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THE INTERNATIONAL HYDROGRAPHIC REVIEW

VOL. 29 · Nº 1
MAY 2023

IHO
International Hydrographic Organization

CENTENARY EDITION
1923 — 2023

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About the Journal

The International Hydrographic Review (IHR) is an international scientific journal publishing peer-reviewed papers on all aspects of hydrography and associated subjects, ranging from the latest technical developments and significant events to book reviews and historical recollections. The IHR was first published in 1923 and since then has been published regularly.

Editorial

Welcome to the first issue of The International Hydrographic Review (IHR) in 2023. This year is a jubilee year for our publication – the IHR is celebrating its 100th anniversary!

Ever since its first issue published in 1923, the IHR has been a prestigious publication of the International Hydrographic Organization (IHO), adapting its focus, content and format through changing times. Today, the IHR is a reputable international scientific journal that publishes peer-reviewed articles spanning all facets of hydrography. Additionally, it covers related disciplines, including oceanography, geodesy, remote sensing, geo-information science, geophysics, acoustics, marine technology and navigation.

The readership of the IHR is diverse, encompassing academia, industry, organizations and authorities within the international hydrographic community and beyond. We strive to publish articles that appeal to this broad audience, providing relevant insights and perspectives for all.

Patrick Westfeld

The IHO is proud to celebrate the centenary of the IHR this year! To commemorate this milestone, this issue is a special jubilee edition. First, it features a new, redesigned and modern layout in which the IHR will be published from now on. As a special tribute to our readers, a printed copy of this jubilee edition will be presented to each delegate attending the 3rd Session of the IHO Assembly to be held in Monaco from 2 to 5 May 2023.

In the welcoming words to this jubilee edition, Secretary-General Dr Mathias Jonas and the two Directors Abri Kampfer and Luigi Sinapi emphasise the special importance of the IHR as the publication body of the IHO throughout history. The interdisciplinary relevance of the IHR in the fields of oceanography and geodesy become clear in the subsequent welcoming addresses by Ariel Hernán Troisi, Chair of the Intergovernmental Oceanographic Commission of UNESCO (IOC), and Dr Diane A. Dumashie, President of the International Federation of Surveyors (FIG).

The jubilee edition contains five exceptional keynote articles, bringing a unique and valuable perspective on hydrography. Mathias Jonas opens *New Horizons for Hydrography* and gives an insight into the expected future development. Ute Brönner and her co-authors explore the potential of *Digital Twins of the Ocean* and their capacity to support the development of a sustainable blue economy in a protected marine environment. How *Uncrewed Surface Systems* will influence the future of global ocean exploration becomes impressively clear in Larry Mayer's contribution. While technical advancements are crucial, sustainable development cannot solely rely on the technical domain. As Helen Stewart highlights in an impressive manner, *community-led engagement* is essential in achieving sustainable outcomes. Peter Ehlers concludes the keynote articles by reflecting on *100 years of international cooperation in hydrography*.

To celebrate the jubilee, we have also reached out to all Member States, inviting their National Hydrographers to share their perspectives on historical milestones of hydrography, future trends and the role of the IHR. Look forward to many interesting answers and exciting insights into our global hydrographic community.

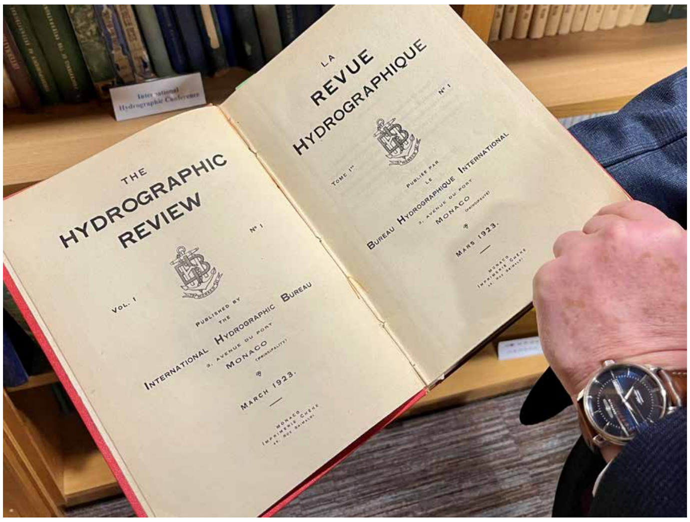
Finally, this jubilee edition contains a compendium of 13 articles chosen by the Editorial Board and the IHO Directing Committee of the more than 4,000 published since 1923 that represent important achievements in hydrography over the last 100 years. The reprints of these manuscripts allow us a unique glimpse into the past, from the 1920s to the present. These reprints

ISSN print: 0020-6946
DOI prefix: 10.58440
URL: https://ihr.iho.int/

Printing/Binding: German Federal Maritime and Hydrographic Agency (BSH)

Publisher:
International Hydrographic Organisation
4b Quai Albert 1er
98011 Monaco

Editorial Board:
https://ihr.iho.int/editorial-team/



The original exemplar of the very first issue of The Hydrographic Review (Vol. 1, Nº 1, March 1923), a technical bulletin and predecessor of the IHR, in the hands of the IHO Secretary-General Dr Mathias Jonas.

are also a fitting conclusion to our jubilee edition and allow us to reflect on the rich history and development of our profession.

I would like to thank everyone who contributed to this jubilee edition.

My sincere appreciation to the IHO Directing Committee, Ariel Hernán Troisi and Dr Diane A. Dumashie for taking the time to contribute greetings to this issue. I am deeply grateful to the authors of the five keynote articles, whose exceptional insights and expertise have greatly enriched this issue. My thanks also go to all 21 National Hydrographers who participated in our questionnaire.

Thank you to the Editorial Board for making this issue possible through your unwavering dedication and hard work!

Without the great work of my colleagues in the IHO Secretariat, the IHR would not exist. My most sincere thanks to Luigi Sinapi, Leonel Manteigas, Sarah Jones-Couture, Isabelle Belmonte, Astrid Alonso, Isabelle Rossi, David Giraudeau and Máximo J. Tobías Rubio. You are awesome!

Last but not least, a special thank you to the German Federal Maritime and Hydrographic Agency (BSH) for their professional printing, binding and sending of this issue from Rostock (Germany) to Monaco.

On behalf of the Editorial Board, I hope you enjoy reading this jubilee edition of the IHR!

Dr Patrick Westfeld
Chief Editor, IHR

Greeting from the IHO Directing Committee

Less than two years after the birth of the IHO, 100 years ago in 1923, the then 22 Member States of the International Hydrographic Bureau decided to launch a technical bulletin, the Hydrographic Review, with the primary purpose of communicating to their community the importance of a young science – the Hydrography - and its scientists - the Hydrographers -, unknown to most at the time, but which would in time attract the attention of the international scientific and maritime communities.

Reading from the very first issue of the International Review in 1923, it was clear how much the small hydrographic community would have to work to convince the world of the importance and usefulness of such discipline: *"... to others the meaning of the word "Hydrographic" is not so evident …"* and *"… Recently I asked a British graduate of Cambridge, to give me his conception of the word "Hydrographic", but apparently he was quite unfamiliar with the expression …".* Such statements had a bitter taste, a harbinger of enormous efforts required on the part of early 20th century hydrographers.

Mathias Jonas

In its first 100 years, the journal continuously evolved, modernised and opened up to the hydrographic, maritime and scientific world. Just to mention a few milestones, in 1947, the journal changed its name and became *The International Hydrographic Review* (IHR), wearing for the first time an international dress, decidedly aimed no longer only at the narrow hydrographic community, but the introduction of subjects and disciplines resulting from the tremendous experience of the Second World War that had just ended.

Abri Kampfer

It was in the 1970s that the Review began to gain true international recognition, publishing original works on all aspects of hydrography and associated subjects, ranging from the latest technical developments to history. This was mainly the result of the gradual enlargement of the membership of the IHO, the consolidation and recognition of the other international organizations involved on and for the sea that were established between the 1950s and 1960s (i.e. IMO, WMO, IALA, IOC), and the increasingly widespread and systematic use of technologies applied to positioning, navigation and sound systems in hydrographic surveys.

Since the 2000s went digital, and in 2009 to be precise, the IHR became a web-based publication, with its two annual issues accessible to all and free of charge. As the most recent evolutionary step in 2021, on the occasion of the celebrations of the IHO's centenary, the new IHR website was launched. Today, using communication and the many social networks on which the IHO is present, the IHR and its articles are presented to the international community and commented on, with an immediate return in terms of popularity and content.

Luigi Sinapi

Finally, a note of credit goes to the editors who have succeeded one another over the years, to all those who have contributed in the first 100 years of the Review's life, and to the passionate contributors and readers from all over the world, who have made the IHR's success possible as a point of reference for national hydrographic services and the international hydrographic and maritime communities.

Happy anniversary to the IHR and fair winds to the present and future editors!

Abri Kampfer
Director

Dr Mathias Jonas
Secretary-General

Luigi Sinapi
Director

Greeting from the Intergovernmental Oceanographic Commission of UNESCO

Ariel Hernán Troisi

The knowledge and understanding of ocean features and processes remain critical aspects to achieving sustainable ocean planning and management. In this sense both hydrography and oceanography, as sister disciplines of ocean science, come to play a fundamental role.

Hydrography is the science of measuring and describing the physical features of water bodies, including their depth, temperature, and currents. Oceanography, on the other hand, is the science of studying the ocean, including its physical, chemical, geological, and biological properties and processes. Both disciplines are naturally intertwined, and often involve the common use of their respective tools, techniques, and methodologies.

From ensuring the safety and efficiency of shipping routes to monitoring the impacts of climate change, and providing for early warning systems, these fields are helping us better understand, protect, and sustainably manage the ocean and its vital resources for future generations.

One of the most significant challenges facing both hydrographers and oceanographers is the vastness of the ocean. Only a small percentage of it has been surveyed or studied in detail, requiring high-quality, reliable, and accessible ocean data. In recent years, advances in technology and the development of new tools and techniques have helped to expand our understanding of the ocean and its properties. It is our responsibility to use the knowledge and information that we generate to protect our ocean and secure its future, and for that we need to continue strengthening partnerships and networks, connecting people and organizations across sectors, disciplines and regions.

The International Hydrographic Review constitutes a platform to communicate the state of development in hydrography, an enabling mechanism to link practitioners, as well as a means to interact with other communities of practice through a cross-domain approach.

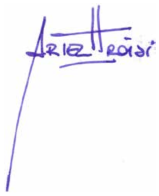
The present Jubilee edition of The International Hydrographic Review comes then at a very special time. The UN Decade of Ocean Science for Sustainable Development (2021–2030) is a global initiative coordinated by the Intergovernmental Oceanographic Commission of UNESCO that aims to advance the science of the ocean, accelerate sustainable development, and support the conservation of the ocean's resources. We have a unique opportunity to provide a transformative framework for science-based solutions to address the challenges facing our ocean. To achieve these goals, collaboration between scientists, policymakers, and other stakeholders, as well as the development of innovative technologies and approaches to ocean research and management, is crucial.

Thus, the partnership between hydrographers and oceanographers is particularly important for achieving the aspirations of the Ocean Decade. We have multiple examples and opportunities such as the development of marine spatial planning (MSP) frameworks through which, inter alia, the Ocean Decade supports with the aim to promote sustainable ocean development. These frameworks require accurate and up-to-date information on the ocean's physical characteristics, such as the location of seafloor habitats and resources, to be effective. On the other hand, the lack of detailed mapping of the ocean seafloor constitutes a significant limitation for understanding the ocean's geology, biogeography, and ecosystems, as well as for identifying and managing ocean resources and potential hazards and providing the necessary early warnings. Hydrography can provide this information, while oceanography can help to interpret and analyse the data.

One major example of such collaboration is framed under the recently endorsed Decade Programme: The Nippon Foundation – GEBCO Seabed 2030 programme under the umbrella of GEBCO, a joint programme of the IOC and IHO.

In summary, hydrography plays a critical role in supporting the aspirations of the Ocean Decade by providing essential data that supports sustainable development and conservation of the ocean's resources.

By drawing on our combined and wide range of skills, knowledge, and experience, we will be in a position to provide more creative and effective solutions, breakthroughs and innovations. Joint design, development, and delivery are essential to achieving our common goals, and together, these fields of ocean science can help to unlock the full potential of the ocean for the benefit of society. I am confident that we can make a real difference in ensuring that our oceans remain healthy, vibrant, and sustainable for generations to come.



Ariel Hernán Troisi

Chair of the Intergovernmental Oceanographic Commission of UNESCO (IOC)

Greeting from the International Federation of Surveyors

Diane A. Dumashie

As President of the International Federation of Surveyors (FIG)[1], it is my pleasure to contribute a few words to IHR's 100 year anniversary edition. One hundred years seems a long time for many of us and yet in our world there are important activities and challenges that will take a much longer time span to address. The FIG and IHO are familiar with this aspect of our profession.

Tackling the greatest challenges of our time often starts with water (ocean and terrestrial) and is reflected in the UN 2030 sustainable agenda. Water is key to future prosperity being fundamental to life; but this resource needs careful stewardship. The challenges of security of food and water supplies, climate pattern change, safe and clean seas, whilst sustaining a growing urban population on our coasts, are some of the key themes. These require the Hydrographers and Geodesists, together with other spatial domain experts and scientists, to lead and to influence through good survey practices, data governance and cooperation. IHO and FIG, through FIG Hydrography Commission IV, will play a part.

The discussion on climate actions at global level has too often neglected key aspects of the roles played by a broad range of surveyors. However, there is now a strong emerging interest in linking land use, land tenure, the blue economy and geospatial information more closely in a practical way and getting to grips with what happens on the ground, above and below the low water mark!

I've said many times before that Surveying is not only about serving the clients – our profession is just as well about serving society and their wellbeing. We are recognised experts in the areas of hydrography, geomatics, geospatial information management and connected survey disciplines. We have a responsibility to respond to this global agenda and to contribute to improving the living conditions in our societies. This is why the FIG strategy has the vision *"Surveyors serving society for the benefit of people, planet and to work in partnership".* Over the next four years, FIG working with partners will be looking to tackle the global challenges in land, marine natural and built environment.

On the centenary year of the founding of the Royal Institution of Chartered Surveyors, in 1968, FIG first created a Hydrographic Surveying Commission, chaired by Rear Admiral Steve Ritchie of the United Kingdom. Then in 1971 the XIII Congress of FIG was hosted by the German Association of Surveyors (DVW), in the year of the 100th anniversary of DVW's existence. It was at this event that a Working Group (WG) was formed by Commission IV (Hydrography) to develop International Standards of Competence within the profession of surveying at sea.

Collaborating with IHO and other partners on blue Surveying, Geodesy and Hydrography is timely as I believe the survey profession, in each of our country and local contexts works tirelessly for the benefit of the public good and we have a huge contribution to make. The surveyors at the inception of these institutions and the later members of FIG, understood the importance and benefits of collaboration and partnerships to achieve sustainable goals and objectives in their professional sectors and to the wider community and society. This collaboration continues today between FIG and various other bodies and organizations.

[1] FIG more than 100 member associations throughout the world representing more than 300,000 professional surveyors. https://www.fig.net/members/index.asp.

[2] Standards of Competence for Category "A" Hydrographic Surveyors (Edition 1.0.2, June 2018), published by International Hydrographic Organization, 4b, Quai Antoine 1er, B.P. 445, Monaco, 2018.

[3] FIG Guide on the Development of a Vertical Reference Surface for Hydrography, Publication no. 37, The International Federation of Surveyors (FIG) Lindevangs Allé 4 DK-2000 Frederiksberg DENMARK, ISBN 87-90907-57-4, 2006.

A strong and sustaining link with the international Hydrographic community can be evidenced through the joint FIG/IHO/ICA International Board on Standards of Competence for Hydrographic Surveyors and Nautical Cartographers (IBSC)[2]; development and adoption of global geodetic reference frames and coordinate reference systems; the development of vertical reference surfaces for surveys[3] and numerous Blue Surveying related activities that support the international efforts to map our oceans, gain knowledge of our seas, their habitats and creatures and of course supporting modern digital navigation and maritime users.

Now in 2023 as we celebrate the centenary of the IHR, it is more important than ever for professional surveyors, geodesists and hydrographers to contribute, through collaboration and cooperation; by collecting information and advancing our understanding and knowledge of our seas and oceans. Publishing work, research, knowledge and learnings is critical to all our communities, the wider society and is a vital resource for the next generation.

Initiatives that elevate and promote our profession are surely common areas for our institutions. Attracting new generations of professionals, with a more diverse, equitable and inclusive demographic, into our community and showing the wider society the positive impact and roles that we have to offer must continue to develop. This is an area of recent focus for FIG with the establishment of a Task force on Diversity and Inclusion. And one that will surely develop and by FIG and IHO acting together, we empower and enable sustainability and resilience to be a core of the professional sphere and society space. FIG Commission IV and IHO can take action on the most important issues of our time and to lead, influence and to deliver together.

The IHR has played a key role in the promotion of and raising awareness of themes, trends and learnings. The good work of the IHR must continue and can complement, promote and inform on key trends and future challenges such as those outlined in the FIG strategy: Climate action and the SDGs; Digital transformation; Equality, Diversity and Inclusion, Future Workforce.

As global professional bodies, we need to respond to these challenges if we are going to ensure that our members deliver confidence in the years ahead and the IHR will play a key role. Reaching this 100 year anniversary marking the establishment of IHR, comes about due to hard work from many. On behalf of the FIG community, I applaud you and give my congratulations.

Dr Diane A. Dumashie FRICS
FIG President

Content

Reprinted articles

New horizons for hydrography

Author
Mathias Jonas[1]

Abstract

Compared to the complexity required to measure other physical quantities, the continuous monitoring globally of water levels, current directions, and velocities, as well as the measurement of underwater topography, do not appear ambitious tasks for modern technologies. The challenges lie in the sheer size of the area to be measured, which makes up about 70% of the Earth's total surface, in its constant variability due to natural processes, the inaccessibility of the seabed, and the still inadequate mathematical modelling of global geophysical processes at the oceanic scale. Since most of the world's population lives on, from and with the oceans, a demand-oriented provision of hydrographic information is of fundamental importance. Hydrography is called upon to serve this need for information in support of informed decision-making. Starting from the present status and the discernible trends in technical development, this article aims to provide a glimpse into the expected future development up to the end of the current decade.

Keywords
Seabed topography · Hydroacoustic measurements · Satellite derived bathymetry · Drifting buoys · Uncrewed surface vehicles · Nautical charts · S-100 data model · Digital twin

Resumé

Par comparaison avec la complexité requise pour mesurer d'autres quantités physiques, le suivi global et continu des niveaux d'eau, des directions et des vitesses des courants, ainsi que la mesure de la topographie sous-marine, ne semblent pas être des tâches ambitieuses pour les technologies modernes. Les défis à relever concernent la dimension de la zone à mesurer, qui représente environ 70% de la surface totale de la Terre, sa variabilité constante due aux processus naturels, l'inaccessibilité des fonds marins et la modélisation mathématique encore insuffisante des processus géophysiques globaux à l'échelle océanique. Étant donné que la majeure partie de la population mondiale vit sur les océans, grâce aux océans et avec les océans, la fourniture d'informations hydrographiques en fonction de la demande revêt une importance fondamentale. L'hydrographie est appelée à répondre à ce besoin d'information en vue d'une prise de décision éclairée. Partant de la situation actuelle et des tendances perceptibles dans le développement technique, cet article vise à donner un aperçu du développement futur attendu jusqu'à la fin de la décennie actuelle.

Resumen

En comparación con la complejidad necesaria para medir otras magnitudes físicas, el seguimiento global de los niveles del mar, las direcciones y velocidades de las corrientes, así como la medición de la topografía submarina, no parecen tareas ambiciosas para la tecnología moderna. Los desafíos se encuentran en la extensión del área que hay que medir, que cubre aproximadamente el 70% de la superficie total de la Tierra, su variación constante debido a los procesos naturaleza, la falta de acceso al fondo marino, y que el modelado matemático de los procesos geofísicos globales a escala oceánica aún no es el adecuado. Dado que la mayor parte de la población mundial vive en, de y con los océanos, el suministro de información hidrográfica según las demandas tiene una importancia fundamental. A la hidrografía se le pide que cubra esta necesidad de información en apoyo de la toma de decisiones informada. Partiendo del estado actual y de las tendencias que se pueden anticipar en los avances técnicos, este artículo tiene como objetivo proporcionar un atisbo del desarrollo futuro que se espera hasta el final de la década actual.

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https://doi.org/10.58440/ihr-29-a01

1 Introduction

Hydrography is an engineering science, which does not seek knowledge for knowledge's sake. The goal is not to get a description of the marine topography and geophysical processes of the oceans just for pure knowledge, instead it is demand-driven. History confirms this. It was the American Benjamin Franklin who, as early as 1769, discovered through systematic observations how the force of the Gulf Stream could be useful to ships navigating between the North American continent and Europe (Fig. 1). Another American, Matthew Fontaine Maury, organized the first systematic deep-sea surveys in the Atlantic in the 1850s to prepare for the laying of undersea telephone cables.

Compared to the complexity required to measure physical quantities, for example at the atomic scale, the continuous monitoring globally of water levels, current directions and velocities, as well as the measurement of underwater topography, do not appear complex tasks for modern technologies. How can it be explained then that only about 25% of the seabed has been covered by modern measuring methods so far (Fig. 2)? The challenges lie in the sheer size of the area to be measured which makes up about 70% of the Earth's total surface, in its constant variability due to natural processes, the inaccessibility of the seabed, which reaches water depths of up to 10,000m, and the still inadequate mathematical modelling of global geophysical processes at the oceanic scale due to the lack of high-resolution data.

This analysis is not new and yet still highly topical, because the demand for more precise, comprehensive and up-to-date information on the physical properties of the seas and oceans far exceeds the available supply. The major need comes from all the stakeholders who deal with political, environmental and economic issues relating to the use and protection of the oceans. Since the majority of the world's population lives on, from and with the oceans, a demand-oriented provision of hydrographic information is of fundamental importance for present and future generations. Furthermore, it should not be forgotten that the oceans are the largest weather and climate machine, whose function has a general impact on all inhabitants of the earth but more specifically on those living on small island states and along increasingly eroding coasts.

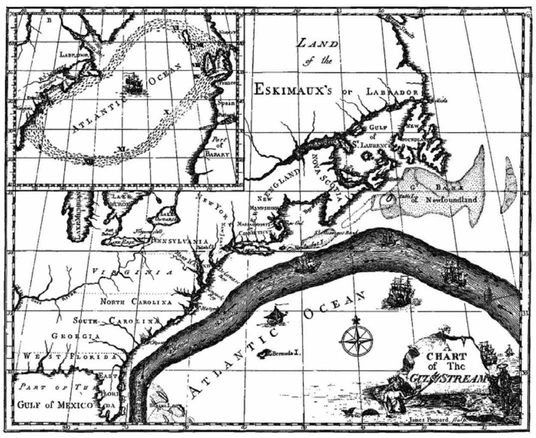

Fig. 1 This map of the Gulf Stream appears in the book by Benjamin Franklin and dates from 1769. The Gulf Stream is depicted as the dark gray swath that runs along the east coast of what is now the United States. Source: National Oceanic and Atmospheric Administration (NOAA).

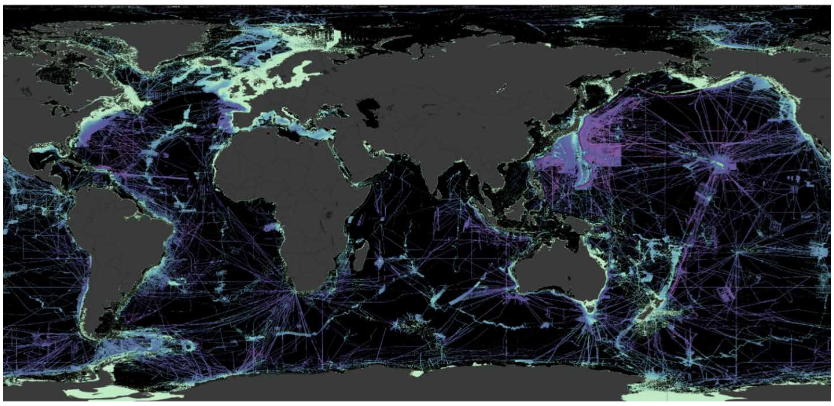

Fig. 2 This map shows the status survey coverage by 2022. The black color shows the unmapped portions of the world ocean. Source: IHO Data Centre for Digital Bathymetry (DCDB).

Hydrography is called upon to serve this need for information in support of informed decision-making. Starting from the present status and the discernible trends in technical development, this article aims to provide a glimpse into the expected future development up to the end of the current decade.

2 The state of the art and the need

The previously mentioned figure of 25% of submarine topography recorded in good resolution requires further explanation. The water depths up to the continental shelf, which extends to a depth of 200m, can be assumed to be well recorded and thus known with sufficient accuracy in many parts of the world. Exceptions are along some coastal areas in Africa, the Antarctic waters and the Arctic, where the dwindling sea ice is constantly revealing new, previously unsurveyed areas. The greatest gap is in the deep sea at depths beyond 200m, which should be considered as mostly unsurveyed so far (Fig. 2). Due to the comparatively low penetration depth of optical signals in the water column, only satellite altimetry provides approximate indications of the shape of underwater formations. For more precise surveys, mainly ship-based hydroacoustic deep-sea echo sounders are used, which are not very economical in terms of their operational costs, carbon footprint and area efficiency. Recent developments rely on crewless operating instrument carriers – the uncrewed surface vehicles (USV), which are confronted with the problem of the high energy requirements of low frequency deep-sea echo sounders.

In navigable shallow waters with high traffic volumes, such as estuaries and harbors, hydroacoustic techniques are used to provide high-frequency and

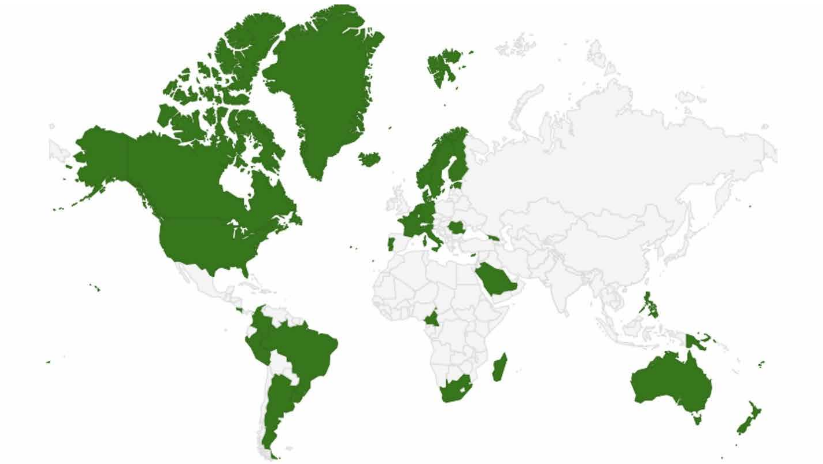

Fig. 3 Map of Member States allow crowdsourced bathymetry within their waters of jurisdiction (some with specific caveats). Source: IHO Data Centre for Digital Bathymetry (DCDB).

very accurate surveying services that enable the safe and efficient passage of ships, as well as to monitor the structural condition of port facilities, bridges and dikes. So far, however, only ports in the Americas, Europe and Asia, and a few in Oceania and Africa that are important to the global economy are capable of providing such ongoing data service provisions to operators and customers.

For shallow waters with water depths of up to 30m, optical and radar-based satellite observation systems provide information on water depths and water levels which, although less accurate than on-site measurements, have advantages due to their wide aerial stretch at comparatively low costs. Their evaluation requires highly qualified algorithms cast in software and qualified personnel for their application.

Water levels and currents are recorded continuously near the coast, especially in areas with significant maritime traffic, and mostly with sufficient accuracy thanks to level measurement systems and current meters. Our knowledge of oceanic parameters such as the global distribution of water temperature and salinity has grown considerably over the past twenty years thanks to the deployment of drifting buoys through the ARGO programme. One day ARGO floats may provide depth soundings as well, however, drifters cannot replace continuous positional high-resolution observations. Certainly, there are continuous and well established global networks for sea level measurements (Global Sea Level Observing System (GLOSS) and the associated Permanent Service for Mean Sea Level (PSMSL)) in place. A permanently financed, global, fine-meshed measurement network, as is standard on land for meteorological data, however, is still lacking for physical (as well as chemical and biological) parameters of the oceans.

The development of such a perpetual measurement infrastructure requires affordable, powerful and robust sensor technology. In the development of such autonomously operating sensor technology, the energy supply and wireless transmission of the recorded measurement data pose particular challenges.

Although the aforementioned deficits exist for the long-range and permanent recording of hydrographic information, the scope of the already continuously recorded measurement data on a global scale is considerable. However, their accessibility is subject to significant restrictions of a geopolitical, scientific-political and economic nature. In a resolution endorsed by the Economic and Social Council (ECOSOC) in 2015, the UN Committee of Experts on Global Geospatial Information Management declared its support for common principles of geospatial data management, which also regulate the provision and availability of maritime geodata. Unfortunately, governmental commitment and practice in the field often do not match when it comes to hydrographic information. Existing knowledge about the topographical nature of one's own coastal waters is rarely shared extensively for national security reasons. A similar situation can be observed for data collected within the framework of scientific projects: their preparation for public availability is costly and is usually not taken into account in project financing. The data itself often provides the basis for the scientific objectives based on it and thus justifies its exclusivity for the current project. Owners of data collected in a costly manner for private-sector purposes expect remuneration for making it generally available or are reluctant to let authorities and competitors share in their information advantage. Positive attempts to improve the situation is the digital strategy of the European Union for promoting reuse of open data codified by means of the Public Sector Information Directive and the commitment of now 33 IHO Member States to allow crowdsourced bathymetry within their waters of jurisdiction (Fig. 3).

The global growth in the sheer volume of data is impressive. Hydroacoustic and satellite-based methods deliver data in enormous resolution in terabytes that grow to petabyte collections. Their transmission requires large bandwidths; the software effort, including Machine Learning and Artificial Intelligence components for their management, processing and interpretation is immense. A holistic view of the state of the ocean cannot succeed by looking at individual phenomena such as the distribution of salinity or global ocean currents in isolation. Their interpretation requires the correlation of the different themes at the data level; their evaluation requires the application of powerful statistical algorithms. In order to bring together the data from the various disciplines, comprehensive data standards are needed that are based on a common data model and that can be expanded without limiting the mutual compatibility of the data sets.

The classic task of nautical hydrography providing shipping with thematic charts for navigation is fulfilled with a worldwide stock of digital and, with a decreasing tendency, printed nautical charts. The fact

https://doi.org/10.58440/ihr-29-a01

that all digital navigational chart datasets (ENCs) for international shipping fully comply with the governing IHO Standard is a great achievement. The technical philosophy underlying the ECDIS system, however, dates back to the nineties of the last century. Today, land-based navigation systems show the enhanced possibilities of specialized software to support navigation, which go far beyond the ECDIS functions. They are achieved through the thematically rich data used and the integrated real-time online components. The generation of users that has grown up with the internet expects the same for ship-based navigation systems. Only with the expansion of the functional scope of a new generation of ECDIS devices can further efficiency and safety gains be realized in shipping and the associated port services. The same applies to the introduction of uncrewed, remotely or autonomously operating watercraft, which require a completely new quality of support with hydrographic information in the form of data services.

3 Expected developments

The fundamental physical principles on which hydrographic measurement systems are based can neither be extended nor overridden. Therefore, it is to be expected that the established hydroacoustic and laser-based methods for on-site measurements and the optical and radar-based methods in remote sensing will remain dominant. Quantum-based measurement methods, should they be developed, will probably not reach practical maturity in the current decade. Further improvements, however, can be expected in the resolution of sensor technology, the interpretation of measurement signals and the correlation of on-site measurements with remote sensing information through the use of artificial intelligence algorithms. Through the intelligent evaluation of hydroacoustic measurement signals, for example, new insights into the nature of the sediment, sea grass and other characteristics of the habitat can be gained if national hydrographic services will not only entitled but also enabled by resources to undertake such tasks which are currently done only erratically with research projects. In particular, the mapping of sea grass meadows as ideal CO_2 reservoirs can make an important contribution to their cultivation and thus to decarbonization.

As instrument carriers, flying, floating and diving remote-controlled or autonomously operating units will become dominant because of their excellent cost/benefit ratio. This development will drive the miniaturization of sensor technology while reducing their energy consumption. This will give a further boost to the accurate measurement of coastlines and thus benefit coastal protection and land-sea transition use enormously. An important demand driver is the installation and monitoring of offshore structures in energy production, submarine cables and pipelines, as well as fish farming and other forms of protein production at sea.

Fig. 4 The NEMO thermally recharging echo sounder float. Source: Seatrec, Vista, CA, USA.

In addition to the lower costs for the units carrying the measuring devices themselves, their area efficiency due to their unlimited usability in terms of time with simultaneously increased surveying speed also enables the reduction of the distance of the sensor system to the object under investigation. This makes it possible to use high-resolution laser detection at short distances, even directly in the body of water. The energy supply remains a challenging problem that can be tackled by solar foils that can be adapted to curved construction forms, thermal energy generation from the temperature differences from water layers of different depths or possibly by miniaturized fuel cells (Fig. 4). Nevertheless, uncrewed units will be the disruptive technology in the hydrographic domain – driven by the regular duties described but also by emerging new national policies and strategies on the protection of sea bed national interests (power and internet submarine cables).

Enormous changes will be brought about by the long-announced but now imminent global availability of affordable broadband communications at sea. Although the lack of broadband underwater communication remains, hydrography will nevertheless become a communication-driven discipline. It remains to be seen whether this will break the current trend of pre-processing data on the instrument carrier with

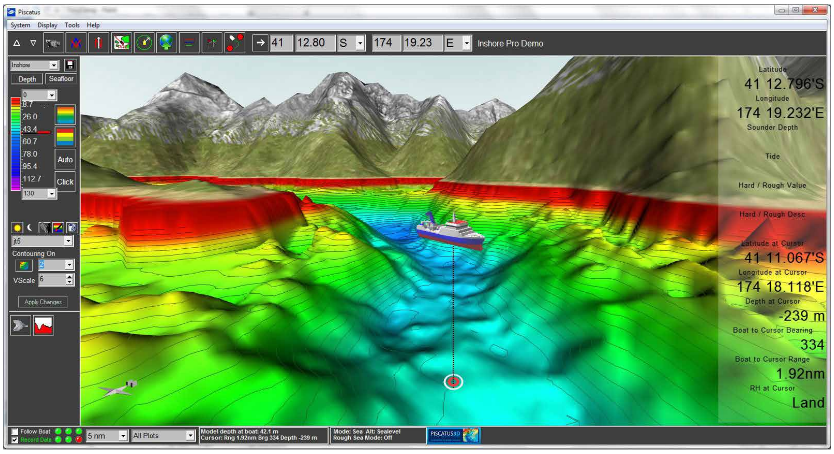

Fig. 5 3D Interpretation of ENC content. Source: Seabed Mapping International Ltd, Port Nelson, New Zealand.

edge computing in order to reduce the amount of data to be transmitted. In any case, it will be possible to transmit sensor data in real time and to combine them in a server-based architecture into a situation picture that can be permanently retrieved by all participants. Technologies that use hydrographic cyber-threat proof information on the basis of decentralized databases in the cloud, as is the case for ECDIS with ENCs, for example, could follow the example of internet-based map services whose central database is constantly kept up to date and thus become a client-server architecture.

The trend towards digital maps is irreversible. However, similar to everyday office life, there will still be a need for a hard copy of digital chart content in various application scenarios. The automation of the main cartographic tasks - levelling, reducing and generalizing - must be made even more user-friendly in order to make the paper map printable by the customer. Generalization is the supreme discipline of cartography, even in the digital world. The nautical-hydrographic information formerly distributed in analogue form, such as nautical handbooks, current atlases and tide tables, have already been converted into digital variants without exception. However, these digital variants have so far mainly followed the printed models: The information streams are separate from each other and their presentation is two-dimensional. Examples of this are the paper-map-like presentation of ENCs in ECDIS and the so far insufficient integration of water level feeds and sea current information into this system.

The second wave of digitization of hydrographic information using the S-100 data model, which is currently being pushed by the IHO, will result in a massive expansion of digital data services that will be compatible with each other at the model level and thus interoperable. Their full potential could unfold through spatial-temporal representation. Some user groups favor the use of the term "hydrospatial" to mark a linguistic distinction from the techniques introduced so far. This argument can be followed insofar as the technique of visual two-dimensional overlaying of constantly new layers of information makes the acquisition of the actual situational relevant information more difficult rather than easier. In order not to overtax the user in his visual perception possibilities, the algorithm-based situational selection of the information to be displayed and new forms of presentation will be necessary. It is questionable whether the general reservations against such a pre-selection, which is difficult for the user to evaluate, will diminish over time. For some years now, there have been discussions about presenting hydrographic information in a way familiar to the world of computer games in three dimensions or by means of augmented reality (Fig. 5). Due to the strong regulation of nautical equipment in professional navigation and the limited market size of the entirety of all watercraft, a broad acceptance or market penetration with such technologies is difficult to predict. However, specialized applications in hydraulic engineering, dredging and offshore applications could soon benefit from these technologies.

Hydrography is the provider of baseline digital information streams when it comes to providing a holistic picture of the state of the seas and oceans. The latest terminology to summarize these efforts is the digital twin of the oceans. Digital twins are virtual representations of physical objects and systems, the physical or real twin, which in this case is the ocean or a part of it. However, the generic term digital twin does not address a single system that completely represents the state of the ocean. According to the current understanding, there will be several topic-oriented twins whose practical application will take place in specially adapted geoinformation systems. Digital twins include predictive and data-driven models that users can interact with to support their needs. Digital twins thus provide the ability to make informed operational, management, and policy decisions for the real twin. This connection between the digital twin and the real one requires a well-formulated interface between the digital twin, environmental data, and the user. User interaction is therefore an essential function that is embedded in the design of digital twins, including visualization, user-driven data transformation and data-science tools.

In order to anticipate the possible lines of development of future maritime geoinformation systems, it has proven useful to compare similar development goals and already existing systems for land applications. Obvious parallels are the trend towards thematic diversity of the data to be combined with each other, the embedding of metadata as a necessary prerequisite, the motivation to expand data types while at the same time maintaining strict semantic standardization to ensure compatibility and the maintenance of loss-free communication between machines. These prerequisites are served by the already mentioned S-100 data model of the IHO (Fig. 6). Its implementation as a high priority project of the member states of the IHO in the current decade can only be considered successful if it is possible to establish

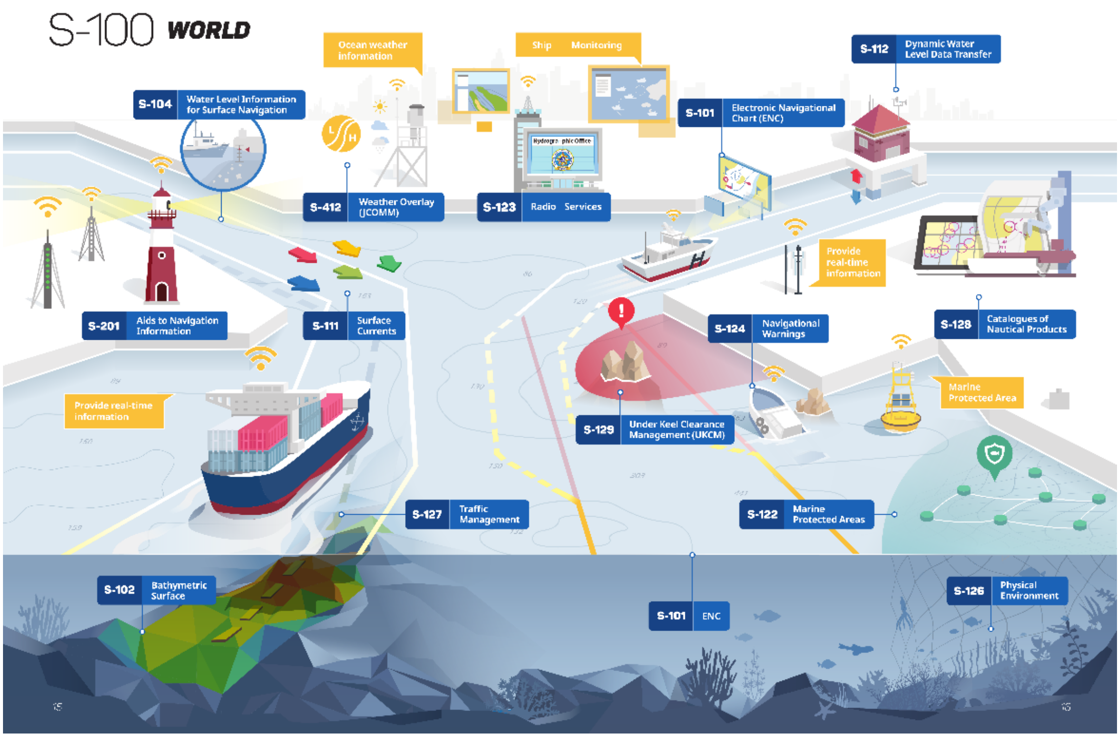

Fig. 6 Elements of the S-100 Environment formed by interoperable datasets containing different hydrographic themes. Source: Korea Hydrographic and Oceanographic Agency.

regular S-100 compatible data streams for the data products covering hydrographic services' core tasks and to motivate industry to develop attractive applications based on these data.

