referred to as hydrospatial science (Hains, 2020) – and autonomous scientific data collection vessels are worldwide growth areas for scientific and technological development within industry and academia. For Canadian academic institutions, this growth has manifested as the development and implementation of ocean mapping teaching and research programs that aid in addressing provincial, territorial, national and international concerns in ocean characterization. For Canada, ocean mapping capacity building, and support for advanced ocean technology industries constitute sound economic strategies.

The Canadian Ocean Mapping Research and Education Network (COMREN), as a knowledge development network (Clark, 1998), will be able to support Canadian economic growth initiatives such as the federally-funded Ocean Supercluster (oceansupercluster.ca). This initiative aims to make Atlantic Canada a global force in the 'blue economy' by harnessing emerging ocean technologies in the realms of digital sensors for ocean mapping and monitoring, autonomous marine vehicles, energy generation, automation, marine biotechnology, and marine engineering. Prior to the global pandemic the Canadian government planned for the Ocean Supercluster to have a 10-year GDP impact of at least $14 billion (CDN) and generate more than 3,000 jobs.

According to the Ocean Supercluster, Canada's blue economy presently contributes more than $36 billion to GDP and supports almost 350,000 jobs. COMREN draws on institutional expertise and resources across Canada. As such, the development focus of the network can be leveraged to help geographically separated regions in the country – Pacific, Arctic, Great Lakes & St. Lawrence River, and Atlantic – benefit from potential growth in the global ocean economy, which was forecasted to reach a value of more than 3 trillion dollars globally by 2030, outpacing broader economic growth by nearly 20% (OECD, 2016). Canadian success in the ocean mapping and hydrospatial aspects of a post-pandemic 'blue economic recovery' will be accelerated by the efforts and the willingness of COMREN members to collaborate on innovative ocean mapping research, teaching, and career development. COMREN is supported through the engagement of interested parties including the Canadian Hydrographic Service (Fisheries and Oceans Canada, 2018).

2. About COMREN – a formal knowledge network

The nurturing of knowledge-based networks has been recognised as integral to sustainable development in Canada (Clark, 1998) – helping people, both domestically and internationally, by sharing experiences and seeking solutions to common economic, social and environmental challenges. COMREN, an independent association of academic institutions and a non-profit, recognizes the need to transition from a somewhat 'open network' to more of a 'development network,' thereby increasing its value to society. Development networks "have a well-defined theme and carefully chosen criteria for participation, exist to create knowledge and to accelerate the application of that knowledge to economic and social development, and have a formal constitution and tight governance (Clark, 1998)." However, for the time being, COMREN members wish to maintain an informal and cooperative governance arrangement.

COMREN was formally established in February 2016 by various educational and applied research stakeholders, each having a number of pre-existing informal connections. By formalizing the association, the intent was to strengthen a pan-Canadian academic, and non-profit, network in ocean mapping, as well to define and coordinate the fundamental objectives and activities to be subsumed by the network. COMREN's structure is designed to enhance collaboration on research interests and educational activities. The primary COMREN stakeholders are the: Interdisciplinary Centre for the Development of Ocean Mapping (**CIDCO** – *Centre interdisciplinaire de développement en cartographie des océans*), Nova Scotia Community College (**NSCC**), Marine Institute of Memorial University of Newfoundland (**MI**), Laval University (**ULaval**), University of

New Brunswick (**UNB**), University of Ottawa (**uOttawa**), York University (**YorkU**) and British Columbia Institute of Technology (**BCIT**). The membership stretches from the Pacific to Atlantic Oceans, with interests in the Great Lakes-St Lawrence freshwater system, and the Arctic Ocean. COMREN operates in both French and English, Canada's official languages at the national level (***Figure 1***).

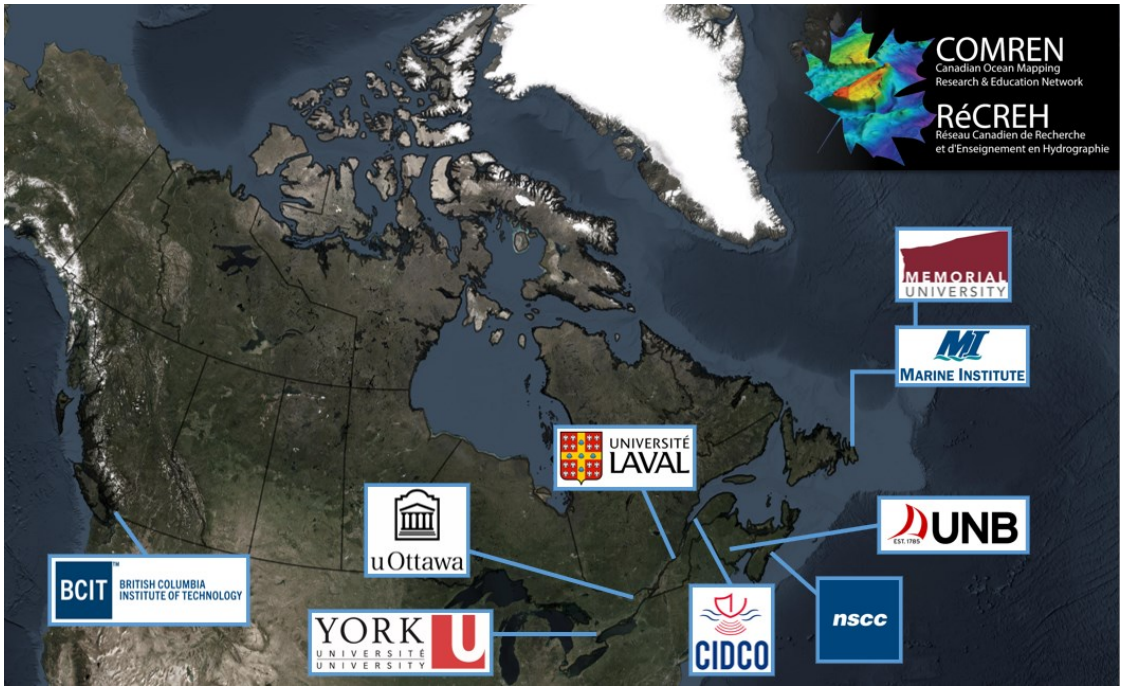

Figure 1 : *Location of current COMREN members*

3. Purpose of COMREN

COMREN aims to develop research activities, achieve technology transfer to industry, develop and run educational programs. The network operates in liaison with government agencies and international organizations, to increase Canada's ocean mapping research and education capacity and presence – both domestically and internationally. Central to this is providing opportunities to train Highly Qualified Personnel (HQP) who can help advance ocean technologies and solve problems — both applied and theoretical — with hydrospatial science (Hains, 2020) and the ideas of neighbouring disciplines. COMREN can help ensure the connections and incentives needed for HQPs to effectively collaborate and innovate in Canada.

The overall goals set out for COMREN are to: collaborate on ocean mapping research programs, from innovation in underlying technologies to implementing challenging applications; to interact with federal, provincial, territorial and international agencies and industry; and to be a focal point for research and education on ocean mapping in Canada and abroad. The network looks to promote ocean mapping research within Canada, and worldwide; to facilitate cooperation between educational institutions and instructors, and to develop and enhance training programs in Canada recognized by the International Federation of Surveyors (FIG), International Hydrographic Organization (IHO), and International Cartographic Association (ICA); and to facilitate student exchanges, graduate research co-supervision, and internships.

For membership in COMREN, institutions must demonstrate an active participation in ocean mapping research and/or education, and willingness to work as a pan-Canadian team. COMREN members commit to: participating in an annual workshop and periodic meetings; establishing and

communicating research priorities; encouraging scientific capacity building methods and activities in ocean mapping; facilitating collaboration and information exchange between COMREN member researchers; and promoting COMREN activities through dissemination of COMREN achievements.

A priority for COMREN is to work closely with Fisheries and Oceans Canada - Science, the Canadian Hydrographic Service (CHS), Natural Resources Canada (NRCan), and other interested hydrographic offices and mapping agencies around the world, to identify and engage in leading-edge ocean mapping initiatives such as surveying through the utilization of Autonomous Surface Vehicles (ASVs), underwater vehicles, shallow water multibeam sonar surveys with associated backscatter analyses, satellite-derived bathymetry, Marine Spatial Data Infrastructure (MSDI) design, the implementation of hydrospatial data management strategies, and educational program development.

Figure 2 *: COMREN Logo*

The members of the network bring a combination of unique, complementary and overlapping expertise, capacity and equipment. These resources, both human and capital, when brought together, maximize Canada's potential for innovation and ambition in ocean mapping. It is envisioned that COMREN members can partner in competitive bids for research funding, or collaborate on ventures for industry, government, international development, and education. With the support of federal, provincial and territorial governments, the network is building capacity for ocean mapping in Canada for global benefit.

4. The eight COMREN members

Figure 3 *– CIDCO Logo*

The "*Centre interdisciplinaire de développement en cartographie des océans*" or Interdisciplinary Centre for the Development of Ocean Mapping (**CIDCO**) is a non-for-profit organization that was founded in 2002, with the objectives of developing new technologies, tools and methodologies for ocean mapping, Through partnerships with the academic sector, the public sector and the industry, CIDCO is a collaborative hub for research and development organization dedicated to

improving state-of-the-art technology in marine geospatial (Hydrospatial) data acquisition, processing and management. Topics of interest at CIDCO include the automation of hydrographic systems calibration, automated data processing, automated quality assurance, artificial intelligence applied to marine geomatics, and autonomous surveying technologies. CIDCO also offers an IHO-FIG-ICA certified Category B programme in Hydrographic Surveying recognized across-the world through, among others, several capacity building programs. CIDCO is an expert contributor to the International Hydrographic Organization (IHO) Crowd-Sourced Bathymetry Working Group (CSB-WG) as an expert contributor. More information at: www.cidco.ca

Figure 4 *– NSCC Logo*

The Nova Scotia Community College (**NSCC**) is committed to building Canadian Nova Scotia's economy and quality of life through education and innovation. Serving the province through a network of 13 campuses, the College offers over 120 programs in five academic schools, reflecting labour market needs and opportunities in Nova Scotia. NSCC's Applied Research department helps the College realize its mission by working with industry partners to grow their businesses. This direct engagement with industry helps drive Nova Scotia's economy, enhances quality of life and builds innovation capacity. Oceans research is one of five focus areas of applied research at NSCC. Within this focus area, research is conducted in the field of ocean floor mapping using the latest ocean technologies such as acoustic remote sensing methods, and seafloor sampling and imaging technologies. The maps generated deliver spatial information for use in a variety of applications ranging from sustainable fisheries to marine protected area management. More at: www.nscc.ca

Figure 5 *– MI Logo*

The Marine Institute of Memorial University of Newfoundland is a world-class centre of advanced marine technology, education, and training. Initially conceived as the College of Fisheries, Navigation, Marine Engineering and Electronics in 1964, the Marine Institute (**MI**) has developed into Canada's leading fisheries and marine institute. MI is now one of the most respected centers for marine learning and applied research in the world. It offers over twenty programs, many with an applied focus, ranging from industrial and technical certificates, to diplomas, to bachelor's, master's, and doctoral degrees. The institute also runs a variety of short courses and industrial response programs designed to provide students with the knowledge and skills required for workforce success.

MI contains three schools – the School of Fisheries, the School of Maritime Studies, and the School of Ocean Technology, which hosts the Ocean Mapping Program. These centres lead the MI, both nationally and internationally in applied research and technology transfer, and in training for a variety of industry clients. In fall 2020, MI is launching two course-based applied ocean mapping graduate programs with a foundational curriculum based on the FIG-IHO-ICA marine surveying (nautical cartographer) competencies: a master's degree, and a postgraduate diploma.