This requires hydrographic services to establish new types of production systems with far-reaching consequences for the technical equipment and skills of employees involved. The transition from the product-centric production of nautical documents to a data-centric production of a diversity of digital data products driven by market demand is thus finally completed. This comprehensive digitalization of the entire chain of collection, processing and dissemination of information is a major challenge in an administrative environment characterized by official procedures. Beyond the associated conversion of the overall system, a special effort must be made to define and apply quality parameter for the data sets used. The regular operation of autonomous surface ships at sea, as they are currently being defined by the IMO, is unthinkable without being able to qualify hydrographic information.

4 Digitalization as the major driver

The ongoing digitalization of all hydrographic processes, starting with sensor technology and continuing with the collection, transmission, processing and dissemination of hydrographic information, will provide data volumes of unprecedented scope and quality. What is still missing is a digital ecosystem to host the diversity of marine data to enable sovereign and sustained handling of such data stocks. It is open at this stage if such an environment can be established under governmental supervision or if it will become an industry-driven commercial model. Maybe a combination of both approaches depending on the different socioeconomic paradigms in regions such as North America and Europe. The challenge for hydrographic services to contribute to such an ecosystem is the management of these data streams for their respective domain, the definition of data products derived from them according to the customer's needs and their continuous quality-assured provision. The most striking visible change will come from the use of uncrewed instrument carriers (Fig. 7), which, in addition to their aforementioned benefits, contribute

Fig. 7 Ocean Infinity's fleet of remotely operated instrument carriers. Source: Ocean Infinity, London, UK.

Fig. 8 Digitally generated impression of the navigation bridge of the future. Source: ULSTEIN Group ASA, Ulsteinvik, Norway.

to the reduction of the carbon footprint of survey and inspection operations, support faster decision-making through real-time insights and ensure safer operations. Industry-wide scaling of these benefits of remote survey and inspection technologies will require a broader transformation in areas such as legislation, ways of working and obtaining new skills and competencies of all parties involved.

As ongoing digitalization is one side of the coin, communications will be the other one. As we know from our daily life, internet access has become the 'fifth element'". If it becomes widely available at sea, this will definitely be a game changer. One of the most promising solutions is the Maritime Cloud: each naval asset will get its individual maritime identity, a globally accessible representation supported by cloud-based digital information technology. Under this concept, the 'ship's avatar' would contain static and operational information associated with the particular vessel and this would even apply to any sort of hydrographic information – predominantely ECDIS data fuel. Other features could include bridge windows that serve as augmented reality displays, identifying potential hazards that might otherwise be difficult to see, such as sea ice or tug boats (Fig. 8).

But whatever solution this whole process will finally present, there are two tendencies which seem clear. First, ECDIS as a stand-alone unit will probably disappear i.e. be absorbed as a function within an integrated environment embedded in a unified user interface. Secondly, more information will be given to machines that is presently confined only to humans. Consequently, it will allow machines to become even more involved in the navigational process. For instance, automated analysis taking into account the integrity of all data could readily merge positional and dynamic information with data that is already available digitally, such as ENCs, maritime safety information, meteorological and tidal predictions, etc. For decisions not involving other vessels, it potentially allows some very sophisticated decision-making processes regarding navigation to be automated. If such a trend materializes, visual presentation of chart items may generally be reduced to relevant information for the situation at hand. Visual detection remains particularly important and a key part of navigation on crewed vessels, enabling decisions to be made when there are other vessels in the vicinity. This is tied to the question as to whether humans will remain as the only detector and user of visual information for navigation purposes onboard vessels. Much research on the concept of uncrewed ships is being carried out nowadays. The relocation of all navigation competencies from ship to shore would see the end of the need to carry electronic charts as an on board device. However, without doubt, graphical presentation of maritime geoinformation will remain the most intuitive way of understanding our environment, whatever the future brings with new technologies and automation.

5 The human element

Coming back to the initial description of hydrography as an engineering science it is evident that the conduct of our discipline needs capable and motivated people. Ocean matters have always attracted younger people and there are numerous ocean literacy initiatives in place to support them. But what are the competencies of the "hydrographer of the future"? The Canadian Hydrographic Office convened an international workshop on this subject in April 2022.

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The starting point was a discussion about the impact on hydrographic offices and the role of humans in this increasingly technology-driven environment. Will this person be predominantly a data manager and organizer or is there still a need for specific marine qualifications? The outcome of the discussion was that the ideal candidates had attended certified education courses and training as hydrographers or cartographers but there was also a tendency to hire staff with educational backgrounds in physical sciences, data science, IT and programming as well as GIS. These new recruits would need additional education & training in core hydrographic themes. This raises the question of the right balance between those two elements – one addressing the skill set and the other one the practice of skills application. Obviously, education is the core; training builds skills and helps hydrographers keep up with rapid advances in technology and hydrographic practices. Elements of marine spatial data infrastructures must be also incorporated as well as time at sea in order to create an informed understanding of hydrographic products in use. In many cases, hydrographers are "testers" for various hydrographic data collection devices as development is ongoing. The idea of "push button hydrographers" can be problematic as organizations are held accountable for the quality of collected data, and hydrographers need to have the skills and expertise required to ensure that the data collected are "good"; they need to understand the how and the why. In this context, it is important to understand that it is essential to evaluate and track the training and the experience of individuals within an organization. There is still a need for some hydrographers to be "jack of all trades", able to carry out a variety of tasks, while others become increasingly specialized, and some aiming for a mix of both. In the end, hydrographic offices and industry are in need of talented employees who belong to either one of the three groups. The last group may be the best messengers to help increase knowledge of hydrography as a discipline among the broader population through outreach with educational institutions, show cool technology etc. This would help demonstrate the various career paths and retain talent. Mentorship through career development could help secure this long-term investment.

In order to get the best talent from around the world, we also need to increase diversity in the field. One area, which needs significant improvement, is gender balance in hydrography. The IHO has recently adopted this topic to its Work Programme under its Capacity Building strategy. Globally, the well-documented imbalance between the participation of women compared to men in the science, technology, engineering, and mathematics (STEM) fields as well as other maritime-related domains is also present in hydrography. This imbalance is apparent at all work levels but it is particularly evident at the more advanced career echelons and in governance and decision-making positions. The ambition to change this is relevant to hydrography because not only will it address issues of gender-equity, but it will open the field to a vast pool of talent that will potentially contribute new perspectives, skills, and creativity to the world of hydrographic sciences.

6 Outlook to the future

Surface navigation has seemingly been the traditional focus of hydrographic products for decades. However, recent estimates suggest that only 10% of all surveys are undertaken for the sole purpose to support nautical cartography. Other aspects related to the use and preservation of the marine environment have become crucial drivers. Therefore, an increased focus on coastal surveys, shallow waters below 10m, the continental shelf in areas far from navigation and the hitherto sparsely surveyed deep sea is to be expected. Despite new cost-effective uncrewed instrument carriers, data acquisition at sea remains complex. Therefore, it is important that the evaluation of measurement data is as comprehensive as possible for all recoverable information such as sediment, underwater habitats and unexploded ordnance. The key to this will be machine learning and artificial intelligence techniques.

The state of the oceans is a human issue. In order to provide the basis for sound political decisions, the engineering and scientific knowledge gained from the data must be translated into forms of communication that are understandable to the interested general public – and this is also true for hydrographic knowledge. It is not enough to limit oneself to the classic hydrographic repertoire of mapping the topography of the seabed and topics relevant to shipping. Spatial-temporal representations that interweave physical measurement data with data on biological and chemical processes of the sea are just as necessary as the expansion in the future of the systematic measurement tasks of hydrography to include maritime gravimetry, plastic particle pollution and underwater noise.

In view of this development, the relationship between hydrography and oceanography will naturally evolve. The measuring, monitoring part of ocean observation may increasingly be carried out under hydrography and be considered a routine government task. Oceanography will benefit from this flow of data delivered by hydrographers and will be able to focus on the analysis of the data streams and their interpretation, thereby gaining a better understanding of ocean processes.

Hydrography is active on a large scale in areas of the earth's surface that either belong to the whole of humanity or are used internationally on a pro rata basis, for example by shipping. It is therefore of a dimension and importance which, for both technical and ethical reasons, can only be addressed as a coordinated mission. An indispensable prerequisite for this is political agreement, as provided by the major international treaties UNCLOS, SOLAS and MARPOL. Global initiatives under the umbrella of the UN, such as the Sustainable Development Goals and the Ocean Decade, address the need for action and trigger coordinated activities that ultimately amount to an expansion of the existing scope of regulation in favor of the conservation and responsible use of the seas and oceans. Coming back to my very first argument of this article: hydrography remains an engineering science but with a greatly expanded scope. Hydrography services a wealth of marine scientific and commercial disciplines. Hydrography is a laboratory for the use of cutting edge technology applied through cross-sectoral and cross-border collaboration. Hydrography is indispensable to gain enhanced marine knowledge, to understand better how this planet functions. An important instrument to make these insights productive is and remains the IHO which celebrated its 100th anniversary in 2022, a sign of its continued usefulness through the ages and capacity to adapt to changing times. The IHO, helps to create the technical standards and the personnel prerequisites in hydrography to help address humanity's great challenges. In doing so the IHO delivers a best practice for the strength and benefits of international cooperation. Hydrographers of the world know: the future will be Blue and stand ready for a new voyage of *Twenty Thousand Leagues Under the Sea*.

Author's biography

Mathias Jonas

Dr Mathias Jonas is the Secretary-General of the International Hydrographic Organization (IHO) since 2017. Prior to this appointment he held the posts of Vice President of the Federal Maritime and Hydrographic Agency and National Hydrographer of Germany with responsibility for sea survey and sea cartography. Being a mariner, Dr Jonas has been involved in integrated navigation matters since the beginning of the nineties. In addition, he has completed the world's first technical certification of an Electronic Chart Display and Information System in 1999 and has continuously contributed to IMO and IHO standardisation activities for navigation equipment, survey and cartography since. As one of the responsibilities of his current post, he holds the Chair of the Hydrographic Commission on Antarctica.

In the running period of Dr Jonas' lead of the IHO Secretariat he managed to raise the profile of IHO as competent body in its key areas - technical standardisation and inter-regional cooperation – and succeeded also to widen this scope to all activities associated with the oceans, seas and navigable waters. His achievements in digitalization of the IHO Secretariats functions helped to keep IHO´s pace on the collaboration with Member States, relations with global partners and the working regime of all the IHO Committees and Working Groups despite the limitations induced by the COVID-19 pandemic.

 https://doi.org/10.58440/ihr-29-a01

Digital Twins of the Ocean can foster a sustainable blue economy in a protected marine environment

Authors

Ute Brönner[1], Maike Sonnewald[2], and Martin Visbeck[3]

Abstract

While the field of hydrography is crucial for maritime navigation and other maritime applications, oceanography is the field that provides the relevant data and knowledge for predicting climate change, monitoring marine resources, and exploring marine life.

Digital ocean twins combine these two exciting fields and combine ocean observations and ocean models to establish virtual representations of a real world system, in this case the ocean or an ocean area, as well as assets in the ocean and processes within ocean industries or the natural environment. They have the potential to play a critical role in optimising and supporting sustainable ocean development.

Digital Twins are synchronised with their real-world counterparts at a specific frequency and fidelity. They can provide valuable insights into the ocean's state and its evolution over time, which can be used to support decision-making in ocean governance and various ocean-related industries. Digital ocean twins can transform human ocean interactions by accelerating holistic understanding, optimal decision-making, and effective interventions. Digital twins of the ocean use ocean observations, historical and forecast data to represent the past and present and simulate possible future scenarios. They are motivated by outcomes, tailored to use cases, powered by integration, built on data, guided by domain knowledge, and implemented in IT systems.

In this article, we explore the benefits of digital twins for the ocean, the challenges in developing them, and the current state of the art in ocean digital twin technology.

One of the main benefits of digital ocean twins is their ability to provide accurate predictions of ocean conditions under expected interventions. Their information can be used to support decision-making in various applications including ocean-related industries, such as fishing, shipping, and offshore energy production. Additionally, digital twins can help to improve our understanding of the ocean's complex processes and their interactions with human activities, such as climate change, pollution, resource extraction and overfishing.

Researchers and IT companies are combining various technologies and data sources, such as the Internet of Things for ocean observations, state of the art data science, artificial intelligence and machine learning, data spaces and vocabularies into digital ocean twins to contextualise data, improve the accuracy of ocean models and make ocean knowledge more accessible to a wide range of users.

Keywords

Digital twins of the ocean · decision making · sustainable ocean governance · blue economy · protected ocean

Resumé

Alors que le domaine de l'hydrographie est essentiel pour la navigation et d'autres applications maritimes, l'océanographie est le domaine qui fournit les données et les connaissances nécessaires à la prévision du changement climatique, à la surveillance des ressources marines et à l'exploration de la vie marine.

Les jumeaux numériques des océans combinent ces deux domaines passionnants en étant des représentations virtuelles d'un système physique, en l'occurrence l'océan ou une zone océanique, ainsi

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https://doi.org/10.58440/ihr-29-a04

que des actifs dans l'océan et des processus au sein des industries océaniques ou de l'environnement naturel. Ils peuvent jouer un rôle essentiel dans le développement durable des océans.

Les jumeaux numériques sont synchronisés avec leurs homologues du monde réel à une fréquence et une fidélité spécifiques. Ils peuvent fournir des informations précieuses sur l'état de l'océan et son évolution dans le temps, qui peuvent être utilisées pour soutenir la prise de décision dans diverses industries liées à l'océan. Les jumeaux numériques de l'océan peuvent transformer l'industrie océanique ainsi que la gouvernance des océans en accélérant la compréhension holistique, la prise de décision optimale et l'action efficace. Les jumeaux numériques de l'océan utilisent les observations océaniques, les données historiques et les prévisions pour représenter le passé et le présent et simuler les prévisions futures. Ils sont motivés par les résultats, adaptés aux cas d'utilisation, alimentés par l'intégration, construits sur des données, guidés par la connaissance du domaine et mis en œuvre dans des systèmes informatiques.

Dans cet article, nous examinons les avantages des jumeaux numériques pour l'océan, les défis liés à leur développement et l'état actuel de la technologie des jumeaux numériques de l'océan.

L'un des principaux avantages des jumeaux numériques de l'océan est leur capacité à fournir des prévisions précises des conditions océaniques, qui peuvent être utilisées pour soutenir la prise de décision dans diverses industries liées à l'océan, telles que la pêche, le transport maritime et la production d'énergie en mer. En outre, les jumeaux numériques peuvent contribuer à améliorer notre compréhension des processus complexes de l'océan et de leurs interactions avec les activités humaines, telles que le changement climatique et la surpêche.

Les chercheurs et les entreprises informatiques combinent diverses technologies et sources de données, telles que l'internet des objets pour l'observation des océans, la science des données de pointe, l'intelligence artificielle et l'apprentissage automatique, les espaces de données et les vocabulaires, pour créer des jumeaux numériques des océans afin de contextualiser les données, d'améliorer la précision des modèles océaniques et de rendre la connaissance des océans plus accessible à un large éventail d'utilisateurs.

Resumé

Aunque el campo de la hidrografía es crucial para la navegación marítima y otras aplicaciones marítimas, la oceanografía es el campo que proporciona los datos y conocimientos relevantes para predecir el cambio climático, controlar los recursos marinos, y explorar la vida marina.

Los gemelos oceánicos digitales combinan estos dos apasionantes campos al ser representaciones virtuales de un sistema físico, en este caso el océano o un área oceánica, así como de recursos en el océano y procesos dentro de las industrias oceánicas o el entorno natural. Tienen el potencial de desempeñar un papel fundamental en el apoyo al desarrollo sostenible de los océanos.

Los Gemelos Digitales están sincronizados con sus homólogos del mundo real con una frecuencia y fidelidad específicas. Pueden proporcionar información valiosa sobre el estado del océano y su evolución a lo largo del tiempo, que puede utilizarse para apoyar la toma de decisiones en diversas industrias relacionadas con el océano. Los gemelos digitales del océano pueden transformar la industria oceánica así como la gestión de los océanos, acelerando la comprensión holística, la toma de decisiones óptimas, y la acción efectiva. Los gemelos digitales del océano usan observaciones oceánicas, datos históricos y previsiones para representar el pasado y el presente, y simular futuros previstos. Están motivados por los resultados, adaptados a los ejemplos de uso, potenciados por la integración, construidos a partir de datos, dirigidos por el conocimiento del dominio, e implementados en sistemas informáticos.

En este artículo analizamos los beneficios de los gemelos digitales para el océano, los desafíos que plantea su desarrollo, y el estado actual de la tecnología de gemelos digitales oceánicos.

Uno de los principales beneficios de los gemelos digitales oceánicos es su capacidad para proporcionar predicciones precisas de las condiciones del océano, que se pueden utilizar para apoyar la toma de decisiones en diversas industrias relacionadas con el océano, como la pesca, el transporte marítimo, y la producción de energía en la mar. Además, los gemelos digitales pueden ayudar a aumentar nuestra comprensión de los complejos procesos oceánicos y sus interacciones con las actividades humanas, como el cambio climático y la sobreexplotación pesquera.

Los investigadores y las empresas informáticas están combinando diversas tecnologías y fuentes de datos, como Internet de las Cosas, para las observaciones oceánicas, la ciencia de datos avanzada, la inteligencia artificial y el aprendizaje automatizado, los espacios de datos y los vocabularios, en gemelos digitales del océano para contextualizar los datos, mejorar la precisión de los modelos oceánicos y hacer que el conocimiento del océano sea más accesible para una amplio abanico de usuarios.

1 Introduction

The ocean is everything to us: life, food, energy, recreation and jobs. Right now, the ocean is under pressure and threatened by overexploitation, loss of biodiversity and habitats, pollution, marine littering and climate change. The value of the ocean economy speaks to its importance: The Organization for Economic Cooperation and Development (OECD) estimates that by 2030, $3 trillion USD will be generated annually from ocean sectors such as transportation, fishing, tourism, and energy (Pendleton et al., 2020). But the ocean and in particular the coastal regions are rapidly changing, and it is not entirely clear how these changes will play out. At the same time, the ocean is increasingly understood as essential for achieving sustainable development, including climate and biodiversity goals (Gaill et al., 2022; Bender et al., 2022).

Digital Twins of The Ocean or Digital Ocean Twins set out to bring relevant ocean data and information from different sources into new contexts (Fig. 1), to understand relations that are crucial for society to develop sustainable economic activities in the ocean. Digital Twins for climate change scenarios, in complement to traditional climate models, provide the knowledge to further understand the ocean's relation with Earth's changing climate, to understand anthropogenic impacts, and empower scientists, politicians and ocean stakeholders with the necessary information for evidence-based decision-making for sustainable management of the Ocean and adaptation to climate change (Larkin et al., 2021). In addition, data are increasingly important to meet the ambitious targets set out in the European Green Deal, and its related Climate Pact, pledging for Europe to be climate neutral by 2050 (EU Commission, 2019).

Digital Twins are famously used in the manufacturing and asset heavy industries and have made it into the complex fields like urban planning, or optimization of supply chain and other operational processes lately. Digitalisation and the use of digital technologies within the marine and maritime industry offer enormous scaling potential in both economic and environmental terms (Biber et al., 2022).

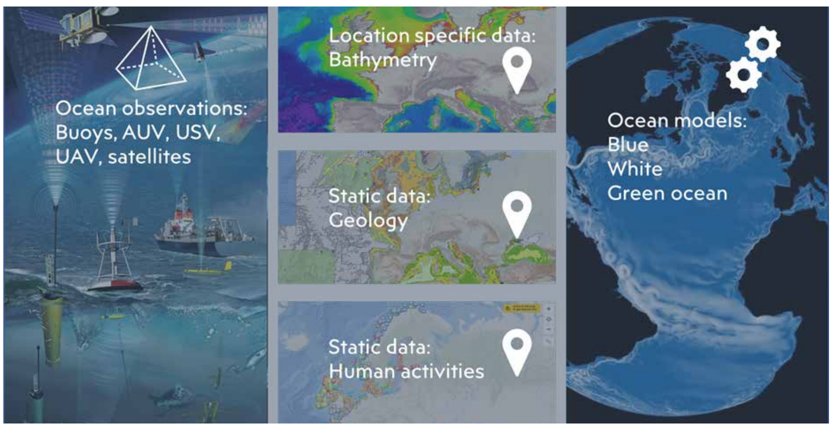

Fig. 1 Digital Twin Data sources: In the figure left – Ocean observations ships, buoys, robots, drones, satellites from science, industry and citizens. Images by DITTO and EMODnet.

Knowledge of the ocean as a dynamical entity with predictable features, for example the regularity of its currents and tides and seasonal variations have been known for millennia. Knowledge of oceanography likely helped the successful colonization of Oceania, and similarly Viking and Inuit navigation, the oldest known dock was constructed with knowledge of the tides dating back to 2500–1500 BCE, and in the 8th century CE the existence of tides was correctly attributed to the Moon's pull (Sonnewald et al., 2021a). In the last century, several institutes have started to compile central repositories with ocean data from ocean observations and ocean models, but still there are only a few applications that analyse data in the context of cross-domain activities. The explosion of data in the last few years with the advent of the fourth industrial revolution and its technologies Internet of things, Big data, Artificial Intelligence and Machine Learning as well as Digital Twins meant a shift towards the integration of diverse data from different data sources and the need for a step change in geospatial and ocean data information systems to move beyond 'data' as a focal point of activity, to processing and synthesising data into contextualized information, so that it can be readily used to gain new knowledge and insights (UN-GGIM, 2022).

Sustainable development of the ocean refers to the management and use of ocean resources in a way that meets the needs of the present generation without compromising the ability of future generations to meet their own needs. This often involves multiple stakeholders, including government agencies, fishing communities, environmental organisations, and corporations, who have competing interests and goals.

Digitalization, particularly through the use of digital twins of the ocean, can play a significant role in promoting sustainable development of the ocean (Hassani et al., 2022; Biber et al., 2022). A digital twin is a virtual representation of a real-world system, such as the ocean, that can be used to analyse and simulate various scenarios and outcomes. In the context of ocean sustainability, digital twins can provide valuable insights into the current state and future projections of ocean ecosystems and the human activities that impact them. This information can be used to inform decision-making and management strategies that promote sustainable use of ocean resources. Additionally, digital twins can support the coexistence of multiple stakeholders in the same ocean space by providing a shared platform for data-driven decision-making and collaboration (Senter for hav og Arktis, 2022).

By creating a virtual representation of the ocean that can be accessed and analysed by multiple stakeholders, digital twins can help to facilitate communication and collaboration among government agencies, ocean industries, and environmental organisations, as well as support the development of more equitable and sustainable ocean management policies.

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Fig. 2 Image source: GISGRO.

In this work, we are introducing the terms Digital Twins of the Ocean (DTO), digital twins that look at the ocean and its importance for climate and biodiversity, and Digital Ocean Twins (DOT), digital twins of the ocean combined with twins of human activity in the ocean, like marine industries, tourism and maritime transport. Like DTO, DOT will be tailored to specific scientific questions or application that look at the ocean system for marine spatial planning, ocean protection and development of a sustainable blue economy.

We are giving examples of DTO and DOT that are already existing or under development and highlight their importance and purpose within ocean science and ocean use.

2 Digital twins of the ocean – a revolution for science and ocean governance

Digital Twins of the Ocean or Digital Ocean Twins will revolutionise ocean science, oceanography, and hydrography as we know it.

Three characteristics of Digital Twins will drive this revolution:

1. Data contextualisation
2. AI-driven data science and analytics
3. New ways of interacting with and presentation of data

Definitions (see also Object Management Group, 2020)

Digital Twins are a virtual replica of the physical world. Changes in the real system are reflected in the digital twin and the twin can be used to modify the real system (feedback).

Digital Twins of the Ocean (DTO) are virtual representations of the ocean with its physical, chemical and biological properties, based on ocean observations and ocean models with the purpose of what-if scenarios for decision making. The feedback of DTO is the implementation of decisions based on the DTO.

Digital Ocean Twins (DOT) are the combination of DTO with digital twins of assets and activities in the ocean for purpose to study their interaction and importance for operational decision making, protection of the marine environment and a sustainable ocean economy that includes marine spatial planning and marine protected areas. The feedback of DOT can include operational changes in (near) real-time triggered by events in the twin for optimisation towards economic and environmental goals.

Both, DTO and DOT are developed for specific purposes and for specific ocean areas (from the global ocean to local areas of interest). This implies that the T in DTO and DOT will always be in the plural form, and some will be a system of interoperable twins.

Asset-driven have already been developed and used for years and are focused on specific assets or components assets (GISGRO, 2023; Fig. 2).

Asset twins can be applied to the ocean domain for ships, fishing gear, wind parks or oil platforms. They provide detailed information on the performance and behaviour of these assets and are typically used to optimize operations and improve efficiency, e.g. through predictive maintenance.

Process-driven twins have been applied successfully in cities for logistics and in production values chains (Jiang, 2021). They can be applied to the ocean domain for ship routing, port logistics or aquaculture operations. The main difference between these twins and DTO/DOT is the geospatial domain. DTO/DOT as geospatial twins include physical location, geography, hydrological and oceanographic information and their associated environmental, social, and economic factors to consider the interconnections between ocean systems and human activities.

3 Data contextualisation

The power of digital twins is their AI-supported ability to combine data from different sources and analyse them in context, often to reveal connections that were unknown before. ESA's Digital Twin Hydrology

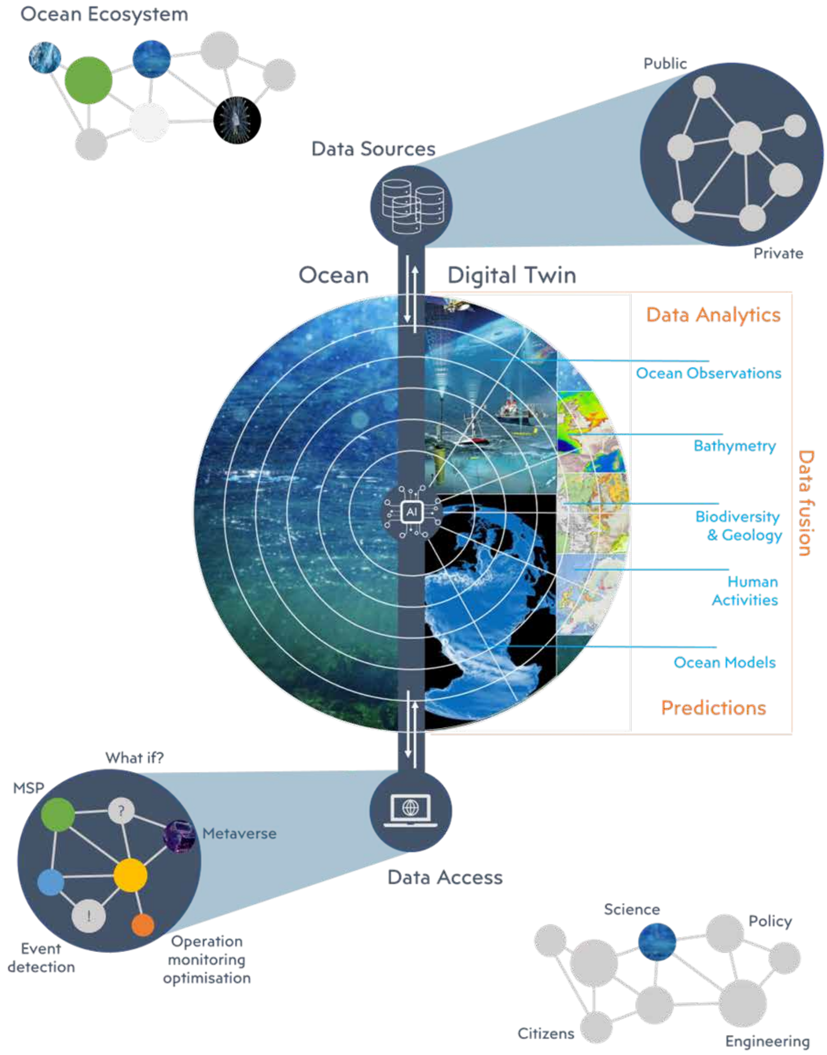

Fig. 3 Digital Twins of the Ocean (DTO) and Digital Ocean Twins (DOT) use AI-supported data fusion, data analytics and predictions for a specific ocean ecosystem, for a specific purpose and target group.

combines data from satellite and ground observations with model results in a warning system for landslides and flooding (ESA, 2021).

The infographic in Fig. 3 visualises this.

Ocean observation systems are developed and managed all over the world. Programs like the global ocean observing system GOOS, deliver a permanent global system for observations, modelling, and analysis of marine and ocean data (GOOS, 2021; EuroGOOS, 2023; ODYSSEA, 2021; NorEmso, 2021; OceanLab, 2023).

Ocean observations play a crucial role in the development of digital twins of the ocean. They provide the data necessary to create an accurate digital twin. Observations can come from various sources, including satellite imagery, localised in situ measurements (Fig.4), and mobile sensors on autonomous systems. Each observation has a specific range and purpose and combined, they provide data for an ocean area from space to seabed, also called the observation pyramid (NTNU, 2022).

The combination of real-time observations creates a comprehensive picture of the ocean's current state and time series help to identify patterns and trends over time.

Data from ocean observatories can be assimilated into ocean models to improve their quality (Fig. 5). An ocean model is a mathematical description of the ocean's physical, chemical, and biological processes. This is also referred to as the blue, white, and green ocean.

Ocean models can describe the ocean state in the past, present and future and results are hindcasts (reanalyses, with assimilated ocean observations), nowcasts (analyses), and forecasts (prediction of future states) (CMEMS, 2021).

Ocean models provide a comprehensive representation of the ocean's state and its evolution over time over a large area and period which has some advantages over ocean observations that cover either a specific location or time. By varying the so-called boundary conditions, which describe the 'outside' world, ocean models can be used to simulate so-called what-if scenarios, an important aspect of digital twins. Scenarios that take into account climate change, extreme weather events or changes to the seafloor or coastal infrastructure and their effects are examples of what-if scenarios. Ocean models can be combined with ecosystem models to assess opportunities and challenges for biomass production, to predict threats like algae blooms, parasites or infections or water quality parameters like temperature, oxygen and nutrition levels. Environmental modelling combines ocean and ecosystem models to understand the natural systems and how they react to acute changes, such as exposure to pollution (noise, litter, hazardous substances) and the temporal and dose effects from this exposure.

Digital Twins of the Ocean will employ models in different spatial and time resolution depending on the purpose of the digital twin. A digital twin for environmental modelling in a fjord has high requirements to resolution as a digital twin that is developed to assess climate change scenarios. In contrast to digital solutions that we know from before, operational DOT will support management and mitigation through more accurate information and recommendations.

4 AI-driven data science and analytics in digital twins

Digital Twins of the Ocean by their nature come with a set of challenges that Artificial Intelligence (AI) and its subcategory Machine Learning (ML) can help address (Google, 2023):

- AI allows a machine to simulate human intelligence to solve problems.
- AI uses technologies to mimic human decision-making.
- AI systems use logic and decision trees to learn and self-correct.
- ML allows a machine to learn autonomously from past data.

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Fig. 4 A location-fixed observation buoy on its way in the ocean. Image source: SINTEF Ocean.

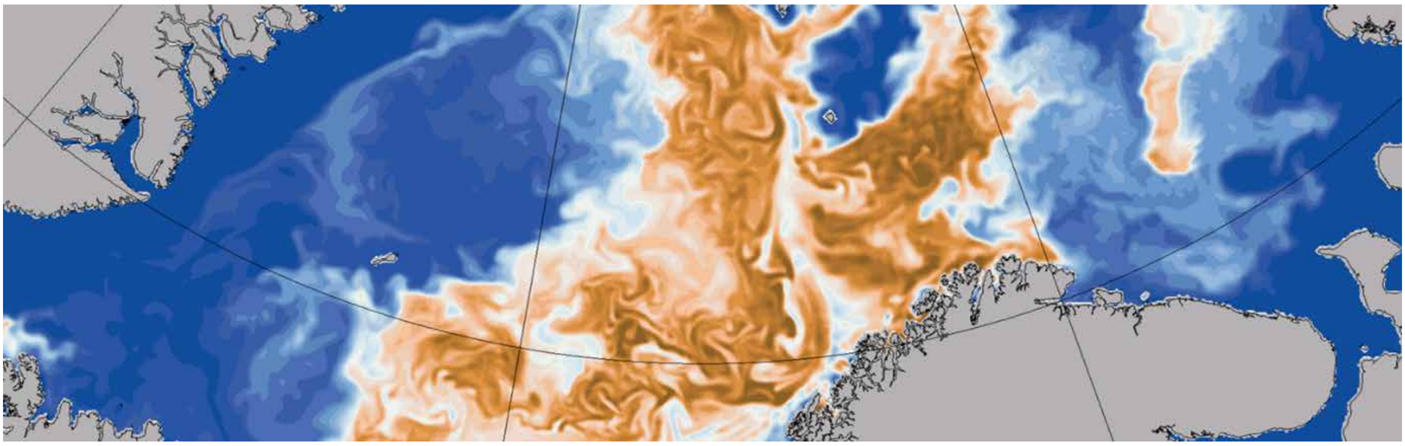

Fig. 5 SINMOD ocean model results showing ocean dynamics in the Barents Sea. Image source: SINTEF Ocean.

- ML uses self-learning algorithms to produce predictive models.

While the adoption of AI and ML within digital twins is not without risk, they are increasingly being recognized as tools that can automate tasks and perform them more reliable and faster, enhance what can be learned from different forms of observations and their comparison with model results, and generate actionable insights as (Sonnewald et al., 2021a; Fig. 6).

Data fusion and analysis: Observational data is often spatially sparse, limited to the ocean's surface, and few time series span decades. Unfortunately, important timescales span seconds to millennia in the real ocean, with strong scale interactions which complicate numerical modelling together with details such as coastlines and islands (Sonnewald et al., 2020; Sonnewald et al. 2021b). ML shows the potential to bridge and fill the gaps in our data record, for example by finding and predicting patterns..

Predictions: A basic goal and a test of the understanding of a process is the ability to predict its behaviour. ML has the power to enhance predictions beyond a few days through pattern recognition and time series analysis.

Enhanced quality and efficiency: ML can improve and enhance ocean modelling especially on edge

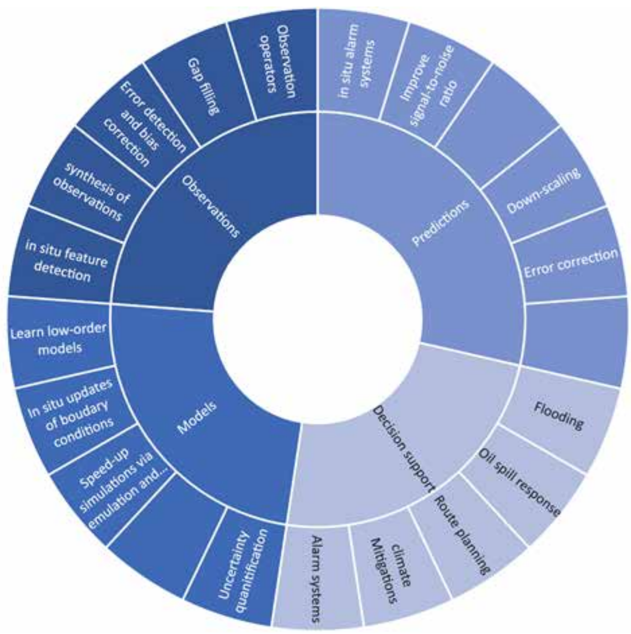

Fig. 6 Examples for the use of ML in Digital Twins of the Ocean. Adapted from Sonnewald et al. (2021a).

(remote) devices with less computational power like mobile sensor platforms or offshore observatories. ML methods will enable the efficient use of hardware and advance processing on edge devices even further (Wehner et al., 2022).

Decision support: As digital twins use datasets from different data sources, on different reference grids and for different variables, these data can be fused and compared using ML techniques. ML can also be used for the quantification of uncertainties within the data and from these processes. This can be accounted for when data is presented for decision making and recommendations (Sonnewanld et al. 2021).

In oceanography, hydrography and their application in digital twins, ML can enhance data exploration. Where traditional approaches to data analysis ground their data in prior knowledge and assumptions, a data-exploration centred approach allows the possibility of serendipitous discoveries and can unveil previously unknown relations and dependencies.

5 Interacting with digital ocean twins

Digital ocean twins have the ambition to open up to new fields of applications and presentations for their data, connecting oceanography and hydrography with new industries, like gaming and other immersive 3D digital environments. Initiatives like Worlding (MIT, 2022) or Immerse (Immerse, 2023) use Digital twinning for engaging storytelling and ideation between participants. Game engine industry companies like Unity and Unreal engage with digital twin communities for powerful visualisations. Digital twinning is a growth market for the game engine industry, in verticals such as manufacturing, architecture, finance, and medicine but also simulation and training for ocean industries. "Digital twinning gives teams the power to ideate", said Elizabeth Baron, a senior manager of enterprise solutions at Unity in her talk at WORLDING. "You can look at many things that maybe aren't even possible to produce. But you're the resource. Impact is very low, but the creativity aspect is very high".

The Maritime Spatial Planning Challenge (MSP-Challenge, 2023) is a next generation planning support game that also features a virtual and augmented reality module called Ocean View. The developers are a partner in the EU funded Digital Twins of the

Fig. 7 FAIR data principles and their relevance to data within Digital twins (Lin et al., 2020).

Fig. 8 TRUST data principles and their relevance to data within Digital twins (Lin et al., 2020).

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Ocean project Iliad (Iliad, 2022), where they aim at further development and linking the platform to the project's Digital Twins of The Ocean. At the International Digital Twins of the Ocean summit (G7FSOI, 2022), presentations featured powerful visualisations by the Unreal gaming engine which used ocean data and weather forecasts for storytelling by The Weather Channel in the US (Epic Games, 2023).

These kinds of visualisations have the potential to play a significant role in promoting sustainable development of the ocean. They allow stakeholders to interact with and explore virtual representations of ocean systems and the impacts of human activities on these systems in a way that is immersive and engaging:

1. Stakeholder engagement: virtual environments where stakeholders, including the public, policy makers, and industry leaders, can interact with and explore the ocean in an engaging way can raise awareness about the importance of sustainable ocean development and encourage action.
2. Environmental education: Interactive visualisations can be used to inform people about the ocean, its biodiversity, and the impacts of human activities on these systems. This can help build a greater understanding of the importance of sustainable ocean development and the need for action.
3. Decision-making support: Visualisations can be used to support decision-making by allowing stakeholders to explore scenarios and the impacts of different management strategies on ocean systems for more effective and sustainable management including protection of ocean areas.
4. Collaborative planning: engaging visualisations can be used to create virtual environments where stakeholders can collaborate on solutions to ocean sustainability challenges. This can foster greater understanding and cooperation among stakeholders that want to operate in the same ocean area.