MI International (**MII**) is the focal point for international initiatives at the Marine Institute. The department's primary areas of focus are international consulting and project management, building international institutional partnerships, and supporting international student recruitment and

services. Through MII, the Marine Institute engages in development projects, contract training, and consultancies across the globe. For over 30 years, MII has successfully implemented more than 200 projects in over 50 countries, making the Marine Institute one of the most internationally active institutes in Canada. More at: www.mi.mun.ca

***Figure 6** : Laval University Logo*

ULaval/SCG and CRDIG: The Department of Geomatics Sciences at Université Laval, which has celebrated its centenary year in 2007, offers a complete and diversified education at both undergraduate and graduate levels in geomatics. Apart from its four graduate programs, two undergraduate programs (4 years /120 credits) are currently offered by the Department: 1: Bachelor's degree in geomatics sciences (B.Sc.A.) : the only program in Quebec that allows access to the *Ordre des arpenteurs-géomètres du Québec (Association of Quebec Land Surveyors)*; 2: Bachelor's degree in geomatics engineering (B.Ing.): the only program in Quebec to train geomatics engineers. More than 350 students are currently enrolled in these programs, including 275 undergraduates, about 50 graduates and more than 30 students in short programs (15 credits). With a team of 14 professors, along with leading-edge infrastructure and installations, the Department offers educational programs that are aligned with the most recent geomatics advances and the labour market expectations. Centre for Research in Geospatial Data and Intelligence (CRDIG) is among the largest of its kind in the world and supports leading-edge scientific research in the geospatial field. Its members actively collaborate with the community in order to apply their research activities in innovative ways for the benefit of society, in three privileged areas of application: marine and fluvial environments, intelligent cities and communities, natural resources and human activities. Established in 1989, CRDIG's mission is to increase scientific knowledge in the geospatial field. This knowledge is used to design and implement advanced and innovative methods and technologies that are at the heart of data science. More at: https://www.scg.ulaval.ca/ and https://crdig.ulaval.ca/

***Figure 7** : UNB Logo*

UNB/GGE: The Department of Geodesy and Geomatics Engineering at the University of New Brunswick (UNB) in Fredericton provides education and research programs at the undergraduate, Master's and PhD level in the fields of GNSS, Geodesy, GIS, Big Data Analytics, Remote Sensing and Ocean Mapping.

Founded in 1785, UNB is Canada's oldest English-language university, and is New Brunswick's premier research institute and largest university. There are two main campuses, located in Fredericton and Saint John, with vibrant and growing undergraduate and graduate programs offered in both locations. UNB is responsible for 75% of New Brunswick's publicly funded research and has a rich history of research partnerships.

The Ocean Mapping Group was established as part of the Department of Geodesy and Geomatics Engineering at UNB in 1988 in response to a national need to develop advanced ocean mapping capabilities. It draws upon faculty and staff with expertise in the fields of hydrography, geographical information systems, digital image analysis, interactive computer graphics and 3-D

data visualization. The research of the Ocean Mapping Group is focused on developing new and innovative techniques and tools for the management, processing, visualization and interpretation of ocean mapping data. More at: http://www.omg.unb.ca/ and http://gge.unb.ca/

Figure 8 *: BCIT Logo*

For more than 50 years, the British Columbia Institute of Technology (BCIT) has been training the experts, innovators, and professionals who shape our economy – across BC and around the world. Through our unique applied education model, BCIT students gain the technical skills, real-world experience, and problem-solving ability needed to embrace complexity and lead innovation in a rapidly changing workforce. Our curriculum is developed through close consultation with industry and delivered by instructors who have direct, hands-on experience in their fields. Land Surveying and Mapping courses have been offered at BCIT since it was established in 1964.

The BCIT Geomatics Department offers a two-year Diploma in Geomatics Engineering Technology with the choice of either pursuing a career in industry upon graduation or continuing for a further two years of study toward a Bachelor of Science in Geomatics. The curriculum for the Bachelor's degree is designed to meet the requirements of the Canadian Board of Examiners for Professional Surveyors (CBEPS) which regulates academic qualifications for Land Surveyors in Training in several provinces. Courses include Geodetic Positioning, Geospatial Information Systems, Advanced Satellite Positioning Techniques, Cadastral Surveying, High Precision Surveying, Remote Sensing, Advanced Digital Mapping and Hydrographic Surveying.

For more information, visit: www.bcit.ca/geomatics

Figure 9 *: uOttawa Logo*

uOttawa: The Department of Geography, Environment and Geomatics at the University of Ottawa is a hub of research and teaching activity for a wide variety of areas including ocean mapping. The research and teaching interests in the Department are as diverse as the nature of geography itself, and we offer training in geomorphology, climatology, biogeography, human, social and cultural geography as well as GIS and remote sensing. The Department is home to recognized experts in the field, including Research Chairs in Glaciology, Environment, Society and Policy, and features a CFI lab for Shallow-Water Earth Observation. As such the Department has substantial expertise in satellite-based ocean mapping, including foci in the areas of satellite-derived bathymetry, seafloor habitat mapping, and land- and sea-ice in the Arctic. More at: https://arts.uottawa.ca/geography/

Figure 10 *: YorkU Logo*

The Department of Earth and Space Science and Engineering at the Lassonde School of Engineering at York University offers several unique and world-class graduate (MSc, PhD) and undergraduate programs, including the Geomatics Engineering program (BEng) established in 2001 and the Geomatics Science stream (BSc) established in 2016. The Geomatics Engineering

program is accredited by the Canadian Engineering Accreditation Board (CEAB), the Association of Ontario Land Surveyors (AOLS) and The Canadian Board of Examiners for Professional Surveyors (CBEPS) Level-2.

Teaching and research related to COMREN themes and activities include: Global Navigation Satellite Systems, Multi-sensor-integrated navigation, Hydrography, Manned and Unmanned Mobile Mapping Systems, Physical and Space Geodesy, Remote Sensing and Photogrammetry, GIS and Spatial Data Infrastructures, Aerial and Terrestrial Laser Scanning, Digital Terrain Modelling, 3D Modelling and Visualization, Survey Law, and Geomatics Sensor Systems development and integration. Faculty members perform world-leading research in many of these subdisciplines, focussed on technology solutions and positive societal impact. More at: https://esse.lassonde.yorku.ca

5. Conclusion and future directions

COMREN is a vibrant, proactive, committed and collaborative network of academic institutions and one nonprofit. The organization is not incorporated and does not currently constitute a legal entity, but it is a genuine network of partners willing to work together on challenging projects. The pan-Canadian members of COMREN will share knowledge, implement joint research and education projects, and strengthen Canada's ocean mapping capacity in order to serve the world.

Canadian and international collaboration in hydrography, ocean-seabed mapping, coastal geospatial, and hydrospatial data projects are welcomed by COMREN. Projects and proposals can be developed and funded using the COMREN "banner" through a COMREN member willing to ensure the coordination of duties and administrative obligations. Such projects or proposals could involve all members of COMREN or a subset; and might involve additional collaborators from anywhere in the world. A typical project will involve at least 2 official COMREN members and can be expanded as needed to maximize outcomes.

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Notes

HYDROGRAPHY IN REMOTE AREAS
Mapping the waters of Saint Helena as part of the British Overseas Territories Seabed Mapping Programme.

By I. Davies, Hydrographic Programme Manager,
United Kingdom Hydrographic Office

Abstract:

In 2018, a team of hydrographers from the United Kingdom Hydrographic Office (UKHO), supported by UK Government funding under the Overseas Territories Seabed Mapping Programme (OTSMP), undertook a bathymetric survey of the coastal waters of Saint Helena. The coastal waters of this environmentally sensitive island were substantially unsurveyed and there was a need to gather information to support Safety of Navigation along with future sustainable management and development of the island's ocean resources. This note discusses the requirements, challenges, results and wider utilisation of this geographically remote survey in the South Atlantic.

1. Introduction

In 2014, the International Maritime Organisation (IMO) introduced its Member State Audit Scheme (IMSAS). In announcing the timetable for audits, the United Kingdom and the Overseas Territories (OT's) by extension would be inspected in 2020. The Implementation of IMO Instruments Implementation Code (IIIC) Audit assesses the current level of implementation of IMO instruments by Member States in their capacity as Flag, Port and Coastal States.

The audit focuses on the 1974 Safety of Life at Sea (SOLAS) Chapter 5 Regulations 4 and 9, with specific reference to the Safety of Navigation. In UK waters, the Civil Hydrography Programme concentrates on safety of navigation surveys, but this does not extend to the Overseas Territories' (OT's). The UK Government Conflict, Security and Stability Fund (CSSF) provides funding to undertake hydrographic surveys in the OT's as part of the material preparations for the audit along with training in hydrographic governance.

One area identified with a pressing requirement for modern surveys was the island of Saint Helena, located 1,900km off the west coast of Africa in the South Atlantic.

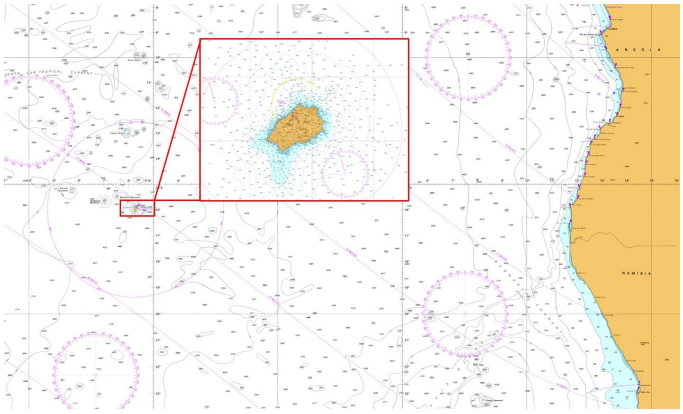

Figure 1 *: Saint Helena - Overview of Location in South Atlantic (BA Charts 4203 and 1771B © UKHO))*

2. Identifying Survey Requirements

Volcanic in origin, the island is fringed by perpendicular cliffs in all but a few places, with the only practical place for landings being in James Bay on the North-west side of the island. Until the recent opening of the airport, the island's only link with the outside world was by ship. Whilst the island is no longer frequented by vessels transiting around the Cape of Good Hope, over recent years visits to the island's new port by larger vessels, such as cruise liners and transiting yachts, have increased. This, along with a growing need to map the waters to assist with fisheries management and environmental monitoring, meant that modern surveys were a priority in assisting the island to meet its international SOLAS obligations.

3. Survey Planning

A number of surveys have been completed in recent years by both the Royal Navy and other UK government organisations, but the coverage was incomplete. The UKHO has developed a GIS based risk assessment tool enabling the assessment and prioritisation of the areas of highest risk to the mariner.

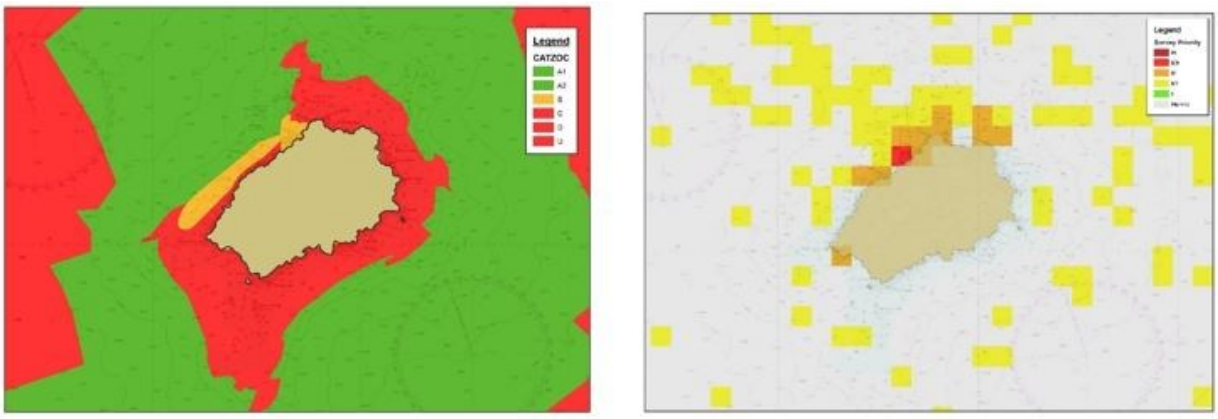

Figure 2 : *UKHO CATZOC Analysis and Initial Survey Prioritisation*

Left *– Image shows CATZOC for area covered by BA Chart 1771B, Deep water areas have been surveyed substantially to modern standards (green) with the inshore areas (amber and red) not having systematic modern surveys.*

Right *– Image shows areas that are a priority for surveys based on CATZOC and AIS data. Highest priority is based around James and Rupert's Bay.*

Analysis of the current data on the chart using the Category Zones of Confidence (CATZOC) revealed that the coastal waters less than 200m in depth were not surveyed to modern standards. When this was examined against AIS data showing typical transit routes to, from, and around the island, priority areas for survey were focused on the approaches to James Bay and the new port in Rupert's Bay, which lay just to the North.