Fig. 9 UN Decade program DITTO.

Researchers do often have different needs to data visualisation as they want to understand relations between data and phenomena and drill down into the data. They will need another type of interactive visualisation to cater to those needs. DTO/DOT will deliver visualisations in the form of interactive dashboards (e.g. Grafana, which is tailored to ocean observations, (SINTEF Ocean, 2023) or embedded in jupyter notebooks with interactive libraries like Plotly (Plotly, 2023), Bokeh (Bokeh, 2022) or Holoviews (Holoviews, 2023) based on accurate and up-to-date data that include clear objectives and an understanding of their assumptions and limitations.

6 Data and twin interoperability

Data contextualisation, AI-driven data science and

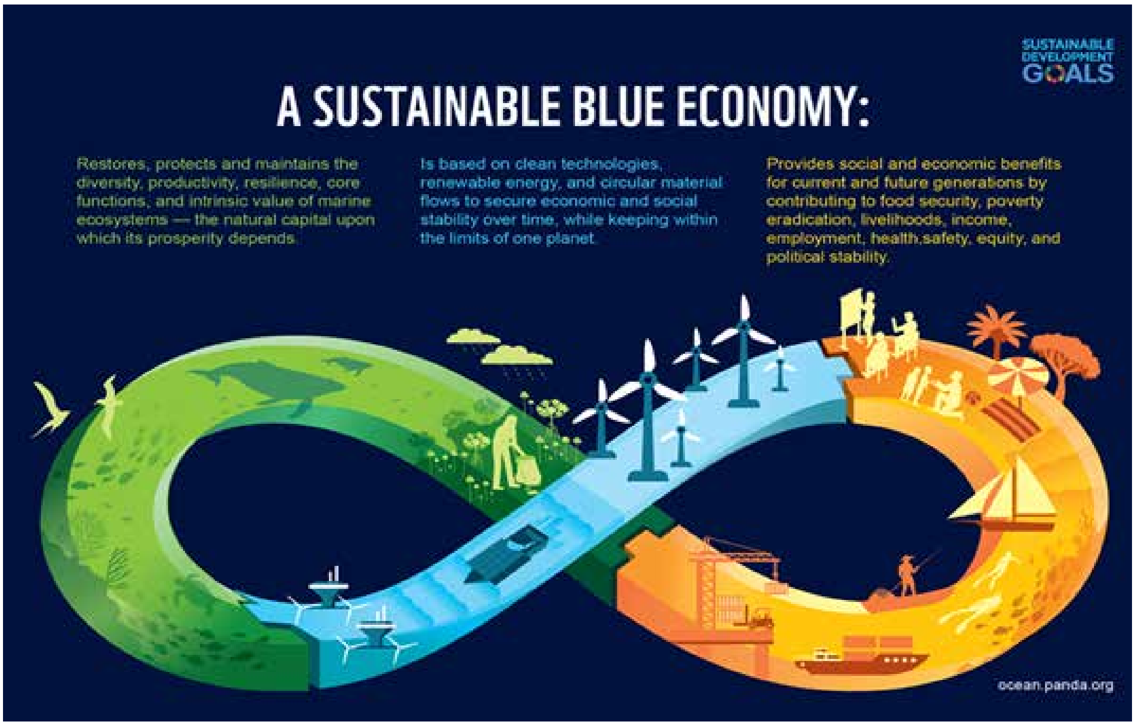

Fig. 10 Image source EURACTIV (2018).

analytics and the presented ways of interacting with data within digital twins come with ambitious requirements for data and twin interoperability.

The FAIR Data Principles define the properties of data objects to ensure that data are reusable by humans, machines, and applications like digital twins: Findable, Accessible, Interoperable, and Reusable (Lin et al., 2020; Fig. 7).

FAIR principles are accompanied by an endorsed set of guiding principles to demonstrate trustworthiness of the data repositories to the user of the data: Transparency, Responsibility, User focus, Sustainability and Technology – TRUST (Fig. 8).

Digital twins require these principles to apply without the human in the loop, i.e. through defined standards and application programming interfaces (API) that ensure machine to machine (M2M) findability, accessibility, interoperability and reusability. The United Nations Decade of Ocean Science for sustainable development has defined interoperable ocean data as one of the necessary building blocks to address the identified challenges and has implemented a Data Coordination Group to provide advice to Decade coordination and governance structures (IOC-UNESCO, 2021) "The ambition of the Decade in relation to data, information and knowledge management includes significant enhancement of infrastructure, common approaches that enable interoperable data sharing and stewardship, and enhanced collaboration between data". The group is accompanied by a technical group for implementation, a corporate data group to unlock data from the private sector on the same grounds and the Decade Coordination Office (DCO) for Ocean Data Sharing.

The UN Decade program DITTO – *Digital Twins of the Ocean* (DITTO, 2022; Fig. 9) as well as the associated program TURTLE – *Interoperability architectures for Digital Twins of the Ocean* (Brönner et al., 2022) have been established to gather Digital Twin communities across the globe to promote standards and building blocks for Digital Twins of the Ocean.

Semantics play a crucial role in data and digital twin interoperability. They describe the meaning of data and the relationships between different aspects of data. In the context of digital twins, semantics are used to describe the relationships between different data sources, modules or building block of twins and the relation between the data and the building block.

With semantic interoperability, different devices and systems can find, understand and interpret data and modules in the same way and in the context of digital twins, semantic interoperability is critical for ensuring that data from different sources can be integrated and analysed seamlessly.

7 How digital twins of the ocean advance sustainable ocean solutions

The objective of the Sustainable Blue Economy is to restore, protect and maintain the ocean with the help of technology that operates within the limits of our planet, while building a diverse, resilient and environmentally sustainable marine economy with social and economic benefits for current and future generations (Fig. 10).

This involves balancing economic, social, and environmental considerations to ensure the long-term health and productivity of ocean ecosystems and the communities that depend on them. Digital Ocean Twins can support this complex task with applications tailored to the ocean area of interest and aggregation of data for these different aspects of sustainable development. Some examples are listed below, more can be found in Hassani et al. (2022).

	Coastal development and responses to the changing environment
Benefits from the use of digital twins of the ocean	The coastal area of our ocean is threatened by extreme weather events, storm surges and sea level rise caused by climate change. At the same time, our coasts become increasingly important as more and more people live in megacities at the coast. Ports need to ensure that they have the right infrastructure to supply these people with the foods and goods that they need. At the same time, infrastructure from offshore energy production like cables and pipelines arrive at the swash zone of the shore and are threatened by coastal erosion. Digital twins of the coastal ocean can help by informing decision making with what if-scenarios for coastal protection against coastal erosion as well as sediment transport for infrastructure protection while at the same time ensure biodiversity protection in infrastructure projects.

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Sustainable development goal(s)	

 Image source: Unsplash.	Offshore renewable energy
Benefits from the use of digital twins of the ocean	Digital twins of the ocean can be used in the planning phase to inform decision making with wind resource predictions, as well as geological and environmental information to find locations for sustainable development of wind parks. In the operation phase, DTO support noise, biodiversity and sea floor monitoring as well as predictive maintenance by fusing environmental twins with asset twins. They can also predict windows of opportunity for safe operations in the wind park from environmental conditions in the construction, operation and decommissioning phase.
Sustainable development goal(s)	

 Image source: Unsplash.	(Offshore) Aquaculture
Benefits from the use of digital twins of the ocean	Digital twin technology is already applied in aquaculture to monitor and optimize various aspects of fish farming operations like monitoring water quality parameters such as temperature, salinity, pH, and dissolved oxygen levels, which are crucial factors that can affect the health, welfare and biomass development of fish. Another application is the prediction for windows of operations as well as potential risks to fish and infrastructure, like changes in water quality or extreme weather which can help to prevent spreading of diseases, loss of biomass or accidents. Optimised feeding, water management, and other aspects of operations can reduce feed waste, costs and environmental impacts and hence improve the sustainability of aquaculture operations.

SUSTAINABLE DEVELOPMENT GOALS — 2 ZERO HUNGER; 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE; 12 RESPONSIBLE CONSUMPTION AND PRODUCTION; 14 LIFE BELOW WATER

 Image source: Unsplash.	Maritime Transport
Benefits from the use of digital twins of the ocean	DOT support maritime transport with ship routing according to environmental conditions to reduce emissions or prevent accidents in the port under harsh conditions. They can support a digital port with risk assessment for invasive species, sediment transport, weather conditions for port operations tailored to cargo or passenger transport. Autonomous vessels like ferries are depending on accurate environmental conditions in real-time and for the near future. Electric vessels depend on environmental conditions to predict the range and plan routes.
Sustainable development goal(s)	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE; 11 SUSTAINABLE CITIES AND COMMUNITIES; 12 RESPONSIBLE CONSUMPTION AND PRODUCTION; 13 CLIMATE ACTION; 14 LIFE BELOW WATER; 15 LIFE ON LAND

	Hydrological Digital Twin for Flood Simulation
Benefits from the use of digital twins of the ocean	A combination of satellite data, precipitation, and irrigation together with sea levels and river run off can be used in a DOT for flash flood prediction and land slide warning. Digital modelling of the physical environment includes terrain, buildings, and bridges. This DOT can save human lives and economic damage from destruction of infrastructure in extreme flood events.
Sustainable development goal(s)	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE; 11 SUSTAINABLE CITIES AND COMMUNITIES; 15 LIFE ON LAND

Image source: SINTEF Ocean.

Fisheries

Benefits from the use of digital twins of the ocean

DOT for fisheries management combine data from fishing vessels on physical ocean data together with fuel consumption and catch data to optimise routing and reduce emissions from fishing fleets. If additionally catch and bycatch data are combined with stock assessments, the DOT can employ catch prediction models to support fish stock management and fisheries productivity while minimising the environmental footprint through optimisation of fishing activity and ecosystem-based management.

Sustainable development goal(s)

Image source: Blue World Institute.

Marine spatial planning with marine business parks and marine protected areas

Benefits from the use of digital twins of the ocean

Marine protected areas (MPAs) are established for the conservation of their natural or cultural resources. While there can be restrictions on certain activities in MPAs, nearly all U.S. MPAs allow multiple uses, including fishing.

Marine business parks, with co-location of several activities in a limited area, will be able to reduce the total area use and form the basis for efficient resource utilization outside of MPAs. Co-operation will be able to utilize infrastructure more efficiently, and reduce costs for both infrastructure, operation, monitoring and preparedness. Great opportunities for data sharing and digitalisation will also reduce costs and at the same time provide a better basis for decision-making than today for both industry and administration. A virtual pilot project ("digital twin") with relevant industry players and other stakeholders can assess the possibilities and gains from establishing a marine business park through a set of what if scenarios.

Sustainable development goal(s)

8 Conclusion

Digital Twins of the Ocean or Digital Ocean Twins have great potential to revolutionise ocean science, oceanography, and hydrography as we know it through data contextualisation and new and better insights from combination of a variety of data sources. Artificial Intelligence for automation of data processes and Machine Learning for data analytics will be essential and support data fusion, provide data insight from pattern recognition and inform and support decision making through recommendations. Additionally, Digital Twins will rely on and support new ways of interacting with the data they are based on and which they produce. Digital twins are different from other digital ocean applications in that they implement a two-way data exchange and feedback loop where the twin changes according to the change in the real-world system and the real-world system changes according to changes in the twin. This can either be a change due to a decision based on twin simulations (what if scenarios), or it can be a direct change of the physical twin triggered by an event observed in the digital twin (alarms, automation, autonomous operations).

Through these capabilities, digital twins of the ocean can support and foster a sustainable blue economy that operates within the limits of nature. It can provide guidance and support on where to establish Marine Protected Areas as well as Marine Business Parks where different ocean industries are co-located to leverage synergies.

The International Hydrographic Organization (IHO) can play a key role in promoting the integration of hydrographic and oceanographic data to create more accurate and comprehensive digital twins of the ocean particularly through its work in establishing standards and best practices for hydrographic data collection and management. The combination of data from the fields of hydrography and oceanography can provide a better understanding of the ocean, improve ocean management, and support sustainable use of ocean resources specifically in the fields of shipping and coastal management.

Digital twins have very ambitious requirements to data availability, as well as data and twin interoperability. Digital Twins of the Ocean or Digital Ocean Twins will always be developed for a specific purpose and / or specific ocean area. This implies that several twins might be combined into a system of twins and need to be interoperable. To facilitate and leverage the capabilities of AI and ML for data fusion, analytics and predictions, data need to follow FAIR and TRUST principles for data availability. While there are several initiatives to promote these ambitions within the UN Decade for Ocean Science there is still a way to go before all data repositories follow these principles.

Digital Twins of the Ocean and Digital Ocean Twins provide powerful tools for ecosystem-based management of ocean industries, marine spatial planning and the development of Marine Protected Areas. They are thereby well-suited as a tool for political decisions in these areas. Governments must support national data management and the development of national data repositories and infrastructures for digital twins which have not been addressed explicitly in this paper.

Acknowledgements

Ute Brönner's time was partly funded through the Iliad project that has received funding from the European Commission's Horizon 2020 Research and Innovation programme under grant agreement No 101037643.

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Martin Visbeck holds the Chair in Physical Oceanography, GEOMAR Helmholtz-Centre for ocean research in Kiel and Kiel University, Germany. Martin Visbeck's research is concerned with ocean and climate variability and change and ocean sustainability. He is developing new conceptual frameworks to advance integrated marine research in the context of ocean sustainable development at the regional and international level. He has contributed to ocean literacy projects and capacity building in Africa. His advice is thought by science bodies and governments in Germany, the EU and at the UN level. He is active in the governing board of the International Science Council (ISC), the leadership council of the Sustainable Development Solutions Network (SDSN) and the Executive Planning Group for the UN Decade of Ocean Science for Sustainable Development (2021–2030) as well as the UN Decade Program DITTO – Digital Twins of the Ocean.

https://doi.org/10.58440/ihr-29-a04

Uncrewed surface systems facilitating a new era of global ocean exploration

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Abstract

There is growing recognition that key to addressing critical issues like climate change, global sea level rise and the long-term sustainability of humankind is a more complete understanding of our oceans and processes within them that account for the distribution of global heat, CO_2 and provide sustenance to so many. Yet, despite years of effort, less than 25% of the global ocean seafloor has been mapped and less than 5% of the ocean volume explored, likely due to the cost and inefficiency of traditional ocean mapping and exploration techniques using large, very expensive, crewed research vessels. Recent advances in the development of uncrewed surface vessels offer the possibility to reduce costs and increase efficiency of ocean mapping and exploration. Such efficiencies can be gained by using small mother ship-deployed uncrewed vessels acting as relatively inexpensive mapping and sampling force multipliers or the use of small uncrewed vessels launched to from a mother ship to monitor and control autonomous underwater vehicles, allowing multiple operations simultaneously and "verified, directed sampling", all while freeing the mother ship for independent operations. We are also seeing the development of larger uncrewed vessels launched from shore with long-endurance and range, capable of carrying a full suite of deep ocean mapping and exploration tools. All of these systems and approaches offer great hope but it is very early in our understanding of their full capabilities, costs and limitations and we must be careful not to overpromise, leading to disappointments and early abandonment of a potentially innovative approach, while at the same time maintaining the patience required to continue the research, investment and innovation that will hopefully bring us to a new world of efficient and effective ocean mapping and exploration that will allow us to meet our goal of complete coverage of the ocean.

Keywords

Uncrewed surface vessels · Ocean and seafloor mapping and exploration

Resumé

Il est de plus en plus reconnu que la clé pour aborder des questions critiques telles que le changement climatique, l'élévation du niveau de la mer et la durabilité à long terme de l'humanité réside dans une compréhension plus complète de nos océans et des processus qui s'y déroulent et qui sont responsables de la distribution de la chaleur et du CO_2 à l'échelle planétaire et qui assurent la subsistance de tant de personnes. Pourtant, malgré des années d'efforts, moins de 25 % des fonds marins ont été cartographiés et moins de 5% du volume des océans ont été explorés, probablement en raison du coût et de l'inefficacité des techniques traditionnelles de cartographie et d'exploration des océans, qui font appel à de grands navires de recherche avec équipage, très coûteux. Les progrès récents dans le développement de navires de surface sans équipage offrent la possibilité de réduire les coûts et d'accroître l'efficacité de la cartographie et de l'exploration des océans. Ces gains d'efficacité peuvent être obtenus en utilisant de petits navires sans équipage déployés à partir d'un navire-mère et agissant comme des multiplicateurs de force de cartographie et d'échantillonnage relativement peu coûteux, ou en utilisant de petits navires sans équipage lancés à partir d'un navire-mère pour surveiller et contrôler des véhicules sous-marins autonomes, permettant ainsi des opérations multiples simultanées et un « échantillonnage vérifié et orienté », tout en libérant le navire-mère pour des opérations indépendantes. Nous assistons également au développement de plus grands navires sans équipage lancés depuis la côte, dotés d'une grande autonomie et d'une grande portée, capables de transporter une gamme complète d'outils de cartographie et d'exploration des grands profonds. Tous ces systèmes et toutes ces approches sont porteurs de grands espoirs, mais nous n'en sommes qu'au début de notre compréhension de l'ensemble de leurs capacités, de leurs coûts et de leurs limites, et nous devons veiller à ne pas faire trop de promesses, ce qui entraînerait des déceptions et l'abandon prématuré d'une approche potentiellement innovante, tout en conservant la patience nécessaire pour poursuivre la recherche, l'investissement et l'innovation qui, espérons-le, nous mèneront vers un nouveau monde de cartographie et d'exploration océaniques efficaces et efficientes, qui nous permettra d'atteindre notre objectif de couverture complète des océans.

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 https://doi.org/10.58440/ihr-29-a05

Resumen

Hay un creciente reconocimiento de que la clave para abordar problemas críticos como el cambio climático, la subida del nivel del mar y la sostenibilidad a largo plazo de la humanidad es una comprensión más completa de nuestros océanos y de los procesos que se dan en ellos que explican la distribución del calor global, CO_2 y sirven de sustento para muchos. Sin embargo, pese a años de esfuerzo, se ha cartografiado menos del 25 % del fondo marino oceánico global, y se ha explorado menos del 5 % del volumen del océano, probablemente debido al coste y la ineficacia de las técnicas tradicionales de cartografía y exploración oceánicas que utilizan grandes y caros buques tripulados de investigación. Los recientes avances en el desarrollo de buques de superficie sin tripulación ofrecen la posibilidad de reducir costes y aumentar la eficiencia de la cartografía y exploración oceánicas. Esta eficacia se puede obtener usando pequeños buques nodriza sin tripulación que actúen como multiplicadores de fuerza en cartografía y toma de muestras relativamente baratos, usando embarcaciones menores sin tripulación botadas desde un buque nodriza para supervisar y controlar vehículos submarinos autónomos, permitiendo múltiples operaciones simultáneas y una "toma de muestras verificada y dirigida", mientras liberan al buque nodriza para operaciones independientes. También estamos viendo el desarrollo de grandes buques sin tripulación que pueden ser botados desde tierra con gran autonomía y alcance, capaces de transportar un conjunto completo de herramientas de cartografía y exploración de las profundidades oceánicas. Todos estos sistemas y enfoques ofrecen grandes esperanzas, pero aún es muy pronto para comprender todas sus capacidades, costes y limitaciones, y debemos tener cuidado de no prometer demasiado, lo que llevaría a decepciones y al abandono prematuro de un enfoque potencialmente innovador, manteniendo al mismo tiempo la paciencia necesaria para continuar la investigación, inversión e innovación que con suerte nos llevará a un nuevo mundo de cartografía y exploración del océano eficientes y eficaces que nos permitirán cumplir nuestro objetivo de la cobertura completa del océano.

1 Introduction

As we celebrate the 100th anniversary of The International Hydrographic Review (IHR) one might ask why we would devote a paper to the topic of the future of ocean exploration. The answer is simple. The mapping tools and techniques that have been pioneered, developed, and implemented by the hydrographic community are, without question, the primary tools of ocean exploration. Almost all great explorations were built around the creation of maps that offered an initial geospatial context for “terra incognita”, and many of the great explorers were either mapmakers themselves or had mapmakers as key members of their team. As early explorers looked outward to the seas, it was innovation in the development of navigation and positioning tools that allowed them to head far offshore and begin to map the extent of new landmasses and the resources they may possess. Even in these earliest days of exploration there was the need to probe and chart seafloor depths to assure safe passage of the vessel as it approached unexplored regions. Over the centuries that have passed since these early days of exploration we have, for the most part, completed mapping the distribution of terrestrial components of our planet and with modern satellite imaging technology, it is hard to imagine that there are new landmasses yet to be discovered. Indeed, given the general availability of high-resolution satellite imagery and tools like Google Earth, almost anyone can produce a high-resolution image (and with overlapping imagery, a digital terrain model) or map of almost any landmass on earth, all precisely positioned through a Global Navigation Satellite System (GNSS).

As our knowledge and understanding of the distribution of the landmasses and peoples of our planet grew, the oceans became highways of trade. The vessels that traveled these highways increased in size and capability, and the need for hydrographic mapping became, and still is, critical to assure the safe navigation of vessels in and out of ports (Jonas, 2023). This evolution of mapping, exploration, discovery, technical innovation, and exploitation (of resources and sadly peoples), led to the remarkable growth of the global economy over the past few hundred years and the recognition that the ocean is vital in sustaining the lives and livelihoods of those who inhabit Earth. As we have come into the 21st century, however, we have also recognized that this rapid growth has put tremendous strains on the health of the earth and that such growth cannot be sustained without a better understanding of its environmental impacts. We have also learned that the earth is a complex system of interconnected systems (land, atmosphere, and ocean) and that understanding the ocean system, which represents more than approximately 71% of the earth’s surface and is central in regulating temperature, climate, CO_2, and other critical parameters, is key to developing approaches for the long-term sustainability of Earth. It is this recognition of the key role that the ocean plays in feeding our planet as well as moderating and sustaining Earth’s climate and other environmental systems that has led to renewed emphasis on a better understanding the oceans as exemplified by the United Nations’ Decade of Ocean Science in Support of Sustainable Development[1]. In developing the goals of the Decade of Ocean Science in Support of Sustainable Develop-

[1] https://oceandecade.org (accessed 12 Mar. 2023).

ment, the complete mapping of the seafloor was recognized as a critical need yet, as we begin the U.N. Decade of Ocean Science, we do so with the sad recognition that at this point in time, less than 25% of the global ocean's seafloor has been mapped[2] and likely only about 5% of the global ocean volume has been explored[3]. How can we hope to understand the oceans we so depend on, when we do not yet know what is there?

In this paper we will explore the efforts being made to correct this situation and look at new technologies that might help us achieve the dream of a fully explored ocean. Much of our focus will be on approaches to increasing the efficiency of mapping the seafloor, particularly the deep ocean seafloor beyond the realm of hydrographic organizations – because as was stated earlier, all exploration must start with the establishment of a geospatial context. For this we will focus on the need to cover large, often totally unmapped regions rather than meeting critical hydrographic standards and thus much of the focus of this paper will be on new, more efficient ways to deploy critical ocean mapping and exploration sensors. We will also look at new approaches for looking at the ocean volume and explore, in general terms, what the future might hold for the development and deployment of new tools that will support and enhance ocean exploration.

2 Mapping the global ocean seafloor

We begin our focus on ocean exploration by examining the state of our understanding of global seafloor bathymetry – a critical boundary condition for many ocean processes including controlling the pathways of deep-sea currents and the frictional loss of heat through generation of turbulence as currents pass over seafloor of various roughness. Knowledge of both these parameters (the flow-path of deep ocean currents and seafloor roughness) is essential for the accurate modeling of global climate (Gille et al., 2004 and references therein). In the polar regions, knowledge of where relatively warm subsurface currents can access margins of glaciers through bathymetric passages is essential to the modeling of glacial melting rates and the associated rise in global sea level (Jakobsson & Mayer, 2022). Bathymetry is also essential for understanding deep sea hazards (slumping and other mass wasting events; Avdievitch & Coe, 2022) and for the prediction of storm surge and tsunami hazards (Parker, 2013). Seafloor mapping is needed for establishing the routes of deep-sea cables and pipelines and has offered key insights into the nature of earth processes including the development of the theory of plate tectonics which was greatly aided by maps of seafloor morphology. With the addition of backscatter, mapping has played a key role in delineating critical benthic habitats (Roberts et al., 2005). Yet, as stated above, at the present time less than 25% of the seafloor has been directly mapped. We say "directly mapped" because nearly complete global seafloor maps have been produced through the remarkable technique of deriving bathymetry from satellite altimetry (Smith & Sandwell, 1997). Satellite-altimetry derived bathymetric maps are based on the principle that the sea surface is, to a first approximation, an equipotential surface of the earth's gravity field that is affected by the gravitational attraction of large masses on the seafloor (e.g., seamounts) or the absence of mass (e.g., trenches) causing the sea surface to change elevation relative to the ellipsoid. These changes in elevation can be measured by accurate satellite altimeters and thus the measured height of the sea surface reflects large-scale changes in bathymetry. Through the comparison of satellite altimetry-derived measurements (for which there is continuous cover over most of the oceans) to actual soundings, Smith and Sandwell were able to predict the bathymetric values for places where there are no soundings. This was a tremendous step forward in providing a global estimate of seafloor depths, however, the lateral resolution is on the order of 10–15 kms and the vertical accuracy is limited (Smith & Sandwell, 1997), meaning that to address many of the critical applications discussed above, the satellite altimetry-derived bathymetry does not have the needed resolution nor accuracy, and instead we must use direct measurements of depth.

Over the past 40 to 50 years, we have seen the technology used to make direct measurements of depth change radically. For literally thousands of years depth measurements were made by measuring the length of a weighted line deployed from a vessel (lead line). With the rapid evolution of sonar systems during the second world war, the single beam echo sounder became the tool of choice for most hydrographic and deep-sea ocean mapping missions. Towards the end of the 20th century, multibeam sonars came out of classified military development and became commercially available. Multibeam sonars (along with concomitant developments in satellite positioning and computer processing) revolutionized deep ocean mapping. A single beam sonar (with a beam width of typically 15–30 degrees ensonifies an area on the seafloor with a diameter of approximately one half the water depth and produces only one depth (the shoalest depth) in the ensonified area with no knowledge of where that depth was within the area. The position of the shoal can only be assumed to be directly be-

[2] https://seabed2030.org/mapping-progress (accessed 12 Mar. 2023).

[3] https://oceanexplorer.noaa.gov/world-oceans-day/reason-1.html (accessed 12 Mar. 2023).

 https://doi.org/10.58440/ihr-29-a05

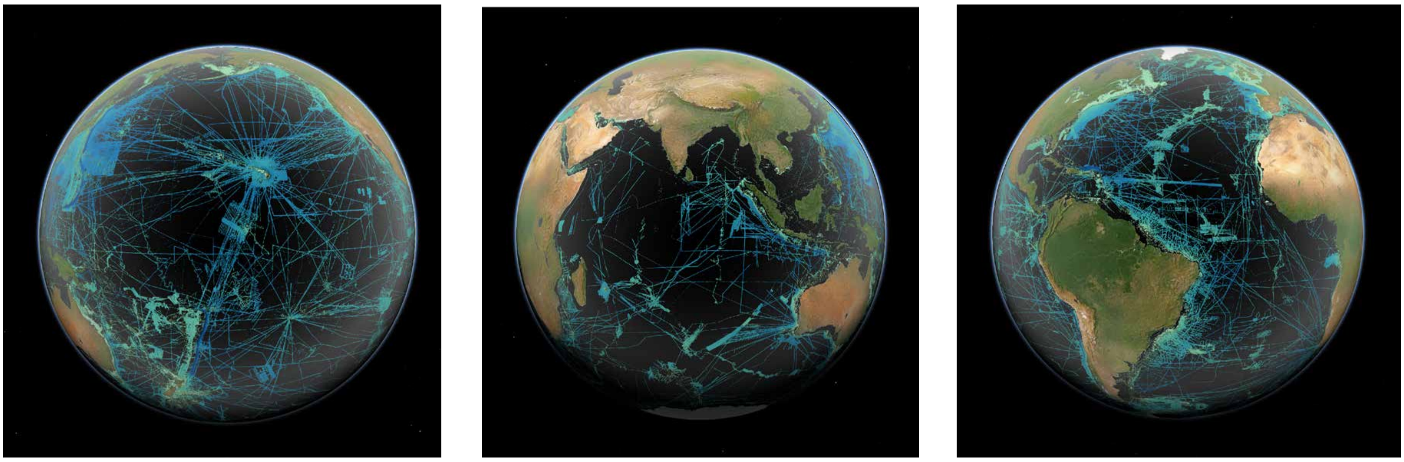

Fig. 1 Global bathymetric coverage in the GEBCO 2022 digital grid, representing most of the publicly available bathymetric data – viewer available at https://gis.ccom.unh.edu. Areas that are black indicate no available direct bathymetric data.

low the vessel. The result is a laterally averaged (over the beam footprint, i.e., half the water depth) portrayal of bathymetry. Multibeam sonars, however, produce many narrow (depending on the model but typically 0.5 to 2 degree) beams in a broad (athwartship), but thin (alongship) swath across the seafloor perpendicular to the direction of travel of the vessel. The result is many (tens to hundreds) of individual, highly accurate depth measurements across a swath that is typically three to five times the water depth wide. With multibeam sonars thus came the ability to produce many individual high-resolution depth measurements from a single ping across a wide swath of the seafloor, revolutionizing our ability to map and visualize the deep ocean floor.

Because of vessel motion and the wide swath achievable, multibeam sonars require complex integration with other ships' sensors (e.g., sound speed profiler, inertial motion sensor) but both sensor integration and post-processing software for these systems has improved greatly over the years and these systems have now been adopted by most institutions that map the seafloor. High-frequency (200–400 kHz) shallow water systems (200 m or less) are small and compact (sonar array dimensions are on the order of 50 cm to 1 m), however, to maintain spatial resolution (narrow beam footprints), array sizes must scale up with the lower frequencies needed for deep-water mapping (12–30 kHz). To achieve a 1-degree beamwidth at 12 kHz (the frequency used for full-ocean depth mapping) the sonar array must be on the order of 9 meters long. Inasmuch as multibeam sonars use separate transmit and receive arrays (orthogonally oriented to create what is known as a Mills Cross or Mills T), if one wants to both transmit and receive 1degree beams, the receive array (which is mounted in the athwartship direction) must also be 9 m long, meaning that the vessel must be able to support a 9m long array along across its keel i.e., it must be a large vessel. Thus, the state-of-the-art for deep-sea ocean exploration requires multibeam sonars mounted on large (typically 60 m or longer) survey vessels.

Recognizing the critical need for more complete maps of the ocean floor, the Nippon Foundation and GEBCO joined forces to create the Seabed 2030 Project, an ambitious effort aimed at establishing an infrastructure to facilitate the complete mapping of the global ocean floor by 2030. The project was organized around four regional data centers (located in New Zealand, Germany, the U.S., and Sweden) and a global data center located at the British Oceanographic Data Center in the U.K. The project began in earnest in 2017 with the data centers inventorying how much data was publicly available in global databases and addressing the difficult question of how much of the seafloor was mapped and at what resolution. This analysis revealed that if the seafloor were divided into approximately 1 km square grid cells, 18% of them had at least one sounding in them and 9% of them had some multibeam data (Mayer et al., 2018). Acknowledging that the beam footprint of a mapping sonar varies as function of depth, Seabed 2030 defined a series of depth-dependent grid resolutions for defining mapping coverage (see Mayer et al., 2018 for details). When these depth dependent resolutions were considered, direct mapping data were available for only 6.9% of the seafloor. Starting with this estimate of coverage in 2018, we have seen, through the concerted efforts of the Nippon Foundation-GEBCO Seabed 2030 teams and collaborating partners, the coverage increase to 24.4% at the beginning of 2023 (Fig. 1)[4] . While this represents a tremendous increase in data availability, much of this increase was the result of discovery and provi-

[4] https://seabed.geo.su.se/stat/#1/0/0 (accessed 12 Mar. 2023).

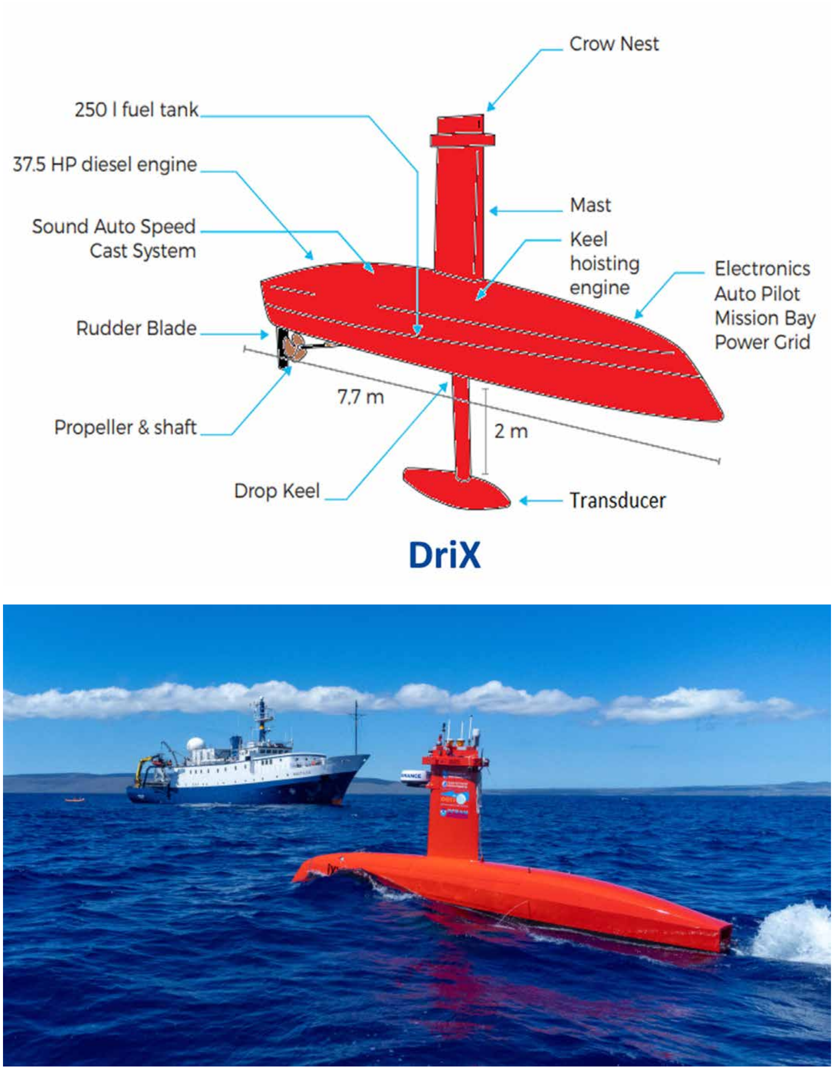

Fig. 2 The 7.7 m long DriX uncrewed vessel used by UNH as a platform to explore the applicability of uncrewed vessels to support ocean mapping and exploration missions.

sion of existing data sets and, as the amount of undiscovered data decreases, new data acquisition will be required to cover the more than 75% of the ocean floor unmapped by direct means.

It has been estimated that it will take between 70,000 and 127,000 ship days to map, with state-of-the art multibeam sonar, the yet unmapped regions of the seafloor deeper than 200 m to the Seabed 2030 defined resolutions. Given the high costs of operating the relatively large vessels needed to carry deep water multibeam sonars, the overall cost of this undertaking has been estimated to be on the order of three to five billion dollars (Mayer et al., 2018). This is a seemingly large number, but it should be noted that there have been many mapping missions to other planets that cost on the same order, raising the question of why we would not be willing to invest this amount in the mapping of our own planet. While efforts continue to seek the funding to complete the mapping and exploration of the global ocean, here we will address whether new technologies can increase the efficiency of ocean mapping (and ocean exploration in general) and thus facilitate the complete mapping and extended exploration of our oceans.

3 Expanding the efficiency of ocean exploration with "autonomous" systems

Exploration of the surface of the earth (both land and oceans) was revolutionized with the advent of satellite imagery and remote sensing. With respect to the oceans, these tools have offered tremendous insights into sea surface temperature, productivity, current and wave patterns. Unfortunately, these insights are limited to the upper few meters of the ocean surface as the electromagnetic waves used for ocean imagery and remote sensing do not propagate far in water. And thus, as outlined above, the fundamental tools for exploring the seafloor and volume of the ocean are acoustic systems, typically carried by large, slow, and expensive to operate, research vessels. If we look at costs for typical sea-going research vessels we see that a significant percentage of the operating costs (in many cases over 50%) are associated with crew-related expenses (salary, travel, food, etc.). Recognizing the significant crew-related costs involved in operating a research vessel, the concept of using uncrewed systems becomes an appealing option for increasing the efficiency of ocean mapping and exploration. Note that we are calling these operations "uncrewed" rather than autonomous. Despite the tremendous advances we have seen in the past few years in the development of uncrewed vessels, none of the current systems can be called truly autonomous; they all require some level of human interaction (pilots, operators, etc.) and thus do not remove all personnel expenses from the equation. However, even at this early stage of development, the potential is there to demonstrate increased efficiencies.

We have already seen the private sector step up and demonstrate remote operation of small autonomous systems for near-shore surveys. These are early days for these types of operations, but initial indications are that such approaches to survey work are enjoying success, demonstrating improved safety (i.e., no one offshore), 24 hour per day operation, and a reduced carbon footprint both with respect to the vessel and much-reduced travel requirements. With respect to offshore ocean mapping and exploration, the use of uncrewed systems is in its infancy and much remains to be learned about concepts of operations and the ultimate viability and cost-effectiveness of operating uncrewed vessels in support of ocean exploration (Schmidt, 2020). In addressing these questions, we will report on our own recent experiences working with funding from the U.S. National Oceanic and Atmospheric Agency (NOAA) to explore the potential use of uncrewed systems in support of mapping and ocean exploration. In relating these experiences, many will be based on the uncrewed vehicles that we are currently working with (DriX built by Exail and Saildrone) but will hopefully be generic enough to draw broader conclusions about the future role of uncrewed systems for deep ocean mapping and exploration.

4 Uncrewed systems as force multipliers for offshore mapping

One of the most obvious applications of uncrewed systems for offshore survey work is as a 'force-multiplier'. Large offshore research vessels typically have capitalization costs of over $100 million and day-rates often over $50,000 per day. The diesel-powered uncrewed systems we have been using have capitalization costs of a few million dollars and operating day-rates (still being determined) on the order $10K per day (including operator costs). Thus, the deployment of one or more uncrewed systems from a mother vessel offers the opportunity to multiply the efficiency of surveying for a fraction of the cost. NOAA-funded work with DriX (Fig. 2) has demonstrated that this is indeed possible with the uncrewed vessel launched from the mother ship and surveying in tandem with the mother ship at speeds up to 10 knots and continuous operation over several days. Full data transmission to the mother ship (typically at the end of each line) was possible when operating within the limits of the marine broadband radio system used to communicate between the mother ship and the uncrewed vessel (maximum about 20 km depending on atmospheric conditions). In this mode, data processing can be done on board the mother ship as data is being collected, and data products produced not long after the survey is completed. NOAA has estimated that such operations will increase survey efficiency by at least 40% (using a single uncrewed vessel). Carrying more vessels should further increase efficiency but this has yet to be demonstrated.