The conduct of a bathymetric survey purely for safety of navigation in such a remote location may not necessarily meet all stakeholder requirements and nor fully capture wider issues impacting on the ability of the authorities to meet their maritime responsibilities. In May 2018, a technical visit was therefore undertaken to Saint Helena where meetings were held with the government and all maritime stakeholders to identify any local priorities which were not captured. What became clear during this visit was the need to ensure that any data collected was capable of being used by other UK government agencies engaged in programmes around the island (e.g. The Blue Belt Programme) and also for the data to form part of a comprehensive Spatial Data Infrastructure which was being developed by the island's GIS Office to assist in future development and coastal zone management. As a result of these meetings the following priorities were identified from key maritime stakeholders.

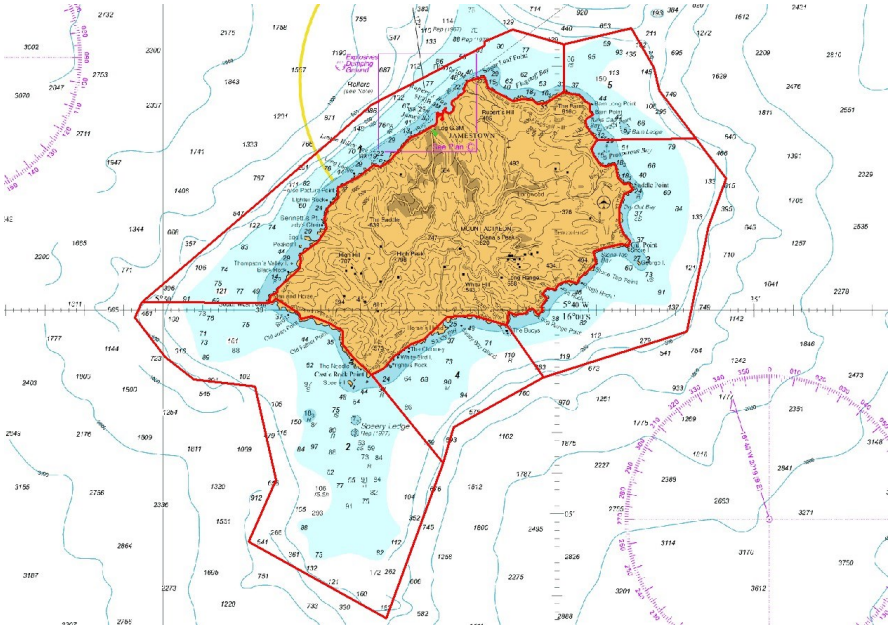

Figure 3 *: Local stakeholder Priorities following technical visit.*

Top Left *– Land Survey and Mapping identified 3 areas, green being the highest priority and blue the lowest. Bottom Left – Search and Rescue identified two areas with a need to cover inshore areas on NW and E side of the island for Search and Rescue.*

Top Right *– Fisheries identified 3 areas driven by the need to identify new fishing grounds and potential protection of existing sites to maintain fish stocks. Bottom Right – Ports and Harbours main priority were areas in which increasing numbers of vessels are now visiting (cruise liners to yachts) and the areas typically used by vessels engaged in whale-watching activities. (Extract from BA Chart 1771B © UKHO)*

Following a review of all requirements, a final block of prioritised survey areas was then designed based on the both UKHO's and the local requirements with the highest priority being the north-west coast.

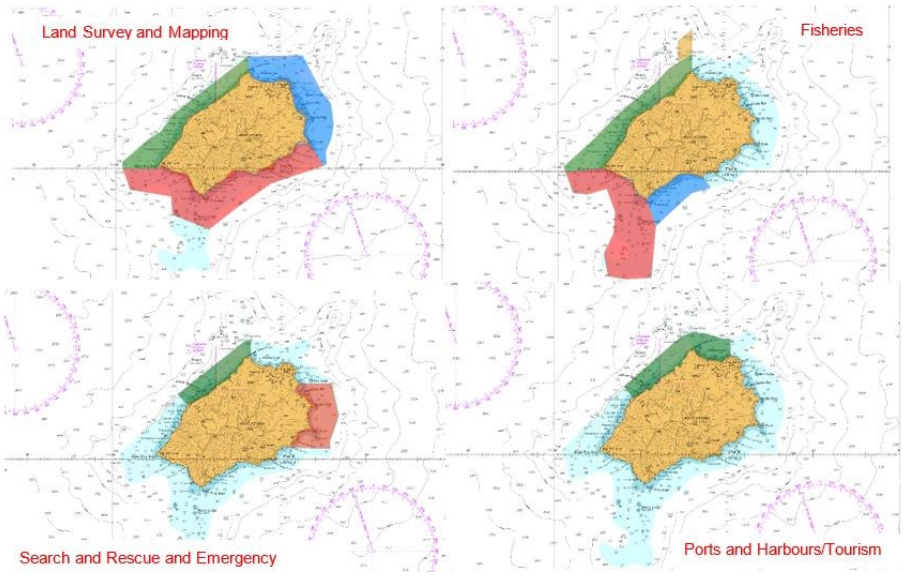

Figure 4 *- Final Survey Requirements extract from BA Chart 1771B © UKHO*

4. Conduct of Surveys

Having identified the areas that would benefit all marine stakeholders, the decision on how to undertake the survey was the next task. Geographically remote from the main areas of current survey activity, mobilising contractors to undertake the survey would be challenging and potentially expensive. With a number of major oil and gas and mineral exploration centres on the west coast of Africa, the decision was taken to issue an open tender for the survey work using UKHO's Acoustic Specifications for Surveys which provided amplifying information to S44 – IHO Standards for Hydrographic Surveys. Following review of the tender submissions, whilst all were technically compliant the cost of mobilising the vessel far outweighed the cost of the actual survey and was not delivering value for money. An alternative solution would need to be found.

Having already identified costs as a challenge, the alternate solution was to deploy a team from UKHO to undertake the survey. UKHO employs a number of qualified hydrographers, both in the Scientific Advisory Group, who undertake data validation, and within the Hydrographic Programmes team, who lead a number of data collection and capacity building activities. In recent years, this team of hydrographers have deployed on vessels of opportunity to undertake a number of surveys in the Caribbean and SW Pacific in support of UK Government funded programmes being led by UKHO.

In order to ensure the smooth running of the project, a reconnaissance was undertaken to establish any potential problems or risks for a team deployed so remotely and to also establish potential challenges with chartering vessels, import of equipment and how the local infrastructure could support a deployed team during survey operations.

The survey areas were defined prior to the survey reconnaissance to allow any last-minute changes to be incorporated into planning when liaising with local government officials. Critically, during the reconnaissance the opportunity was taken to check existing information held at UKHO for survey geodesy, particularly benchmarks for the tidal observations which were over 30 years old. Two existing radar tide gauges were operating but there have been reliability issues, so the decision was taken to establish an independent station to provide redundancy during operations.

5. Unique Challenges of Remote Area Surveys

A number of challenges are always present in any detached survey where there may be limited local resources or access problems, therefore proper planning based on reconnaissance is essential. Potential challenges include issues with permitting, authorisation for personnel to work, local support facilities, weather conditions, communications and most importantly support from manufacturers in the event of a defect.

i. Accessibility - Saint Helena has one or two flights per week (dependent upon the time of year) and a single vessel visit (delivering containerised cargo) every 4 weeks and so preparation and shipping of equipment and flights to meet its arrival are critically important to avoid undue delays. Due to its location and the siting of the airport, flights are subject to last minute cancellation and the potential for this had to be factored in for scheduling and costing purposes.

ii. Personnel – Sufficient personnel need to be available to operate the vessel during daylight hours and also process the data to ensure that any data gaps or poor-quality data is re surveyed at the time. At the outset, the need for a Survey Engineer to be on site for the entire duration of the survey was also identified as a key requirement which would mean any equipment faults or defects could be addressed immediately.

iii. Vessels – During the technical assessment visit, several potential vessels were identified that could be chartered for operations. Deconflicting activities would be critical as these vessels are limited in number and used for multiple purposes already, for example: tenders for

visiting ships, support for local environment departments work, and other local activity. As equipment would need to be deployed over the side of the boat during survey operations it was important to ensure the chosen vessel could support this and have sufficient power onboard to operate all hardware. During the reconnaissance it became clear that facilities to manufacture a suitable mount locally in the short time frame of the survey were not available. As a result, detailed measurements were taken to allow the pole to be fabricated in the UK and shipped with all of the other equipment. This would speed up mobilisation once the equipment was on site.

iv. Equipment Requirements – All goods are imported by ship, as the aircraft supplying the island have limited cargo capacity due to fuel restrictions on the inbound flight to Saint Helena. As a result, all equipment for the survey would need to be shipped in several weeks in advance to allow for it to be unloaded and transported from the port to Jamestown where it would be cleared by Customs prior to the survey team arriving. In total, 7 pallets of equipment were sent, and the decision was made to duplicate all equipment to provide sufficient spares on site in the event of failures.

vi. Environmental Conditions – lying in the tropics, weather conditions are generally stable, however significant sea and swell conditions can build up at any time of the year. Following local advice, the planned dates for survey were adjusted to conduct operations in what was expected to be the best conditions around the whole island.

vi. Environmental Protection – Saint Helena's entire Exclusive Economic Zone (EEZ) was declared a Marine Protected Area (MPA) in 2016 (St Helena's Marine Protected Area, 2016). Saint Helena's waters are feeding grounds for commercially important tuna species, sharks and billfish and provide seasonally important habitats for whale sharks and humpback whales. Survey operations represent a potential threat to whale sharks and cetaceans, therefore ensuring that appropriate permitting and deconfliction measures were in place was a key requirement identified by the Environmental Management Division.

vii. Communications – Saint Helena has internet access, but is limited to dial-up speeds and is relatively expensive to use. Identification of this constraint enabled the team to take all documentation and materials they may need to minimise requirements for large downloads.

6. Data Capture

Equipment was deployed and arrived in Jamestown in early November. After leaving the UK on Thursday 15th November, the UKHO survey team finally arrived in St Helena on Friday 23rd November to commence seabed mapping operations having been delayed by poor weather on St Helena (poor visibility and high winds), impacting on the safe operation of the new airport.

Survey operations commenced on the 26th November following the rapid mobilisation of the MV Enchanted Isle and completion of the shore-based observations. Due to the delay in arrival, survey operations for the first four days took place over 19 hrs a day to catch up the lost time which was made possible by the additional personnel deployed for the survey.

***Figure 5** : Kongsberg 2040 mobilised to MV Enchanted Isle prior to lifting back in the water*

Prevailing sea states focussed operations around the west side of the island until day 5 when it was possible to run a series of lines along the east coast. The survey areas had been designed with a number of areas to minimise downtime and allowed survey operations to continue during planning. Operations continued until the 10th December when a partial planned demobilisation took place to allow the vessel to be used for a previously arranged contract.

Following remobilisation, survey operations continued until the 14th December, with a total of 155km^2 of the planned 243km^2 area being surveyed. The difference in the areas surveyed was down to only operating into 4m of water, reaching the extinction depth of the sensor (>200m) and the unseasonably poor conditions experienced on the east side of the island.

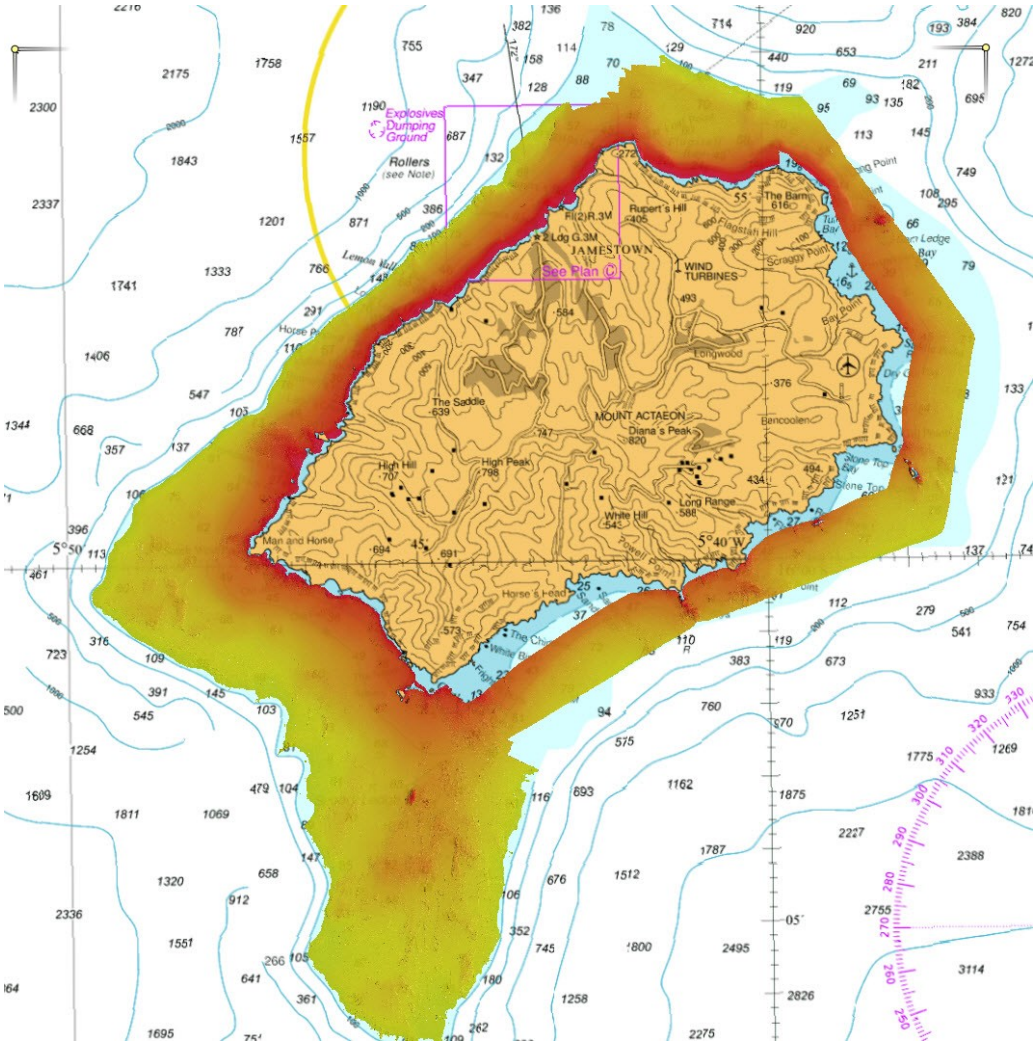

Figure 6 *: Wreck of the Papanui, James Bay, Saint Helena*

During the course of the survey, 8 hydrographic notes were raised covering uncharted wrecks and shoals. 7 existing wrecks and 6 new wrecks were located and investigated during the survey. A characterisation of the seabed was undertaken using the results of ROV dives and backscatter analysis, and 32 Conductivity, Temperature and Depth (CTD) observations were completed around the island.

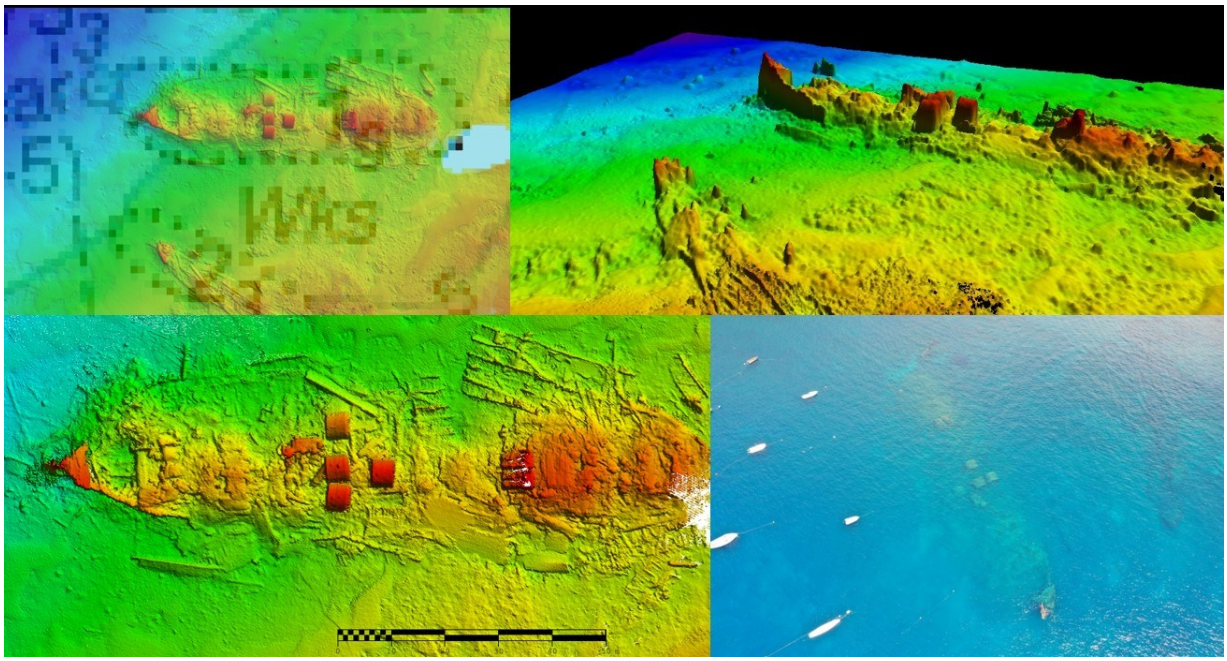

Figure 7 *: Final Survey Coverage (BA Chart 1771B © UKHO*

A number of faults and failures of cables, tide gauges, and remotely operated vehicle occurred during the survey, but resulted in very little lost time and justified the additional equipment carried.

7. Utilisation of Data

New navigational products have already been produced and have resulted in much improved charting around the island, particularly around Speery Ledge. All of the data has also been provided to the government of Saint Helena for use in their Spatial Data Infrastructure. Initially this will be used in ongoing coastal zone management which will be used to sustainably manage sewage, pollution and sand extraction which are threats to the nearshore marine environment. This data will also be used by the Blue Belt programme to undertake habitat mapping to improve knowledge and sustainable management of currently exploited inshore fish species such as Grouper.

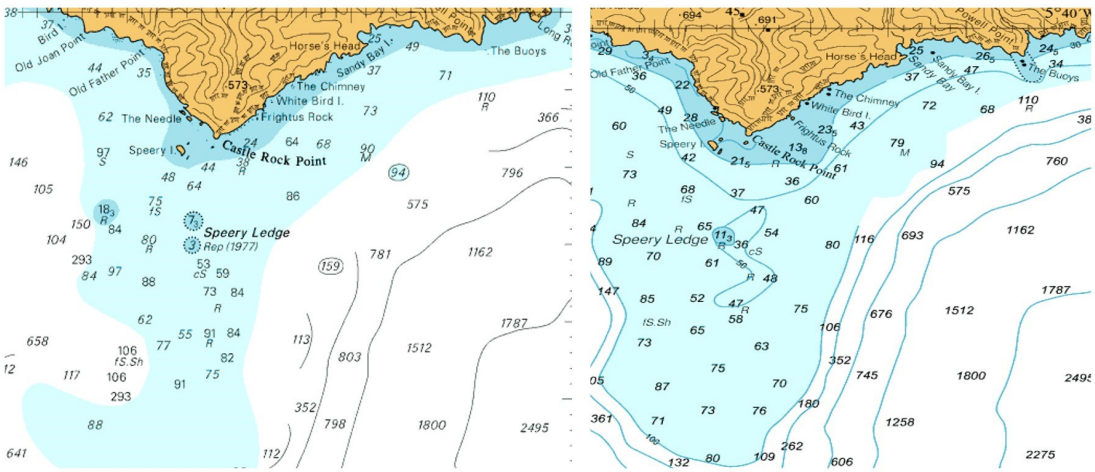

Figure 8 *: Comparison of old and new standard nautical charts extract from BA Chart 1771B © UKHO*

8. Conclusion

Comprehensive planning, risk management and data collection has delivered a high-resolution multi-use dataset in a remote area with minimal support. This project has not only enabled Saint Helena to meet its International Obligations under the United Nations Convention on Law of the Sea and the Safety of Life at Sea Convention, but will also enable the island to sustainably manage and develop its economy through tourism and exploitation of marine resources whilst also protecting the marine environment through increased knowledge of coastal resources and fisheries.

Notes

HYDROGRAPHIC SURVEY WITH AUTONOMOUS SURFACE VEHICLES

By V. Schmidt.

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1. Overview

Increasingly, hydrographic offices are turning to robotic, unmanned, and "autonomous" surface vehicles (ASVs) to conduct systematic seafloor surveys for hydrographic applications (nautical charting) (***Figure 1***). The term "autonomous" is set in quotes to acknowledge the spectrum of capability of these vessels, which varies from those that are remotely piloted (but possibly either manned or unmanned), to those that have some auto-pilot capability, to those that have the ability to react to their local environment, for example to avoid hazards and other ships while optimizing data collection. Data on which these reactions are based may be provided to them or sensed on their own.

Figure 1. *The Center for Coastal and Ocean Mapping's Bathymetric Explorer and Navigator (BEN) conducting seafloor survey within the U.S. Thunder Bay National Marine Sanctuary, Lake Huron, 2018.*

The practice of hydrographic survey is categorically different from general navigation of transiting commercial vessels whose operation may fall under other guidance. Hydrographic survey involves the systematic ensonification of the seafloor, usually in "lawnmower" patterns whose lines extend along contours of constant depth. During survey, launches do not often follow prescribed or traditional transit lanes but often operate within those lanes. Survey launches may operate in tandem or independently, covering separate areas within a region; their base of operations may be on shore or a parent survey vessel.

This document seeks to provide a set of best practices for operation of ASVs conducting hydrographic survey, and whose operations are focused on this unique application. The intent of this document is to propose guidance for safe operation and good seamanship based on real-world experience and by complying with the intent of the Rules set forth by the 1972 International Regulations for the Prevention of Collisions at Sea (COLREGS)[1] and other provisions that may be in force in U.S. or other State regulations. In a few cases, recommendations made here may conflict with existing regulations, either because those regulations do not explicitly address autonomous systems or because in our experience the capabilities of autonomous systems, and the expectations of other mariners, are such that additional caution is warranted. Organizations should augment or modify these recommendations to ensure safe operation and comply with regulations as necessary.

2. Levels of Environmental Risk, Autonomy and Supervision

To provide a framework for operation of ASVs one must define some basic terminology. Not all scenarios and conditions can be covered practically, but from these descriptions one may extrapolate best practices as capabilities and conditions change.

3. Environment

Operational environments range geographically from harbor areas in which navigation hazards, fishing gear, and other vessels are sure to be encountered, to the remote areas in which it is unlikely that an autonomous vessel will encounter either obstacles or other vessels at all. Similarly, areas with high currents require different considerations from those without, particularly when the currents may push a vessel not under command into shoal areas or traffic channels. Weather and sea state further complicate these environments, often requiring a reassessment of the levels of autonomy and supervision required to meet a given level of tolerable risk. Low, Medium and High risk environments are defined here to guide decision making when operating ASVs.

- **Low Risk Environment:** A low risk environment is one in which other vessels, fishing gear, and navigational hazards are unlikely to be encountered. Weather and seas are benign.

- **Medium Risk Environment:** A medium risk environment is one in which other vessels may be encountered, but neither recreational boaters, which do not typically carry AIS and are difficult to detect, nor fishing gear are expected. Other navigation obstacles, such as rocks, reefs, and kelp, may be encountered but are unlikely, or can be avoided through careful mission planning. Weather may include winds to 25 knots, and chop and swell conditions that require additional caution when deploying and retrieving the vehicle, either normally or manually.

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[1] *In the United States, rules pertaining to safe navigation from COLREGs and other U.S. provisions are provided for mariners in a single document titled "Amalgamated International & U.S. Inland Navigation Rules", the authoritative version of which is available in text form online and within the U.S. Coast Pilot (See References).*

- **High Risk Environment:** A high-risk environment is one in which other vessels and/or fishing gear are likely to be encountered, possibly including recreational boaters. Other navigation obstacles such as shoals, rocks, reefs and kelp may be present and unavoidable to achieve the survey objectives. While unforeseen conditions do arise, weather and sea state conditions that are considered high-risk should simply be avoided, period.