To date the uncrewed systems that we have deployed from larger ships have been relatively small (7–8 m long) and capable of carrying high-resolution, shallow water multibeam sonars (200–400 kHz) along with broadband water-column mapping sonars (EK-80s), however, we have recently installed a new compact, 70–110 kHz multibeam sonar (EM-712) providing mapping capabilities to depths beyond 2000 meters and offering the option for using even our smaller uncrewed systems as force multipliers for deeper water mapping. Depending on mission requirements, the uncrewed systems can be equipped with a range of sensors, including winch-deployed sensors (e.g., CTD) offering the opportunity to act as force multipliers for a range of oceanographic measurements. At described above, at present, operation of uncrewed vessels can be carried out from a mother ship with full situational awareness and data transmission to ranges supported by marine broadband radio (~20 km). Operations can be carried out beyond the range of the marine broadband radio (and even from shore-based facilities anywhere in the world) using satellite-based systems like Iridium's Certus, however the bandwidth provided by these systems can currently can only support the transmission of situational awareness information and limited data rather than full data transmission. The recent introduction of low-earth orbiting satellites supporting the maritime domain (e.g., Starlink) now offers the possibility of high-bandwidth communications with uncrewed systems and opens the possibility of full data transmission to and from uncrewed vehicles, world-wide. These systems have just been introduced and their full capabilities and limitations have yet to be demonstrated but many efforts are currently underway to assess these systems including the recent installation of a Starlink system on our own uncrewed vehicles. Testing of this system will begin over the next few months.

5 Shore-deployed uncrewed systems for deep-water mapping and exploration

As we seek to extend the efficiency of deep-water mapping and other open-ocean exploration measurements, the size of the uncrewed vessel becomes an issue as the sonar arrays, winches, and wires, all need to be larger or longer to work in deeper water. How large of an uncrewed vessel (or vessels) can be carried by a mother ship (and how large must the mother ship be)? At some point it becomes impossible to efficiently carry, deploy and recover uncrewed systems that are fully capable of undertaking deep water mapping and exploration activities and we must look to the concept of large, shore-deployed uncrewed vessels, capable of long-range deployments and carrying a full suite of ocean exploration tools. A commercial entity, Ocean Infinity has been pioneering this approach through the development of a fleet of very large (78 m), fuel-efficient, offshore controlled vessels that will initially be crewed but are designed to eventually operate in an uncrewed mode. Other manufacturers are also building larger platforms with extended range and the ability to carry deeper water exploration tools. As these capabilities evolve and are implemented, the community will learn if these approaches prove to be a cost-effective and energy efficient approach to addressing our need to map and explore the global ocean, but the potential is clearly great.

As these purpose-built large uncrewed vessels are being built and approaches to autonomous operations being further developed, a concept to be explored is that of a mapping and exploration barge (Fig. 3) whose form-factor could accommodate a very large mapping sonar array (e.g., ~ 30m × 15m which would result in beamwidths of ~ 0.25 deg × 0.5 deg or a lateral resolution on the seafloor of on the order of 17.5 m × 35 m at nadir in 4000 m of water). Such a platform would be relatively inexpensive to build (or acquire) and initially could be transported by a sea-going tug with a small crew at a fraction of the cost of a fully crewed research vessel. The deck

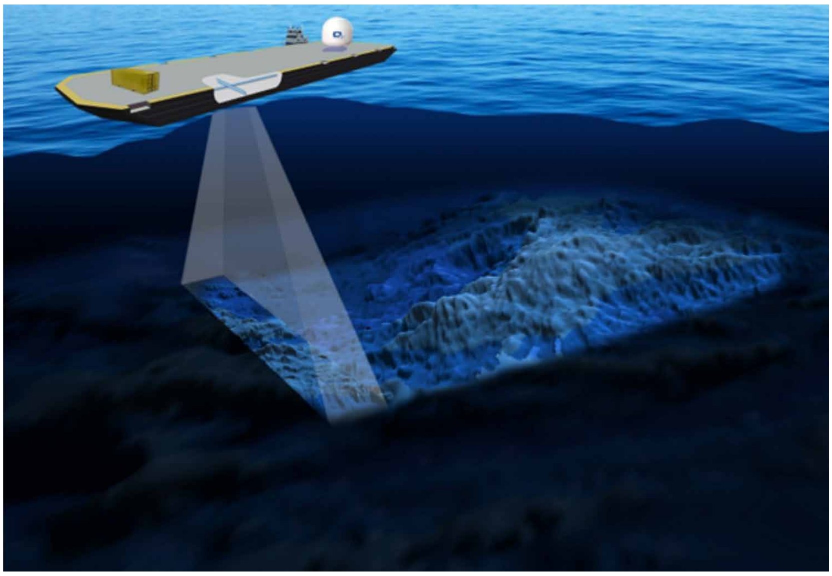

Fig. 3 The concept of an ocean exploration barge capable of carrying a very large MBES system and many other sensors. Such a barge can be deployed with an ocean going tug at a fraction of the cost of a crewed research vessel and eventually could be designed to be a fully autonomous platform. Image drawn by Ines Jakobsson.

Fig. 4 The 20 m long Saildrone Surveyor arriving in Hawaii after a 28-day transit from San Francisco. This prototype Saildrone Surveyor is equipped with a 30 kHz EM-304 and 200–400 kHz EM2040, a full suite of EK-80 broadband sonars and environmental sensors as well an ESP-3 eDNA sampling system from the Monterey Bay Aquarium Research Institute.

space available on a barge could accommodate a range of other ocean and atmospheric sensors providing a relatively inexpensive means of collecting a suite of ocean measurements (including sensors that need to be deployed by wire to probe the depths). Sonar systems and other sensors could be operated remotely (the technology for this exists now) and with improved bandwidth from low earth orbiting satellites, these remote capabilities will increase. As uncrewed ship operations evolve, we could envision a time when the entire barge could be a self-contained autonomous platform and a platform from which to launch other autonomous systems.

6 Reducing fuel costs and extending range

The uncrewed vessels discussed above are all dependent on engines for their propulsion and while we are seeing exciting and important innovations in low-carbon footprint propulsion systems (i.e., hydrogen and ammonia-based), the dependence on any source of combustible fuel places limits on endurance of the vehicle. The introduction of sail powered uncrewed systems has offered the intriguing possibility of mapping and exploration vessels with long endurance and a very low carbon footprint. Several years ago Saildrone introduced a 7 m long, wind and solar powered uncrewed vehicle (Explorer) that has now demonstrated the ability to undertake long endurance (>6 months), long-distance (>20,000 kms) missions surviving hurricanes and tropical storms[5]. These vehicles are equipped with an array of oceanographic and atmospheric sensors and have been equipped with single beam echo sounders, but they currently do not have the energy budget to support multibeam sonars. Two larger vehicles are being introduced, however, the 10 m long Voyager and the 20 m long Surveyor (Fig. 4), each of which is equipped with an auxiliary diesel/electric power system that allows them to support multibeam sonars and winch-deployed sensors. While the Voyager will be equipped with shallow water multibeam sonar systems, the 20 m Surveyor has already been deployed with a 30 kHz, EM-304 multibeam sonar, along with a shallow water EM-2040 and a full suite of EK-80 water column sonars creating a platform that is well-suited for deep-water ocean mapping and exploration. Saildrones are operated from a shore-based control center with a sophisticated mission portal offering full situational awareness but not full data transmission. With the advent of low earth orbiting satellites, full data transmission may be a possibility.

The Saildrone Surveyor underwent sea trials, funded by NOAA's Ocean Exploration Program, in June of 2021 and then undertook its maiden voyage, an uncrewed mapping transit from San Francisco to Hawaii, funded by the Nippon Foundation/GEBCO Seabed 2030 Program, in July of 2021. The Surveyor collected high-quality mapping data during this 3650km long transit, especially while under sail where the swath widened due to reduced noise (Fig. 5). In the course of the transit, many lessons were learned about transit speed capabilities and how often the engine needed to be run in order to keep the bat-

[5] https://www.pmel.noaa.gov/ocs/ocs-saildrone-mission-blog-tpos-2019-mission (accessed 12 Mar. 2023).

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teries appropriately charged. In 2022 the Saildrone Surveyor conducted work on behalf of NOAA's Office of Ocean Exploration in remote areas of the Aleutian Islands (Fig. 6) and it is currently undertaking surveys of the U.S. EEZ off the coast of California. As these surveys are completed, we continue to learn more about the capabilities and limitations of this innovative system particularly respect to endurance, speed, trade-offs between motoring and sailing, data quality, and overall cost-effectiveness of this approach to addressing our long-term mapping and exploration needs. Saildrone is also using lessons learned to upgrade the design and produce a new generation of Surveyors with faster hull speed and extended capabilities.

Along with its acoustic systems, Saildrone Surveyor also carried a suite of environmental sensors including an exciting Environmental DNA (eDNA) sampling system from the Monterey Bay Aquarium Institute (MBARI). eDNA is a relatively new approach of analyzing the nuclear or mitochondrial DNA that is released by organisms into water (Pillioid et al., 2013). Analysis of eDNA allows the detection and identification of species that were present in the water mass and is a powerful new tool for understanding biodiversity. MBARI has created an eDNA sampling system (ESP-3) that can be deployed on autonomous systems, filter water on command and preserves the samples for later analysis (Truelove et al., 2022). On each of the completed Saildrone Surveyor missions, a complete suite of eDNA samples were taken with the ESP-3, demonstrating the viability of making these important environmental measurements from platforms much less expensive to operate than large, crewed research vessels as well as the potential of collecting these important measurements in remote and unexplored regions.

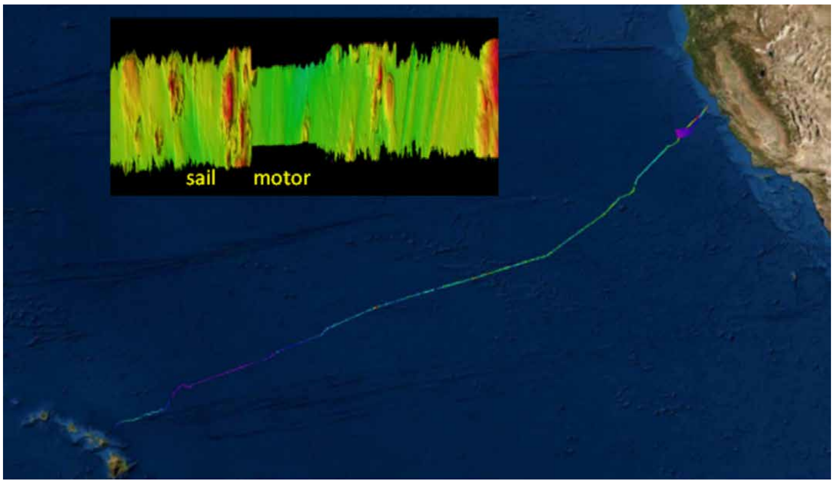

Fig. 5 The maiden voyage of the Saildrone Surveyor as it transited from San Francisco to Honolulu covering 3650 km over 28 days. Insert shows increase in achievable swath width coverage going from using diesel motor to pure sailing mode.

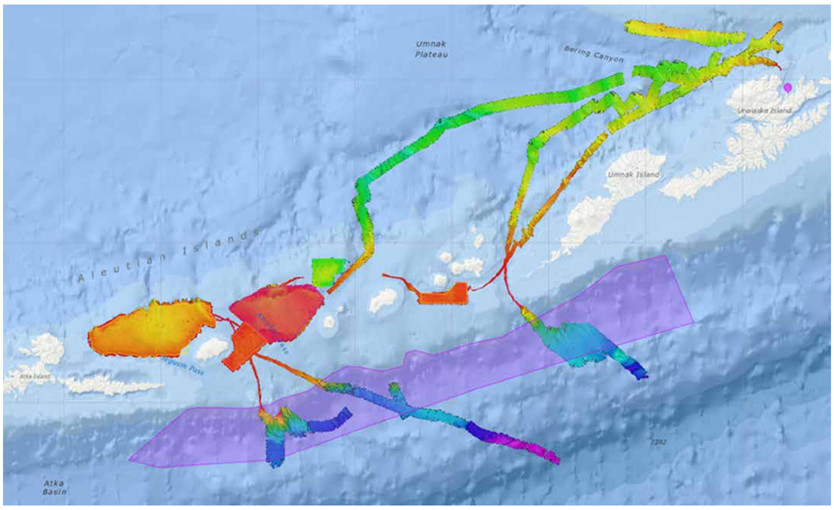

Fig. 6 Saildrone Surveyor surveys of remote regions of the Aleutians conducted during two missions over 51 days. For this mission Saildrone departed from San Francisco, had a port call in Dutch Harbor and returned to San Francisco.

7 Every measurement counts

While our aspiration is to see the ocean completely mapped and explored with the greatest resolution possible, the unmapped and unexplored regions of the oceans are so vast that we must recognize that any additional measurement adds to our knowledge base. ARGO floats are freely drifting floats that are deployed through an international program and designed to collect temperature, salinity, and pressure measurements over the upper 2000 m of the ocean. The floats use a buoyancy engine to profile down to depth, drift (typically at 1000 m) for about 10 days, profile down to 2000 m, and then return to the surface to transmit their data via satellite. They repeat this cycle until their batteries are depleted (typically about 3–5 years). A new suite of floats can also collect biogeochemical measurements and some floats are being designed for deeper depths (to 6000 m). There are currently about 4000 floats drifting around the oceans providing measurements of ocean temperature and salinity distribution that have revolutionized our understanding of ocean warming and other ocean processes. With 4000 floats drifting around the ocean basins, it has been estimated that approximately 8% of these floats will ground in regions where bathymetry is poorly constrained and van Wijk et al. (2022) have cleverly proposed that in these situations, information on grounding depth can supplement our bathymetric data base and provide additional bathymetric information in remote regions.

Taking the concept of using a profiling float for bathymetric data acquisition one step further, Seatrec Inc. is developing, though funding from Schmidt Marine Technology Partners, the infiniTE™ (infinite Thermal Energy) float, a profiling float powered by an energy harvesting system that derives power from the thermal differences in the upper ocean (Fig. 7; Jones et al., 2011). The energy harvesting system provides enough power for the profiling float to make as many as three profiles per day and to use an active echo-sounder to collect bathymetric information along with the standard oceanographic data collect-

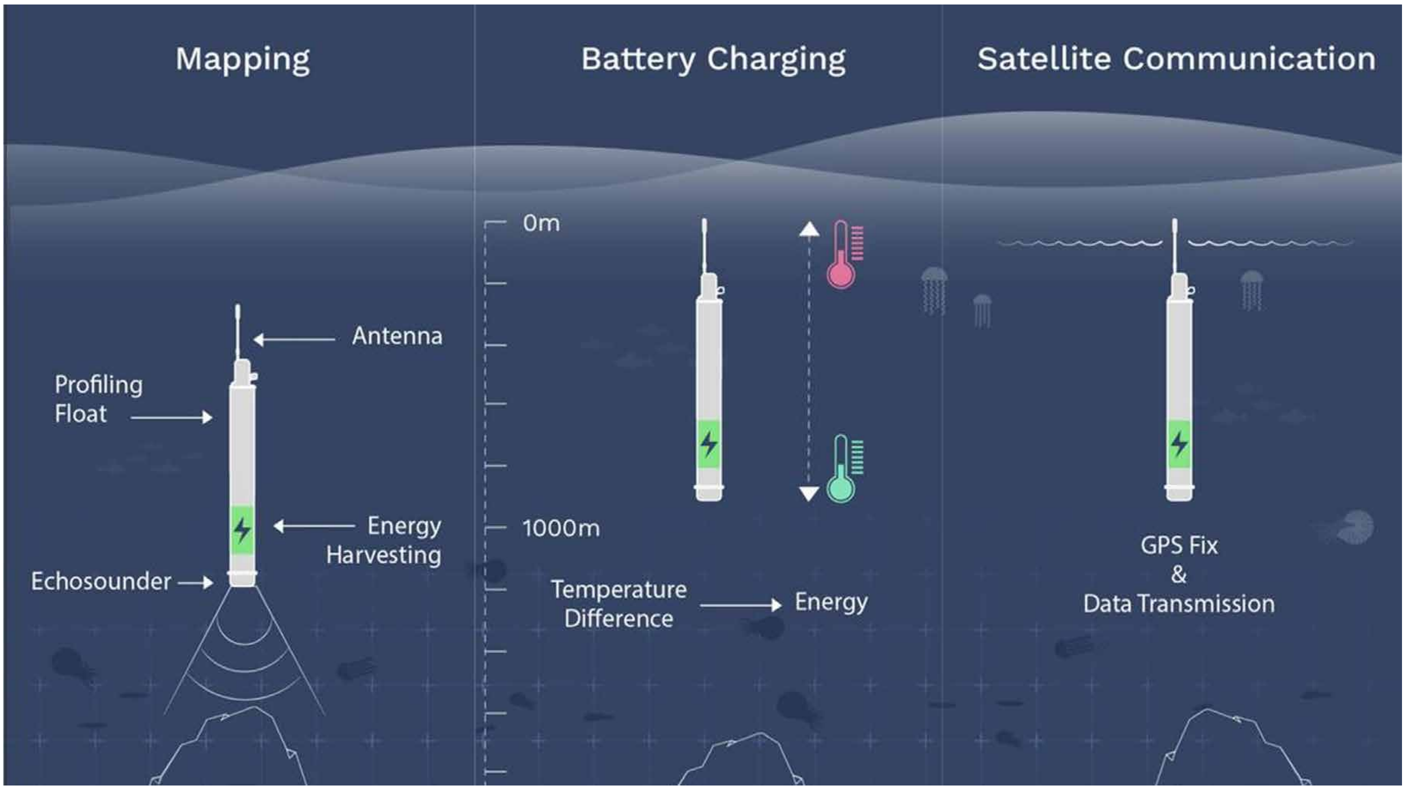

Fig. 7 Seatrec infiniTE profiling float uses a solid to liquid phase change caused by the thermal difference in upper water column to provide enough energy to drive a deep-water echo-sounder along with other profiler instrumentation. The profiler will dive to depth and make a sounding then drift and make another sounding before returning to surface getting another GPS fix and transmitting data via satellite. Image courtesy of of Yi Chao, Seatrec Inc.

ed with a CTD. Like Argo floats, the infiniTE floats are navigated by GPS and transmit their data via satellite link when they surface (Coley, 2023). The first two prototypes of these new echo-sounding floats will be deployed for the first time in the spring of 2023. Should these floats prove successful, they offer a relatively inexpensive approach for long-term bathymetric data collection in remote regions of the oceans where ships rarely venture and where existing data coverage is very sparse.

Beyond their ability to provide single beam sounding measurements in remote regions, it may be possible to use a group of profiling and echo-sounding floats to form a large baseline sparse array that can make very high-resolution bathymetric measurements over a wide area (Ryu et al., submitted). Envision an array of echo-sounding infiniTE floats deployed over an area of say 20–40 km. If the floats are commanded to profile at the same time, they can capture the three-dimensional sound speed field of the ocean volume. When the floats return to the surface, several of the floats could be used as acoustic sources and the rest used as a disaggregated sparse array of receivers, all precisely positioned with GNSS. The combination of the precise location of sources and receivers along with knowledge of the three-dimensional sound speed field offer the opportunity to solve the more difficult aspects of providing a coherent 3-D solution for the ray paths leading to the possibility of very high-resolution bathymetric solutions over a wide area. Certainly speculative, but research efforts are currently underway at MIT Lincoln Labs to explore the use of sparse arrays for bathymetric measurements.

8 Expanding the ocean exploration footprint

While we have emphasized the role of uncrewed systems as a force multiplier that has the potential to greatly increase the efficiency with which we can map and explore the oceans by providing more cost-effective and fuel-efficient means to cover large areas of the oceans, there is another important role that uncrewed vehicles can play in enhancing our ocean exploration capabilities. Ocean exploration missions often begin with regional mapping to set the geospatial context before more detailed exploration and prosecution of targets takes place. Regional mapping is indeed a role where we have argued that uncrewed systems can provide increased efficiency by covering large areas at reduced cost with respect to ship time, personnel, and fuel. But once targets are selected for detailed mapping and exploration (e.g., a hydrothermal vent field), a large mother ship typically deploys high-resolution mapping and imagery systems (e.g., ROVs and AUVs) to provide detailed analyses and sampling. Typically such operations involve the deployment of a single system at a time and require the dedicated support of the large mother vessel. We have recently, however, demonstrated how, through the use of relatively small uncrewed systems, multi-

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ple underwater uncrewed vehicle operations can be supported and the mother ship freed to pursue independent activities.

On a recent expedition of the E/V NAUTILUS (NA-139; May 2022), sponsored by NOAA's Office of Ocean Exploration, teams from the University of New Hampshire, the Woods Hole Oceanographic Institution and the Ocean Exploration Trust, worked together to demonstrate collaborative behaviors among multiple vehicles and the mother ship (NAUTILUS) to demonstrate the potential for simultaneous, multiple vehicle deployments, and thus increased efficiency in the use of these expensive assets. On board NAUTILUS was the 7 m long DriX uncrewed system described earlier, the Mesobot, a slow moving autonomous underwater vehicle designed to track particles in the mesopelagic (midwater) and collect eDNA samples (Yoerger et al., 2018), and NUI, a hybrid ROV/AUV designed to travel 10s of kms laterally underwater connected to the mother ship by a thin fiber but then act as an AUV when the fiber is cut (Barker et al., 2020; Fig. 8). NUI carries a full suite of cameras and acoustic systems as well as a manipulator arm for sampling.

The initial step in developing collaborative behaviors was to establish a common acoustics communication system among the vehicles. This was achieved through the use of a Sonardyne HPT 3000 tracking and communications transceiver mounted on the DriX and acoustic transponders mounted on the AUVs. The team also developed a series of standard Robot Operating System (ROS) messages to allow the transfer of data and commands among the vehicles. Once deployed, the DriX was able to track, communicate and follow the AUVs using the HPT 3000. Inasmuch as the AUVs move very slowly (1–2 knots) and DriX tends to travel much faster, a special behavior was created to allow DriX to circle above the vehicles and thus always stay centered above the vehicles (Fig. 9).

Full situational awareness of the position and status of all vehicles was provided by CAMP – CCOM Autonomous Mission Planner (Arsenault & Schmidt, 2020), an application that serves as a backseat driver for autonomous vehicles and allows for monitoring the progress of multiple vehicles and the mother ship as well as the ability to quickly and easy make and revise mission plans, all on top of raster images (e.g. charts or bathymetry; Fig. 10). Most importantly, the sonars on the DriX were able to provide real-time (while within range of the marine broadband radio – ~20 km) information on potential targets for investigation by the AUVs. For example, while Mesobot was deployed, the EK80 on the DriX which was following, tracking, and communicating with Mesobot, located a strong midwater scattering layer that was seen in real-time through data transmitted from DriX to the mother ship (Fig. 11). Commands were sent to Mesobot to move to the layer and when

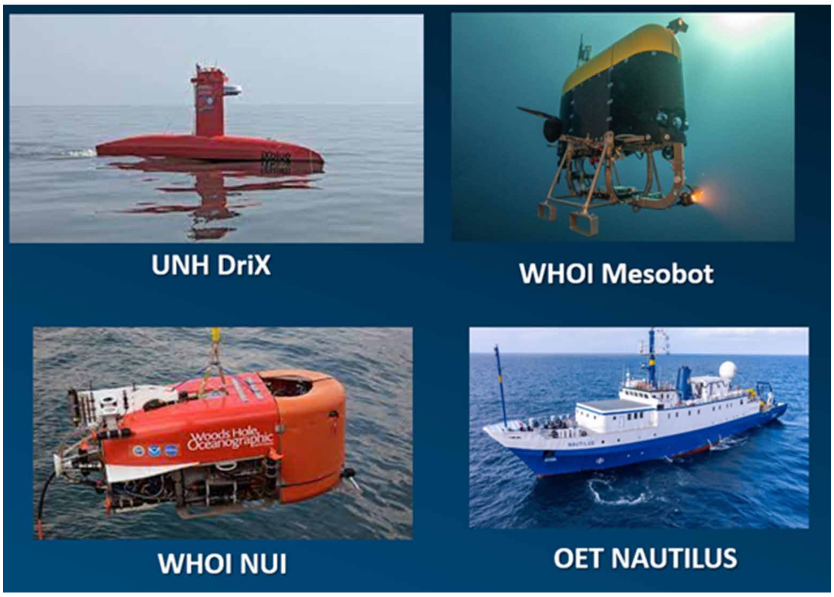

Fig. 8 The vehicles associated with the multi-vehicle collaboration mission and E/V NAUTILUS.

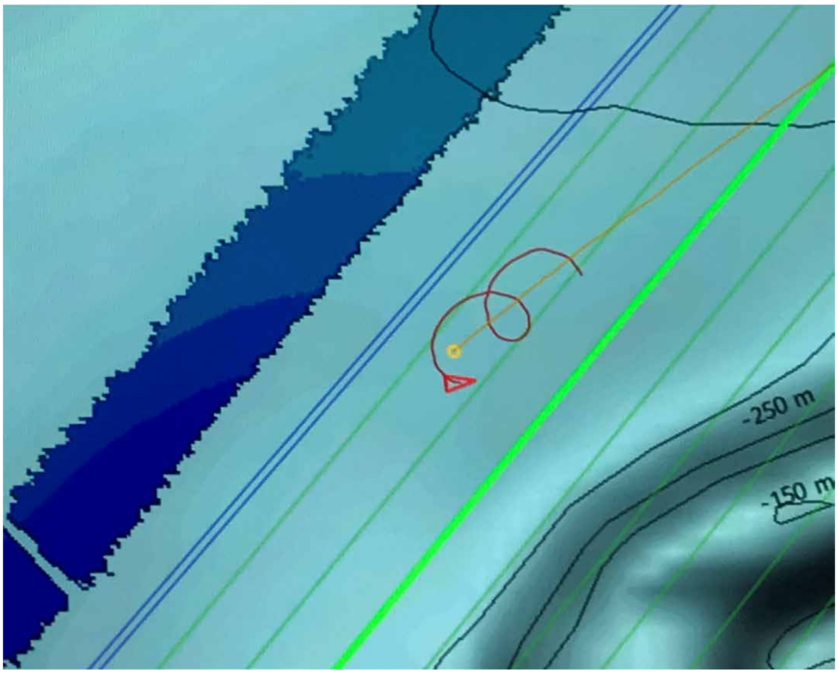

Fig. 9 Behavior developed to allow fast-moving uncrewed vessel DriX (represented by red arrow) to follow and stay on top of slow-moving mid-water AUV Mesobot (yellow dot).

Mesobot was in the layer (visually confirmed by the ability to see Mesobot in the EK-80 display), Mesobot was sent commands to begin sampling for eDNA (Fig. 12). This ability to see, in real-time, the location of the AUV and its sampling systems with respect to the target layer opens a new world of "verified directed sampling". This ability will remove many ambiguities and uncertainties associated with the sampling or measurement of oceanographic phenomena as well as help address questions of sample bias and avoidance. Through the combination of surface and subsurface autonomous vehicles we will be able to see exactly where samples or measurements are being taken and how the targets being sampled behave

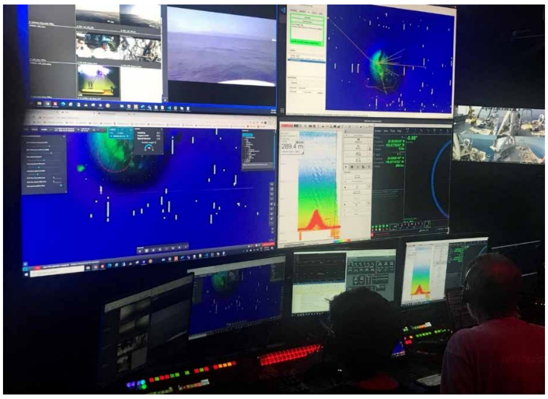

Fig. 10 The UNH CAMP applications providing full situational awareness of the location of multiple vehicles in the context of underlying raster mapping data.

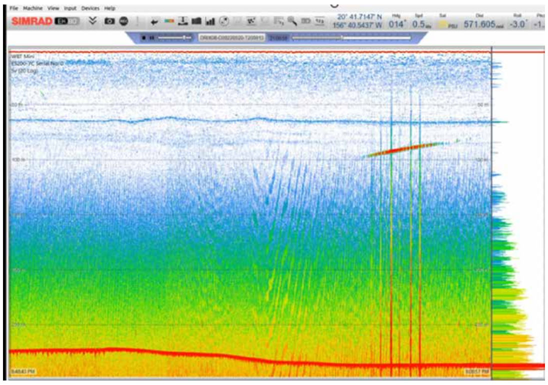

Fig. 11 Display of 200 kHz EK80 data from EK-80 on DriX, transmitted in real-time via marine broadband radio to mother ship (NAUTILUS). The blue horizontal line at about 70 m depth is the scattering layer that scientists wanted to sample. The red diagonal line is the reflection of Mesobot traveling underneath DriX as it is being directed by commands from the mother ship to move to the scattering layer.

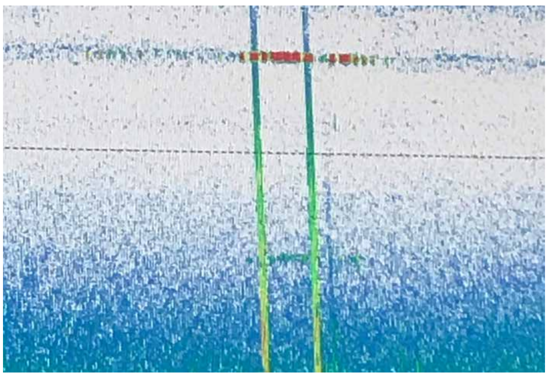

Fig. 12 The Mesobot (red horizontal target) confirmed to be directly in the scattering layer. At this point sampling is triggered assuring that eDNA samples were taken directly in the targeted layer.

during sampling.

With respect to gained efficiencies, we were able to operate with Mesobot, NUI and DriX simultaneously, with DriX on the surface, Mesobot exploring the midwater, and NUI mapping and exploring the seafloor. Throughout this exercise, the DriX served as the communications link between the vehicles and the mother ship, tracking their location and transmitting data and commands to and from the ship. When NUI went into full AUV mode (i.e., off the fiber tether), the NAUTILUS was free to leave the direct vicinity of the AUVs and carry on its own activities. During this mission we were limited by the range of the marine broadband radio and thus the NAUTILUS could not go beyond about 20 km from the AUVs' operating area but with the implementation of low earth orbiting satellite communications from the uncrewed surface vehicle, there should be no limit to the range at which the uncrewed surface vessel could operate from the mother ship while following the AUVs, and thus the AUVs could easily be monitored and controlled from a shore-based facility anywhere in the world.

Carrying this one step further, as demonstrated in the Shell Ocean Discovery XPrize competition, we are already seeing the introduction of large-format shore-based uncrewed surface vessels that can carry and deploy their own ROV (Zwolak et al., 2020). With such systems we can envision the uncrewed surface vessel using its suite of sensors for broad exploration and initial mapping and when targets of interest are found (perhaps by automated processing and detection algorithms on board the vessel), the ROV can then be deployed for detailed study and mapping of the targets without human intervention. With the advent of high-bandwidth communications through low-earth orbiting satellites in combination with growing capacity for telepresence (Raineault et al., 2018) shore-based scientists can remain in the decision and control loop offering tremendous opportunities for truly expanding the footprint of ocean exploration while bringing the wonders of deep-sea exploration to school children and the public at large, world-wide.

9 Conclusions

The global community is recognizing that the long-term sustainability of humankind is inextricably linked to our understanding of the oceans and the processes within them that control the distribution of heat, CO_2, nutrients, and other critical parameters. Yet our oceans are vast and despite more than 100 years of effort, our traditional approaches to studying the oceans using large, crewed research vessels, have resulted in less than 25% of the seafloor mapped and on the order of only 5% of the ocean volume explored. If we are to address the pressing problems associated with climate change, sea level rise, and many other ocean-related issues in a timely fashion, we will need to accelerate our efforts to map and explore the deep global ocean as we cannot understand what

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we do not know. Uncrewed surface vessels are being developed that may offer the chance to greatly reduce the cost and increase the efficiency of global mapping and exploration. Multiple approaches are being taken. The deployment of relatively small uncrewed vessels that can be carried from larger mother ships has already been demonstrated as a force multiplier offshore, but there are limits to the size of the uncrewed vessels that can be carried aboard a mother ship and this limits the size of the sensor systems that can be carried (and thus the water depths that can be mapped and explored.) Additionally, the range over which full data sets can be transmitted from the uncrewed vessel to (and from) the mother ship has been limited by the capabilities of marine broadband radios (typically on the order of 20 km depending on atmospheric conditions), but with advent of high bandwidth transmission through low-earth orbiting satellites, we may be able to operate uncrewed vessels (and transmit full data sets) much further from the mother ship or from shore-based stations anywhere in the world. Uncrewed vessels can also play an important role as command-and-control stations, monitoring and controlling the location and behavior of underwater autonomous systems and relaying data and commands from the mother ship or shore stations to underwater vehicles, while freeing up the mother ship to pursue independent tasks. The ability for operators to see, in real-time through the uncrewed surface vessel link, the location of underwater vehicles with respect to seafloor or midwater targets combined with the ability to direct the underwater vehicle to those targets, opens a new world of verified directed sampling where there is no ambiguity about what has been sampled or imaged.

Larger uncrewed vessels are being developed that can be launched from shore, with ranges of many 1000s of kms, that can carry deep-water sonars and exploration tools, and can spend extended time offshore. These systems are exploring the use of energy efficient fuel systems and some can deploy their own remotely operated vehicles. Large uncrewed sail-powered vessels are also being developed that offer a very low carbon footprint, the ability to carry large mapping systems and other sensors and the potential for long deployments to remote regions.

It is clear that much is going on with respect to the use of uncrewed surface vessels for ocean exploration and mapping, however, the critical words in the paragraphs and pages above are "being developed", "may be able to", "have the potential to", and "exploring the use of". We are at the very early stages of understanding just what role uncrewed and eventually truly autonomous systems will play in our quest to map and explore the oceans. We need to fully understand the capabilities, limitations, and trade-offs associated with these systems with respect to gained efficiencies and overall costs. The great challenges we face with respect to mapping and exploring the oceans impel us to seek new technologies and there is great potential that uncrewed systems will revolutionize our efforts, but the change will not be instantaneous and will not come without continued research, investment, innovation, and the steep learning curves associated with technological revolutions. We must find the balance between too quickly jumping into approaches that are really not mature enough to appropriately serve our needs and thus lead to disappointment and abandonment of what might eventually be a very effective tool, and the frustration associated with long-term research and development projects. The broad recognition of the great potential of uncrewed vessels across the private sector, government agencies, academia and NGOs, and the collaborations being established among these organizations is helping us find this balance and will hopefully expeditiously bring us to our collective objective of much more efficient mapping and exploration of the world's oceans.

Acknowledgements

While any misstatements made are solely my responsibility, many of the experiences and ideas discussed are the result of numerous interactions and phenomenal collaboration with wonderful colleagues. First and foremost, I must thank the UNH ASV team, led by Val Smith, along with Roland Arenault, K.G. Fairborn, Andy McLeod, and Avery Munoz, who have worked so hard pioneering the use of uncrewed systems in support of hydrographic and ocean exploration missions. Along with the UNH team Basile Rose from Exail has been remarkable for his tireless efforts and near limitless knowledge of every aspect of DriX. Also at UNH, Paul Johnson and Kevin Jerram have provided invaluable support in their analyses of MBES systems and the creation of tools and map services to serve data. Colleen Peters and recently Neah Baechler from Saildrone have been great partners as we explored the capabilities of the Saildrone Surveyor. Dana Yoerger and Eric Hayden from WHOI led the Mesobot team and have been brilliant and enthusiastic collaborators as we developed joint vehicle strategies, as were Mike Jakuba and Molly Curran who led the WHOI NUI team. Allison Fundis, Jason Fahy and the captain and crew of NAUTILUS, all from the Ocean Exploration Trust, provided coordination, leadership, and a comfortable and well-functioning mother ship that served so well as the base for many of our missions and finally, we must thank those that have funded our uncrewed systems efforts, NOAA's Office of Coast Survey, Office of Marine and Aviation Operations and NOAA's Office of Ocean Exploration who has been a steadfast partner in our efforts though the Ocean Exploration Cooperative Institute. Specifically, the UNH uncrewed system efforts described herein have been supported through NOAA Grants; NA20NOS4000196 (JHC), NA19OAR4320072 (OECI), NA19OAR0110409 (NOPP). Work on the InfiniTE float with echo-sounder is being funded by the Schmidt Marine Technology Partners.

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Author's biography


Larry Mayer

Larry Mayer is a Professor and Director of The Center for Coastal and Ocean Mapping at the University of New Hampshire. He received a Ph.D. from the Scripps Institution of Oceanography in Marine Geophysics in 1979 and after being selected as an astronaut candidate finalist for NASA's first class of mission specialists, Larry went on to a Post-Doc at the School of Oceanography at the University of Rhode Island where he worked on the early development of the Chirp Sonar and problems of deep-sea sediment transport and paleoceanography. In 2000 Larry became the founding director of the Center for Coastal and Ocean Mapping at the University of New Hampshire. Larry has participated in more than 95 cruises (over 78 months at sea!) including 14 mapping expeditions in the ice-covered regions of the high Arctic, 10 of them on the USCG Icebreaker HEALY. He is the recipient of the Keen Medal for Marine Geology and an Honorary Doctorate from the University of Stockholm. He was a member of the President's Panel on Ocean Exploration and chaired National Academy of Science studies on national needs for coastal mapping and charting and the impact of the Deepwater Horizon Spill on ecosystem services in the Gulf of Mexico. He is currently the Chair of the National Academies of Science's U.S. Committee for the Decade of Ocean Science, a member of the State Dept.'s Extended Continental Shelf Task Force, the Navy's SCICEX Advisory Committee, and Vice Chair of the Board of Bob Ballard's Ocean Exploration Trust. In 2016 Larry was appointed by President Obama to the Arctic Research Commission, in 2017 he was elected to the Hydrographic Society of America Hall of Fame. In 2018 he was elected to the National Academy of Engineering and in 2019 he was elected as a foreign member of the Royal Swedish Academy of Sciences. In 2020 Larry became the first recipient of the Walter Munk Medal from The Oceanography Society and was elected a Fellow of the American Geophysical Union. In 2021 he was elected to the Norwegian Scientific Academy for Polar Research and in 2022 he received the Sam Masry Prize from the Canadian Hydrographic Association for outstanding contributions to the hydrographic profession and its related disciplines. Larry's current research deals with sonar imaging and remote characterization of the seafloor as well as advanced applications of 3-D visualization to ocean mapping problems and applications of mapping to Law of the Sea issues, particularly in the Arctic.

The future is CLEAR: Community-Led Engagement for Adaptability & Resilience

Author
Helen Stewart[1]

Abstract

Climate change poses an existential threat to communities living on the water's edge. It is possible to design climate adaptation and climate resilience policies that safeguard communities and support sustainable living, but implementing such policies is difficult without understanding the needs and cultural practices of the people living there. *Community-Led Engagement for Adaptation and Resilience* is a way to bring community members into policy and planning stages of adaptation and resilience efforts. This Keynote discusses different types of community-led engagement that the International Hydrographic Organization (IHO) practices to support its member states, how it can improve its own policies, and how the IHO and member states can collaborate to support their needs and those of people who are at greatest risk of climate change-related hazards.

Keywords
Climate change · Community engagement · Safety of navigation · People and places

Resumé

Le changement climatique constitue une menace existentielle pour les communautés qui vivent au bord de l'eau. S'il est possible de concevoir des politiques d'adaptation et de résilience au climat qui protègent les communautés et soutiennent un mode de vie durable, il est difficile de mettre en œuvre de telles politiques sans comprendre les besoins et les pratiques culturelles des personnes qui y vivent. L'engagement communautaire pour l'adaptation et la résilience est un moyen de faire participer les membres des communautés aux étapes de planification et d'élaboration des politiques d'adaptation et de résilience. Cet article traite des différents types d'engagement communautaire que l'Organisation hydrographique internationale (OHI) pratique pour soutenir ses Etats membres, de la manière dont elle peut améliorer ses propres politiques, et de la manière dont l'OHI et les Etats membres peuvent collaborer pour répondre à leurs besoins et à ceux des personnes les plus exposées aux risques liés au changement climatique.