4. Levels of Autonomy

In 2015, NOAA's Hydrographic Systems and Technologies Branch (HSTB) hosted a workshop to explore and evaluate the state of the art of autonomous systems. Although definitions of autonomy have been proposed in other communities, attendees at this workshop defined a set of *practical* levels of autonomy to provide a common understanding through the discussions. The group envisioned levels of autonomy for navigation, sensors (payload sonars and subsystems) and vehicle self-awareness. An abbreviated version of these are adopted here.

Note that the capabilities of a given ASV do not always fall cleanly into one level or another. For example, an ASV might be equipped with a LiDAR based collision avoidance system (Level 4 – Advanced Autonomy) but is unable to monitor the depth beneath the keel to keep from running aground (Level 1 – Piloting). These nuances become important during operations to ensure a proper level of supervision is applied for the available level of autonomy.

Level 1 - Remote Piloting: Remote piloting of a vessel is the act of manually controlling thrust and rudder movements through a telemetry link to the vessel. It involves no autonomous behavior.

An ASV attains Level 1 Autonomy through "manual mode" with a joystick control interface.

Level 2 - Basic Autonomy: Basic Autonomy involves the ability to follow a pre-planned fixed mission consisting of a sequential list of waypoints, lines, loiter points and combinations of these without operator interaction. With some exceptions the only inputs are the vessel's position and heading (from onboard sensors) and the desired point to reach. Generally, the only outputs are thrust and control surface (rudder) angles.

An ASV provides Level 2 (Basic Autonomy) through the layout of a multi-point track-line on a graphical user interface. In addition, in hydrographic survey applications line files created in other software such as Hypack and exported in the "L84" format or in Qinsy through other mechanisms might be loaded into the ASV mission planner. These track lines are then "executed" programmatically through the interface and the ASV will follow these lines, automatically.

Level 3 - Intermediate Autonomy: Intermediate Autonomy involves the ability to adjust a pre-planned mission in a reactionary way to fixed (i.e. not dynamically sensed) input according to fixed rules, for example, to avoid shallow water, charted hazards to navigation, or a polygon of prohibited operational area.

An ASV provides Level 3 (Intermediate Autonomy) by providing the ability to specify a "geofence" within which the ASV will not enter when in any autonomous mode, or to load a chart and use it to avoid hazardous areas.

An ASV may also have the ability to follow the path of the operator's vessel at a fixed distance astern and with optional fixed athwartships offset.

Level 4 - Advanced Autonomy: Advanced Autonomy involves the ability to adjust a pre-planned mission in a reactionary way to dynamically sensed conditions, for example, to detect and avoid previously unknown buoys, lobster pot floats, other vessels, to follow and/or track another vessel and to moor by anchor or pier without user intervention.

An ASV provides Advanced Autonomy when it can dynamically avoid AIS contacts, or contacts detected in radar or LiDAR. Note that these sensors can "detect" obstacles at different ranges and vehicles that can detect and avoid objects at one range but not another can only be said to have limited advanced autonomy.

Level 5 - Planning: Planning involves the ability of an ASV to make a major adjustment or totally create a mission based on a deliberative consideration of objectives, fuel/power physical constraints, and both previously known fixed obstacles, and real-time sensed, possibly dynamic ones as well as sensor states and other parameters.

No ASV can yet provide autonomy at this level.

5. Levels of Supervision

Attended: Attended operation involves continuous supervision of an autonomous vehicle by vigilant watch-standers, ready to take action in the event of any untoward event. Remote piloting (Level 1 autonomy) is attended operation, by definition. However, any other level of autonomy may be attended or not. Operations without constant telemetry cannot be "attended" operation, but rather qualify as "Monitored" or "Independent".

Monitored: Monitored operation involves cursory supervision of a vehicle, affording an operator the ability to focus on other tasks, but ensuring normal operation at regular periodic intervals and relying to some extent on warnings and alarms from the vehicle in the event operator assistance is required. Monitored operation requires basic (Level 2) vehicle autonomy at a minimum (the ability to follow a sequential mission plan), but also the ability to invoke remote piloting and even physical intervention when necessary. Therefore, monitored operation requires a suitable telemetry link and operation within sufficiently close proximity to intervene if required.

Independent Operation: Independent operation involves little direct supervision of a vehicle other than periodic review of operations and status, relying largely on warnings and alarms to notify the operator of faults and events requiring assistance. Independent operation also requires a complete mission plan composed of a sequential list of mission objectives and/or vessel behaviors under various circumstances, autonomously executed (Levels 2-3 or above), for both the vessel and its payload sensors. When under independent operation, telemetry links may be inadequate to support remote piloting and distances may be too far for any timely physical intervention.

6. Levels of Risk

For any given operation, the environment, level of autonomy, and level of supervision of the system determines a level of risk, where risk is broadly defined as risk to property and personnel as well as risk of not successfully achieving the mission. No operation is risk free, and these recommendations are designed to mitigate the different kinds of risk involved in operating unmanned systems.

Many hydrographic offices are already familiar with the practice of Operational Risk Management (ORM) and the application of those procedures to small boat operations. These procedures are particularly suited to ASV operations, and we recommend the adoption of this kind of model. However, because ASVs are complex robotic systems in early stages of development, additional consideration must be paid to the health of the system and the operator's ability to respond to failures of the system should they arise.

7. Best Practices

ASV Color, Lights, and Signals

These items can be controversial because there remains no explicit guidance for unmanned systems within the Navigation Rules (including COLREGs). What is proposed here is a common sense approach designed to adhere to existing guidance where possible and to mitigate risks otherwise.

1. **The ASV should be conspicuously marked with bright yellow, orange, or red paint.**

   Such paint schemes are atypical for other vessels and will serve to make the ASV clearly visible and distinguish it from others.

2. **The ASV should operate navigation lights at all times, day and night.**

   Although not required from sunrise to sunset, the shape of some ASVs can be so different from manned vessels that their apparent heading can be difficult to discern. Operation of navigation lights can aid other mariners in discerning the ASV's heading.

3. **Operate an alternately flashing red and yellow light signal aboard the ASV at all times, located so that it does not interfere with other navigation lights.**

   Operation of a red and yellow flashing light clearly signals to other vessels the unusual nature of the ASV. In our experience, safety is increased when other mariners recognize an unmanned vessel conducting survey operations as out-of-the-ordinary. This particular light configuration is recommended by the U.S. "Inland Rules" for public safety operations, and it is in the spirit of that provision, namely to provide special indication for a vessel conducting a public safety activity (seafloor survey) that it is recommended here, for both inland and international waters. The recommendation to also adopt this configuration for international waters comes with careful regard to guidance provided by "Rule 20" of COLREGS, which generally discourages "alternative" lighting configurations so as not to cause confusion with those required by the Rules. Alternating flashing red and yellow lights do not otherwise exist in the international rules and would be highly unlikely to be mistaken for other configurations.

The exact text for this lighting configuration and its precautions warrants repeating verbatim:

Annex V, Section 88.12 "Public Safety Activities":

(a) Vessels engaged in government sanctioned public safety activities, and commercial vessels performing similar functions, may display an alternately flashing red and yellow light signal. This identification light signal must be located so that it does not interfere with the visibility of the vessel's navigation lights. The identification light signal may be used only as an identification signal and conveys no special privilege. Vessels using the identification light signal during public safety activities must abide by the Inland Navigation Rules, and must not presume that the light or the exigency gives them precedence or right of way.

By adopting the guidance for public safety activities when operating in both inland and international waters one can increase the awareness of other mariners to the peculiar behavior and appearance of ASVs conducting those operations. ASV Operators are warned to heed the cautionary statements above; that such a light configuration conveys no privilege.

4. **Use of other lights or day-shapes, such as those for vessels "not under command" or "restricted in their ability to maneuver" is not recommended.**

It has been argued that an unmanned vessel, either because no human is aboard, or because the situational awareness can be limited, should fall into the categories of "not under command" or "restricted in their ability maneuver" as defined in COLREGS, Rule 3. COLREGs, indeed, lists vessels engaged in "surveying" in a list of examples of those restricted in their ability to maneuver. Such a designation would afford some right-of-way to ASVs conducting survey operations in meeting situations with other vessels not otherwise encumbered.

However, the utility of such a designation is in practice quite limited and serves to only provide a false of security. ASVs conducting hydrographic survey are typically small relative to other vessels and by the very nature of their nautical charting mission are often traversing relatively shallow waters that place a far greater constraint to navigation by others. Any vessel constrained by its draft in a meeting situation with a surveying ASV would have right of way giving no utility to these designations. Experience has also shown that the lights and shapes for these designations tend to go unheeded by other mariners and can give ASV Operators a false sense of security, when the experimental nature of ASVs and the unfamiliarity on the water with them by other mariners warrants extra caution. Because these designations provide no practical utility and do not invoke the necessary caution that ASV Operators should exhibit it is recommended not to assume these designations.

8. Operations

1. **Use a risk management guide to quantify and mitigate the risk associated with each deployment.**

Prior to each deployment a risk management guide should be evaluated and reviewed by ASV operators, supervisory personnel (the ship's Captain, Officers and Mates when operating from ships at sea, or Operational Supervisors when operating from shore) and support staff (Engineers, Deck Hands and others). Risk management guides often come in the form

of score sheets in which various elements of the deployment are evaluated either quantitively or qualitatively, or both. Elements include the capability and proper operation of vessels and equipment, weather and seas, prevalence of navigation hazards and other vessel traffic, experience of the operators, operator fatigue, and the availability of rescue equipment and staff in the event a vessel recovery is required. The scores in such a form provide helpful guidance in identifying risk in any operation and mitigating those risks whenever possible.

As part of this review ASV operators should explicitly identify the level of supervision (Attended, Monitored, or Independent Operation) required for the operational environment, autonomy level of the ASV and its mapping systems, and capability of the operator's interface to indicate and warn operators of events. ASV operators should note when the appropriate level of supervision is expected to vary.

For examples of risk management guides for manned vessels ASV Operators are directed to NOAA's Small Boat Standards and Procedures Manual and U.S. Coast Guard Risk Management documentation (*COMDINT 3500.3A* and *Risk Management Fundamentals*) and risk management tools such as the *NOAA Small Boat Operational Risk Assessment (GAR) Form* and the US Coast Guard *PEACE-STAAR-Job-Aid* (see the references for links to these documents). However ultimately it is recommended that ASV Operators generate their own scoring system, borrowing from these documents, tailoring the categories to their own systems and tuning the overall assessment of risk to the risk tolerance of the organization. (The risk tolerance for Coast Guard search and rescue is likely higher than that for hydrographic survey operations, for example.)

While the scores in the risk management form provide a useful guide, ASV Operators are cautioned not to place undue emphasis on the numeric result. Studies by the National Academy of Sciences have noted that non-quantitative information is often as important as quantitative measures of risk to decision makers. Further the study found that attempts to aggregate widely disparate sources of risk with a common metric is likely to be misleading. (See "A Review of the Department of Homeland Security's Approach to Risk Analysis", National Academy of Sciences, pg 10.) **The most important function of the form is the candid discussion that it facilitates.** A cursory scoring without thoughtful deliberation can provide a false sense of the real risks involved and be even more dangerous. The scoring requires judgement for which no single point of view is likely to see all the implications, therefore ASV operators should seek to give voice to all involved and provide adequate time for this review.

Because decisions made with regard to risk mitigation are rarely black and white some examples are provided here to illustrate useful ways of thinking for ASV Operations.

- Even fully Attended operation may not be a high enough level of supervision, particularly if the ASV's sensors and operator interfaces do not provide good situational awareness. In this case additional monitoring can be provided by limiting operations to within visual line of sight or with other ancillary systems. In some cases, any ASV operation may be deemed too risky altogether.
- ASVs with little to no ability to automatically detect and identify hazards in their environment (Basic Autonomy and below) incur too much risk to be operated in Monitored or Independent levels of supervision when these hazards are likely to be present. In this case a human operator must be attentively monitoring telemetered sensor feeds to ensure vehicle safety.
- ASV's with no ability to autonomously maneuver to avoid hazards in their environment (Intermediate Autonomy and below) incur too much risk to be operated at an

Independent level of supervision when those hazards are likely to be present.

- When considering the appropriate level of supervision it is important that the ASVs sensors, detection capability, and ability to autonomously react to those detections are matched to the hazards an operator expects to encounter. For example an ASV with no depth sounder and no autonomous ability to avoid shoals requires a higher level of supervision when operating near shore than when operating on the open ocean.
- User interfaces and data collection systems with no ability to audibly alarm may warrant fully Attended operation to ensure faults within these systems do not go unnoticed.

2. **When operating in the likely presence of other vessels, issue a Notice to Mariners, and VHF Sécurité calls at 4-hour intervals to provide indication of your operations.**

   Notice to Mariners or Navigational Warnings will notify local commercial mariners and Coast Guard facilities of your operations. VHF Sécurité calls will provide more immediate warning to your presence. Use the following or similarly concise script:

   - "SÉCURITÉ" x3
   - "ALL STATIONS IN THE VICINITY OF [Local point of Interest]" x3
   - "THIS IS [Your ship/station identification]"
   - "UNMANNED VESSEL OPERATIONS ARE UNDERWAY IN THE VICINITY OF [or WITHIN X NM OF] [Local point of interest] FOR SEAFLOOR SURVEY. OPERATORS ARE STANDING BY CH 16"
   - "OUT"

3. **Follow COLREGS's guidance for good seamanship, and follow the *spirit* of COLREGS when you cannot comply with Rules intended for manned vessels.**

   Simply put, no ASV can comply with the requirements set forth by COLREGS as they were envisioned for human vessel operators. The nuanced rules, which require the ability to properly detect and interpret lights, signals, day shapes, vessel type, vessel size, and many other conditions in addition to proper application of the "rules of the road" are beyond the capability of artificial intelligence for the foreseeable future. However, every ASV and its operator can comply with the spirit of COLREGS, namely, *the proactive prevention of collisions at sea*.

   Rules regarding Look-out (Rule 5), Safe Speed (Rule 6), Risk of Collision (Rule 7) and Action to Avoid Collision (Rule 8) are simply good practice for any mariner and should be adhered to by ASV Operators and provided for manually when warranted and not otherwise provided through automated technologies. While there may be no human look-out aboard the vessel, cameras, LiDAR, radar, audio monitoring equipment and other sensor systems can allow an operator or its artificial intelligence counterpart to "make a full appraisal of the situation and the risk of collision". Similarly, an ASV operator should

navigate the ASV "at a safe speed so that it can take proper action to the prevailing circumstances and conditions" (Rule 6). Rule 6 also specifies that vessels should adjust their speed accordingly based on the state of the wind, sea and current, the proximity of navigation hazards and shallow water, the "efficiency and limitations" of its sensing equipment, and the number and extent of hazards. These considerations remain good guidance for any ASV Operator. Rule 7 cautions the mariner to assume the worst when assessing the risk of collision, advises them to interpret sensor data skeptically, particularly when little information exists, and warns mariners of conditions indicating a possible collision situation such as a constant bearing rate to other vessels. Finally, Rule 8 states plainly that any action to avoid collision shall be "made in ample time", "large enough to be readily apparent to another vessel", "result in a safe passing distance", and to "slacken speed" to allow more time to assess the situation. These same actions should be adhered to by ASV operators and provided for manually when the autonomy level of the vehicle is insufficient to do so for the anticipated risks.

4. **Never impede the passage of another vessel.**

ASVs for hydrographic survey remain small vessels whose capability and intent are difficult to interpret for other mariners. Thus, to ensure safety, always consider the ASV to be the "give-way" vessel in any crossing situation.

In doing so, give other vessels a wide berth, anticipate the effects of control failures when considering maneuvers, and hail other vessels in the immediate vicinity of the ASV to arrange passage when necessary. When hailing other vessels via VHF use the terms "unmanned vessel" or "robotic vessel". Do not use the term "autonomous" to describe the ASV on the radio, as it is difficult to understand.

Experience has shown that it is extremely difficult for ASV Operators viewing a map display, radar, or camera feed to apply the appropriate amount of caution for a given range to another vessel (or even stationary hazard). The difficulty results in part from displays that represent the ASV or other vessels with an icon whose size is a fixed number of pixels regardless of zoom level. Other contributing factors include misperception that comes with varying map zoom levels, camera lens distortion and a general inability to translate 2D representations provided by maps and cameras into the mariner's intuition afforded by a 3D environment. Great care should be made in determining safe passing distance from these interfaces with additional consideration for Rules 6 (Safe Speed) and 8 (Action to Avoid Collision).

5. **Mitigate the risks of near-shore operations.**

Near-shore operations afford little room for equipment failure, as any untoward event can put the ASV into shoals or surf and lead to equipment loss. Therefore, carefully consider the health of telemetry and control systems, prior knowledge of the seafloor (or lack thereof) and prevailing winds, waves and currents. Navigate the vehicle over mapped portions provided by previous survey swaths that have been shown to be hazard free. Prepare and pre-position recovery teams such that they can field a recovery in a timely manner if necessary. Operate only in an Attended level of supervision.

9. Telemetry

1. Operate at least two independent telemetry systems.

Failed connectors, heavy rain or system failures can drop a telemetry link unexpectedly. Having a backup mechanism is important to keep any unmanned vehicle safe. These systems need not have the same range and bandwidth capability, but any backup system should afford the ability to establish a second connection to the vehicle (possibly repositioning operators to do so) and retask (at a minimum) or pilot the vehicle to safety.

2. Operations outside real-time telemetry range should be done with caution, and routine monitoring.

Operation outside the range of real-time telemetry systems can increase flexibility by tasking vehicles to complete a survey without attended supervision. However, because of the difficulty in reliably detecting and avoiding navigation hazards and other vessels autonomously, these operations should only be conducted in areas in which encounters with these hazards and other vessels are unlikely. Routine monitoring can be achieved either by non-real-time telemetry updates, such as Iridium messaging, or by design of survey tasking such that portions of the survey are in sufficient proximity to operators to periodically re-establish real-time telemetry.

3. Understand and anticipate the effects of a loss of telemetry.

No telemetry installation is perfect, and most have relative bearings in which the link is likely to be degraded or lost. Measure the quality, in terms of SNR and bandwidth, of telemetry links as a function of bearing and range to the operator station, so one can anticipate their loss.

Some ASVs secure the vehicle's engine on loss of telemetry, others may station keep, and others may continue their last navigation tasking until that tasking is complete. It is important that operators understand the expected behavior and consider the implications of that behavior operationally. For example, an unexpected telemetry loss that causes the ASV's engine to shut down and sets it adrift can place the ASV in danger when operating near shore. Similarly, a loss of telemetry when the ASV is operating in the presence of nearby or moving hazards can prevent operators from intervening to redirect or pilot the ASV. Operators should select the behavior most appropriate to their operating environment when possible.

4. Ensure survey data transfers over telemetry links shared by command and control do not compromise control of the ASV.

Often it is desirable to transfer the acquired survey data over the telemetry link to operators for troubleshooting or processing during survey operations. Care must be taken to ensure the increase in bandwidth consumed by the transfer does not preclude an operator's ability to monitor or interact with the ASV when an Attended level of supervision is necessary.

Some ASVs operate dual telemetry links for the purpose of protecting command and control messaging from sensor payload bandwidth usage. When this is the case, it is important to continue to provide redundancy for the command and control link (item 1 above), which may be provided through the payload's telemetry system or through another system altogether.

10. ASV Safety Features.

1. **Have an Emergency Stop button, in arm's reach of the operator station.**

In the unlikely event of a control system failure while the ASV is operating in a confined environment, it is important to have a safety mechanism that can secure the ASV's propulsion immediately.

2. **Have an immediate "hover" capability in the ASV Operator's user interface.**

The ability to quickly hover a vehicle at an operator specified location with as few mouse clicks as possible greatly increases the safety of ASV operations. Immediate hover reduces the cognitive loading of the operator by placing the vehicle in a safe navigational state. An operator may then let a complex navigational situation develop or focus on configuration and operation of other systems without incurring additional risk while their attention is elsewhere. Immediate hover also facilitates multi-ASV operations allowing an operator to place one more vehicle in low risk conditions while focusing on the tasking or configuration of another.

3. **A Note on "Orbit" vs "Hover" behaviors:** ASVs often provide the capability to "orbit" the vehicle, in which the vehicle turns in tight circles at a constant speed around a stationary point. What is less common is the ability to "hover" in which the ASV repositions to a stationary point and maintains that position within some tolerance by drift-and-reposition or through low speed maneuvering to offset the effects of external forcing of wind and current. Both behaviors provide the ability to "park" a vehicle indefinitely while other vessel traffic develops. However, experience has shown that orbit behaviors are confusing and disconcerting to other mariners as they continuously try to anticipate the ASVs next maneuver. Human mariners expect a hover, however, as this behavior is precisely the method used by human operators to maintain position. Hover behaviors are always preferential to orbit behaviors for this reason.

4. **Provide an integrated map display showing ASV and operator station position to supervisory personnel (e.g. on the operator ship's bridge).**

Experience has shown that the mental image of the navigation and environmental situation held by an ASV Operator at their station and supervisory personnel (who may be on a ship's bridge several decks away) is rarely the same. To accommodate, parties must attempt to share sometimes complex information over a radio link between stations. The ability to rapidly convey concise meaningful information from one station to another to gain a shared understanding for both parties over radio communications is exceedingly difficult. The condition is greatly improved when the operator's station is within a short walk of the bridge, affording quick face to face point-and-clarify discussions between stations. But there is no substitute for the benefit of providing a common map display.

A good map display should contain the following:

- Position and heading of the ASV.
- Position and heading of the operator's station. The display of the operator vessel's heading is particularly important, as it allows rapid identification of the relative bearing to the ASV.
- A nautical chart and other background information affording a common perspective and scale to both parties. Without this information individuals are forced to mentally map positions of the ASV, the operator's ship, navigation hazards, other vessels, and

mission objectives between displays. Invariably the displays are not adjacent to each other, not zoomed to the same scale, do not use the same color encoding - the task is almost impossible.

- Basic status of the ASV, including emergency conditions, the status of the radio telemetry link and the ASV's expected track. These indications allow the bridge to anticipate the actions of the ASV, and understand when to inquire about its safety and when an unexpected maneuver is, in fact, normal.

An integrated map display is purposely placed under "Safety Features". Without such a shared view of ASV operations, the Officer on Watch and ASV Operators are tasked with overwhelming cognitive loading as they manage the safety of their respective vessels. A simple display can greatly increase the operational safety of both operations.

11. Conclusion

It is an exciting time to be a hydrographer! The advent of unmanned and autonomous survey launches will bring about immense gains in survey efficiency, while increasing the safety of operations at sea and decreasing personal discomfort. New sensors, system interfaces and algorithms are being developed for unmanned systems at an increasing rate and these systems will have positive impacts on manned operations as well.

While there is not yet much in the way of regulations specifically for unmanned systems, there is plenty of guidance. That guidance can be found in all the usual places for manned vessels at sea and can be applied with common sense and an eye toward its intent when the guidance is clearly meant for humans aboard the vessel.

No operation at sea is risk free. Responsible organizations establish protocols and best practices to identify the risks and mitigate them wherever possible. When those risks cannot be mitigated to an acceptable level, one simply does not go to sea. Clear and open communication in this process is extremely important and made more so during the adoption of these new and relatively immature technologies.

12. Acknowledgements

The author thankfully acknowledges NOAA's Office of Coast Survey for support of this work under NOAA Grant NA15NOS4000200. Immensely helpful feedback was provided by Lynette Davis, Kenneth Fairbarn, Andy McLeod, Dr. Larry Mayer and Captain Andy Armstrong in preparation of this manuscript. In addition, this work was informed by numerous deployments, including those from NOAA Ship *Shearwater* (2017), NOAA Ship *Fairweather* (2018), NOAA Ship *Thomas Jefferson* (2019), Ocean Exploration Vessel *Nautilus* (2017, 2018 and 2019), with support from NOAA Ship *Storm* while deployed from shore within the Thunder Bay National Marine Sanctuary, as well as numerous deployments from our own Research Vessel, *Gulf Surveyor*. Guidance provided by the captain and crew of these vessels and their staffs have been invaluable and are greatly appreciated.