Resumen

El cambio climático supone una amenaza existencial para las comunidades que viven a orillas del agua. Es posible diseñar políticas de adaptación y resiliencia climática que protejan a las comunidades y apoyen un modo de vida sostenible, pero es difícil implementar esas políticas si no se comprenden las necesidades y prácticas culturales de las personas que viven allí. La Participación dirigida por la Comunidad para Mayor Adaptabilidad y Resiliencia es una forma de incluir a los miembros de la comunidad en las fases de política y planificación de las actividades de adaptación y resiliencia. Esta Presentación examina diferentes tipos de participación dirigida por la comunidad que practica la Organización Hidrográfica Internacional (OHI) para apoyar a sus Estados miembros, cómo puede mejorar sus propias políticas, y cómo la OHI y los Estados miembros pueden colaborar para apoyar sus necesidades y las de las personas que sufren el mayor riesgo de los peligros relacionados con el cambio climático.

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 https://doi.org/10.58440/ihr-29-a06

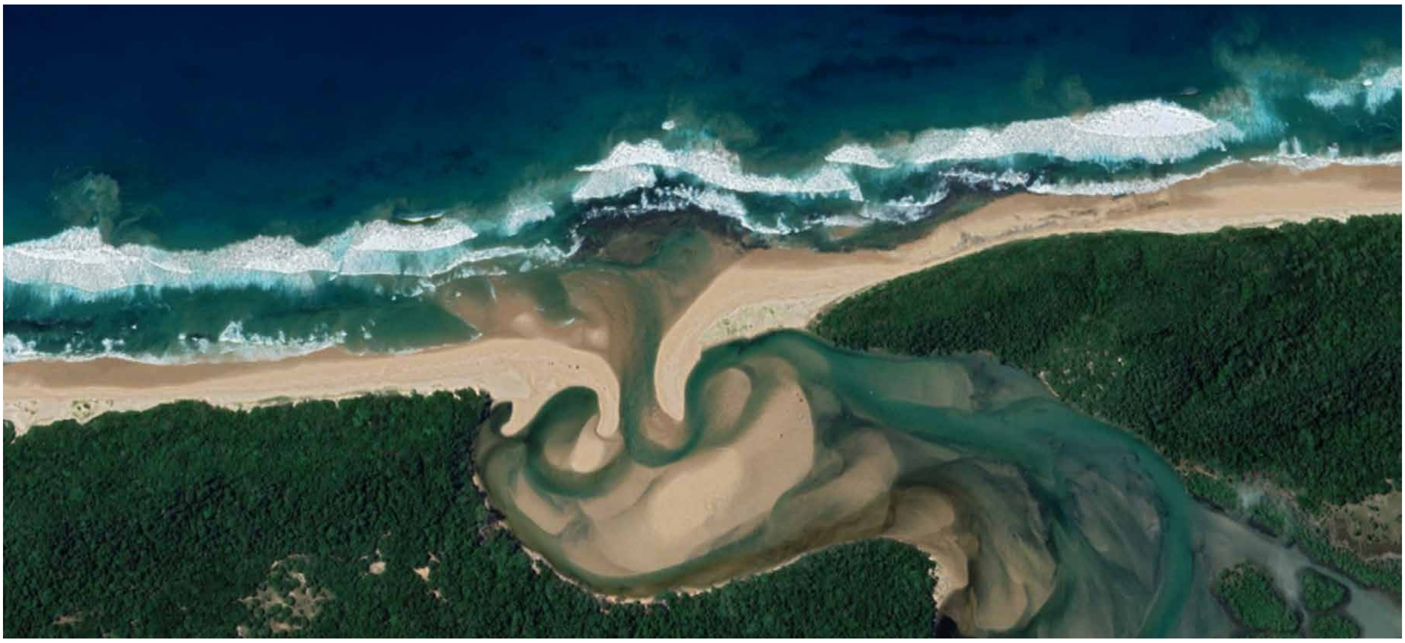

Fig. 1 Kosi Bay Estuary, eNkovukeni, South Africa. Maxar Satellite photo.

1 Lifting the clouds for a CLEAR future

Many years ago, as a young graduate student at the University of Cape Town, I was fortunate enough to help another graduate student with her research on shellfish population dynamics in the Kosi Bay region of South Africa, located in the northeastern part of KwaZulu Natal province (Reaugh, 2006; Fig. 1). Rocky nearshore reefs in the area were home to a local subsistence and artisanal fishery that was under threat due to over-harvesting and the need to provide quality protein food to a growing population of residents.

Over a period of several years, researchers from the university and members of the KwaZulu Natal provincial government worked with community residents to gain a baseline level of knowledge into the shellfish populations. The comprehensive field research included several aspects of hydrospatial data collection, from bathymetric surveys to sediment sampling, shellfish larvae harvesting and water column chemistry samples. Community members partnered with the provincial government agency to form a locally managed sustainable fisheries co-management council, among the first of its kind in post-apartheid South Africa. The hydrospatial domain inclusive of hydrographic and marine biological research established the scientific basis for what a "sustainable fishery" in the blue economy meant, and the elected representatives of the community together with representatives of the provincial government agency shared the management duties.

While the above retelling is succinct, factually accurate, and feels good to read – everyone likes a success story! – telling the story of the Songimvelo ("Let Us Conserve" in the isiZulu language) Mussel Committee in this way does a profound injustice to all the people who were involved in its creation. The foundation research took place in a region whose residents historically had extremely good reasons to be suspicious of and hostile towards government interventions, in a time of great political and governmental change in South Africa, and with a pressing need to address the immediate future of the fishery itself to prevent its collapse. The university researchers and government officials spent close to a year on outreach and engagement efforts before finding a coastal community whose residents were willing and able to engage with the lead researcher and other members of her team. This represented a major leap of faith on the community's part as only a few years before, the provincial government agency could arrest and jail people for harvesting shellfish in the bay. This also represented a major investment of a valuable resource – time. In a community whose people were living at a subsistence level, time spent having tea and talking with the scientific party was time that could be doing other activities that would put food on their tables.

It took many more months of work with those community residents to explore and understand the historical and cultural fishery practices, especially in engaging with the local women who traditionally harvested the shellfish. The researchers discussed their scientific work with the women of the community, who added their own insights from their years of observing the marine and hydrospatial environment they called home. This again required significant trust on the part of community members: that the information they provided to the researchers and provincial government agency would be used for their benefit. The Songimvelo Mussel Committee could not have happened without this years-long effort from everyone – university professors, graduate students, civil servants, and most importantly the community mem-

Fig. 2 Women recording shellfish catch weights in Sokhulu Co-Management Area (Harris, 2002), a predecessor to the Songimvelo co-management project, Eastern Cape Province, South Africa. Images courtesy World Resources Institute.

bers themselves – to guide the research, so that it met community needs and not an abstract concept of sustainability in the blue economy.

As a graduate student, I was thrilled to be invited to work in the Kosi Bay projects with my colleagues. Like many students, I was wholly task-driven, on site to use the instruments and make sampling equipment on-site and collect samples. I was also young and did not have much life experience, and in my youth and inexperience I focused my attention in general on scientific work. I assumed that human work was someone else's job. That assumption clouded my perspective of what I was doing and why I was there, and it clouded my perspective of my own master's research, in another bay and another ocean on the other side of the country. With time and life experience, I learned that understanding the human dimensions to a scientific question is a fundamental part of designing a successful project. If I want clear eyes to see the problem and a clear mind to understand the complexities of the questions I want to answer, the first step to finding that clarity is to engage and openly communicate with people whose lives and livelihoods depend upon getting that answer right. We do not go to project sites to collect sediment samples and record water column profiles that will go into a storage container or database somewhere and be forgotten, we go to project sites in order to provide expert hydrospatial data and analysis to people who need our support and our services to live safely and with dignity at the boundary of land and sea.

We now know that at least some of the effects of climate change cannot be reversed in our lifetimes. The overall impact is still yet unknown; models give us estimates that are only as good as the initial assumptions. Sea level rise is guaranteed – but how much? Coastal erosion is guaranteed as we face increased flooding and stronger storms – but how much? Groundwater and landmasses uplift or subsidence, nuisance flooding, and tidal range amplification will affect people living in coastal margins and especially around bays – but how much? And while we have the possibility of adaptation and mitigating some of the effects of climate change through offshore carbon capture and storage and offshore renewable energy, how will that affect the 40% of the world's population living within a 100-kilometer distance of the all the blue of our blue planet and its contiguous zones, the world's coastlines and hydrospatial domain?

While we do not know what we do not know with certainty how climate change will affect a particular community, we do know that there are things society can do to blunt the effects to those communities to some extent. We call these mitigation tools climate adaptation and climate resilience. Climate adaptation is defined as *"the process of adjusting to new (climate) conditions in order to reduce risks to valued assets"*, while the definition for resilience is *"the capacity of a community, business, or natural environment to prevent, withstand, respond to, and recover from a disruption"*. Assigning meanings to words gives us a guide to follow in general, but for any individual community living on the coastal margin, which includes freshwater as well as saltwater coasts, what does it mean to be resilient? What specific problems do we need to address to help a community adapt? We also talk about the Blue Economy, which the United Nations defines as "sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of the ocean ecosystem". Again, what does that mean? If we consider that definition from a global perspective, we will find ourselves asking a very different set of questions about "what is sustainable" and "how are livelihoods improved" than we would if we were considering small subsistence-level communities. Although there are no one-size-fits-all answers to these questions, they are all questions that surveyors, hydrographers, and other hydrospatial scientists can help answer …*if* we are willing to do the work with the people and communities that are affected.

This statement leads to another question: what does it mean to "do the work"? Community-led engagement is pivotal to building trusted relationships with stakeholders in order to inform, consult, and empower them as part of working towards a long-term goal. Beyond these broad brush strokes, what it means to "do the work" will vary according to the type of community involved and the end goal. The communities might be communities-of-place, who

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Fig. 3 Mozambique Buoy Tender 'Bazaruto', before (left) and after (centre, right) 2019 Cyclone Idai. Images credit E. Tarasov, MarineTraffic.com (left) and The International Hydrographic Review (centre, right).(Harris, 2002), a predecessor to the Songimvelo co-management project, Eastern Cape Province, South Africa. Images courtesy World Resources Institute.

are residents of a geographical area, communities-of-identity, who are people with common affiliations or experiences (such as ethnic background), or communities-of-practice, which are defined by things that they do, such as professional organizations (Reid & Schulze, 2019). Regardless of the specific membership of the community in question, **CLEAR: Community-Led Engagement for Adaptability & Resilience** engagement will always mean *finding the people who are most affected* by an issue *and elevating them to a position where they can effectively advocate for themselves* as respected colleagues if not as equals.

2 Community-led engagement starts at home: CLEAR-ing up IHO policies and standards

In discussing community-led engagement for climate adaptation and resilience, let us begin with our own community: Hydrographers.

For a century, the International Hydrographic Organization (IHO) has been doing community-led engagement for professional hydrographers and navigation experts. Viewed through a CLEAR lens, the Capacity Building and Education committees do continuous community-of-practice engagement: finding out what member states need in order to practice hydrography effectively and in accordance with best practices and help them work up to those levels. Member states receive technical evaluations, training, workshops, and grant funding from the IHO, which in turn assists those member states in meeting the IHO's long-term objectives. Member states that develop their Hydrographic Office (HO) capabilities to a certain level are then able and encouraged to to assist other member states in the region – bringing them in as peers and partners.

Although the community-of-practice engagement work done by the Capacity Building and Education committees have good engagement processes in place for their respective roles, climate change-related adaptation and resilience will require adjusting those processes or adding new ones. In the May 2020 edition of The International Hydrographic Review journal (IHR), Hydrographers from the Mozambican HO, Institu Nacional de Hidrografia e Navegação, or INAHINA, described the devastating 2019 Intense Tropical Cyclone Idai on their vessels and facilities (Canhanga et al., 2020; Fig. 3). Despite their best efforts to safeguard their vessels and equipment, INAHINA lost a considerable amount of its departmental capacity literally overnight. Sadly, just over a month after Tropical Cyclone Idai made landfall in Beira, the extremely dangerous Intense Tropical Cyclone Kenneth made landfall near the city of Pemba, exacerbating INAHINA's difficulties.

The INAHINA Hydrographers wrote about their experiences and the lessons they learned from the storm's passage, including the "need to … develop standard operating procedures where the support from the international community may be of paramount importance" (Canhanga et al., 2020). This specific request shows how a community-of-practice, a community-of-identity, and a community-of-place can intersect: Hydrographers (practice) in Mozambique (place) requested post-disaster Capacity Building activities, preferably delivered in the Portuguese language (identity). A non-governmental body like the IHO will typically engage with a community-of-practice first and foremost, but it must be willing to engage with communities-of-identity or communities-of-place as a means to that end. Understanding the needs of people working for HOs and understanding the needs of HOs as organizations are not interchangeable. This is a CLEAR request for community-of-practice engagement from the IHO, where INAHINA are the community of Hydrographers most affected by the cyclone. This request implicitly acknowledges that community-of-identity engagement is a fundamental part of the overall engagement effort. South Africa and France (through Réunion and Mayotte), the nearest IHO member states and among the first nations to provide emergency aid to Mozambique, have different official languages and cultural practices than Mozambique. It is important for all stakeholders in a regional partnership such as this to be able to understand one another's languages and cultural practices, and the process of establishing communication roles for different stakeholders is a community-led engagement task.

The INAHINA Hydrographers highlight the need for CLEAR engagement within the IHO itself. If climate change-related events cause a member state HO to lose some or all of its capacity in a short period of time, how do the IHO and other member state HOs support their peer? Certain areas of the world may be well-practiced in this type of cooperation – the HOs of nations bordering the Caribbean Sea have decades of hard-won experience in coordinating navigation safety responses after tropical cyclones – but other HOs or Regional Commissions may need guidance and assistance in developing their own protocols. How do HOs effectively provide guidance to mariners and to the residents of coastal communities? Methods that acknowledge the climate risk, such as assisting member states in building remote survey capacity or cloud-based data handling systems, both of which make the HO less vulnerable to physical infrastructure disruptions, are one way to answer that question. I note that the IHO Capacity Building Committee has added the workshop "P-41: Hydrographic Data Managements to Support Disaster Relief", which appears to be a CLEAR initiative towards this goal.

CLEAR engagement for climate resilience from a professional governing body requires assessing existing best-practices and procedures and verifying that they still serve the needs of the organization. I recently listened to a discussion about non-contact methods of acquiring bathymetry (such as radar-derived bathymetry) and their suitability for charting. One person advocated for non-contact methods, to which another person responded that soundings from non-contact methods do not meet existing error specifications. This is CLEAR-ly a problem: while there are very good reasons for the IHO to define rigorous error standards for charting, if the *practical result* of those rigorous standards is that HOs will leave white space or known incorrect soundings on a chart rather than use non-contact methods with lower absolute accuracy but much higher temporal resolution, are we truly acting in the best interests of safe navigation? If the IHO doesn't make room for methods that give HOs tools to efficiently map previously underserved communities at risk of sea level rise disruptions, such as non-contact radar or satellite-derived bathymetry, are we living up to our goals to support sustainability and resilience?

These are not rhetorical questions. The residents of Raposa, Brazil (Fig. 4) are no less deserving of modern Hydrospatial data collection to support safety of life at sea and their ability to mitigate climate risk than residents of Rio de Janiero, but Raposa is the community surrounded by uncharted waters. For all of the capability and wonderful talent possessed by the Brazil Directorate of Hydrography and Navigation (DHN), they have 7,800 kilometres of coastline, the world's largest navigable inland river system, and several globally important ports in their remit. The DHN must allocate its limited resources while meeting IHO sounding accuracy standards as best as it can, and choosing to focus its efforts on critical navigation areas and energy development are prudent and reasonable decisions. But what if DHN were able to do more? What if a nation like Canada, that also has a well-established HO with a huge territory in their remit, could do more? The IHO could engage with member states to develop standards that accommodate less-accurate non-contact methods, preserving navigational safety and the Blue Economies of Brazil or Canada (or any other member state!) as a whole while also supporting local climate resilience

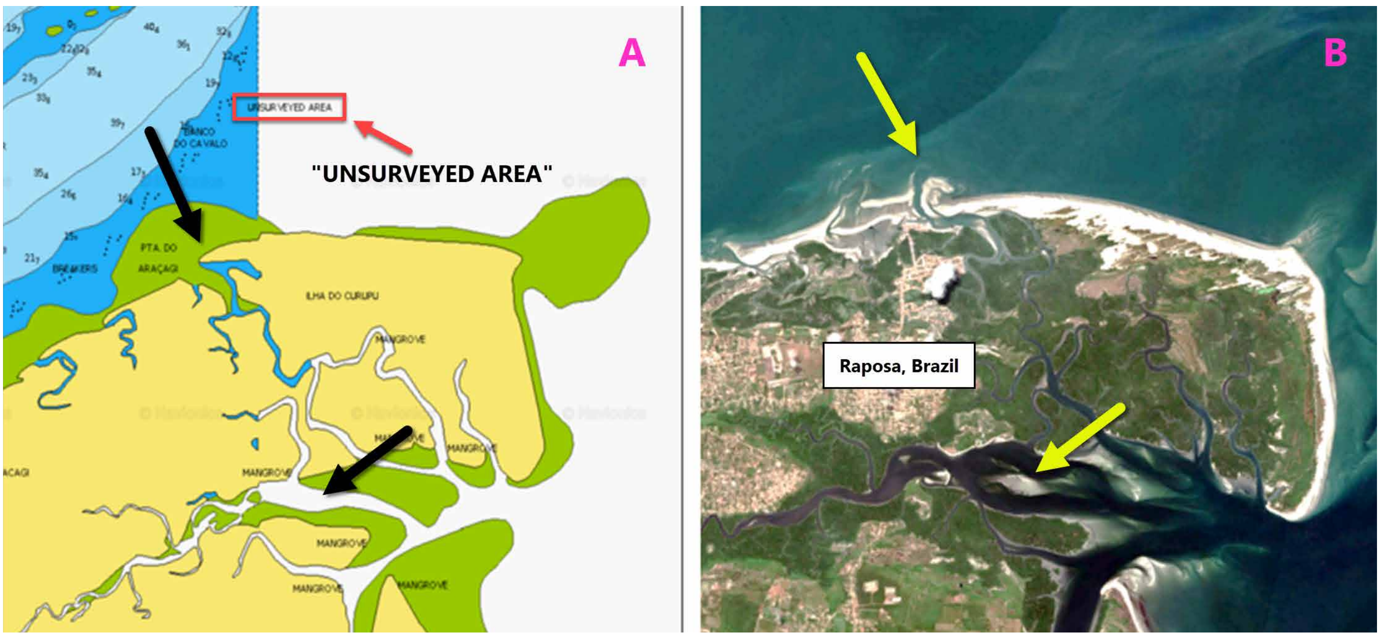

Fig. 4 Rasposa, Brazil. Navionics ENC ("A") with unsurveyed area in white. Maxar image ("B"). Black arrows in "A" and yellow arrows in "B" point to areas of visible differences between the chart and the coast.

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and economic development initiatives. These conversations will be challenging, but with the certainty of seafloor and coastline change and sea level rise, the sooner we start, the better.

3 Supporting community engagement with the IHR

In cases where the primary community engagement needs is community-of-identity or community-of-place, it is not expected that an organization like the IHO itself will be the facilitator in the engagement. Given the importance of these types of engagement, there is still room for the IHO to participate, and one way to engage is via The International Hydrographic Review. The IHR can act as a teaching tool and library for how Hydrographers and Hydrospatial scientists can approach and engage with national to local-scale stakeholders in ways that are practical, tactful, and lead to good scientific understanding of adaptation and resilience for community members. With some forethought, the IHR can support CLEAR initiatives as a teaching tool without putting too much of an extra burden on its editorial staff.

The IHR is already fulfilling this role to some extent, although it is not formally classifying or tagging articles and notes as such. One note from November 2022 discusses intergovernmental cooperation between the Hydrographic Office of Portugal and the Hydrographic Offices of Portuguese-speaking African countries (Delgado Vicente, 2022). Another note from November 2021 discusses the National Oceanic and Atmospheric Administration's (NOAA) Hydrographic Services Review Panel (HSRP) Federal Advisory Committee in the United States (Mersfelder-Lewis et al., 2021). This panel was designed to be an engagement tool for the national hydrographic office to interact with private-sector and academic stakeholders. One of the HSRP's stated goals in the article is to "discuss adaptive resilience to climage change, including how NOAA can make an impact in this area". The seated members of the panel can act as liaisons to their respective industries and solicit analysis and advice from other professionals. Public commentary is both desired and actively sought. These articles both offer insights in how Hydrographic Offices can successfully engage with one another and with other Hydrospatial industry professionals outside of their respective governments. The IHR editorial board could choose to specifically tag these articles as related to community engagement (Fig. 5), and they can consult with the authors to retroactively tag existing articles with a strong community engagement component.

Another area that the IHR can support CLEAR initiatives is by one of the most basic functions of a scientific journal: references. Trust and open communication are important parts of community engagement, and they are both difficult to achieve. By encouraging authors to include references to community engagement projects in their work, such as

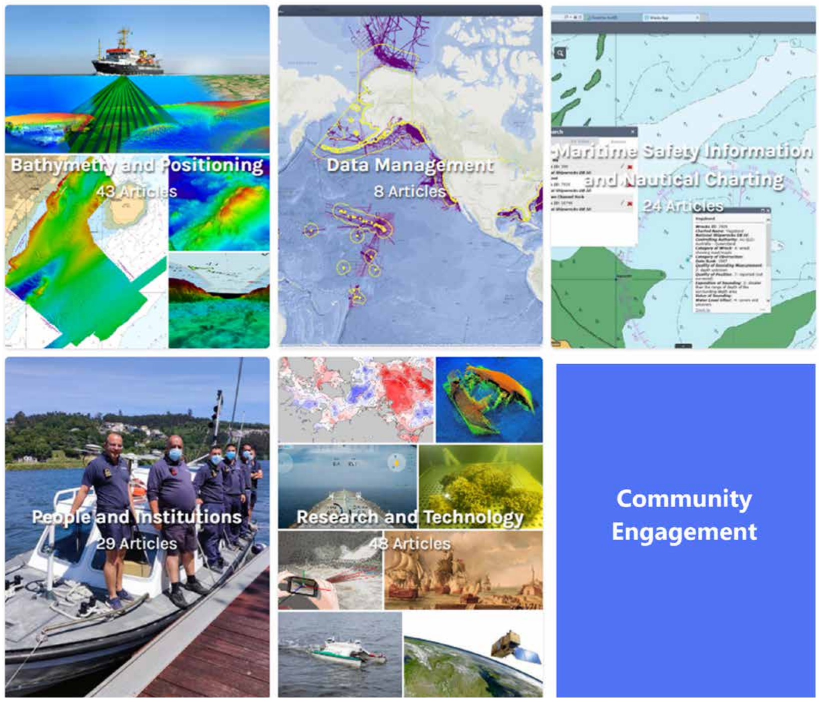

Fig. 5 Suggested New Category of IHR Articles and Notes?

newspaper articles or publicly-available government proceedings, Hydrospatial scientists going to work in a community will have a better understanding of that community's needs and a way to open communication with residents before ever going to site or talking to the first person. Scientists can also give references to community members, giving them a means of verifying that what the scientists say is true and that it is likely to be useful to them. As a community member, hearing the concerns of other people like them and seeing the process in action is powerful and empowering, which is our goal. The NOAA HSRP does this by making its proceedings available to the public through a U.S. federal government website (United States Federal Register, 2023). Like adding a new category tag to IHR articles and notes, this is achievable immediately and will have immediate benefit.

Projects that involve community-of-place and community-of-identity engagement are more commonly seen in grey literature (conference papers, minutes of public meetings, etc). This is not entirely surprising, given that a technical journal will want to focus on technical articles. This grey literature is a wealth of information, and authors will have already written at least some material for their presentations. This is an opportunity for the IHR to support its membership in learning how to successfully navigate CLEAR initiatives: publishing a special edition on CLEAR topics. Articles in a special edition need not be vastly different than articles in previous editions: articles about SeaBed 2030, the Empowering Women in Hydrography project, and the NOAA HSRP process all discuss different forms of community engagement. Articles about successful crowdsourcing projects are by definition community engagement projects and should be encouraged. It would be appropriate for

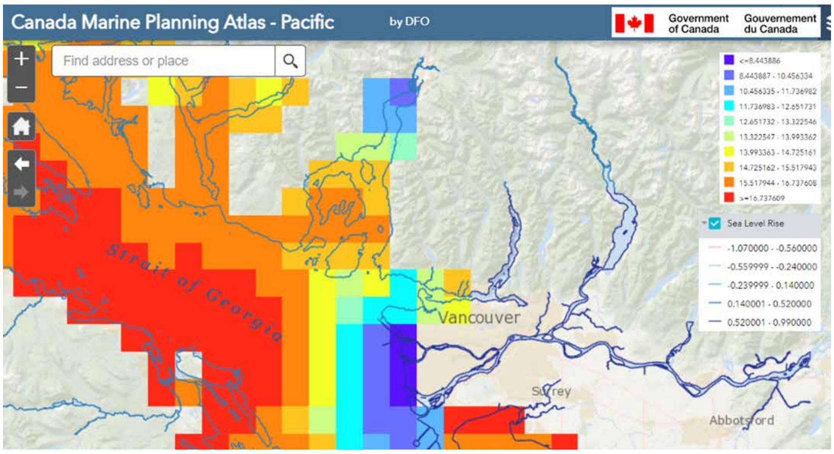

Fig. 6 Lower Fraser River watershed and Strait of Georgia, Canada Marine Planning Atlas – Pacific. Courtesy of Department of Fisheries and Oceans Canada.

Fig. 7 Harvesting mussels, Mapelane, South Africa. Image courtesy World Resources Institute.

officials from HOs in member states already involved in community-led engagement, such as NOAA in the USA and the Canadian Hydrographic Service, be invited to act as peer reviewers. It is also a good idea to specifically invite peer reviewers and CLEAR initiative authors from low or middle-income nations, who will have very different perspectives than people in high-income nations, and from minority or indigenous authors.

4 Supporting CLEAR initiatives through mapping

At its heart, community engagement is creating a framework for storytelling. Community members tell stories about things that are important to them and outline what they need based on those stories. Hydrospatial scientists listen to those stories and requests and use them to develop their research and surveying programmes. The scientific data they find tells a story on its own, and scientists must interpret what the data is telling them and weave it into a set of recommendations. Governing bodies collect these stories and use them to build good policies. The challenge in CLEAR initiatives is to take stories of the past – cultural information, environmental data, community needs – and combine them with stories yet to be written (also known as forecasts and model results) in ways that all participants can meaningfully use. Again, while the IHO as an intergovernmental body will not be involved in local or regional-level CLEAR initiatives, it can support them indirectly through its cartographic activities and support member states who are trying to build their own public-access maps.

Maps condense different types of spatial data into a common, easy-to-understand visual format. Whether they are simple hand-drawn sketches or aesthetically pleasing marriages of science and art, maps are powerful and transformative tools of engagement. Maps can connect local sustainability and climate resilience needs with broader Blue Economy development needs and resources available in the region, and with modern software advances, local community members only need a smartphone or tablet to be able to design their own maps or contribute to existing maps. If a CLEAR goal is to elevate and enable communites to advocate for themselves, maps are perhaps the single best tool to elevate community-of-place members.

The Department of Fisheries and Oceans Canada (DFO) has recently created interactive online maps for spatial planning and community engagement in Canada. Electronic Nautical Chart (ENC) data in S-57 format (soon to be S-100 format) is available as a layer, as are layers for expected sea level rise and modeled sea surface temperature. These maps assist region planners in determining what specific threats a region will face and what types of coastal protections are necessary. With the ENC data, regional planners can connect land-based climate resilience projects with marine or riverine projects and highlight specific problem areas, such as what might happen if sea level rise causes overwash of an important roadway.

The example shown in Fig. 6 is the lower Fraser River valley, British Columbia, Canada, which experienced a severe flooding event in late 2021. The Nooksack River, visible in the lower right hand corner in the city of Abbotsford, breached levees around the city and forced over 3,000 people to evacuate their homes. City and provincial officials consulted with city residents, an Indigenous community bordering the city to the north, and other stakeholders to determine the preferred flood mitigations (City of Abbotsford, 2022). The map in Fig. 6 shows that the Nooksack River is expected to experience between 0.5 meter to 1 meter of sea level rise under current climate predictions. These predictions, and maps similar to this one, were used in community engagement meetings.

The operational debut of S-100 standards offers many more possible ways for stakeholders to use Hydrospatial data than an ENC alone. This is an exciting achievement. As the rollout of S-100 progresses, member states may choose to build public-access maps featuring ENC and Hydrospatial data in order to assist CLEAR initiatives within their national remits. The IHO can encourage and support HOs

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who want to build their own publicly-available planning maps based on S-100 data by developing a set of best-practices or even a common template for member state HOs to adjust for their unique needs.

5 There are no CLEAR happy endings

The past may be prologue to our lives, but it is not the end. Climate change is here and some of its effects cannot be undone, but this does not mean we are doomed to sit on our hands and do nothing. Quite the opposite: as a community of trained knowledge workers, we have the power to share our knowledge with people who need it and support our peers as they embark upon their own CLEAR initiatives. Through community engagement, we can get better solutions to complex problems and overcome resistance to change. We are our own best advocates, and we are our own best supporters.

As a final note, the short story version of the Songimvelo Mussel Committee with a happy ending does a further injustice to the participants, for these women's lives are not a short story and there was no happy ending because their work never stopped (Fig. 7). The local fisheries co-management projects in the Kosi Bay region have had to adapt and change in the past twenty years as they face other changes in the region, particularly from tourism pressures on the fishery and related land use restrictions. Community engagement projects continue to this day. Nonetheless, with regards to the scientific research, the future of the food resource is a success story. The kind of work I have outlined for the IHO itself, the IHR, and individual member states likewise will not stop. We can write our own stories, though, and draw our own maps. We can build our own CLEAR futures with clear eyes and clear minds, and we can choose to involve the people who need our collective skills and work with them to obtain the best results that we can by building a scaffold of Community-Led Engagement for Adaptation and Resilience to support us all.

Postscript: *While I was finishing the final draft of this keynote, Very Intense Tropical Cyclone Freddy was re-emerging in the Mozambique Channel after its first landfall in Madagascar and second landfall near Vilankulos, Mozambique. By the time of publication, the storm will have re-intensified to at least 110 km/hr sustained winds and made landfall for a third time near Quelimane, Mozambique, four years and six days after the formation of Intense Tropical Cyclone Idai.*

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Author's biography


Helen Stewart

Helen Stewart is a member of The Hydrographic Society of America (THSOA). In her eclectic career, she has worked on projects starting with nautical chart hydrography for NOAA and deep-ocean geological research as a graduate student to deep-water geohazard surveys and unexploded ordnance removal surveys for offshore wind energy. In 2020, she introduced a novel hydrographic survey method using multispectral satellite imagery for detecting dangers to surface navigation, which she is now developing for structural health monitoring surveys in inland waterways. She has a Bachelor of Science degree from the University of Texas and a Master of Science degree from the University of Cape Town.

Helen firmly believes that "Y'all Means ALL" and is grateful to be in a position in her life to support others as they have supported her. Since July of 2021, she has been involved in the IHO Empowering Women in Hydrography Project, including writing two Notes for The International Hydrographic Review on the subject. She has since expanded her advocacy on the subject of the first Note on women's safety to other professional societies and universities in the United States and Canada. In her home city of Houston, Helen advocates for green-infrastructure projects to supplement existing flooding and neighbourhood cooling projects. In her personal time, she is an artist, a cyclist, a gardener, and a summertime windsurfer.

https://doi.org/10.58440/ihr-29-a06

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IHO International Hydrographic Organization

100 years of international cooperation in hydrography

Author

Peter Ehlers[1]

Preamble

This manuscript is a reprint of the original paper previously published in 2021 in the Journal of Applied Hydrography (Hydrographische Nachrichten, https://www.dhyg.de/index.php/de/hydrographische-nachrichten): Ehlers, P. (2021). 100 years of international cooperation in hydrography. *Hydrographische Nachrichten · Journal of Applied Hydrography, 119*, 62–70. https://doi.org/10.23784/HN119-10

Abstract

Peter Ehlers was to give a speech at the 2nd Session of the Assembly (2020) in Monaco, which was to mark the 100th anniversary of the International Hydrographic Organization (IHO). Sadly, the speech was cancelled due to the exceptional circumstances posed by the COVID-19 pandemic. His words were left unspoken. Nevertheless, as Peter Ehlers still had something of significance to say, we are now publishing the manuscript of his intended speech.

Keywords

IHB · IHC · EIHC · GEBCO · RHC

Resumé

Peter Ehlers devait prononcer un discours lors de la 2ème session de l'Assemblée (2020) à Monaco, qui devait marquer le 100ème anniversaire de l'Organisation hydrographique internationale (OHI). Malheureusement, le discours a été annulé en raison des circonstances exceptionnelles provoquées par la pandémie de COVID-19. Ses propos n'ont pas pu être prononcés. Néanmoins, comme Peter Ehlers avait encore quelque chose d'important à dire, nous publions aujourd'hui le manuscrit du discours qu'il avait prévu de prononcer.

Resumen

Peter Ehlers iba a dar un discurso durante la 2ª Sesión de la Asamblea (2020) en Mónaco, que iba a señalar el 100º aniversario de la Organización Hidrográfica Internacional (OHI). Por desgracia, hubo que cancelar el discurso debido a las circunstancias excepcionales generadas por la pandemia del COVID-19. Sus palabras quedaron sin pronunciarse. A pesar de ello, como Peter Ehlers aún tenía algo relevante que decir, publicamos ahora el manuscrito del discurso que tenía previsto. (IHO) practices to support its member states, how it can improve its own policies, and how the IHO and member states can collaborate to support their needs and those of people who are at greatest risk of climate change-related hazards.

1 Call for cooperation

Maybe that some time in future the past 100 years will be noticed as the initial period of globalisation. The bad experiences from two world wars led to ever closer international cooperation, which aimed to maintain peace, but also intensified the exchange of information on many technical issues and promoted common, uniform standards. The different parts of the world came closer and closer together. This was particularly evident in the economic relationships that

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 https://doi.org/10.58440/ihr-29-a02

were characterised by ever-increasing world trade. Since world trade is predominantly carried out by sea, safety of navigation has become increasingly important, also in the interest of protecting the marine environment. A basic requirement is the availability and provision of current and precise hydrographic information. While in old times states used to keep hydrographic information more like a secret treasure – it is no coincidence that the first Danish hydrographer Jens Sorensen was called »Spy and Hydrographer« – since the end of the 19th century the voices increased that advocated closer international cooperation. At international maritime conferences 1889 in Washington and St. Petersburg in 1908 and 1912 the advantages of uniformity in nautical charts and publications through international cooperation were highlighted. However, only after the First World War time had come for a first International Hydrographic Conference (IHC), which was initiated by the British and French hydrographers and held in London in 1919.

2 The IHB Statutes

The 1919 conference in principle adopted a proposal to establish an International Hydrographic Bureau (IHB) as a permanent international body to maintain a close association among the participating hydrographic offices. For preparing the statutes and specific directions of the IHB a special committee was appointed which after the conference elaborated draft Statutes. By April 1921 they were approved by 19 States. The Statutes formally established the IHB and defined as its object a close and permanent association between the hydrographic services of the Member States to coordinate their efforts with a view to rendering navigation easier and safer in all the seas of the world, causing the national offices to adopt the rules taken by an international hydrographic conference, obtaining uniformity as far as possible in hydrographic documents, and advancing the theory and practice of the science of hydrography. In order to discuss questions concerning hydrography and in particular to review and guide the work of the IHB, an ordinary IHC was to be arranged originally every six years, but it was changed to five years before the first instance. The IHB, which was a consultative body only should be controlled by a Directing Committee, composed of three Directors of different nationalities, elected by the IHC, a Secretary General and further staff. The director elected with the highest number of votes should be the President of the Committee, acting as primus inter pares. The expenses should be borne by subscriptions from the Member States, divided into shares which are dependent on the total tonnage of a Member State. English and French are determined as official languages. The Statutes declared that Monaco should be the official seat, following an invitation of Prince Albert I. These Statutes did not create an international organisation in the modern understanding but were restricted to jointly setting up and operating a bureau to be led by a triumvirate with decisive powers and supervised only in long intervals by meetings of the »owners« who acted as shareholders. From the very beginning the question as to whether such a construction was adequate and efficient for international cooperation was raised again and again.

3 Start-up and persistence in hard times

Following the approval of the Statutes the first three Directors were elected by postal ballot. The counting of the ballots took place on 21 June 1921 at a meeting of the special committee in London in the presence of representatives of several States. This date has to be seen as the official date of the establishment of the IHB. The Directors immediately moved to Monaco and started work, concentrating in particular on internal administrative measures. A quite urgent issue was the relationship with the League of Nations. On 5 October 1921 the Council of the League adopted a resolution stating that the IHB »shall be placed under the direction of the League«. Step by step the general and technical work of the IHB progressed including the collection of surveys carried out, their methods and progress, studies relating to navigation, lights, tides and magnetism as well as information on the methods and processes used for compilation, updating and publication of charts and other nautical documents. For distributing all relevant information about new developments to hydrographic offices (HO), the IHB started in 1923 to publish the International Hydrographic Review, and to edit Special Publications. On specific technical and administrative subjects Circular Letters were sent out. Annual Reports describing progress made, including a business and financial report, provided further information and were complemented from 1927 by an IHB Yearbook. In addition, from 1928 prompt information was disseminated by the International Hydrographic Bulletin, which initially was published monthly. A Repository of Technical and Administrative Resolutions was gradually built up.

The first IHC organised by the IHB, which was counted as the second IHC after 1919, took place in the Oceanographic Museum of Monaco in 1926 with the participation of 42 delegates from 21 of 22 Member States and two non-Member States. The conference agenda addressed 69 topics, including charts, sailing directions, lists of lights, notices to mariners, catalogues, geographical names, instruments, ocean currents, tides and hydrographic surveys, but also modifications of the Statutes, the financial administration and the election of the Directors and the Secretary General for the next five-year period. As not all issues could be fully examined a Supplementary Conference, counted as the first Extraordinary International Hydrographic Conference (EIHC), was held in April 1929 discussing among other issues for the first time the problem of copyright of hydrographic publications. During the conference, the foundation stone for new premises of the IHB was laid. After completion the building was inaugurated by Prince Louis II of Monaco on 14 January 1931, so that in 1932 the 3rd IHC could be held in the chartroom of the IHB premises. At that conference a specific proposal dealt with the definition of hydrography as the »science by which data concerning the true configuration of the earth, as far as navigation demands, are determined and laid down in charts, Sailing Directions and appertaining publications«. This definition reflects the perception at that time that hydrographic data were relevant for navigation only. The conference also accepted responsibility for the production of the General Bathymetric Chart of the Oceans (GEBCO), originally initiated by Prince Albert I, which since then has been a subject of particular interest.

In the 1930s the IHB negatively suffered from the world economic crisis and adverse political developments. Several Member States withdrew from the IHB. A considerable decrease of the contributions decreased forced the IHB to reduce salaries and the expenses for publications. The difficult financial situation dominated the 4th IHC in 1937, which was only attended by 20 representatives from twelve of 17 Member States. Amongst the various resolutions adopted, was the decision to compile a standard dictionary of hydrographic terms, a task that has quickly proved to be permanent, and therefore continues to this day.

The situation became far more difficult with the outbreak of World War II. Four more States withdrew their membership, two Directors went to their home countries, several staff members left the IHB. The one remaining IHB Director, Pierre de Vanssay de Blavous (France), carried on conducting and maintaining the work as best possible under wartime constraints despite of discussions to suspend all activities and to stop the payment of contributions. In December 1943 and August 1944 the building was severely damaged by bombing, but recovery plans were initiated soon and repairs were carried out by August 1945.

4 Securing a firm basis

At the end of 1945 the IHB could return to normal operation. The Hydrographic Dictionary was published in which hydrography was now defined more comprehensive, but still concentrating on navigational purposes. Relations with other international organisations were renewed or newly established. In spring 1947 the 5th IHC could be held, 16 of 17 Member States participated together with observers from seven former Member States as well as from the recently established United Nations, UNESCO and some other international organisations. Spanish was introduced as a third conference language. Initiatives to considerably re-organise the IHB resulted in a revised version of the Statutes without changing the legal character, the leading principles and the general structure. A proposal to become an integrated entity within the framework of the United Nations was rejected as the conference was in favour of having an independent international organisation of mere technical character, free from general political issues. In the following years quite a number of States returned to IHB membership. The 6th IHC in 1952 was attended by 26 out of then 30 Member States, two non-Members and twelve international organisations, proving the great interest in the work of the IHB. The conference was also used to disseminate broader information by lectures given by participants and by an exhibition of instruments, which as a side effect became increasingly important at following IHCs.

At the 7th IHC in 1957 again items relating to constitutional and administrative issues were brought forward, in particular concerning the legal status of the IHB. Therefore, the burdensome process for elaborating a formal convention to achieve recognition of the IHB as an intergovernmental organisation was initiated. After laborious inter-sessional approaches, the issue was re-discussed at the 8th IHC in 1962 with participants from 35 of now 41 Member States and three non-Member States. The conference approved that a convention should be prepared to be adopted some months later on an extraordinary IHC. However, it took additional five years before the 9th IHC in 1967 finally approved the text of an IHO convention. The legal adoption process took further three years, but at last on 22 September 1970 the IHO Convention entered into force. And by this the IHO came into existence as a truly intergovernmental organisation with its own juridical personality. The convention maintained full continuity with the preceding IHB Statutes by taking up their substantial principles, basic objects, goals and functions. The IHC became now the assembly of the members of the organisation and the IHB, composed of the Directing Committee and the professional staff, the executive body or secretariat of the organisation, whereas the additional post of Secretary General was waived. As the Convention was more or less restricted to some main principles and provisions, it was supplemented by General Regulations and Financial Regulations, containing specific rules of procedure. In addition, a Host Agreement was drawn up, which after lengthy negotiations was signed by Monaco and France in 1978.

5 Consolidation in a changing world

Although the period after 1957 was essentially marked by the struggle for a convention, a new focus was also set on other topics. In the 1960s and 1970s great significance was attached to the improvement of hydrographic surveys. This included specifications for hydrographic survey operations, the compilation of an index of those areas, which had not been surveyed to a standard appropriate for modern navigation requirements, but also the development of a curriculum reflecting the basic standards of excellence, which should be common to all surveys. Together with the International Federation of Surveyors (FIG) a joint Inter-

https://doi.org/10.58440/ihr-29-a02

national Advisory Board on Standards of Competence for Hydrographic Surveyors was established.

At the 9th IHC in 1967 a first step was made to establish an international charting system, initially confined to charts at small scale. After the publication of the first INT charts in 1972, the 10th IHC extended the concept to medium and large scale charts, so that international shipping could navigate along all the major sea routes and enter all major ports of any country by using standardised INT charts.

It became more and more obvious that hydrographic data and information were not required for navigation only, but also for other purposes related to the use and protection of the seas and as a basic tool for countries to manage their marine areas. Whereas the fishery industry had since long been interested in specific hydrographic data, the increasing offshore activities, aiming at the exploitation of hydrocarbons, created a growing need for precise hydrographic data.

Another issue that took more and more prominence was technical assistance in the field of hydrography. The 10th IHC in 1972 explicitly decided that the IHB should serve as a source of technical advice and as a coordinating body for the promotion of measures to establish or strengthen the hydrographic capabilities of developing countries, taking into account that at least 50 coastal States had no hydrographic services at all, whereas the hydrographic capabilities in many other developing countries were extremely limited.

In the field of navigation and oceanography cooperation with other international organisations became more and more important. The IHO closely collaborated inter alia with the IMCO, now the IMO, the IOC of UNESCO, IALA, WMO, and also participated in the UN conferences on the law of the sea, starting in 1973 with the aim to elaborate a new convention. To strengthen the cooperation between neighbouring HOs the 9th IHC formally accepted and encouraged the establishment of Regional Hydrographic Commissions (RHC) to cooperate in the solution of common regional problems of charting, research or data collection. At the beginning of the 1970s six RHCs were active. The IHO membership steadily increased and in 1972 reached 43, the 10th IHC was attended by 37 of the 43 Member States, six non-Member States and 24 intergovernmental and other international as well as national organisations and associations. Due to the large number of participants the IHC could no longer be held at the IHB premises, but was organised in the »Centre des Rencontres Internationales«. As an important platform for the hydrographic community the conference was supplemented by lectures, an exhibition of hydrographic, oceanographic and navigational instruments and products, and the visit of several hydrographic vessels. In 1977 the 11th IHC introduced Russian as a fourth working language together with English, French and Spanish.

As the workload steadily grew, the IHB made more and more use of the knowledge and experience by groups, formed of specialists from Member States. If appropriate such groups were established in partnership with cooperating international organisations. Confusingly, the naming of these bodies differed between working groups, ad hoc groups, commissions, committees and even advisory boards. Due to increasing tasks and responsibilities in the 1960s the IHB staff, not including the Directing Committee, had been expanded to 19 persons, but in the 1970s was reduced again to 15 persons because of economic menaces, despite considerable increase in contributions to be paid by the Member States.

6 New challenges

In the 1980s the IHO had to face new challenges. Hydrographic activities were more and more influenced by technological developments, in particular by the increasing use of computers, which opened a wide field for digitisation. Close international cooperation gained further weight. The workload of expert groups constantly became heavier. In the mid-1980s there existed ten commissions, committees, sub-committees and working groups in total. A decade later the working load had further increased. The 1993 Annual Report cited 24 commissions, committees and working groups of the IHO, including joint bodies with other organisations, and contacts with 37 international organisations and associations. Yet the now existing eight RHCs also took on specific projects, which they carried out for the benefit of the whole hydrographic community, in particular as concerns INT charts. Additionally, because of increasing activities in Antarctica, in 1992 the 14th IHC established a Permanent Working Group on Cooperation Concerning Hydrographic Surveys and Charting in Antarctica. The efforts were intensified to increase awareness in developing countries that hydrography was needed for the safety of navigation as well as for tasks relating to the marine environment, coastal research and coastal engineering. These technical assistance activities included contacts with Governments, expert missions and workshops together with other organisations, training courses at several maritime academies and the encouragement of HOs to transfer excess equipment to needy nations.

The setting up of a committee on the exchange of digital hydrographic and charting data between HOs by the 12th IHC (1982) may be marked as the very beginning of the development of an electronic chart system. Some time later the considerations led to the creation of an IMO/IHO Harmonization Group on ECDIS. At the beginning of the 1990s the development of ECDIS became a major issue of the work of the IHO and resulted in the elaboration of precise standards and specifications. The 14th IHC (1992) set up a special committee to examine matters related to the establishment of a Worldwide Electronic Chart Data Base (WEND) as an indispensable prerequisite to introduce Electronic Navigational Chart (ENC) services. In November 1995, the IMO Convention on

Safety of Life at Sea was amended for an electronic chart display and information system to be accepted as satisfying the chart carriage requirements, referencing the IHO performance standards for ECDIS. An important milestone in the history of hydrography and navigation was the introduction of the first operational ENC service, offered by the regional electronic navigational chart centre PRIMAR in Norway in 2000, which was opened by King Harold of Norway.

Another crucial issue was the publication of nautical documents by private publishers, resulting in the decision that no HO may grant permission for reproduction, if the area in question includes data collected by another HO, as the data belong to the originator.

Since the entry into force of the IHO Convention the IHC repeatedly discussed internal matters of the organisation, in particular concerning the most effective structure and composition of the Directing Committee. The 13th IHC (1987) even amended the convention to introduce a new election procedure. However, this amendment never came into effect, as the necessary quorum for formal approval was not achieved. Another issue were the service conditions which at the 14th IHC led to the approval of further convergence with the relevant conditions in the UN system.

In the 1980s the annual income of the IHO grew steadily because of increasing membership. At the end of the decade 57 States were members of IHO. Yet the workload of the IHB and all the different expert bodies significantly increased accordingly. The output of publications informing about the results of the various activities tripled, not the least thanks to the acquisition of modern printing equipment and computerisation that speedily advanced in the 1990s. The internet dramatically facilitated communication. More and more digital versions of publications and documents were made available. The use of the Spanish language was enhanced, when the 14th IHC tasked the IHB to use Spanish for certain periodical publications, Circular Letters and correspondence.

7 Facing the third millennium

In late 1996, 75 years after its inauguration, the IHB premises were moved to the opposite side of the harbour to the new location 4 Quai Antoine 1er. This heralded a phase of great change. With about 300 delegates from 52 of 63 Member States, 18 non-Member States and 15 organisations and associations the 15th IHC (1997) was larger than ever before. The conference was marked by the growing awareness that changing and adapting to new developments had become more and more urgent in order to survive in the future. A more systematic internal structure of the IHO and a clear strategic orientation were needed. The conference adopted clear principles for the formation of inter-sessional subsidiary bodies and general guidelines for the creation of RHCs, which were understood as part of the IHO. With regard to the question of how to cope with future challenges in the field of hydrography to be prepared for entering the 21st century, an inter-sessional Strategic Planning Working Group (SPWG) was established.

Acknowledging that the copyright of the data belongs to the HO that is the originator of the data which are included in a chart or a nautical publication, the 15th IHC approved principles to be applied by HOs when permitting private publishers to reproduce charts or nautical publications. Furthermore, new rules for the exchange and the reproduction of nautical products on the basis of bilateral agreements between HOs were accepted.

The growing importance of assisting countries in developing hydrographic capabilities was reflected in 1998 by a UN General Assembly Resolution on oceans and the law of the sea, which on the occasion of the International Year of the Ocean for the first time made reference to hydrography and explicitly invited States to carry out hydrographic surveys and to provide nautical services. The IHO concentrated on capacity building activities by conducting technical assistance visits and accompanying development projects to be implemented with the support of donor organisations. Not the least these activities encouraged additional States to establish hydrographic services and to become members of the IHO. In 2000 the membership had increased to 69 Member Governments. At the same time twelve Regional Hydrographic Commissions and the Committee for Antarctica existed, covering most of the major sea areas worldwide.

In a time of globalisation when maritime transport was steadily growing and the risks for the marine environment in case of casualties were expanding, accurate hydrographic information became more important than ever for safe navigation. It was only logical that the IMO in 2000 revised Chapter V of the International Convention for the Safety of Life at Sea (SOLAS) to introduce new regulations that oblige Contracting Governments to carry out nautical and hydrographic services in the manner most suitable for navigation. Charts and nautical publications must be issued by or on behalf of a relevant Government institution. These regulations, which entered into force in 2002, may be seen as a quantum leap for HOs. For the first time international law created an obligation for States to maintain hydrographic services, as well as a firm commitment to cooperate, standardise and coordinate activities on a worldwide scale. The increasing interest in hydrographic matters was also shown when in 2001 the IHO, though for good reasons still not interested in becoming a UN organisation, was granted observer status to the UN General Assembly.

Based on an analysis of the strengths and weaknesses of the organisation and the opportunities and threats facing it, the SPWG developed strategic goals and priorities of IHO, examined necessary structural or constitutional changes to enhance the future effectiveness, proposed a strategic planning cycle and presented a strategic plan. To speed up the process the results of the SPWG were discussed at a supple-

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mentary conference, the 2nd EIHC, in 2000. The conference adopted the proposed new Strategic Plan, which highlighted as main strategic issues the transition to the digital era, a global hydrographic data coverage, the response to developments of Government policy, the adequate funding for the provision of hydrographic services, the building up of effective national organisations and the provision of services other than for navigation. For implementing this plan, a work programme for the next five-year period and the future planning cycle were approved. The SPWG continued to study especially the need of structural changes and was tasked by the 16th IHC (2002) to carry out a study on the need to revise the IHO Convention.

Considerations, which had started in the 1970s, that hydrographic data were not only important for navigation, became more and more evident. The demand grew for hydrographic data for other purposes, especially for fishing, offshore activities, coastal protection, harbour construction, and marine scientific research; non-navigational applications had to include the determination of national maritime boundaries, coastal zone management, modelling of marine areas, study of habitats, assessment of the state of the marine environment and exercise of national rights in maritime zones. Accordingly, the IHO understood the provision of hydrographic data for geomatic applications as an important new policy direction.

8 Renewing the IHO

The work to reform and modernise the IHO, especially done by the SPWG, came to a conclusion by a 3rd EIHC in 2005 in agreeing on far reaching amendments of the IHO Convention. The main objectives of the amendments were to maintain the strengths, eliminate the weaknesses, achieve the vision, mission and objectives of the IHO and establish a more effective and cost-effective system. The new version of the convention clarifies that the IHO is the competent international organisation for hydrography and defines its vision, mission and objects. The organisational structure and procedures are drastically changed. The IHC is now named the Assembly, being the principal organ of the IHO, and has all the powers of the organisation unless otherwise regulated. The period between ordinary sessions of the Assembly is reduced to three years. In addition to the Assembly a Council is created. It is composed of one fourth, but not less than 30 Member States. The functions of the Council are to guide and coordinate the IHO activities during the inter-Assembly period. The term International Hydrographic Bureau (IHB) is replaced by the term Secretariat, which comprises of a Secretary General as the chief administrative officer, Directors and other personnel. Supplementary detailed provisions were adopted by the 17th IHC in 2007, including General Regulations and Rules of Procedures for the Assembly, the Council and the Finance Committee. In anticipation of the Convention amendments, which had not yet entered into force, the 17th IHC also decided on a new structure for the subordinate bodies by establishing the Hydrographic Services and Standards Committee (HSSC) and the Inter-Regional Coordination Committee (IRCC) as main committees. The hitherto unclear legal nature of the existing 15 RHCs was explicitly regulated, as being regional bodies established by Member States, but recognised by the Assembly. A special status was maintained for the Hydrographic Commission on Antarctica.

Capacity building, in particular, gained more and more importance and was strongly influenced by the RHCs and further enhanced by annual UN General Assembly Resolutions on the Law of the Sea, which repeatedly welcomed the work of the IHO and its Regional Commissions. The importance of international cooperation and the support for developing States in building up hydrographic capabilities became highly obvious after the tsunami disaster in December 2004 and was reconfirmed in response to the earthquake and tsunami in Japan in 2011. The 18th IHC in 2012 agreed on revised guidelines and procedures with the aim of helping Member States to develop contingency plans in case of anticipated disasters.

In 2005 the UN General Assembly explicitly welcomed the adoption by the IHO of a »World Hydrography Day« to be celebrated annually on 21 June, as the date of creation of the IHB, with the aim of giving suitable publicity to its work and of increasing the coverage of hydrographic information on a global basis.

Especially concerning ECDIS, the collaboration with IMO became even more intensive, as the work of the IHO depended on the acceptance of performance standards and carriage requirements to be determined by IMO. As a first step, in 2006 the IMO made the carriage of ECDIS mandatory for high speed craft. Three years later in 2009 the mandatory carriage for other than high speed craft was introduced by IMO in a phased manner from 2012 onwards. In the light of this development the 17th (2007) and 18th IHC (2012) underlined the importance of full ENC coverage and the need in many parts of the world for improving the collection, quality and availability of hydrographic data.

In order to manage the many different seaborne uses and interests, the need for precise marine data became more and more evident, not the least as an indispensable basis for the development of marine spatial planning programmes. Hydrographic data were seen as an important part of an adequate marine data infrastructure. HOs had to move from map production as their primary focus to the management and operation of, or the participation in, marine spatial data infrastructures (SDI) from which nautical charts and other products were derived. The 4th EIHC (2009) adopted a Marine Spatial Data Infrastructure Policy, in 2011 the IHB launched a specific IHO Publication on »Spatial Data Infrastructure – the Marine Dimension«, which explained the way that HOs might provide hydrographic-related data as part of the national SDI.

Another further remarkable step towards the modernisation of the IHO was made by the 4th EIHC. The starting point was a new definition of hydrography as »the branch of applied sciences which deals with the measurement and description of the physical features of oceans, seas, coastal areas, lakes and rivers, as well as with the prediction of their change over time, for the primary purpose of safety of navigation and in support of all other marine activities, including economic development, security and defence, scientific research, and environmental protection«. The broad new definition was reflected in the revised Strategic Plan that was not a mere updating of the earlier version but introduced a new systematic approach and the use of modern management tools, which was to be implemented by a new structured Working Programme, including annual performance monitoring. The 4th EIHC also invited the relevant RHCs to encourage through appropriate liaison bodies the consistent use of hydrographic standards and mutual cooperation for the enhancement of safety in navigable inland waters within and between regions, as no other organisation was in a position to foster this harmonisation.

In the 2000s cooperation with private industry steadily became closer. The exchange of information and experience with stakeholders from academia, industry, government and non-governmental organisations was intensified through stakeholders' forums. A special information session, held at the 5th EIHC (2014), in particular dealt with the collection of bathymetric data collated by private crowd-sourcers, as new technologies could be used by private entities leading to the development of open-sea-map behaviours.

The conferences in 2012 and 2014 devoted particular attention to the progressively increased workload and scope of the IHO, which was mainly due to the rising number of Member States, more RHCs and more regular RHC meetings, secretariat functions for IHO bodies, the implementation and management of the capacity building programme, the maintenance of the very comprehensive IHO documentation and website, the introduction of programme performance monitoring, the involvement in outreach activities and the active recruitment of new Member States, implementation measures related to ECDIS, participation in the development of the IMO e-navigation strategy and representation in a number of new intergovernmental initiatives. At the same time the transition from paper to digitally-based hydrographic products and the broader use of the IHO data transfer standard placed an increased responsibility and obligation on the IHO to ensure the reliable maintenance of the standard.

9 IHO today

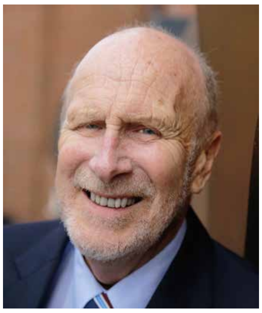
After twelve years the necessary quorum for the approval was met and the Protocol of Amendments to the IHO Convention entered into force on 8 November 2016. The new structure of the IHO was put in place without significant problems. The IHC now became the IHO Assembly. As an additional powerful organ, the Council was established to act in operational control of the organisation for the inter-sessional period. And the former IHB was renamed to IHO Secretariat. The now 87 Member States held the first Assembly meeting in spring 2017, adopted the necessary organisational and procedural adaptation measures, approved the composition of the Council, and elected Mathias Jonas, the former head of the Nautical Hydrographic Department of the BSH (Federal Maritime and Hydrographic Agency, Germany) as Secretary General as well as two assisting Directors. The Assembly also dealt with numerous technical issues, such as the use of ECDIS, information to mariners about submarine cables, improvement of the availability of bathymetric data worldwide, including crowd sourcing, and participation in geospatial information management activities. Some months later the Council started its annual meetings, focusing on strategic planning, the Work Programme and financial control, including the approval of the budget for the following year. Due to the global effects of the COVID-19 pandemic the second Assembly was moved from April to November 2020 and was only conducted as a remote event by combining Assembly Circular Letters to be decided on in advance and virtual assembly sessions. This hybrid format resulted in 52 decisions, including the future of the paper chart, the further development of the technical standardisation of ENCs, as well as the Work Programme and budget for the next three year-period. Thus, IHO's ability to remain agile and decisive under extraordinary conditions was demonstrated, though the paramount benefit of in-person meetings was recognised by all online participants.

10 Conclusion

At its 100th anniversary the IHO, which has begun as a Bureau with 19 shareholders, has become the competent global organisation for hydrography, comprising of 94 Member States from all parts of the world, and with an annual budget that increased from originally 242,000 Swiss francs to 3.6 million euros. Over the past 100 years, IHO has consistently succeeded in modernising itself, adapting and expanding its range of tasks and activities in the light of new developments and challenges. Despite all changes and modifications, however, an unbroken continuity has been maintained. It has been proved advantageous that the IHO is not a political, but a technical organisation only. Nor has it been a hindrance that the IHO is of consultative nature only, as technical standards reflect the state of the art and therefore in the end are accepted and applied even if they are not legally binding. While the IHO, for well-considered reasons, is not part of the UN system, it is nevertheless an indispensable element in global efforts concerning safety of navigation and the sustainable development of the oceans.

 https://doi.org/10.58440/ihr-29-a02

Author's biography



Peter Ehlers

Prof. Dr. Dr. h.c. Peter Ehlers was born 1943. He studied law at Marburg and Kiel University. After having written his doctoral (PhD) dissertation about IMO he joined the German maritime administration in 1970. He worked for many years in the Maritime Transport Department of the Federal Ministry of Transport where he became Deputy Director General. From 1989 to 2008 he was the President of the German Federal Maritime and Hydrographic Agency (BSH). He represented his country in various international maritime organizations, e. g. IMO, IHO, UNESCO-IOC, Helsinki-Commission; he was twice Chairman of the Helsinki Commission and chaired two International Hydrographic Conferences of IHO. He became a member of numerous German maritime institutions and organizations. He retired in 2008.

Since 1992 he taught law of the sea at Hamburg and Rostock University. In 2002 he became Professor at Hamburg University; in 2007 he was awarded Dr. h.c. at Rostock University. Until its closure in 2014 he was a member of the Board of Directors of the International Max-Planck Research School for Maritime Affairs, Hamburg.

After his retirement he was appointed Chairman of EUROGOOS, an association of European oceanographic institutes; the chairmanship terminated end of 2013. From 2011 to February 2022 he was a member of the Board of Governors of the World Maritime University, Malmö. He is teaching as a guest lecturer for law of the sea and marine environment law at the World Maritime University, Malmö, and the International Law Institute, Malta. In 2018 the Federal Minister of Transport and Digital Infrastructure appointed him as ombudsman for the safety of traditional ships.

In 2016 he became an officer of the German Federal Order of Merit, awarded by the German Federal President.

https://doi.org/10.58440/ihr-29-a02

Interviews

Preface

The International Hydrographic Organization (IHO) currently has 98 Member States (as of February 2023). The Member States are usually represented by their National Hydrographer, the head of the national hydrographic service. We have asked them all three identical questions about milestones in the history of hydrography, future developments, and the jubilee journal The International Hydrographic Review (IHR) itself. Look forward to many interesting answers and exciting insights into our global hydrographic community!

Question 1	What are the most important milestones or evolutions in the history of hydrography and how have they impacted hydrography in your country?
Question 2	What technological developments fundamental to your work do you expect to see in the next few years?
Question 3	Do you have a favourite IHR article and why?

Renato Arruda

Brazil

Q1

In the 19th century, Brazil received French hydrographic campaigns that conducted surveys on the Brazilian coast and helped to train the first Brazilian hydrographers. These Brazilian hydrographers led to the creation of the Brazilian Hydrographic Office in 1876.
The creation of the International Hydrographic Bureau (today IHO) in 1921 reverberated on the standardization of cartographic products by the Brazilian Hydrographic Office. Subsequently, the acting of IHB/IHO and the interaction with other national Hydrographic Offices in the International Hydrographic Conferences induced the Brazilian Hydrographic Office to create the advanced course in hydrography in 1933, to adopt the First Brazilian Nautical Cartographic Plan in 1935 and to purchase two new hydrographic vessels in 1958.
The adoption of the IHO standard on the specifications for hydrographic surveys (S-44) in 1968 significantly conditioned the hydrography carried out by public and private entities in Brazil, bringing important consequences for the safety of navigation, for a better knowledge of the seabed in the Brazilian jurisdictional waters and to improve the training of Brazilian hydrographers."

Q2

The automation of data collection and processing, including the automatic calibration of hydrographic systems. Additionally, the implementation of new nautical products based on S-100 standard will be of fundamental importance for safer and more integrated navigation.

Q3

Article "Multibeam Processing for Nautical Charts", issued in the November 2009 edition of IHR. It was developed a reliable and efficient semi-autonomous workflow for processing multibeam data that supported the charting production.

Geneviève Béchard

Canada

Q1

The fundamentals of the science of hydrography (to measure and describe the physical features of those parts of the globe covered by water) and the reasons to do so (for safety of navigation), have remained largely unchanged since the first edition of the IHR, while we have benefitted from significant technological advances to revolutionize how we work. For Canada, with its vast water area, this has meant that technologies such as multibeam echosounders and GPS have facilitated the surveying of great swaths of that area. Further, databases and high-speed data communications has enabled the processing and management of the massive amount of data collected.

Separately, the grounding and oil spill of the Exxon Valdez in 1989 provoked substantial investment in Canada in the infrastructures to prevent similar disasters and accelerated the development of 'smart' electronic charts (e.g., ENCs) and the systems that can use them. For CHS, this meant developing and implementing production environments capable of generating products, and now services, for these systems. By June 1997 Canada released its first official S-57 ENC, and now has an ENC portfolio of 1,269 ENCs.

Q2

While the coverage and quality of data in CA has improved considerably, substantial challenges, particularly in northern waters, remain. Here, we know that developing technologies will play a key role. Uncrewed survey vessels (USVs) can act as force multipliers and operate in areas where the risk to traditional assets, like humans and icebreakers, is very high. USVs can also reduce the carbon footprint and environmental impacts compared to most current hydrographic survey operations. Remote sensing and satellite-derived bathymetry are becoming essential tools in the kits of hydrographers and planners. Underlying all new technologies and capabilities is the technical backbone that enables the secure and rapid transmission of data and information from collection to hydrographic offices then on to end users. Marine spatial data infrastructures will continue to develop as a framework for providing findable, accessible, interoperable, and reusable information. Lastly, the development of applications capable of exploiting S-xxx data will further drive the demand for data from hydrographic offices and other data providers.

Q3

Since its inception, the IHR has documented evolutions, indeed revolutions, in technology and in society which have changed the face of hydrography and how it is used. I have particularly enjoyed the earlier publications which we can now peruse since they have been scanned and digitized.

Arturo Oxley Lizana

Chile

Q1

We believe that the most important evolution in the history of hydrography is the massive gathering of bathymetric data that nowadays we are able to collect when conducting hydrographic surveys. The exponential growth of the volume of data collected from the single "leadline" to the existing arrays of "multibeam echosounders" and other modern systems, surely have impacted hydrography in Chile. Such impact has had an effect on the need to improve the professional preparation of the personnel and the development of new procedures, methods and software to manage these data and transform it in usable information.

Q2

We think that it is a fundamental issue to ensure that data, information and services provided by Hydrographic Offices reach end users, not corrupted. We believe that advancing on technological development that could minimize this concern would help and ensure a more reliable accomplishment of the work Hydrographic Offices are entitled and responsible for. Furthermore, we are of the opinion that in the next few years, our office should be provided new trusted navigational services, considering that more users will be demanding new hydrographic products like the S-100 "IHO Universal Hydrographic Data Model" specifications layers, this development will start with the implementation of the S-101 product specifications for our national electronical nautical chart.

Q3

We are of the opinion that each article has its merits on its own and therefore we think that it is not fair to intent to identify a favourite IHR article. Historical articles as well as recent articles elaborating on the new technologies and their application are fantastic records of the "a live" spirit that is strongly embedded in the behaviour of hydrographic surveyors worldwide.

Elikkos Elia

Cyprus

Q1

We distinguish various milestones in the development of hydrography. However, Cyprus as a state with short history in hydrography, has not been affected significantly by them. Since the establishment of the National Hydrographic Committee in 2007, the systematic evolvement of hydrography in Cyprus began. Cyprus has been investing in the knowledge of maritime space by making use of cutting-edge technologies such as: LiDAR, MBES, GIS, etc. It is obvious that the development of the S-100 standard and the concept of Digital Twin, introduces us to a new era.

Q2

Although we are not yet users of Artificial Intelligence (AI) technologies, it is obvious that the use of AI is increasing. We have already witnessed the use of AI in Unmanned Surface Vehicles, in the development of algorithms for the data collection and data processing, and many other fields. The development and use of AI will be the next technological revolution that will affect, not only hydrography, but also our lives in general.

Q3

The International Hydrographic Review is a useful tool in our work as it is a pool of the latest findings, trends and ideas in the science of hydrography. IHR articles contribute to advancing our knowledge in hydrography. In this context, it is difficult to distinguish a specific article.

Pia Dahl Højgaard

Denmark

Q1

The invention of the sonar represented a revolution in the determination of the ocean depths. Using acoustic waves, even the measurement of the deepest parts of the ocean takes only a few seconds. Sonar-based bathymetry has hugely improved our knowledge of the seafloor.

Since the first launch in the 70s, Global Navigation Satellite Systems (GNSS) have been continuously improved to the point that it is now difficult to imagine surveying without satellite positioning. The Danish Navy has been among the first performers of ellipsoidally referenced surveys.

The development of ECDIS has played a central role in the digital transition of the hydrographic community. The advent of digital nautical cartography has triggered huge innovations in how Denmark was managing and publishing geospatial data.

Finally, the S-100 family of standards is setting the path for a new generation of navigation services, which will ultimately replace the current traditional products. S-100 represents a great opportunity for a paradigm shift on how we support safety of navigation. S-100 will also support optimized ship-routing and, thus, the reduction of the environmental footprint of global shipping.

Q2

Although shipborne acoustic sensors will maintain a fundamental role for the coming years, a variety of other measurement technologies and platforms will be increasingly used.

Remote sensing will play an important role in this context. Specifically, spectrally derived bathymetry (SDB) has evolved considerably, and machine learning will likely play an important role in developing effective depth predictors.

Trusted Crowd-Sourced Bathymetry (TCSB) is ready for becoming operational, benefiting from the implementation of the VDES (AIS 2.0) technology for data transfer prioritization and scalability. The installation of a network of smart devices aboard designated partners' vessels has potential for becoming one of the primary sources of hydrospatial information.

The use of autonomous surface vehicles (ASVs) will also gain momentum in the next few years. However, to fully embrace autonomous surveying smarter sensors, system interfaces and algorithms still need to be developed. Nevertheless, we foresee ASVs becoming the primary platform to conduct systematic hydrographic surveys in the long term.

Q3

This is a very difficult question. There are so many great technical articles that have been published in the 100 years of IHR activity. Naming one about a specific technology or innovation would be somehow unfair for the many great ones not mentioned. As such, I prefer to mention a recently published article that is a bit different from the ones usually published on the IHR: "The Empowering Women in Hydrography Project" (https://doi.org/10.58440/ihr-28-n09). I feel the relevance of this project to finally overcome any unconscious bias and discrimination. If we do not support and cultivate the talents, skills, and creativity of women in Hydrography and hydrospatial disciplines, we will not succeed in our own mission to provide data and services for the benefit of society.

Jervis Marvin Robinson

Fiji

Q1	The most important evolution is the global move to digital methods of navigation. The move from conventional hydrographic and cartographic means is outstanding and is a strong indication of the interest in the subject globally. The intention to move to S-100 is strong willed and will see a lot of advancements in the near future.
Q2	The move from paper to electronic charts. The move to autonomous survey techniques.
Q3	No, not any.

Laurent Kerléguer

France

Q1

Of course, considering technology, one would immediately think of acoustic sounding and multibeam echosounders as key milestones and indeed they are! But sticking to the 100th anniversary, acoustic sounding is anterior. For me the game changer is the satellite positioning which has really and universally revolutionized the way we conduct surveys and their accuracy. It has been for the better, although there is still a taste of nostalgia when you think of field work that was required in the age of optical positioning with signals on shore.

The accuracy we have reached on moving vessels is just amazing. Autonomous navigation that develops would not be possible without Global Navigation Satellite System that seems so easy and natural to anyone nowadays.

More generally, hydrographers are metrologists, accuracy is a second nature for them. One has to admit that from ping to chart we have made significant progress on so many parameters that can spoil the result if you do not master them: speed of sound in the water, attitude of the platform, tide, data processing…

Q2

Massive data, how we get it and what we do with it.

The next biggest challenge for our community will be to bring quicker and more accurate answers to users.

We are still a long way from knowing our ocean from a holistic prospective, encompassing physical, chemical and biological parameters from shore to abyss. The high resolution in the deep that we need to survey ecosystems, will require a disruptive approach.

The technology is there, already dramatically accelerating our capacity to collect data at sea thanks to unmanned vehicles. Still we have to be able to deploy these systems in number, and the economic model to do this cannot be based on profit because there is not “deep sea B” and if we spoil it for exploitation it will probably be forever.

Another issue is our capacity to process massive data to deliver smart products. The ultimate smart product might be the digital twin of the ocean that will model the ocean in all its complexity and interfaces so that we can anticipate, at the laboratory, the consequences of our actions. That is ambitious and exciting challenge where Hydrographers have a major role to play.

Q3

Actually, all the articles are interesting for hydrographers. The editorial line is a good balance between articles on the evolution of methods, articles on future challenges and articles on experiences. It is also a good balance between writers from institutional organizations and industry.

I was particularly interested in the article Portugal’s cartographic responsibility in Africa as it is a good example of a positive approach to capacity building. Capacity building is essential for the IHO to progress as a collective organization as our standards and techniques are constantly evolving. The Portuguese experience described in this article has strong resonance for the Shom, which is engaged in similar processes. In particular, long-term support is an essential key to success. Congratulations to Portugal for what they are doing and for letting us know about it in this very nice article.

Thomas Dehling

Germany

Q1	I would name three milestones: The invention of the echosounder, the digitalization in hydrography and the widening scope of users and uses of hydrographic data. All three led to revolution or at least drastic changes and developments far beyond the technological changes.
Q2	On the surveying part, I foresee a regular combination of acoustic and optical sensors on all kinds of platforms from the subsea to space. On the processing part, I see a major development in the use of artificial intelligence. On the product part, there might be a disaggregation of ENC-data from a flat screen to diverse and tailored applications on-board and onshore. This will make use of the S-100 family of product specifications and will serve the broad range of automation in shipping and all other uses of hydrographic information.
Q3	Not really. I think it usually is the latest issue of IHR (currently 28) and at least a few of the articles. I will not name just one of them.

Dimitrios Efstathiou

Greece

Q1	1905 – Institution of the Hellenic Hydrographic Office under the Hellenic Navy General Staff 1908 – First Hellenic nautical paper chart 1919 – Greece cofounding member state of IHO 2004 – First edition of Hellenic ENCs
Q2	We expect HNHS products to be delivered in S-100 standards and an acquisition of a new hydrographic/oceanographic vessel.
Q3	IHR it of our most interest with its variety and importance of its articles.

Masayuki Fujita

Japan

Q1

Japan has conducted numerous hydrographic surveys within the vast national water. In 1960s, we started to use the LORAN-C system to determine the position of a survey vessel, whose value, however, generally included the error within a few hundred meters. After the GNSS service became available for public, not only positioning errors in the sea have been drastically improved, but also Japan has adopted the WGS84 instead of the Japanese local system, as GNSS services connected Japan, an isolated island country, to the rest of the world from the coordinate perspective. We established DGPS stations in 1997 along the coast of Japan, and successfully reduced the positioning error to approximately 1 meter. This success was doubly helpful for safety of navigation, that is, providing ships with their more precise locations and enabling creation of even more precise nautical charts than before. Moreover, we developed new technology using GNSS services for detecting seafloor movement in centimeters. This technology is essential for understanding the occurrence of earthquakes and is acclaimed in terms of contribution both to disaster prevention and mitigation, and to earth science.

Q2

Artificial Intelligence (AI) technology has been evolved rapidly and been utilized in various fields in recent years. I wish to see the introduction of the AI technology into hydrography, such as action control of autonomous survey vehicles, automatic compiling of nautical charts and processing huge LiDAR and/or MBES data, in the next few years.

Q3

None.

Toine Barten

Netherlands

Q1

Some of the most important evolutions in the history of hydrography for the Netherlands are the addition of the multibeam-echosounder and the implementation of GNSS on board of our hydrographic survey vessels. For a seafaring nation such as the Netherlands, that is so reliant on the ocean, being able to map the ocean detailed and accurately gives a huge boost to safety at sea. Our adoption of these systems has helped the Netherlands hydrographic service become a reliable and respected partner and a valuable addition to our national infrastructural management.

Q2

The advent of new technological advances in hydrography has the potential to change the way hydrographers will work in the future. Some of the most influential changes I expect to see in our own fleet are the use of drones, remote surveying, AI, and the implementation of S-100 standard. As a naval hydrographer, hydrography is split into two categories for me; military hydrography and civilian hydrography and therefore I will look at the future of both.

Military hydrography: One of our main military tasks is conducting rapid environmental assessments in, or close to, hostile territories. The improvement and further implementation of autonomous vehicles will make it easier and safer to operate in these environments. Especially the development of high-tech and reliable UUV's that can travel further away from the operator has the potential to be very important for military hydrography. Being able to operate closer to shore without being seen, as well as not risking any personnel means that it will be easier to use specialized hydrographic knowledge without the hydrographers themselves becoming a liability. Thus making both our work as well as the work of the forces we support easier and safer. Further developments in this area will create an increasing demand for the use of hydrography in the frontlines of any amphibious operation.

Another important development is the use of drones and deep learning/AI object detection in seabed warfare. Subsea cables and pipelines are vital infrastructure that has often been neglected in maritime warfare. However, the recent incident with the Nord Stream pipeline proves how vulnerable our subsea infrastructure really is. The implementation of autonomous drones with automated object detection would give us the ability to protect our cables and pipelines

Civilian hydrography: The use of autonomous vehicles, AI and the introduction of the S-100 standard will not only change hydrography, but will change shipping in general. The use of these autonomous systems will potentially accelerate the shift to online-hydrography thus changing the way hydrography has traditionally been carried out. Furthermore, these developments can facilitate an increase in survey speeds as well as the production of even more reliable data. This could prove vital for the advancement of autonomous shipping, which comes even closer with the new S-100 standard. When looking at it from a larger scope, these developments have the potential to reduce shipping costs and increasing efficiency – having an impact on the global economy.

Q3

While it is always difficult to pick a favorite, a very important article for us is: "Survey Plan Improvement by Detecting Sea Floor Dynamics in Archived Echo Sounder Surveys" by L. L. Dorst in the Vol. 5(2) released in August 2004. One of the main tasks of the Netherlands hydrographic service is charting the North Sea and Dorst's research gave us a better understanding of what is necessary to achieve this goal, on which other research projects have built further. It also gives us an understanding of why we approach surveying the way we do in the Netherlands and creates a solid foundation for our current operating procedures.

Chukwuemeka Ebenezer Okafor

Nigeria

Q1

The most important milestones or evolutions in the history of hydrography are evolutions from "Hand Lead line and Three Point Sextant" to "Wire Drag Survey in 1904", "Use of Single-Beam Echo Sounders in the 1930s" and finally the evolution of 2Side Scan and Multi-Beam Sonar Technologies in the 1950, 1960, and 1970s". The sonar technologies offered hydrographic surveyors the opportunity of obtaining seafloor images, thereby improving the ability to identify submerged wrecks and obstructions, with quantitative100 percent depth information of the sea bottom. These evolutions in the history of hydrography greatly increased the survey operations in Nigeria, and also offered a more accurate information, as well as redundant data that are relevant in other applications other than charting for safety of Navigation.

Q2

In the next few years, I expect to see more technological developments in the use of unmanned platforms for deployment of modern hydrographic survey equipment and the use of satellite for hydrographic data acquisition. These would not only increase coverage of Nigerian waters but will also ensure that some areas that have access difficulties could be easily surveyed.

Q3

Yes, The Article on "Variance in the Accuracy of Tidal Levels with Increasing Data Length" by D. R. Metters is my favorite because Nigeria will soon embark on a systematic installation of permanent tide gauges along its coast to commence systematic water level observation and measurement with a view to determining various National water levels for Nigeria. Therefore, this article further educated me on the confidence to be placed on levels obtained at varying time frame.