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Notes

NEW PROGRESS REPORT OF UNMAPPED U.S. WATERS

By Meredith Westington[1], Jesse Varner[2], Andrew Armstrong[1], Jennifer Jencks[3]

1 National Oceanic and Atmospheric Administration (NOAA), National Ocean Service, Office of Coast Survey

2 Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado Boulder at NOAA, National Centers for Environmental Information (NCEI)

3 NOAA, NCEI - International Hydrographic Office's Data Center for Digital Bathymetry

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In support of ocean and coastal mapping strategies, in 2017, the United States designed a method for assessing gaps in bathymetry through a visualization of sounding density. The November 2018 edition of the International Hydrographic Review reported on this analysis (International Hydrographic Organization, 2019).

The United States has continued this analysis, and in March 2020, the United States released its first annual report on the progress made in mapping U.S. waters. Pulling from an analysis of publicly available bathymetry at the IHO's Data Centre for Digital Bathymetry, the report presents the percentage of unmapped U.S. waters by region and shows our progress toward filling these basic bathymetry data gaps with each passing year.

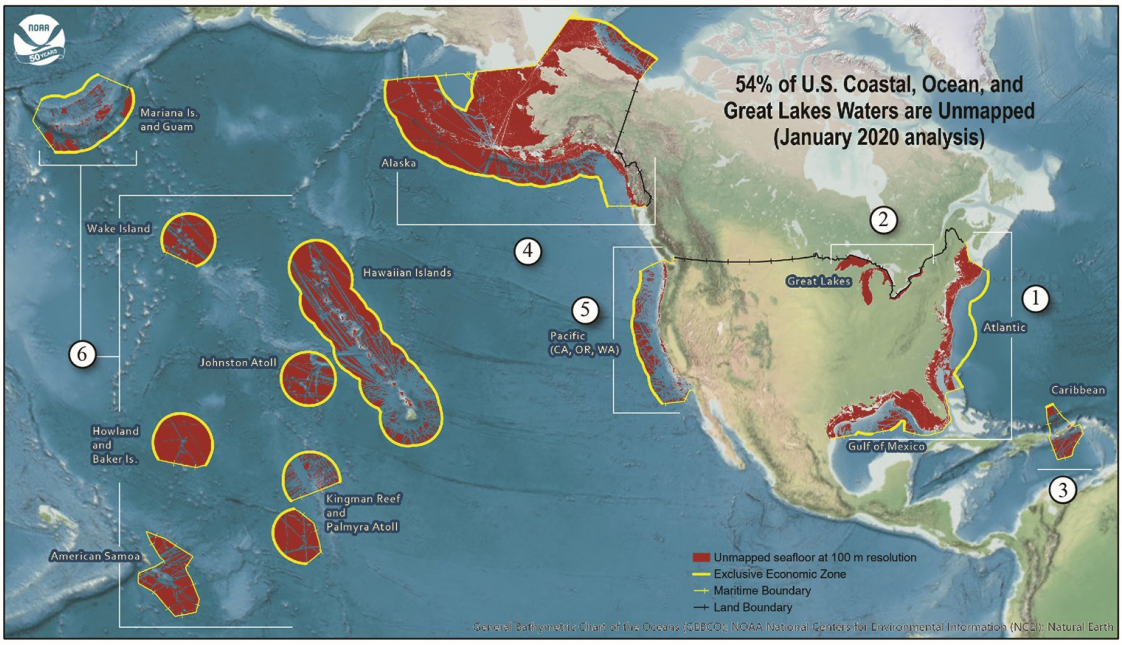
[***Figure 1***] See next page

At the end of 2019, the analysis showed that 54% of U.S. ocean, coastal, and Great Lakes waters (3,592,000 square nautical miles total) remain unmapped. A large percentage of the remaining unmapped areas are in waters deeper than 200 meters; however, further analysis showed that significant effort is needed to fill bathymetry gaps in shallower waters (Westington, et al., 2019).

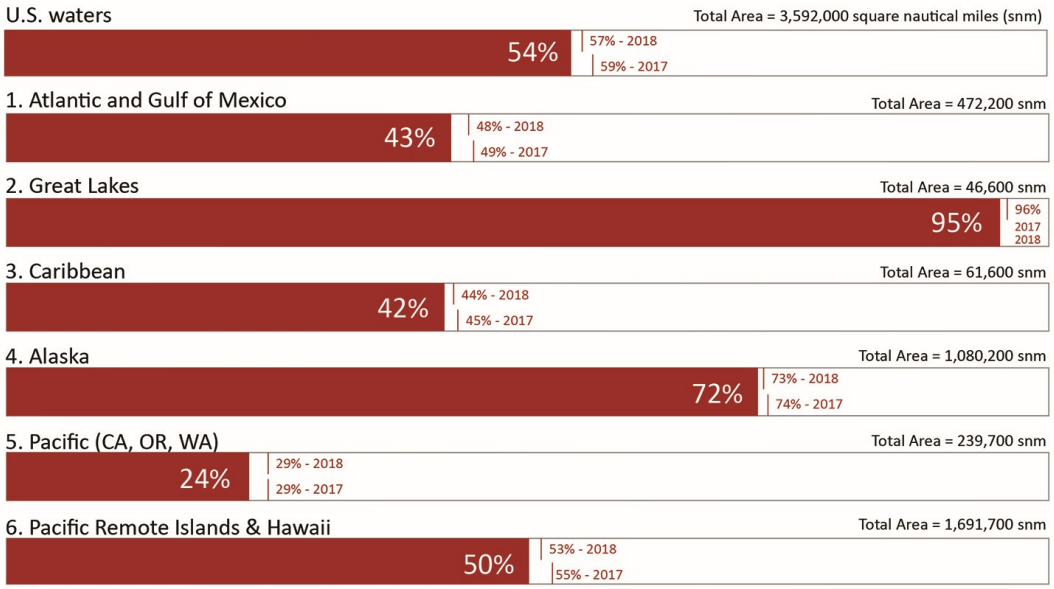
Although the bathymetry coverage and gap analysis includes modern singlebeam bathymetry, multibeam and LiDAR surveys are the two primary sources of bathymetry desired to fill these gaps. The depth, shape, and composition of the seafloor are foundational data elements that we need to understand in order to explore, sustainably develop, conserve, and manage our coastal and offshore ocean resources. The international Seabed 2030 initiative as well as the newly released National Strategy for Mapping, Exploring, and Characterizing the United States Exclusive Economic Zone make comprehensive ocean mapping a priority for the coming decade (Ocean Science and Technology Subcommittee, 2020). The *Unmapped U.S. Waters report* tracks progress toward these important goals. In support of the integrated ocean and coastal mapping goal to "map once, use many times," all of the data collected in this effort are publicly available to benefit numerous user communities. For the latest status on these efforts, visit https://iocm.noaa.gov/seabed-2030.html.

PROGRESS REPORT: Unmapped U.S. Waters

Knowledge of the depth, shape, and composition of the seafloor are foundational data elements necessary to explore, sustainably develop, understand, conserve, and manage our coastal and offshore natural resources. The 2019 **Presidential Memorandum on Ocean Mapping of the United States Exclusive Economic Zone and the Shoreline and Nearshore of Alaska** and the global **Seabed 2030** initiative make comprehensive ocean mapping a priority for the coming decade. This report, updated annually, will track our progress to this important goal.



Percent of U.S. Waters Still Unmapped in 2019



National Oceanic and Atmospheric Administration — March 2020

Figure 1 : *The front page of the new Progress Report of Unmapped U.S. Waters, published March 2020.*

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Notes

HYSPEC V2.0 PUBLISHED

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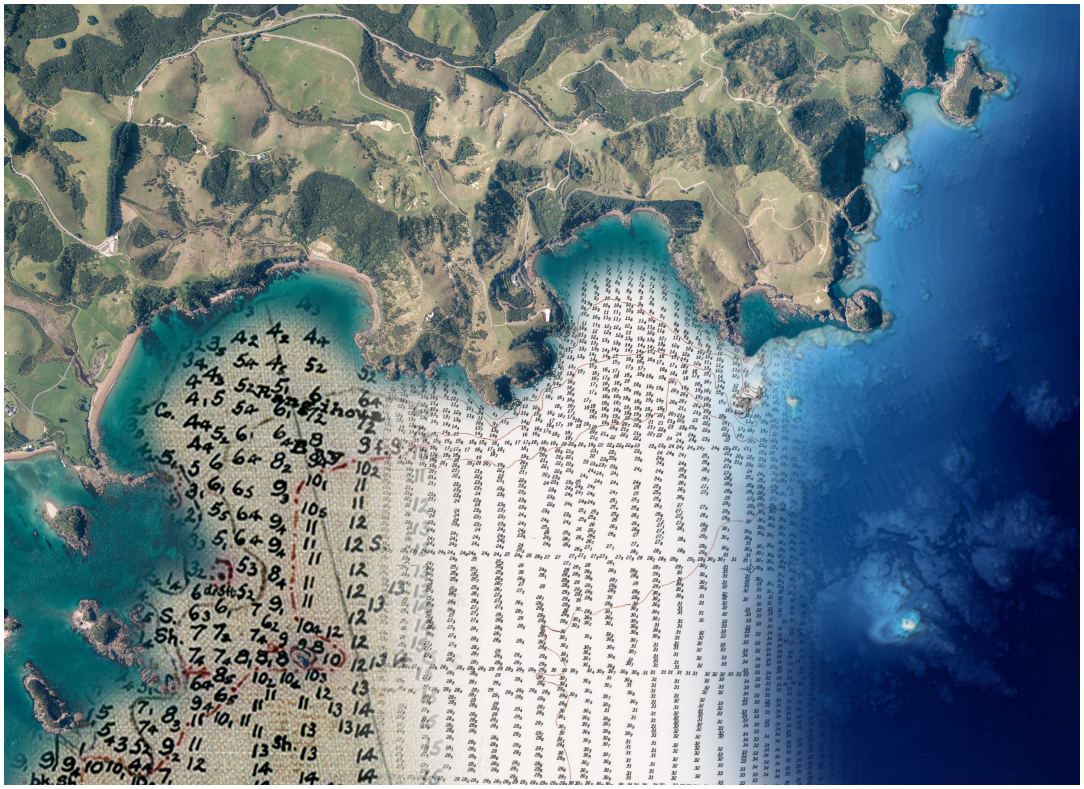

Land Information New Zealand (LINZ), the New Zealand Hydrographic Authority, has recently revised and published an updated version of HYSPEC, the overarching specification for LINZ contracted hydrographic surveys. This major revision sees a move to a digital first, data centric environment and reflects the changes in technology and methodology for the collection, processing and delivery of digital marine geospatial data and information.

In 1996, the New Zealand Government tasked Land Information New Zealand (LINZ) with the responsibility for the purchase of the Crown's core hydrographic services, including hydrographic surveying. LINZ identified the need for a hydrographic and bathymetric strategy, recognising that it wasn't just hydrography for safety of navigation, but also a need to define the shape and depth of the seabed within New Zealand's Exclusive Economic Zone and the Ross Sea. One objective of the strategy was to develop a full set of standards and to review such standards from time to time.

LINZ was one of the first Hydrographic Offices to contract out survey work and was instrumental in establishing a hydrographic specification for out-sourcing surveys. The subsequent development of a New Zealand technical specification was, and still is, recognised around the world as a first of its kind.

In 1998, HYSPEC was created. Based on the International Hydrographic Organization (IHO) Standards for Hydrographic Surveys, Special Publication No 44 or S-44, HYSPEC was very prescriptive on how to conduct the survey. It even included a section on 'Survival in Remote Locations'.

With the introduction of multibeam echo sounder (MBES) systems and the future objectives of LINZ to map the extended continental shelf, LINZ published another world-first in 1999, the Hydrographic MBES Survey Standards. This was a result of work undertaken by John Hughes Clarke of the Ocean Mapping Group, University of New Brunswick, to develop a specification that covered the acquisition, management and delivery of multibeam data. This specification was subsequently incorporated into HYSPEC in 2001.

Until now, LINZ had made relatively minor changes to HYSPEC. More recent changes reflect the move away from a paper-centric environment to a digital one.

This latest version, published June 2020, is a comprehensive overhaul of the content and reflects the changes in technology and methodology for the collection, processing and delivery of digital marine geospatial data and information. Hydrographic surveys now include technologies such as Satellite Derived Bathymetry, Airborne Laser Bathymetry and the use of autonomous platforms such as Unmanned Surface Vessels and Unmanned Aerial Vehicles.