João Paulo Ramalho Marreiros

Portugal

Q1

The most important milestones in hydrography are the ones that allowed the improvement of data acquisition and processing, with better resolution and accuracy, making it available for nautical chart production and other applications. It is remarkable the evolution in hydrography with the invention of the single beam echosounder and the positioning of soundings by electronic systems. More recently, the availability of GPS and multibeam. With the development of computer systems, the processing of hydrographic data is becoming more efficient and evolve to the creation of the Electronic Nautical Charts.

All the above-mentioned improvements had impact in Portugal that has a strong tradition in nautical cartography. The establishment of the Portuguese Hydrographic Institute, in 1960, was a significant milestone. Since then, the practice of hydrography, keep evolving in pace with modern technologies, multibeam surveying and electronic nautical chart production, in the 1990's. The recognition of education and training in hydrography, IHO CAT, in 1983, was a relevant milestone, as well as the acquisition of two oceanic type hydrographic ships in the 1990's, the D. Carlos I class.

Q2

The transition to autonomous systems is a promising development. The advantages of such systems are immense. The process towards increased use of these new technologies seems unstoppable, however some hurdles still need to be overcome. Autonomous marine operations is not yet a mature technology requires improved regulation and training of specialized personnel.

Nautical cartography will evolve with less demanding for the traditional paper chart. The new Hydrographic Geospatial Standard for Marine Data and Information, known as S-100, together with its supporting geospatial information infrastructure, that is under development and implementation by the IHO will have transformative impact in maritime navigation and in the support of the marine environment and costal infrastructures with significant economic, commercial, technical, risk avoidance and environmental benefits.

With the ever-increasing and affordable capacity computing power to process and store data, the emergence of artificial intelligence in hydrography and ocean sciences is full of challenges and opportunities. This is an exciting and important developing field to follow by the hydrographic community.

Q3

The first article I remember to read at the IHR, was devoted to a new survey vessel built by the Portuguese Navy, published in 1989, LXV (I), "New survey vessels for the Portuguese Navy", by P. Fiadeiro and A. Silva Ribeiro. It was the first ship where I served as a midshipman, the same year when it was published.

Also the article published just after the creation of the Portuguese Hydrographic Institute, in 1962: Vol. XXXIX (I) "The Portuguese Hydrographic Office" and, in the same volume, I should refer the article "Prince Henry of Portugal and the Progress of Nautical Cartography" by Teixeira da Mota, because of its historical relevance.

The IHR is well known by the Portuguese hydrographic community for publishing the latest technical developments in hydrography. Among them, just to mention two articles: one published in 1976: Vol. LIII (I), "Satellite Navigation in Hydrography", by Eaton, R. M., Wells, D. E. and Stuifbergen. More recently the article published in May 2017 "Navigation Sonar: More Than Underwater Radar — Realizing the full potential of navigation and obstacle avoidance sonar" by Ian Russel and R. Glenn Wright.

Gustavo Adolfo Gómez-Pimpollo Crespo

Spain

Q1

Hydrography, being a science, has evolved hand in hand with technological developments mainly occurring in the last few decades. On this regard, the following milestones should be highlighted:

- GPS positioning. It meant an improvement in logistical and operational planning of hydrographic cruises, resulting in greater efficiency in survey performance as well as greater accuracy in data captured.
- Introduction of the multi-beam echo sounder. It meant a notable leap forward in quality compared to the single-beam echo sounder, by attaining total coverage of the seafloor, which made it possible to identify potential dangers to navigation not detected with the previous technology, and to improve data used to produce nautical charts, increasing the safety of navigation.
- The use of unmanned vehicles, not as a part in the history of hydrography, but due to their current and future relevance, they will have a great impact in the development of hydrographic surveys.

Q2

The main technological development in the hydrography field will be using Artificial Intelligence (AI) in the cartographic production line (such as using AI to edit bathymetric data) regularly.

Indeed, there are already companies that have developed AI algorithms to edit acquired bathymetric data, but these algorithms are the first steps of research, considering that much more advanced algorithms will be achieved for use in the field of hydrography, oceanography and geodesy, both in machine learning and especially in deep learning.

The employment of AI will allow the collection of a large amount of bathymetric data obtained by a large number of vessels sailing with multi-beam echo sounders around the world. All this information will be stored in clouds for processing and integration into their companies or hydrographic services.

This is another great challenge for humankind, to have better knowledge of the seafloor because we have already mapped about a quarter of our seas and oceans, especially in deep waters. That is to say, we are still far from knowing what we have underwater, and the resolution of our global map is lower than that of the Mars surface.

Q3

It is complicated to choose only one because there are many interesting articles. However, there is one that I want to highlight, the article "Review of active and passive optical methods in Hydrography" written by Dr. Gottfried Mandlburger. I liked this article quite a lot because it is very complete. It is very complicated to explain clearly in one article the different employed optical methods (active and passive), their use on board platforms (satellites, crewed or unmanned aerial vehicles and remotely operated vehicles), the available different acquired data processing techniques, as well as indicating the great variety of applications these methods have.

Roshan Ranaweera

Sri Lanka

Q1

The National Hydrographic Office (NHO) of the National Aquatic Resources Research and Development Agency (NARA) was established in 1984 and is accredited by the International Hydrographic Organization (IHO) as the focal point for Hydrography in Sri Lanka. The project “Strengthening of the National Hydrographic Office of the National Aquatic Resources Research and Development Agency of Sri Lanka” was initiated in 1984–1986 and commenced in 1988 as a technical cooperation project between Sri Lanka and the Federal Republic of Germany. The project's objective was to enable the NHO to provide better and more comprehensive hydrographic information to users, thus contributing to the overall goal for a better and improved management of aquatic resources of the country’s exclusive economic zone. The Project was successfully concluded, and NHO was vested in its legal power in 1996. Since 1988, the NHO has been surveying Sri Lankan waters to ensure their safe, sustainable, and navigable use.

Q2

Sri Lanka has been making efforts to position itself as a maritime hub in the Indian Ocean region. The island nation’s strategic location on major shipping routes and its modern ports make it an attractive destination for transshipment and other maritime activities. In this regard, assurance of navigational safety and efficiency for international and domestic vessels is essential, besides developing port infrastructure. Therefore, Sri Lanka plans to undertake a digital transformation initiative to fully modernize traditional products and services, deliver high-quality data and digital services to our users, and provide data-driven services for more efficient shipping to boost our blue economy.

Q3

Research and technology articles are my preferred section – a way to advance understanding of new frontiers in ocean mapping. IHR always features cornerstones in research/technological development of the hydrography.

Bernice Mahabier

Suriname

Q1

Suriname was a colony of the Netherlands until 1975 hydrographic surveys and production of paper charts were responsibility of Netherlands.
Various missions of experts from the Netherlands came to Suriname and, in the field of shipping, for the then Shipping Service, with the support of various departments of the Dutch Ministry of Traffic and Public Works, a program for rehabilitation was drafted. This emergency plan that was proposed in 1989 was called project 'Improvement Accessibility Surinamese Ports' and its final goal was an independent Maritime Authority Suriname (MAS). The MAS was cable of conducting their own surveys and the chart production was still done by the Netherlands. In 2005 the MAS renewed it membership at the IHO and with that, the training and partnership opportunities were endless. The MAS trained the personnel to not only advanced their capabilities in survey, but produce paper charts, ENCs and aids to navigation. Partnerships were established with neighboring countries France, Brazil and other service supporting organizations UKHO and IC-ENC.

Q2

The transition to autonomous shipping, whereas hydrographic offices like Suriname must facilitate this development with the new S-100 and S-200 standards .
The transition to a full digital service means transition of the Hydrographic service to meet the obligations and standards. The processes, human resources, digital infrastructures need to be adjusted to meet the development.

Q3

The article of TCarta , using Satellite-Derived Bathymetry in areas with high turbidity.

Magnus Wallhagen

Sweden

Q1

During the past century the technical development in hydrography has been tremendous, but I would like to highlight three important milestones. First the establishment of IHO 1921 as the competent organization to standardize hydrographic information. Sweden was one of the founding Member States of the IHO and Sweden was also founding Member State of the first Regional Hydrographic Commission (RHC), the Nordic Hydrographic Commission. The establishment of RHCs to implement the standards and measures taken within IHO is the second important milestone I would like to mention. Last but not least the implementation of the first global standard for electronic geographic information, namely the S-57 standard for ENCs, was a remarkable success for the IHO. Already during the 1990-ies, many years before Google Maps was invented, IHO had a standard ready for usage internationally in navigational systems, which we today call ECDIS. This has established IHO as the reliable International Governmental Organization for standardization of existing and future products and services for the e-navigation era.

Q2

The development of the new generation of standards for hydrographic products and services, S-100, is critical to take the next step in the usage of hydrographic information. The existing ENCs, in the S-57 format, is more or less an electronic version of the paper chart. From an HO perspective and also from IHO we know that we and other stakeholders have much more data which could be useful for navigation and also usage beyond navigation. S-100 is needed to standardize these data and to make it possible to combine different datasets in a structured way. This will contribute to not only safer navigation, but also to more efficient navigation when you could optimize your route and optimize the loading of your ship. Optimized routes and optimized loading will also contribute to less environmental impact from the shipping industry. S-100 will also be an important step towards more automated navigation, with machine readable datasets.

Q3

The 12th edition of the IHR, which was issued in November 2014 was a special edition with articles and notes submitted by members of the Baltic Sea Hydrographic Commission (BSHC). The Editor of that time, Ian W Halls, states in the Editorial that "this edition provides an excellent example for how other regional hydrographic commissions can learn from one another and cooperate". I have always considered the cooperation within the BSHC to be very unique, which has contributed to a well-established political commitment for a re-surveying plan for the Baltic Sea and cooperation projects with substantial EU-funding. This special IHR BSHC edition gives an insight of the level of cooperation within this RHC.

Rhett Hatcher

United Kingdom

Q1

There are so many landmark moments to highlight from the history of hydrography, and we are all aware that today's innovations are built on the achievements of our predecessors.

Hydrography is a discipline that has always benefited from tremendous international cooperation, which has spurred much of our progress. This goes back to when zero-degree longitude was agreed by the main chart producing nations in 1884. We should also point to the work of the United States Coast and Geodetic Survey's Nicholas H. Heck in developing and perfecting wire-drag surveys between 1906 and 1916, as well as the discovery of the 'echo sounding' technique by the German physicist Alexander Behm, following the Titanic disaster.

From a UK perspective, we can point to the use of constant radar ranges to assist the surveyors of HMS Seagull in 1947, and the first sidescan sonar that was undertaken by HMS Bulldog in 1987 of Mounts Bay in Cornwall.

We then saw a rapid series of advances from the advent of the systems that enabled full bathymetric coverage of the seabed in the 1980s and 1990s, including the ECDIS trials undertaken in the North Sea in 1988. In 1994 Global Positioning System (GPS) become fully operational for navigation systems and in 1997, the UKHO produced its first ENC, foreshadowing the digital era that is now well and truly upon us.

I also believe that we will look back on the Nippon Foundation's GEBCO Seabed 2030 Project as a very significant initiative in the history of hydrography, bringing together global expertise from a wide array of partners, including the UKHO, as it strives to achieve the complete mapping of the world's oceans by 2030.

Q2

It is hard to look beyond the S-100 standard when it comes to the technological innovations that will define the next decade for digitally-focussed hydrography. This new standard will underpin the next generation of marine data products, including gridded data, high-density bathymetry, dynamic ECDIS, under-keel clearance management, web-based services and more.

By equipping them with far more granular bathymetric data, seafarers will enjoy significantly enhanced situational awareness, helping them to make better navigation decisions. More than this, S-100 will also play an important role in helping shipping to meet the new challenges and goals of our era, including decarbonisation and autonomy, by enabling safer and more efficient voyage planning, passage execution and traffic management.

We also see great promise in the potential of Artificial Intelligence and Machine Learning as technologies that can significantly speed up and automate our work. We have seen already through our Generalise Addictive Model (GAM) Service that machine learning can make an important contribution in tackling the increasing levels of bathymetric data cleansing and verification tasks that we face, delivering the same levels of certainty and accuracy but at unprecedented speed.

From a UK perspective, we are also excited about the possibilities for the new UK Centre for Seabed Mapping (UK CSM). The shared vision of the UK CSM members is for it to become the key focal point for the UK's seabed mapping community. The UK CSM has over 20 members and will play a vital role in co-ordinating the collection, management and sharing of seabed mapping data through collaboration, as well as championing the importance of marine geospatial data in the UK.

Q3

It's hard to choose! Perhaps because it reflects so much of our thinking at the UKHO, I thought the article in Volume 27 of IHR on NOAA's decision to retire its paper chart portfolio and transition to ENCs was a very significant article and also a compelling explanation of the reasoning behind the decision (https://doi.org/10.58440/ihr-27-n03). The authors set out a very clear rationale for NOAA's decision to focus exclusively on ENC production, highlighting the considerable benefits to the mariner, as well as the rapid decline in demand for paper charts. As the article rightly concluded, NOAA may have been the first hydrographic office to take this step, but it will not be the last. The UKHO has since followed suit, setting out our own plans to withdraw from the production of paper charts and increase our focus on digital navigation products and services, for the same reasons that were so well outlined in this article.

José Pedro Domínguez Viloria

Uruguay

Q1

We have had many milestones, among which stand out the beginnings of the surveys in the Río de la Plata at the beginning of the last century, in the Uruguay River, these being our bordering rivers with the Argentine Republic, the Merín Lagoon, which is the border with the Federative Republic of Brazil, from which we actively participated in the different Boundary Treaties of those geographical spaces that are so important to our countries. Another very important challenge recently was being in charge of the survey to establish the Outer Limit of the Continental Shelf in accordance with Article 76 of UNCLOS. And without a doubt at present the development and maintenance of the official Electronic Nautical Cartography according to the S-57 standard of the IHO. Boundary Treaties signed with our neighboring countries give Uruguay legal strength in matters of maritime space ordering, in the different uses of natural resources and their conservation, some even shared as it is related to fishing in the front with the Argentine Republic, or the Uruguay-Brazil Waterway in Laguna Merin proyected.

Q2

We hope that in the short term the hydrographic acquisition systems will be more accessible in terms of cost, which are often difficult for developing countries to achieve and thus be able to access them to achieve more effective surveys of our jurisdictional waters in the process of develop new products according to the IHO S-100 standard.

Q3

Not specifically.

Benjamin K. Evans

United States of America

Q1

Selecting a single milestone in hydrography with its long history of innovation is nearly impossible. However, a major step forward which revolutionized the full arc of the hydrographic workflow, including field surveying, nautical cartography, and the use of our data by mariners was the advent of full bottom coverage survey techniques. The ability to fully ensonify the seafloor to produce a high resolution model of the bathymetry and seafloor features completely changed hydrographers approach in the field. While these systems undoubtedly made hydrography more accurate and efficient, they ushered in a new set of requirements for supporting technologies. These dense datasets and the uncertainty estimates possible from multiple measurements of the seafloor in each location gave rise to a whole new class of surface-based products for navigation, modeling, and resource management. The promise of this is realized with the advent of high resolution bathymetric overlays using the S-102 standard. These new products, made possible by full bottom coverage survey methods, are allowing mariners to increase safety, optimize use of available water, and reduce congestion in the world's seaports.

Q2

Increases in our capacity and efficiency of hydrographic data acquisition, and more importantly, our ability to convey data to stakeholders in fit for purpose format in a timely fashion. In the field, we see the value of uncrewed systems to amplify the effectiveness of traditional platforms. UxS will capitalize on advances in bandwidth, low-latency connections between platforms and shore, quickening data ingestion and product creation. Ashore, AI will aid in analyzing data from a wider range of sources for ingestion into authoritative, current seafloor models like NOAA's NBS. Marine modeling, guided by high-res bathy and other data, will improve our forecasting of water levels, currents, and other marine phenomena. Automation will increase efficiency of transforming data streams into products for users needing authoritative geospatial data for our oceans and coasts. Advances in data models plus next-gen ECDIS and other chart displays, will allow mariners unprecedented use of data to meet their needs, like customized depth curves derived from S-102 overlays. The S-100 model displays these products in a unified operational picture, increasing safety, and efficiency of navigation.

Q3

The Navigation Surface: A New Database Approach to Creating Multiple Products from High-density surveys by then-LT Shepard Smith, NOAA, Dr. Lee Alexander, and CAPT Andy Armstrong, NOAA (ret.). This article from 2002 set the vision which has guided much of our work over the course of my career. The navigation surface concept was a major shift in hydrography and charting, transitioning from individual depth soundings to a gridded model of the seafloor in which depth estimates and uncertainties went hand-in-hand. This opened the door to the "chart of the future", in which bathymetry, water levels, currents and other data could be combined into a unified picture for the mariner. We've been working toward this vision since this article was published, and our Precision Marine Navigation program and the S-100 framework put us on the cusp of achieving it. Link to article: https://journals.lib.unb.ca/index.php/ihr/article/view/20584/23746

John Nyberg

United States of America

Q1

There have been incredible changes to the way we collect and present our information throughout hydrographic history, but there have also been massive changes to the way we manage our workforces, data, and products. NOAA found its origins in coastal exploration during a time when it needed to acquire modern scientific tools from across the Atlantic. In my opinion, the recognition of the importance of hydrographic and geospatial science, from a national perspective, to support marine navigation is the most important milestone in US hydrographic history. This commitment to science and exploration has lasted for over 200 years and we recognize it as foundational to our program and work. The transition to a digital world encompasses a large number of significant independent milestones – lead line to multibeam sonar data collection, celestial to satellite positioning, copper plate engraving to database driven chart production, paper to electronic navigation systems, and many more. These have had profound impacts on the way the US manages its hydrographic programs, the skill sets that makeup our workforces, the types of information we manage, and the tools that we use for our daily work.

Q2

Moving to S-100 based navigation is the hydrographic milestone of our era. This impactful transition will allow us to visualize a wide variety of data for mariners to use in a single system. With S-101 underpinning a wider array of high resolution bathymetry, surface currents, weather and more, we will be supporting safer, more efficient, sustainable marine transportation. The way data is managed will be fundamentally different as we progress through the transition to S-100. We will need to build partnerships within our countries, internationally, and with the private sector. Some S-100 products will likely overlap and may be available from multiple sources. We can expect to see non-hydrographic offices as the responsible producers for information that is intended for use in an ECDIS. We will have to consider both technological and administrative measures to manage these new arrangements, including system based solutions in the ECDIS, new methods of data delivery, and increased attention to sharing data through a federated approach. I imagine a distribution system that delivers data from the producer to the user with a thin system in the middle to manage product usage and currency.

Q3

Singapore's National Marine Spatial Data Infrastructure 'GEOSPACE-SEA': Enabling Hydrospatial Context and Applications in a Changing Ocean and Seascape by P. Y. Pang, P. Oei. I really enjoyed this article because it highlights the benefits of MSDI and more importantly the values of making data available and how our data is imperative for uses beyond navigation including coral reef management, coastal planning, and many more. I also really appreciated the discussion on partnerships and operational sustainability for ensuring MSDI success. Link to the article: https://iho.int/uploads/user/pubs/ihreview_P1/IHR_November2020.pdf

Hydrographic datum planes

Author
Harry A. Marmer

Preamble

This manuscript is a reprint of the original paper previously published in 1929 in the Hydrographic Review, a predecessor journal of The International Hydrographic Review (IHR, https://ihr.iho.int/): Marmer, H. A. (1929). Hydrographic datum planes. *Hydrographic Review, 6* (1), 37–51. https://journals.lib.unb.ca/index.php/ihr/article/view/28153

1 Introduction

In order that the navigator may readily determine safe lanes of travel, it is of prime importance that he have at hand charts showing the depth of water in the region through which his vessel is to pass. But the rise and fall of the tide causes the depth at any point to vary continually. How then is the depth to be represented on such charts? Manifestly the first step in the solution of the problem is to consider the depth as consisting of two parts, the first invariable and the second variable. The variable part depends on the stage of the tide, data for determining this being given in tide tables. The invariable part is shown on hydrographic charts as the depth below some fixed datum. Thus arises the need for hydrographic datum planes.

In the tide tables too, the rise and fall of the tide must be given with reference to some datum. Obviously it is of advantage, for any region whatsoever, to use the same datum for both tide tables and charts; since the depth at any time will be derived immediately on applying the data in the tide table to the depths shown on the chart. It would therefore appear at first thought as if it made little difference what datum plane was used on hydrographic charts, so long as the same datum was used in the tide tables. This, however, is not the case, as will appear presently.

The first datum plane that suggests itself as suitable for referring depths in the sea is that of mean sea level. Indeed, in a sense the depth at any point may be said to be its depth at mean sea level, for it is clear that while the actual depth at that point is continually changing, being sometimes more and sometimes less than the mean sea level depth, its average depth is that reckoned from mean sea level. And for many purposes mean sea level is the most satisfactory datum from which to reckon depths.

For the purpose of the navigator, however, a low water datum is much more satisfactory. The critical depths in navigation are those in shoal areas in which the depth is insufficient for the draft of the vessel. The approximate minimum depth at any point obviously occurs when the tide is at low water. Hence, by using a low water datum, the depths shown on the chart give directly the approximate minimum depths. Another advantage a low water datum has for hydrographic purposes is that with such a datum the corrections to depth for stage of tide are predominantly positive, while with the datum of mean sea level these corrections would be half positive and half negative. For these reasons nautical charts, without exception, make use of some low water datum plane to which the depths shown are referred.

If the tide fell to the same depth at each low water the problem of hydrographic datum planes would be a simple one. Under such conditions there would be but one low water datum and a single low water observation would be sufficient for its determination. But, unfortunately, the fall of low water varies from day to day, this variation being in part periodic and in part non-periodic. At the very outset therefore the hydrographer is faced with the two aspects of the problem, namely, the choice of a suitable low water datum plane, and the accurate determination of this plane.

2 Types of tide

Not only does low water vary from day to day, but this variation is found to be different at different places. In fact, at first glance it appears as if the tides at different places have nothing in common except the bond which relates them to moon and sun as the exciting causes. In the time of occurrence of low water, in the extent of its fall and in the character of the variations which it exhibits, there is bewildering variety. Various classifications of the tide may therefore be made depending on the characteristics chosen as criteria.

In connection with the problem of datum planes, it is of advantage to classify the tide into various types,

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so that as soon as the type of tide be comes known, its general characteristics become known and the hydrographer is then in a position to choose the most suitable datum plane. The most satisfactory classification of tides is that with reference to the form of the tide curve and to the periods of rise and fall. In accordance with this classification, tides may be grouped under three general types known respectively as semidaily, daily, and mixed types of tide. Instead of semidaily and daily, the terms semidiurnal and diurnal are frequently used.

The semidaily type is one in which two high and two low waters occur in each tidal day, the morning and afternoon tides resembling each other closely. The daily type is one in which there is but one high water and one low water in a tidal day. The mixed type of tide is one in which there are two high and two low waters in a tidal day, but with considerable differences between the morning and afternoon tides. In this connection it is to be recalled that the tidal day has the same length as the lunar day, namely 24 hours and 50 minutes.

The well-known sine or cosine curve may be taken to represent, in idealized form, the semidaily and daily types of tide, the semidaily having two maxima and minima in a day and the daily but one maximum and one minimum. These types of the tide are therefore of a relatively simple character. The mixed type is more complex, consisting as it does of a mixture of the daily and semidaily types. Numerous forms of the mixed type arise, depending on the relative magnitudes of the daily and semidaily constituents and on their differences in phase.

The distinctive feature of the mixed type of tide is the difference between consecutive high or low waters, that is between morning and afternoon tides, this difference being known as diurnal inequality. As an example of the mixed type of tide, the tide at San Diego, California, may be cited, the tide curve for two days, April 22–23, 1920, being shown in Fig. 1.

For the two days shown, the average range of the tide at Seattle was about 9 feet. The greatest difference between morning and afternoon high waters during these two days was less than a foot, but morning and afternoon low waters differed by 8 feet. A comparison with Fig. 1, which is the tide curve for San Diego for the same two days, brings out clearly the difference between these two forms of the mixed type of tide.

As an example of the third form of the mixed type of tide, in which the inequality is exhibited principally by the high waters, the tide at 'Honolulu, Hawaii, may be instanced. And for comparison it will be interesting to take the tide curve for the same days as in Fig. 1 and 2. The tide curve at Honolulu for these two days in April 1920, is shown in Fig. 3.

At Honolulu, for the two days shown in Fig. 3, the range of the tide averaged 1.2 feet. Morning and afternoon low waters differed by something like one-tenth of a foot, but morning and afternoon high wa-

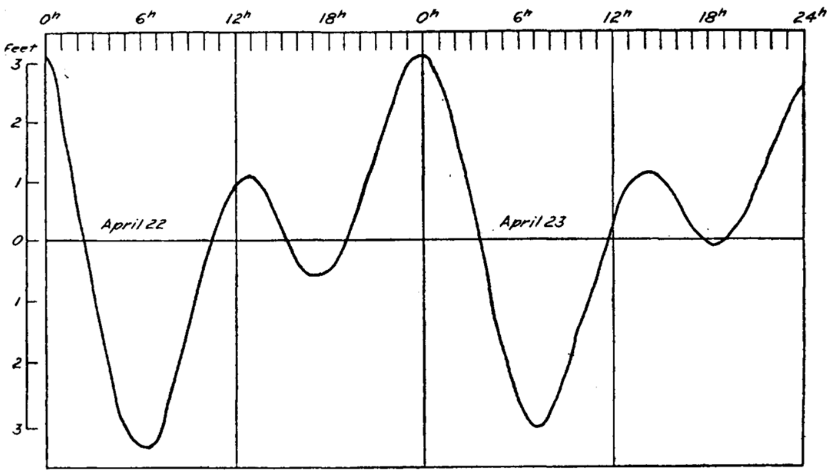

Fig. 1 Tide Curve · San Diego, California, April 22–23, 1920.

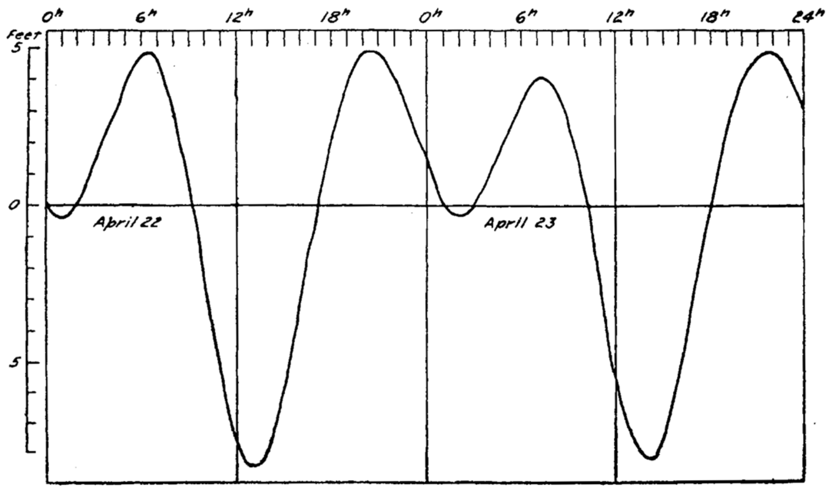

Fig. 2 Tide Curve · Seattle, Washington, April 22–23, 1920.

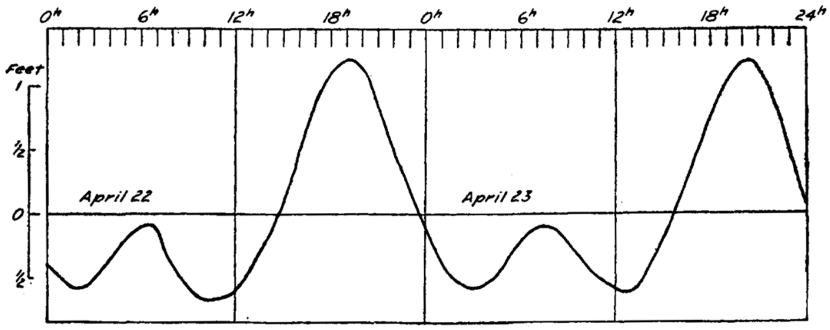

Fig. 3 Tide Curve · Seattle, Washington, Honolulu, Hawaii, April 22-23 1920.

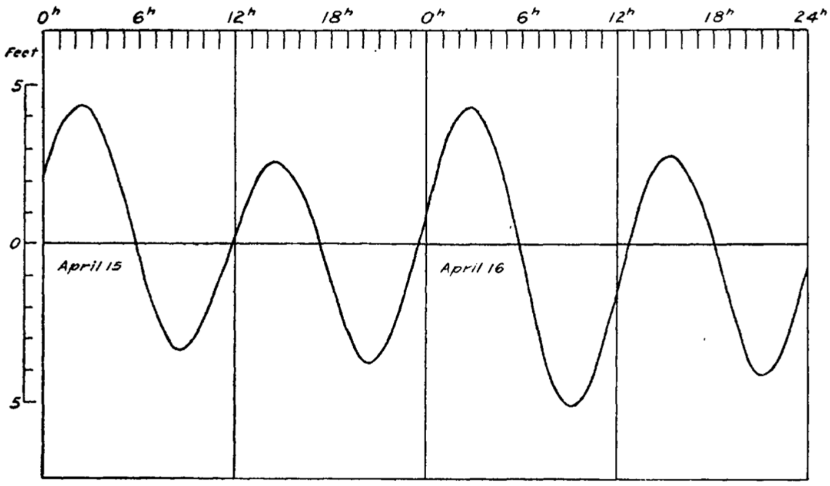

Fig. 4 Tide Curve · Seattle, Washington, April 15–16, 1920.

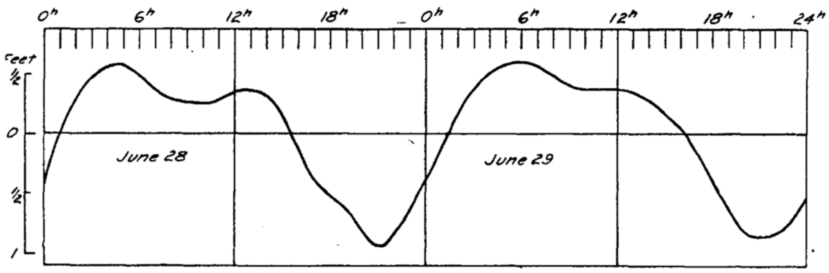

Fig. 5 Tide Curve · Galveston, Texas, June 28–29, 1920.

ters differed by 1.3 feet. It is of interest to note too, that the lower high waters for each of the two days did not rise as high as sea level, which is represented by the horizontal line in the figure.

The diurnal inequality in the tide at any place varies throughout the month in accordance with the declination of the moon, being least when the moon is closest to the equator and greatest when the moon is near its maximum semimonthly north and south declinations. This is true of both the mixed and of the semidaily types of tide. Therefore at the times of the moon's maximum semimonthly declination the semidaily type of tide exhibits some diurnal inequality; and likewise, when the moon is close to the equator the diurnal inequality in the mixed type of tide is much less than at other times. An example of this is seen in Fig. 4, which represents the rise and fall of the tide at Seattle for the 15th and 16th of April, 1920, a week prior to the time shown in Fig. 2.

A first glance at Fig. 4 would lead one to conclude that it represented a tide on the border line between the semidaily and mixed types of tide. And it is only when we correlate it with the moon's declination that its relation to Fig. 2 becomes clear. During the month of April, 1920, the moon was over the equator, in Seattle time, on the 15th, and at its greatest north declination on the 22nd. The variation in diurnal inequality as related to the moon's declination is brought out by a comparison of Fig. 2 and 4.

In view of the variation in diurnal inequality throughout the month it is obvious that there can be no very sharp line of demarcation between the semidaily type of tide on the one hand and the mixed type on the other.

By means of the harmonic constants, ratios between the daily and semidaily constituents of the tide may be used to define each type of tide, but for purposes of datum planes this is unnecessary. It is sufficient to define the semidaily type as that exhibiting little diurnal inequality and the mixed type as one exhibiting considerable inequality.

It is to be noted too, that in assigning the tide at a given place to a particular type, the reference is to the characteristics of the predominating tide at that place; that is, to the characteristics which the tide at that place generally exhibits. If the tide for the greater part of the time shows considerable diurnal inequality, it is to be classed with the mixed type, if little inequality, with the semidaily type.

Not only is it difficult to draw a sharp line of demarcation between the semidaily and mixed types of tide, but it is also difficult to draw one between the mixed type and the daily type. As the inequality in the tide increases it is evident that the difference between the lower high water and higher low water becomes less and less, and in the extreme case the two finally merge, giving rise to a daily tide. This is exemplified by the curve at Galveston for June 28–29 1920, shown in Fig. 5.

On June 22nd, the moon was on the equator and there was but little diurnal inequality in the tide at Galveston that day. Thereafter, however, with the increasing declination of the moon the inequality increased, the higher low water approaching in height the lower high water so that on the 28th, as shown in Fig. 5, these heights differed by but 0.1 foot and on the following day they merged, giving but one high and one low water in the day. At a number of places the tide becomes of the daily type part of the time, while the rest of the time it exhibits the characteristics of the mixed type of tide.

It is evident that the existence of different types of tide introduces a complicating factor in the choice and determination of suitable datum planes for hydrographic purposes. For the semidaily type of tide, for example, the plane of mean low water furnishes a very satisfactory datum since, insofar as diurnal inequality is concerned, there is but little difference between the low waters. But obviously such a plane is unsuitable at a place like Seattle where consecutive low waters may differ by 8 feet or more.

In addition to the variations in low water arising from the existence of diurnal inequality, there are other variations due to other causes. All these variations, however, may be treated under the same head.

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3 Variations in low water

On investigating the fall of successive low waters it is found that the variations to which low water is subject are of two classes. There are, first, the variations due to changes in wind and weather; and since such changes are primarily not periodic in character, the variations in low water brought about by them are likewise nonperiodic. Secondly, there are periodic variations depending on the changes in the phase, parallax and declination of the moon, the periods of which are approximately 29½ days, 27½ days and 27½ days, respectively. These periodic variations may be summarised briefly as follows.

At times of new and full moon the fall of low water is greater than the average, while at times of the moon's first and third quarters the fall is less than the average. Low water falls lower than usual when the moon is nearest the earth, or in perigee, and less than usual when the moon is farthest from the earth, or in apogee. When the moon is close to the equator, that is, when its declination is small, the two low waters of a day are approximately of the same height; but as the declination increases they differ in height, the difference between the two being a maximum about the time of the moon's greatest north and south declinations.

The low waters corresponding to the maxima and minima positions of each of the periodic monthly cycles of the moon have been given distinctive names. The low waters coming at the times of new and full moon are called spring low waters, and those coming at the times of the moon's first and third quarters are called neap low waters. The low waters occurring when the moon is in perigee are known as perigean low waters and those occurring when the moon is in apogee are known as apogean low waters. The low waters that come at the times of the moon's maximum semi-monthly north and south declinations, when the diurnal inequality is a maximum, are called tropic low waters, and those coming at the time the moon is close to the equator are called equatorial low waters.

It is to be noted, however, that at most places there is a lag between the maximum or minimum positions of the moon and the corresponding maxi mum or minimum low waters. For example, on the Atlantic coast of the United States spring low waters come, not on the day when the moon is full or new, but about one day later. Likewise neap low waters come about a day after the moon's first and third quarters. The interval by which spring or neap tides follow the corresponding positions of the moon is known as the phase age of the tide; the interval separating perigean or apogean tides from the moon's corresponding position is known as the parallax age of the tide: the interval between tropic or equatorial tides and the moon's corresponding position is known as the tropic age of the tide : these various ages differ from place to place and are generally ascribed to the effects of friction.

It is to be further noted that while the three periodic variations in low water discussed above are exhibited by the tide the world over, they are not alike at all places. In many regions the variation from spring low water to neap low water is the principal variation; in certain regions it is the variation from apogee to perigee that is the principal variation and in other regions it is the variation from equatorial to tropic tides that is the predominant variation.

Since the three monthly variations in low water do not have the same periods, it follows that various combinations of the variations may occur. For example, the low water that comes at the time when the moon is in perigee and at the same time is also full or new, will fall very much lower than the low water coming when the moon is in perigee and at the same time is in its first or third quarters. Fig. 6 illustrates the variation in successive low waters at San Francisco, California, for the month of June 1920, as related to the position of the moon.

In Fig. 6 the small circles give the depth of each low water below mean sea level, which is represented by the horizontal line. To indicate clearly the succession, each low water is joined by a straight line to the preceding and succeeding low waters. During the first few days of the month the tide is responding to the moon's extreme southerly declination which occurred on the first of the month. The moon was then also full, but close to apogee, so that the effects of each of these are very nearly neutralized. On the 9th the moon was over the equator and this is shown in the low water by but little diurnal inequality for the following few days. On the 16th the diagram shows the combined effects of the moon near its maximum northerly declination and in perigee at the same time that it is new. It is of interest to note that at certain times during the month low water did not fall below mean sea level.

It is to be noted that the periodic variation in the fall of low water from day to day is a function of the range. Moreover, in terms of the range the percentage variation is approximately the same over relatively

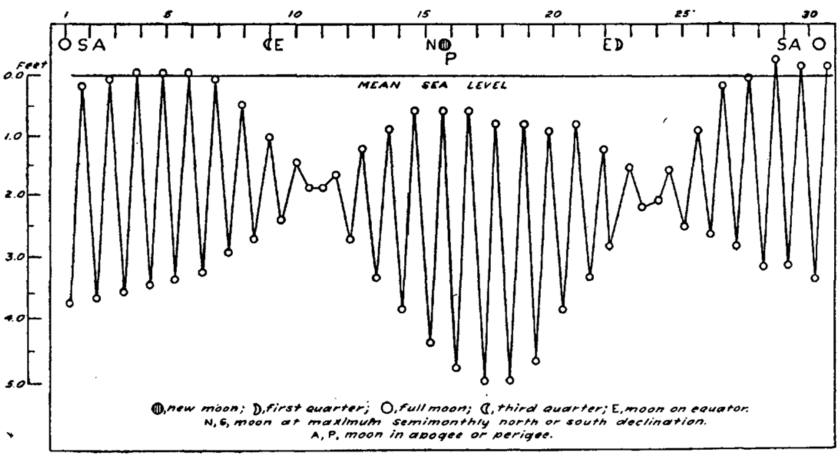

Fig. 6 Relation of low water to moon's position · San Francisco, California, June 1920.

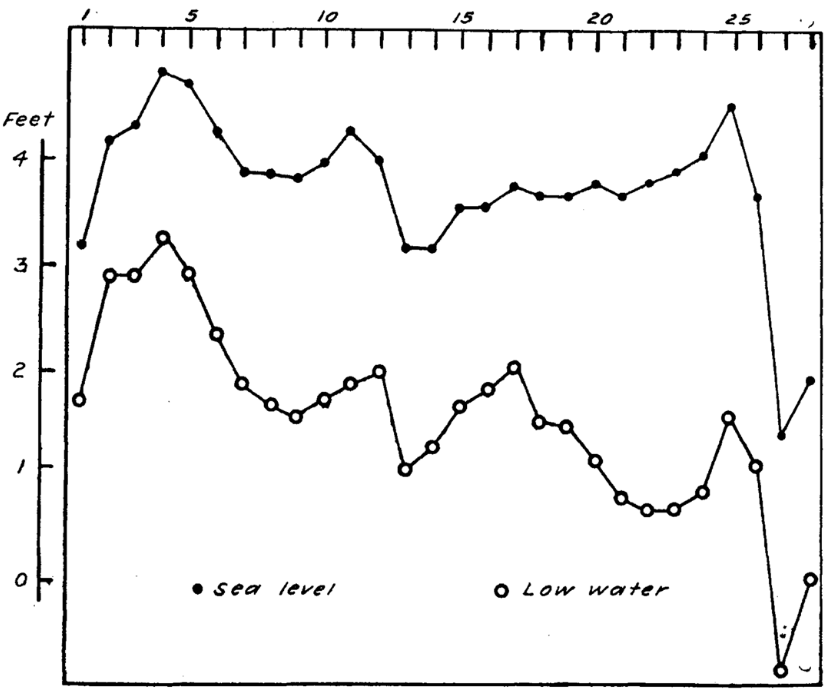

Fig. 7 Daily Sea-level and low water · Atlantic City, N. 3., February 1925.

wide areas. For example, all along the open Atlantic coast of the United States from Maine to Florida, which is a distance of considerably more than a thousand miles, the variation in the fall of low water from neaps to springs is from fifteen to twenty per cent of the range of the tide. This means, in other words, that the greater the range of tide, the greater the variation in the fall of low water. Thus at Eastport, Maine, the mean range of the tide is feet and the average variation in the fall of low water below sea level from neaps to springs is from 7.7 feet to 10.3 feet, while at Fernandine, Florida, where the mean range of the tide is 6.0 feet the average variation in low water from neaps to springs is from 2.5 feet to 3.5 feet. At Eastport, therefore, this variation is 2.6 feet while at Fernandine it is only 1.0 foot.