Since 2015, LINZ has partnered with other organisations to fund the collection of datasets such as seafloor backscatter and water column backscatter for scientific purposes, enabling analysis to better understand and manage the marine environment. These datasets are now the norm for a LINZ hydrographic survey.

Survey deliverables have moved away from traditional hard copy sounding sheets depicting a selection of depths at a given scale. Bathymetric surfaces are now required, along with vector point/line/area information in IHO S-57 format with S-100 ready metadata. This streamlines the end-to-end process from data collection to populating a central source database, enabling the automation of several processes. HYSPEC also makes provision for delivering bathymetric surfaces derived from a statistical analysis method, such as CUBE.

In compiling the latest version, LINZ reviewed standards and specifications created by other hydrographic offices including Norway, Australia, UK and US; as well as the draft version of IHO S-44 6th Edition. LINZ considered using the S-44 standards instead of continuing with the LINZ defined standards. However, as S-44 provides only the minimum standards to be achieved; and since today's technology is capable of easily achieving and exceeding these minimum standards, it was decided to retain and refine the LINZ-defined standards which remain more stringent than S-44.

Over the past two years LINZ has trialled HYSPEC v2.0 with our hydrographic survey panel of suppliers, making adjustments where necessary and we are grateful for the input received from several other organisations and individuals. LINZ continues to keep an eye on future developments, emerging technologies and processes to futureproof our specifications and to lead good practice.

HYSPEC is available from the LINZ website https://www.linz.govt.nz/sea/charts/standards-and-technical-specifications-for-our-chart-and-hydrographic-work.

Notes

FIG COMMISSION 4 – HYDROGRAPHY WORK PLAN (2019-2022) AND COMMISSION ACTIVITIES

By M. R. Mahmud, N. Hewitt, G. Johnston, S. Ironside and A. H Omar
FIG Commission 4 - Hydrography

Abstract

The International Federation of Surveyors (FIG) technical work is led by ten Commissions. Hydrography is represented by Commission 4. FIG Commission 4 is focusing on development and recognition of standards of competency, development of technical standards and guidelines, developing and promoting the need to manage the oceans and seas in a sustainable manner, and a comprehensive investigation of plastic pollution at source that is concerning global environmental problem ("Mapping the Plastic"). Through all its Working Groups, Commission 4 has been actively involved in implementing its policy by working in close cooperation with relevant organisations and institutions. Commission 4 is committed with the continuous collaboration between educational institutions, non-government organisations and the Young Surveyors Network in research and development, as well as, community engagement and the realisation of United Nations Sustainable Development Goal 14 (UN SDG 14).

1. Introduction

The International Federation of Surveyors (FIG) was founded in 1878 and is a United Nations and World Bank recognised non-government organisation of national member associations, cadastral and mapping agencies and ministries, universities and corporations from over 120 countries. FIG's technical work is led by ten Commissions. The responsibilities and work plans of Commissions are approved by the General Assembly during the FIG Congress. The work of each Commission is led by the Chairperson who is elected for a four-year term of office by the General Assembly at the Congress. The Chairperson is assisted by the Commission Vice-Chairperson also appointed by the General Assembly. The Chair-Elect is elected by the General Assembly two years before the Congress. The Commission Chair is also assisted by a Vice-Chair of Administration who is in charge for the administration of the Commission. Every Commission has established at least three working groups on special topics. All member associations have the right to nominate a national delegate to each of the ten Commissions. The affiliates, academic members and corporate members have a right to nominate a correspondent to each commission. The responsibilities and privileges of national delegates are published in the Internal Rules.

2. FIG Commission 4 - Hydrography

For the term 2019-2022, the Chairperson of FIG Commission 4 is Mohd Razali Mahmud and the Vice-Chair is Gordon Johnston. The commission comprised of the following Working Group with its respective Chairs:

a) WG 4.1 – Standards and Guidelines for Hydrography (Neil Hewitt)
b) WG 4.2 – Blue Growth & UN Sustainable Development Goal 14 (Gordon Johnston)
c) WG 4.3 – Mapping the Plastic (Simon Ironside)
d) WG 4.4 – Marine Development and Administration (Abdullah Hisam Omar)

3. Working Groups

The following are a brief description on the work of each Working Groups for the term 2019-2022. For the full work plan, please visit https://fig.net/organisation/comm/4/ workplan_19-22.asp.

⇒ Standards and Guidelines for Hydrography (WG 4.1)

Working Group 4.1 has been in existence for a while compared to the other three working groups. It assists in the development and recognition of standards of competency. Also, the working group assists in the development of technical standards and guidelines. Furthermore, it assesses the impact of international standards on current industry practice. Moreover, the working group review standards from alternate reputable sources relevant to hydrography.

⇒ Blue Growth & UN Sustainable Development Goal 14 (WG 4.2)

The Blue Economy involves the geodesy to delimit marine and coastal areas and their jurisdiction, measurement and monitoring of the coastal and ocean areas for habitat, access and security of food sources, and good environmental status. The Blue Economy is concerned with the revenues, taxes and socio-economic benefits that the coastal seas and marine areas can generate for the local communities and states. It is hydrography and associated spatial data that underpins this. In this specific contribution, surveyors do have a role to play, among the elements to note are : the Blue Economy is important as it provides a vital source of food and benefits from a host of industry sectors, technology and innovation; the UN SDG's, especially SDG 14, cannot be obtained without a much more systematic survey coverage of the oceans. The GEBCO Seabed 2030 project has this objective (refer to https://seabed2030.gebco.net/). Johnston (2019) summarised in his presentation at KL GeoHydro 2019, among which he mentioned that there is not enough survey data to support the initiatives of UN SDG's; more skilled staff and cost effective solutions are required to offset and mitigate the threats to our oceans; the rate of Blue Growth suggests more interest and benefits will come from our oceans, so it is imperative, according to Johnston, that we steward our natural resource wisely.

⇒ Mapping the Plastic (WG 4.3)

This working group is a joint initiative of FIG Young Surveyors Network and FIG Commission 4. The 2019 Leadership Group is Chair Simon Ironside and Vice-Chair Melissa Harrington along with Gordana Jakovljević and Miro Govedarica. Mapping the Plastic brings together scientific, surveying, spatial and engineering skills and expertise to accurately determine the amount and type of plastic litter in the waterway. Mapping the Plastic will provide accurate data at specific locations to better inform land use control. The survey methodology uses high resolution satellite and drone data that will be processed using a developed algorithm to detect floating plastic in the surface water. Combined with the 'ground truthing' land surveying measurements, bathymetric depth data, and water current data, this information will enable the working group teams of volunteers to accurately map plastic concentrations at 'global hot spots'. The survey results will enable regulators to more fully understand the extent of the phenomenon they are facing and inform decision-making to address the problem(s).

⇒ Marine Development and Administration (WG 4.4)

This working group is led by Abdullah Hisam Omar with members Dietriech Geoffrey Bengen, Isa Adekunle Hamid-Mosaku, Rizqi Abdulharis, Mohd Zaid Abdullah and Mohd Hilmi Abdullah. The working group assists in the development of institutional policy and framework. Apart from that, the group assists in the development of conceptual and technical standards, guidelines and practice. Furthermore, it assists in the land and sea governance for a marine cadastre. This working group also assists in the development of indigenous marine management systems. The needs for Sustainable Marine Administration and Development are important because marine spaces are often not managed by a single public institution but managed by several stakeholders thus creating complex, uncertain and conflicting situations in determining the resolution of authority area for true governance. The proper standards of marine space are needed for sustainable development as stated by the United Nations Sustainable Developments Goals.

4. Cooperation with IHO

FIG and IHO cooperate under a Memorandum of Understanding (MOU) which was signed in Athens in May 2004. Commission 4 offers ongoing support to the IHO on a number of initiatives. FIG actively participates in the IHO Hydrographic Services and Standards Committee (HSSC) and the activities of the International Board on Standards of Competence for Hydrographic Surveyors and Nautical Cartographers (IBSC). FIG Commission 4 looks forward to assisting its capacity building and other initiatives through representation on the IHO Regional Hydrographic Commissions.

⇒ IBSC

The International Board on Standards of Competence for Hydrographic Surveyors and Nautical Cartographers (IBSC) was formed in 1977. The role of the IBSC is to develop and up-date international standards of competence for hydrographic surveyors and to review the academic programme of educational institutions that are seeking IHO accreditation of their hydrographic training courses. The IBSC has ten members, four appointed by FIG, four appointed by IHO, and two appointed by ICA. Currently the four FIG representatives in the IBSC are Gordon Johnston, Adam Greenland, Sobri Syawie, and Harald Sternberg. Harald joined IBSC this year and replaces Keith McGowan Miller who steps down after an impressive 8 years on the Board. Both Gordon Johnston and Adam Greenland were the past chairman of IBSC. The work of the IBSC meets annually to review submissions from academic and naval institutions. The ten Board members are distributed worldwide so the only practical way to review and maintain the course submissions and the Standards, involves a two-week annual Board meeting plus the inter-sessional reviews of some 16-18 courses.

⇒ HSSC

FIG Commission 4 provides support to the International Hydrographic Organisation through the work of its Hydrographic Services and Standards Committee (HSSC) by participating in HSSC working groups to review hydrographic standards and guidelines, most recent is the S-44 (IHO Standards for Hydrographic Surveys) (Edition 6.0.0, September 2020).

5. Activities

⇒ KL GeoHydro 2019 (Conference & Exhibition)

The first event of KL GeoHydro 2019 was held in Kuala Lumpur, Malaysia for two days from 18-19 November 2019. FIG is the main organiser for this event together with The Association of Authorised Land Surveyors Malaysia, Royal Institution of Surveyors Malaysia, Land Surveyors Board Malaysia, Department of Survey and Mapping Malaysia, National Hydrographic Centre Malaysia, Universiti Teknologi Malaysia and the Malaysian Hydrographic Societies. All four Working Group Chairs including the Chair of Commission 4 gave a presentation in this event. The topics of presentation by the Chairs are as follows: Hydrographic Surveyors Certification (WG 4.1), Blue Growth, Developing the Blue Economy and the Surveyors Contribution (WG 4.2), Mapping the Plastic – A Surveyor's Response (WG 4.3) and Roles of Marine Cadastre for Nation Development: Potential, Requirement and Challenges (WG 4.4).

The next KL GeoHydro 2020 will be held from 7-8 December 2020 in Kuala Lumpur, Malaysia (www.geoinfo.utm.my/klgeohydro/2020/).

***Figure 1**: Standing second from Left to Right, Gordon Johnston (Vice-Chair of FIG Commission 4 and Chair of WG 4.2), follow by Mohd Razali Mahmud (Chairperson of FIG Commission 4), standing seventh from Left to Right, Simon Ironside (Chair of WG 4.3), follow by Neil Hewitt (Chair of WG 4.1) at the KL GeoHydro 2019.*

⇒ FIG Working Week 2021

The FIG Working Week 2021 will be held in Utrecht, Netherlands from 21-25 June 2021. Commission 4 will be involved in the technical sessions. The theme of the working week is "Smart Surveyors for Land and Water Management: Challenges in a New Reality". Please visit the event's website at https://fig.net/fig2021/index.htm.

⇒ **Annual Meeting**

The annual meeting of Commission 4 was held in Kuala Lumpur on 18 November 2019 during the conference of KL GeoHydro 2019. The Chairperson of Commission 4 and all four of the Chair of the Working Groups attended the meeting. This year the annual meeting will be held virtually online, and it is hoped that most national delegates of Commission 4 will attend the online meeting.

4. Conclusions

Commission 4 will assist and participate in the United Nations programmes on guidance by the FIG Council and in circumstances where Commission expertise can contribute towards successful programme outcomes. Since its inception at the FIG Congress 2018 in Istanbul, the work of WG 4.3 on "Mapping the Plastic" has been very active and there is every indication that it's workload will only increase. It has been formed to better understand plastic pollution in waterways by providing accurate and reliable information of the magnitude of the problem at source, thereby highlighting unsustainable practices, identifying infrastructure shortcomings and informing robust land use controls with the ultimate goal of eradicating the dumping of plastic waste into rivers.

5. Acknowledgements

The continued support and assistance from the FIG Office especially the President, Vice-Presidents and FIG Director is acknowledged and most appreciated.

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