There are other periodic variations in low water depending on the moon's motion with respect to the earth. Thus the variation in longitude of the moon's node, which has a period of 18.6 years, introduces a variation in the fall of low water with a period of the same length. All these periodic variations to which low water is subject may be summarized by the statement that in consequence of the variations in the position of the moon relative to earth and sun, low water at any place varies from day to day, from month to month, and from year to year.

Superimposed on the periodic variations in low water discussed above are non-periodic variations due to changes in wind and weather. Heavy winds and marked changes in barometric pressure are accompanied by variations in the fall of low water of considerable magnitude. And at places situated on tidal rivers the variations in the run-off from the territories these rivers drain likewise give rise to variations in the fall of low water.

Such nonperiodic variations in low water are most advantageously regarded as arising from variations in sea level. For it is obvious that the mobility of the water permits wind and weather to raise or lower its normal level by considerable amounts. And since the rise and fall of the tide takes place from sea level, it follows that any cause that brings about a change in sea level must change in much the same way the depth to which low water falls. This is illustrated in Fig. 7 which gives in graphic form the daily heights of sea level and of low water at Atlantic City on the open coast of New Jersey.

The small solid circles of the figure represent the average height of sea level for each day, while the open circles represent the fall of low water below sea level each day. For the purpose of exhibiting the relationship between low water and sea level it will be sufficient to take the average height of the two low waters of each day, and this was done in Fig. 7. The upper diagram of this figure gives the change in the height of sea level from day to day during the month, and the lower diagram gives the average height of the two low waters of each day with reference to sea level.

A glance at Fig. 7 is sufficient to show that, notwithstanding the changes in the height of low water from day to day due to changes in the position of the moon, there is a variation also that corresponds to the daily variation of sea level. To the nearest tenth of a foot the average fall of low water at Atlantic City is 2 feet below sea level. For the month shown in Fig. 7 the fall of daily low water varied from less than 1½ feet on the 2nd to more than 3 feet on the 25th, this variation reflecting primarily the periodic changes due to the changes in the position of the moon. On the 2nd of February, 1925, the moon was one day past her first quarter and only two days before apogee; hence a much-reduced fall of low water. On the 23rd new moon occurred, and at the same time the moon was only two days past perigee; hence a much increased fall of low water.

As between the 4th and 27th of the month, Fig. 7 shows that the low waters differed by exactly four feet. This difference in only in part due to the change in the position of the moon. In greater part it is due to the difference in sea level between those dates. Fig. 7 brings out clearly how closely the low waters from day to day follow the corresponding changes in sea level.

Sea level is subject not only to daily variations but also to seasonal variations and to variations from year to year. And just as low water follows sea level in its daily variation so does it follow sea level in these longer period variations. The seasonal variation is of special interest since this is different for different places. Fig. 8 shows the curves of seasonal variation in sea level at three stations, one each on the Atlantic, Gulf and Pacific coasts of the United States. In Fig. 9 the seasonal variation in low water is represented for the same stations. A glance is sufficient to show that

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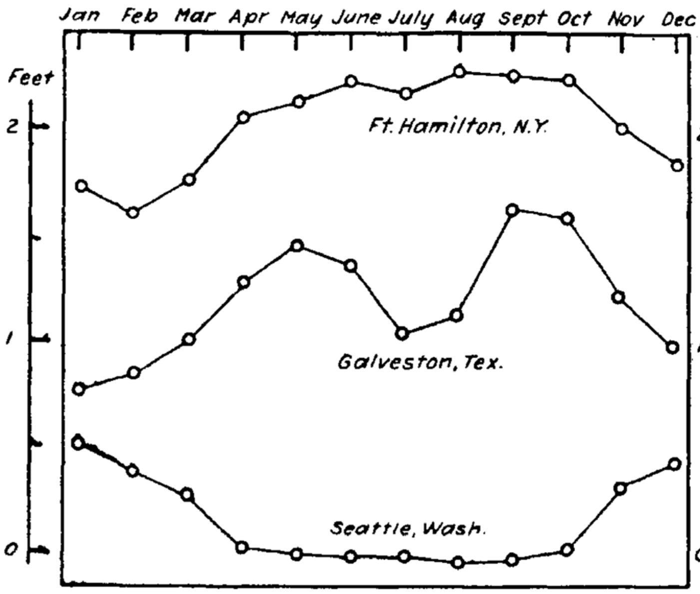

Fig. 8 Seasonal variation in sea level.

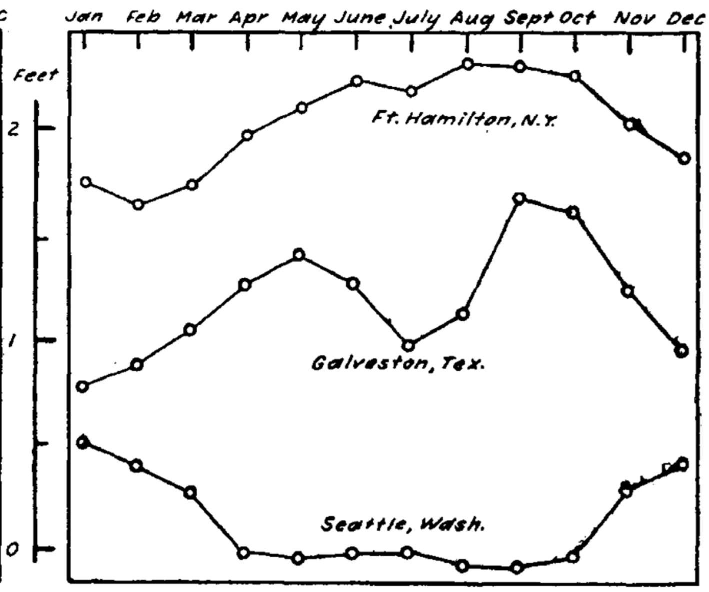

Fig. 9 Seasonal variation in low water.

at each place the variation in low water follows closely the corresponding variation in sea level. In both figures each curve is based on a number of years of observation.

The net effect of the periodic and nonperiodic variations is to make the fall of low water at any place a variable quantity. At Seattle, for example, the depth to which low water fell during the year 1920 varied from 10.5 feet below mean sea level to 2.0 feet above mean sea level. And for the twentyfive year period from 1900 to 1925 the fall of low water varied from 11.1 feet below mean sea level to 3.7 above, giving a difference between the two low waters of nearly 15 feet.

4 Choice of datum

Even after eliminating all but low water datum planes for hydrographic purposes, it is evident that the choice oi the most suitable datum is not a simple matter in view of the different types of tides and of the variations to which low water is subject. At first thought it might appear as if the lowest low water would constitute the most suitable datum for the hydrographic chart of a region. For, it may be argued, by the use of this datum the chart will show the least depths possible during unfavourable meteorological conditions. Furthermore, the corrections necessary for the rise and fall of the tide to give the actual depth of the water at any given time will always be additive, which obviously is an advantage.

Several serious objections, however, may be urged against the use of the datum of lowest low water. In the first place, what precisely is lowest low water and how can it be determined practically? For it is to be kept in mind that in the hydrographic survey of any locality a tide gauge is kept in operation for but a relatively short period of time, generally not exceeding several months. And the lowest low water during this period of observations – which almost without exception corresponds with the period of least variable weather conditions – may be several feet higher than the lowest low water during an exceptionally severe storm. Indeed, the very term "lowest low water" is so vague and indefinite as to preclude its use as a hydrographic datum plane if any pretence to precision is to be made.

But even if it were possible from a short period of observations to determine with precision the lowest low water that may occur in a given locality, are there not serious disadvantages in the use of a datum which makes the depths shown on the chart such as occur only at very rare intervals during periods of exceptional storms? At the present time, with the draft of vessels approximating the normal low water depths in the channels of many of the most important harbours, the datum of lowest low water would make the depths shown on charts so shallow as to give a totally erroneous idea of the navigability of such channels.

Still another objection to the adoption of an extremely low low-water datum has been raised by Rear-Admiral Phaff[1]. He directs attention to the fact that with the use of such a datum a positive danger may arise. For banks or rocks, which at normal low water are very nearly uncovered, will be shown as visible on charts making use of an extremely low low-water datum. Being shown as visible on the chart the navigator would attempt to use them as aids in navigation with the resulting danger of serious mistakes.

[1] International Low Water (International Hydrographic Bureau – Special Publication Nº 5, p. 8).

The most suitable datum plane for the hydrographic chart of a given region is the one that will most satisfactorily fulfil the following conditions: (1) show the least depths that normally prevail; (2) admit of easy and accurate determination; (3) represent some natural and easily-understood phase of the tide; (4) make necessary the use of only small negative corrections for the rise and fall of the tide, and only relatively few of these in number. The importance of the first condition follows from the preceding discussion on the use of lowest low water as a datum, and the importance of the second is self-evident. The third condition, however, requires further consideration in view of the advocacy, from time to time, of datum planes based on harmonic constants.

Such terms as low water, spring low water, and lower low water are easily understood and refer to phases of the tide with which the mariner is thoroughly familiar. Datums depending on these phases of the tide are not only readily understood but refer to easily observed phases of the tide. And it is to be noted that such datum planes admit of endless choice. That is, if for example a datum is desired which is found to be n feet lower than mean low water, we may specify it by stating that it is datum n feet below mean low water without in any way losing the advantages inherent in this natural datum.

At times, however, datum planes based on harmonic constants are advocated. It cannot be too strongly emphasized that for the purposes of the tidal mathematician the harmonic analysis provides the most satisfactory and most powerful method for the analysis and prediction of tides. But the harmonic analysis is a highly specialized mathematical process and necessitates a considerable amount of time-consuming numerical computations. The mariner and the hydrographic surveyor may well question whether the time and effort required for mastering the technique of harmonic analysis and acquiring adequate understanding of its results are not out of all proportion to its possible benefit for their purposes.

From a given series of tide observations the precision with which a datum plane can be determined is the same whether derived from an harmonic analysis or from a low water tabulation. But it is a much simpler matter to tabulate a tidal series with regard to some low water phase than to put it through the harmonic analysis. A natural datum plane, such as defined by or related to some observed phase of the tide, is therefore to be preferred to one derived through harmonic constants.

The fourth condition to be fulfilled by a suitable datum plane, namely, that it make necessary the use of only small negative corrections for the rise and fall of the tide, and only relatively few of these in number, requires but little discussion, for it is almost self-evident. In general, negative heights in tide tables are somewhat troublesome; but if they are small they may, as a rule, be totally disregarded by the mariner. For he realises that since it is impossible to make advance predictions of the weather in connection with the prediction of the tides as given in the tide tables, the predicted heights are to be regarded as approximations to the heights which will actually occur, because of the disturbing effects of wind and weather.

On examination, the datum used on the hydrographic charts of the various countries are found to vary. As a rule, however, these datums may be grouped under the following heads: spring low water, mean low water, lower low water, monthly lowest low water. In every case it may be assumed that mean or average values are intended and frequently this is indicated by the prefix, "mean".

A great deal of confusion has, however, resulted from the fact that datums were derived from short series of observations, without any attempt at correction to mean values. And as a rule it was impossible to make an accurate correlation between the datums of charts of contiguous areas because the relation to mean sea level of the datums used was not stated. It is altogether unlikely that radical changes will be made in the near future in the datum planes now being used. If these are referred to some well-known phase of the tide, are accurately determined and the relation to mean sea level given, the requirements for a good datum will be fulfilled.

It is to be observed that from a given series of tidal observations the best determined mean values will be for those phases of the tide for which the greatest number of observations are at hand. This means that as regards accuracy of determination from a given series of tide observations, the various datums that may be used for hydrographic purposes would list as follows: (a) mean sea level, (b) mean low water, (c) lower low water, (d) spring low water, (e) monthly lowest low water.

For the semidaily type of tide mean low water constitutes a very desirable datum for hydrographic purposes, especially in regions of moderate range of tide. It gives approximately the least depths that normally prevail and it can be accurately determined from relatively short series of observations. Where the mean range of tide is less than l0 feet the difference between mean low water and spring low water or even perigean spring low water is only a few feet so that large negative corrections for the tides are infrequent.

Where the tide is of the semidaily type but has a considerable range, it is frequently of advantage to use a datum lower than mean low water to obviate the necessity of large negative corrections for stage of tide. In this case spring low water, or as it is frequently called, mean low water springs, furnishes a satisfactory datum. If desired, however, a datum a given number of feet, say 2, 3, 4 or more feet below mean low water, may be used. This latter procedure has all the advantages inherent in the use of the datum of mean low water.

For the mixed type of tide, the plane of lower low water is very satisfactory. It fulfils the condition that by its use the chart shows the least depths that nor-

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mally prevail, since it is the average of the lower low waters. It is a well-known phase of the tide and may be derived with considerable accuracy from several months of observations. And since it is lower than the datum of mean low water, large negative corrections for stage of tide, which would arise because of the diurnal inequality in this type of tide, are obviated.

It is to be observed that in the use of the datum of lower low water, the existence of considerable diurnal inequality in the low waters is implied. And as a general rule this is true of the mixed type of tide. However, in any locality in which the mixed type of tide exhibits the diurnal inequality almost wholly in the high waters, the datum plane of mean low water would differ so little from that of lower low water that the former datum might be used if desired.

The datum of lower low is applicable even where the tide becomes diurnal at times. For where there is but a single low water in a day due to the tide becoming diurnal, it is obvious that it arises from the merging of the higher low water with the lower high water and hence the single low water is a lower low water.

Where the tide becomes wholly diurnal, the average of all the low waters may properly be called mean low water and therefore this datum may be used in such regions. If in any particular locality large negative corrections arise from the use of this datum, a lower datum may be used, this being defined by its distance below mean low water.

To the hydrographic surveyor there is a great advantage in the use of some natural datum which is referred to an observed phase of the tide, and which may be readily derived from a relatively short series of observations. For he is then in a position to derive the datum during the field season and to draw up a preliminary sounding sheet. If a longer series of observations determines the datum more accurately, it will differ from the preliminary determination only by a small amount. And since this difference is a constant, a note on the sounding sheet that all soundings shown are to be increased or decreased by this difference refers the depths to the well-determined datum.

Quite apart from their importance in connection with charts, accurately determined hydrographic datum planes are of importance in bringing to light changes taking place in the depth of a waterway. Such changes may arise from silting or erosion in the channels or from changes in the rise and fall of the tide. Accurate determinations of hydrographic datum planes at different times separated by years furnish the necessary data for determining not only whether changes in depth have taken place, but also to which of the causes the changes in depth are due.

The accurate determination of datum planes is a problem that falls within the province of the subject of tides. For the methods used and principles involved in the determination of datum planes, reference must be made to tidal manuals dealing with this phase of the subject[2].

[2] See for example Tidal Datum Planes, U, S. Coast and Geodetic Survey Special Publication Nº 135.

Definition of the words "Hydrographer" and "Hydrography"

Author
John Dodd Nares

Preamble

This manuscript is a reprint of the original paper previously published in 1934 in the Hydrographic Review, a predecessor journal of The International Hydrographic Review (IHR, https://ihr.iho.int/): Nares, J. D. (1934). Definition of the words "Hydrographer" and "Hydrography". *Hydrographic Review, 11* (1), 8-11. https://journals.lib.unb.ca/index.php/ihr/article/view/28159

Since the establishment of the International hydrographic bureau as a result of the London Conference of 1919, the question has often been discussed as to the correct definition of the word *Hydrography*, as on this depended to a certain extent the scope of work to be dealt with by the Bureau. The first President of the Directing Committee, Admiral Sir John PARRY, felt the necessity of clearly defining its meaning and to this end wrote an article in the first volume of the *Hydrographic Review* in which he tabulated the definitions of the words *Hydrographer* and *Hydrography* as given in some of the well-known dictionaries, and in the succeeding volume a letter from the Director of the Hydrographic Service of the French Navy was published in which he pointed out the confusion which existed on account of the different acceptations of the words (see *Hydrographic Review*, Vol. I, No. 2, page 171). At the International Hydrographic Conference of 1926, the questions of the scope of the work of the Bureau and the advisability of incorporating a description thereof in the Statutes was fully discussed but the latter was not considered necessary.

The question was again raised at the 1932 Conference when the Netherlands Delegate put forward a proposed definition of *Hydrography* (see pp. 127 and 128 of Report of Proceedings); as a result of which the Bureau was instructed to examine the question of the definition of the words *Hydrographer* and *Hydrography*, to collate the opinions of the States Members and publish the results of its enquiry in the *Review or Bulletin* (See p. 420 of Report of Proceedings).

Circular Letter No. 1-H of 1933 was issued accordingly and the replies received show, as was expected, that there is a considerable difference in the number of subjects with which the Hydrographic Offices of the different countries have to deal. Certain subjects, such as Marine Surveying, the Preparation and Issue of Charts, Sailing Directions etc., are of course common to all, but others such as the preparation of Air Maps, Meteorology, upkeep of Buoyage, etc. in some cases come directly under the Hydrographic Office whereas in others they are separate departments which, however, work in close touch with the Hydrographic Office. In the case of the U.S.A. Coast and Geodetic Survey, the *land* survey, with all its allied subjects such as Gravity observations etc., and the marine survey are under the same department and the officers may be transferred from one type of work to the other at the discretion of the Head of the Department.

Broadly speaking, *Hydrography* is a science particularly affecting the sea, but the carrying out of a Marine Survey entails a considerable amount of geodetic and topographic work ashore and it is therefore impossible to separate *Hydrography* from Geodesy; again, certain sections of Oceanography are essential to *Hydrography*, for instance it is necessary to know the density of the water before accurate Echo Soundings can be placed on the chart, and again the ocean currents are influenced both by the density of the water and by the prevailing winds, which brings Meteorology into the picture. Air Navigation is closely allied to Sea Navigation (both surface and sub-surface) and Sea Navigation is dependent on Marine Surveying so that the development of one is of the utmost importance to the others.

It will thus be realised how difficult, and well nigh impossible, it is to lay down hard and fast rules as to what definitely constitutes *Hydrography*.

In summarising the replies to Circular Letter No. I-H of 1933 as to what is considered to be work of the Hydrographic Services, the various subjects are grouped under three categories: (A) those common to all Services, (B) those common to the majority and (C) those to certain States only.

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CATEGORY A.

Comprises –

(1)	Marine Surveying, which entails Sounding, Triangulation, Tidal and Current Observations, Coastal Topography and Geographical Coordinates of coastal areas.
(2)	Compilation and publication of Charts of the Ocean, Coasts, Harbours and Navigable Rivers.
(3)	Compilation and publication of Sailing Directions, Light Lists and Tide Tables.
(4)	Issue of Notices to Mariners.
(5)	Magnetic Observations.
(6)	Purchase and supply of Hydrographic Instruments and Surveying Equipment.
(7)	Measured Distances.

CATEGORY B.

(1)	Compilation and publication of Distance Tables and Lists of Wireless Signals.
(2)	Meteorological Observations, including observations of Upper Air, Visibility of Lights, Fog etc.
(3)	Compilation and publication of Pilot Charts, both Sea and Upper Air.
(4)	Study of Oceanography, so far as it affects Marine Surveying (Temperatures, Densities etc. of Sea Water).
(5)	Purchase and Supply of Chronometers.

CATEGORY C.

(1)	Publication and issue of Nautical Tables, Navigation Manuals and Text Books	Italy, Japan, U.S.A., China
(2)	Publication and issue of Nautical Tables, Navigation Manuals and Text Books for Air Navigation	U.S.A., Brazil, Japan
(3)	Compilation and publication of certain Air Maps	France, Brazil, U.S.A., Japan
(4)	Compilation and issue of Notices to Airmen	U.S.A., Brazil, Japan
(5)	Publication of Lists of Buoys	Denmark, U.S.A.
(6)	Publication of information relating to Ice Movements	China, U.S.A
(7)	Publication of Nautical Almanac	Japan, Italy, Argentina, Greece
(8)	Purchase and supply of Navigational Instruments	Italy
(9)	Location of Leading Lines, Light Sectors and all Aids to Navigation	Norway
(10)	Publication of International Code of Signals	France, U.S.A

In addition, the Heads of the Hydrographic Services work in close collaboration with their Meteorological Offices, Lighthouse and Buoyage Authorities, Nautical Almanac Offices and National or State Observatories, even if those Offices do not actually come under their jurisdiction; they are also called upon to advise on Scientific Expeditions, Dredging questions, Jurisdiction and the improvement of Ports and of River Estuaries; in fact their duties may be said to include everything that tends to make Navigation easier and safer.

It is therefore considered that Hydrography *must* include all subjects listed under Categories *A* and *B*, and may include those under C also, and that so far as the work of the International Hydrographic Bureau is concerned it should include all the above subjects, the order of procedure in which it is taken up being that given under the above Categories.

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The terms Oceanography and Hydrography are both often used to designate the study of the Physical Properties of Sea Water, but it is considered that *Hydrography* should be confined solely to work in connection with the production and publication of Charts used for Navigation (with their complementary documents), thus keeping to the modern acceptance of the word *graph*; and that that section of oceanography which deals with the determination of the Temperature and Density of Sea Water should be termed *Hydrology*.

The following alternative definitions of the word *Hydrography*, based on the opinions expressed by the majority of the States Members, are therefore submitted for consideration:

1. HYDROGRAPHY is that branch of Science which deals with the measurement and description of the physical features of that portion of the Earth's surface which embraces the Oceans, Seas, Lakes, Rivers and other waters and their adjoining coastal areas, with special reference to their use for the purpose of Navigation.

   It embraces the carrying out of Marine Surveys including Triangulation, Sounding, Magnetic and Astronomical work; the Study of Tides, Tidal Streams and Currents, also of Oceanography and Meteorology so far as they affect Navigation; the compilation and publication of Charts, Sailing Directions, Lists of lights, Tide Tables, Lists of Wireless Signals, Notices to Mariners and other information useful to Navigators.

   Note. – The term Navigation is specially meant to apply to the movement of a vessel on the surface or below the surface of the water, but may include that through the air also.

2. HYDROGRAPHY is the science of measuring Oceans, Seas, Lakes, Rivers and other waters with their marginal land areas, inclusive of all the fundamental elements which have to be known for the safe Navigation of such areas, and the publication of such information in a suitable form for the use of Navigators.

3. HYDROGRAPHY is the science by which data concerning the true con figuration of the Earth, as far as useful to Navigation, are determined and published in a suitable form for the use of Mariners.

   It embraces the Triangulation and Survey of Coasts; the Measurement of Oceans, Seas, Estuaries, Rivers and other navigable waters; the observation and study of Tides, Tidal Streams and Currents; Magnetic, Astronomic and Oceanographic work as far as is deemed useful for the Survey and for Navigation; the compilation and publication of Charts, Sailing Directions, Light Lists, Tide Tables, Lists of Wireless Signals, Notices to Mariners and other information referring to the above-mentioned task.

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As regards the definition of the word *Hydrographer*, opinions differ as to whether this refers only to the Head of the Hydrographic Service or to all those who have specialised in hydrography, but whereas a majority of the States Members appear to be in favour of the latter more embracive term it is interesting to note that the official title of the Heads of the Hydrographic Service of 6 States is "Hydrographer"; of 5, "Chief" of the Department; of 4, "Director"; and of 2, "Director General".

As it is obviously necessary to differentiate between the Head of the Service and the Officers serving under him, and as it seems desirable that the same title be used in all countries, it is suggested that the term *Hydrographer* be restricted to the Head of the Hydrographic Office only and that the officers working under him who have specialised in Hydrography should be termed *Marine Surveyors* or, alternatively, *Hydrographic Engineers*.

J. D. N.

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The Directing Committee will be glad to receive comments from the States Members on the above, and will publish these in the *Hydrographic Review* or the *International Hydrographic Bulletin*.

https://doi.org/10.58440/ihr-29-a08

The nautical mile

Author
Alton B. Moody

Preamble

This manuscript is a reprint of the original paper previously published in 1950 in The International Hydrographic Review (IHR, https://ihr.iho.int/): Moody, A. B. (1950). *The nautical mile. The International Hydrographic Review, 27*(1), 77–85.
https://journals.lib.unb.ca/index.php/ihr/article/view/26967

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1 Preface

Curiously enough, the nautical mile, familiar as it is to any seaman, is but little understood by the majority of them.

Of course, one of the most elementary lessons the neophyte sailor learns is that a nautical mile is equal to one minute of latitude. This definition, found in nearly any textbook on navigation, is sufficiently accurate for ordinary purposes, but it is grossly inadequate for scientific purposes such as calibration of instruments or surveying, since a minute of latitude varies from 6046 feet at the equator to 6108 at the poles.

For such purposes a standard value is needed. The need for some standard is much more important than the value selected as the standard. How can the work of various scientists be compared and evaluated, for instance, if they ascribe different lengths to the units they use? The average length of one minute of latitude might do if we knew precisely the size and shape of the earth. But, we do not know this with sufficient accuracy – not for these days when the Bureau of Standards speaks in terms of accuracy to within 0.000,000,000,000,000,2 inch.

Then just what is a nautical mile, where did it originate, and when did it have its beginning?

To answer these questions fully, it is necessary to go back to very early times, for the nautical mile, like so many other things, did not spring up in full bloom in a day, but evolved by slow degrees.

2 Primitive units

Early man, in seeking units of measurement, logically looked about him for something in nature that he might use as a standard. One of the earliest units of length was the *cubit*, of biblical fame. This was taken as the length of the forearm, from the elbow tfo the end of the middle finger. This unit was widely used, but the "standard" forearm was not everywhere the same. The cubit varied from country to country and was not even constant within various parts of some countries. The usual ancient Hebrew cubit is believed to have been 17.58 inches long; the Greek, 18.22 inches; the Roman, 17.5 inches; and the Egyptian, 20.7 inches. In ancient India and other parts of the East, the *hasta* (cubit) was 25.26 inches in length. In several parts of the world this ancient unit has survived, the modern cubit (English), hasta (Singapore), or hath (India) usually being 18 inches long, although its value still varies somewhat from place to place. The modern Spanish *codo* is 16.5 inches long.

That the cubit was used anciently as a nautical measure is shown by the fact that Noah's ark, built to specifications given by God, himself, was 300 cubits in length, had a beam of 50 cubits, and a depth of 30 cubits. (Gen. 6:15). The remains of this ark were recently reported to have been discovered high up on Mt. Ararat, and the dimensions agreed closely with those given in the Bible. The cubit was also used anciently as a measure of depth, for in Gen. 7:20 it is recorded that during the flood the land was covered to a depth of 15 cubits.

However, the cubit has no modern lineal descendent among nautical units of measurement, although it is a distant relative of the nautical mile, through the ancient Indian *dhanush* and *crosa*, discussed later.

Another unit widely used by ancient man was the *foot*. This unit, considered the length of the human foot, varied from about n to 14 inches.

When a longer unit was needed, the pace was used. This was occasionally considered to be the length of one step, but the double step was more generally used, the distance from the heel of one foot to the heel of the same foot the next time it touched

 https://doi.org/10.58440/ihr-29-a21

the ground. This unit varied considerably from place to place. In Rome the *passus* (pace) was 5 Roman *pedes* (feet) or 4.86 U.S. feet. The ancient Indian *dhanush* or *denda* was equal to 4 *hastas* (cubits) or 8.42 feet.

While the units described thus far were adequate for short measurements, longer units were needed for expressing greater distances. In Greece the length of the Olympic stadium, as measured from the foot race course, served as a useful length. This was 630.9 U.S. feet long, or 600 Greek feet. But as the length of the Greek foot varied in different locations, the length of the stadium also varied. The Attic stadium, for instance, was 607.9 U.S. feet long, or almost exactly one-tenth of a modern nautical mile.

Although the Greeks used the stadium as a measure of distances on land, the Romans adopted it and used it for nautical and even astronomical measurements. The Roman stadium was 625 Roman feet long, or 606.3 U.S. feet.

The term *stadium* has come down to us today not only to refer to the huge structures used to seat spectators of athletic events, but also in connection with measurement of distance, in the form of the familiar graduated rod used by the surveyor. In fact, even a graduated stick held at arm's length to determine distance to a remote object is properly called a "stadia".

A modern unit of comparable length to the Greek stadium is the cable, a unit not otherwise related. The cable was originally defined as the length of a ship's anchor cable, sometimes considered to be 100 *fathoms* or 600 feet, about one-tenth of a nautical mile. In the British Navy the length of the cable is now officially set at 608 feet, and in the U.S. Navy at 120 fathoms or 720 feet. Thus, the fathom, cable, and nautical mile constitute approximately a decimal system, apparently by pure chance, since each unit was developed independently. The origin of the fathom is obscure, but it was used anciently as a measure of the outstretched arms, from which the term is derived. That the term was common in early times is indicated by the detailed account given of the Apostle Paul's voyage to Rome, as recorded in the 27th chapter of *Acts*. This account, attributed to Luke, was obviously written by one familiar with the sea.

According to Herodotus and Xenophon, use of the ancient Greek stadium spread into Persia, where it was defined as one-thirtieth of the much larger *parasang*. Thus the Asiatic stadium varied from 492.1 to 738.2 U.S. feet, since the ancient parasang varied at different times and places between 14,763 and 22,146 U.S. feet (about 2.43 to 3.64 nautical miles).

The parasang survives today, its modern value being 3.37 nautical miles. In fact, it is one of a group of units of comparable length which have been used during many centuries. Ancient India had its *crosa* of 8000 hastas (cubits) or 2.77 nautical miles. Later this unit became known as the *legue*, or marine league, which has generally varied from country to country, and at different times from 2.4 to 4.6 nautical miles. The old Spanish *legua* was 3.19 nautical miles in length, the French *lieue marine* (marine league), and the British sea league 2.43 nautical miles, and the Dutch German mile was 2.97 nautical miles. Columbus used the Italian *legua* of 4 *miglia* (Roman miles) or 3.18 nautical miles. The modern league is somewhat indefinite, but generally considered to be about 3 miles, either statute or nautical. The term has now become chiefly poetic. It is curious that units of the same order have been so widely used since ancient times, suggesting similar thought processes in various parts of the world at about the same time, or, more likely, common origin, especially since travelers were the ones chiefly concerned with distances. A few units, however, did not become widely accepted. In ancient Greece, for instance, there was a *diaulos* of 2 stadia (1215.2 U.S. feet in Attica). Ancient India had a *gavyuti* of 16,000 hastas (cubits) or 5.54 nautical miles. The mansion of 80,000 Assyrian feet (13.81 nautical miles) was used in ancient Assyria, Chaldea, and Persia. A comparable unit used in ancient Greece and Persia was the *stathmos* of 13.89 nautical miles. A more recent unit was the *kenning* of old Scotland and England, probably introduced there by the Vikings. This was the distance at which ships could be ordinarily discerned under conditions of excellent visibility at sea, generally considered to be about 20 to 21 miles, a somewhat indefinite unit.

3 The mile

Thus, in ancient times the use of the cubit, foot, pace, stadium, and league seems to have been rather general, with several other units having been used at scattered times and places. But in our discussion thus far we have left a wide gap between the stadium of about 0.1 mile and the league of about 3 miles.

Ancient Greece bridged this gap with a unit of 12 stadia (1.20 nautical mile in Attica), called a *dolichos*. Another unit, widely used during the middle ages, became known as the *Mediterranean mile*. The origin of this unit of 4035.42 U.S. feet is obscure, but has been attributed to the Greeks, perhaps representing an attempt to further bridge the gap between the stadia and the dolichos, which was never so widely used as the Mediterranean mile. The *Roman mile* of 4858.59 U.S. feet or about o.8 nautical mile (6/5 of a Mediterranean mile), became even more widely used and gradually, replaced the shorter Mediterranean mile. It was probably the Roman mile mentioned by Christ in the Sermon on the Mount (Matt. 5:41), since Palestine was at that time a province of Rome.

There is difference of opinion as to which of these miles preceded the other, but it is probable that the Mediterranean mile came first. However, the term "mile" may have been applied first to the Roman mile, since the word comes from the Latin *mille*, meaning thousand. The term was applied because the Roman mile was defined as a thousand paces. This was also the length of the Mediterranean mile and the ancient

Arabian *mille* or *mil* of 1.03 nautical mile, or 6,000 Arabian feet. The three units varied in length because of the different lengths of the pace. The Roman pace, most widely used, was considered to be 5 Roman feet or 4.86 U.S. feet, as we have seen.

It is to be observed that all of these early miles were defined in terms of other units, and were in no way connected with the size of the earth. The earth was believed by some to be "round" at least as early as Pythagoras (about 540 B.C.) and by Aristotle's time (384–322 B.C.) attempts were made to define its size. Eratosthenes of Alexandria attempted to measure the size of the earth during the third century before Christ and determined the circumference as 250,000 stadia, which he rounded off to 252,000 stadia so that each degree would have 700 stadia (or 70 nautical miles). But during the centuries that followed, men were more concerned with its shape then its size.

It was not until the period of the great discoveries, when charts and greater distances became important to the mariner, that the association of units of length and degrees of latitude became a serious consideration. Then it became customary to show one or more scales of miles on a chart. The units of these scales were sometimes identified by name and sometimes merely by their relation to the latitude scale.

The lengths ascribed to these miles thus depended upon the size of the earth accepted by the individual.

Estimates varied considerably, ranging from about 44.5 to 87.5 modern nautical miles per degree of latitude. The estimates were generally too low. Thus, in the 14th century, 20 French lieues marines or British sea leagues of 2.43 nautical miles (48.6 nautical miles) were considered equivalent to one degree, as were 15 Dutch-German miles of 2.97 nautical miles (44.5 nautical miles). In the 15th century, 17.5 Spanish *leguas maritima* of 3.19 nautical miles (55.9 nautical miles) were considered equal to one degree.

The Roman mile of 1,000 paces or 5,000 feet persisted for several centuries, the number of such miles considered equivalent to a degree being changed from time to time as the accepted size of the earth changed. At the time Columbus made his historic voyages to the New World, 56 2/3 Roman miles (45.3 nautical miles) were gene rally considered to be equivalent to a degree. This was the relationship Columbus used. The actual size is about 32 % larger.

However, even before Columbus, some scholars questioned the size generally accepted. The great book by Ptolemy (Claudius Ptolemaeus) *Syntaxis*, better known by its Arabian title, the *Almagest*, was still being published in the 15th century, 1300 years after its first edition. This book considered 62 Roman miles equivalent to one degree. An edition appearing in 1466 contained a chart of southern Asia on which 60 Roman miles were shown to a degree. The chart was drawn by Nicolaus Germanus, author of the 1482 edition which was published in Ulm, Germany. Whether the shift from 62 to 60 miles to a degree was considered a correction or an adaptation to provide a more convenient relationship between the mile and degree is not clear, but this is the first known use of the relationship that has gradually replaced all others. The modern minute-mile thus came into being quite naturally and unpretentiously.

But the shift to a minute-mile, now universally accepted, did not come about at once. Originally it was 60 Roman miles of 4858.59 feet (0.8 nautical mile) which were considered equal to one degree. As later measurements of the earth began to reveal the error of earlier accepted values, the relationship of 60 Roman miles to a degree was seen to be in error. Two methods of correcting this relationship were common. Some authorities of the period favored retention of the mile without change, since it was much older than the custom of associating it with a degree of latitude. These increased the number of units per degree. By the 16th century they considered 70 Roman miles equal to a degree. By the 18th century, this number had been increased to 75, resulting in a degree of 59.9 miles, a close approximation to the value now accepted.

But there was logic in dividing the degree of 60 minutes into 60 miles, and many of the earlier units were gradually lengthened. Thus the Dutch-German mile (or league) of 2.97 nautical miles became 3.99 nautical miles in length, so that 15 of them were still shown per degree, making the degree 59.85 miles long. Similarly, the Anglo-French marine league was kept at 20 per degree, but the length was increased from 2.43 to 2.97 nautical miles, so that the degree was 59.4 nautical miles.

In 1735 an expedition from the Paris Academy was sent to "Peru" (within the present borders of Ecuador) to measure an arc of the meridian, to provide a more accurate determination of the size of the earth. The work was completed in 1743. Pierre Bouguer, a member of the expedition, made the following observation: "The Italians use miles, which count as 1,000 geometrical or double paces, each of 5 feet; and they suppose that 60 of these miles make one degree. This method of counting distances is very convenient – but, it is therefore necessary to modify its length, and increase it by approximately one-seventh." Thus, the order of the size of the earth was established more than 200 years ago, later measurements being chiefly refinements of earlier ones.

The need for a standard had been recognized for some time. When the log appeared as an instrument for measuring speed, the need became acute. The first mention of the log was by Bourne in his celebrated *Regiment of the Sea*, published in London in 1574.

The log in common use for many years, called a "chip log", consisted essentially of three parts: first, the "log chip" – (a thin board in the shape of a quarter of a circle) weighted in such a manner as to float vertically; second, the "log line" – a line attached to the quadrant and knotted at equal intervals; and third, the

https://doi.org/10.58440/ihr-29-a21

"log glass" or sand glass. The log chip was thrown overboard and the log line permitted to run out freely. As the first knot in the log line went overboard, when the log chip was well clear of the wake, the log glass was turned over. The number of additional knots paid out while the log glass emptied itself bore a definite relationship to the speed.

The original log glass marked an interval of 30 seconds, and the distance between knots was 42 feet. Each knot was considered equivalent to a speed of one nautical mile per hour. This is the origin of the modern term knot as a unit of speed. But since the relationship was erroneous, the speed indicated by early logs was too great, resulting in landfalls being consistently late. However, this was generally considered an advantage. Norwood, seventeenth century English geodesist explained it this way: "The ship's way is commonly more than by the log line appears to be, and every man desires to have his reckoning something before his ship, that he fall not in with a place unexpected."

As early as 1639 Norwood had shown that the distance between knots was incorrect. The length of the mile used in England at this time was the Roman mile of 5000 feet and in 1659 J. Collins specifically stated that "our English or Italian mile by which we reckon at sea contains 1,000 paces, each pace being 5 feet and each foot 12 inches." By 1715, the inaccuracy of the Roman mile was well established, as indicated by the English nautical author Henry Wilson, who wrote, "It is indisputable that the length of a knot on the log line must be the 120th part of a mile, because half a minute (the period of a 30-second sand glass) is the 120th part of an hour; but the difficulties arise from the divergency of opinion on the number of yards contained in a degree of the great circle on the earth."

Wilson suggested that the length of the knot be increased from 42 feet to 48 feet 7 inches, and later he suggested 51 feet. Collins had already suggested a length of 50 feet. But the change, when it came, was in the interval of time measured by the log glass rather than the distance between knots on the log line. These remained 42 feet apart, the time being decreased from 30 to 24 seconds. Later, when the length of the nautical mile was established with greater certainty, the time was increased to 28 seconds and the distance between knots to 47 feet 3 inches.

4 The nautical mile

Meanwhile, the length of the mile remained controversial. In 1637 in London there appeared a small booklet entitled *The Sea-man's Practise, containing a Fundamental Probleme in Navigation, experimentally verified*. Norwood, author of the preface of this booklet, had measured an arc of the meridian and writes in the preface that, "It appears not only from this experiment, but even by all others, that there is a greater number of feet contained in a degree than the common opinion, that a thousand paces (of 5 feet) make a mile."

The nautical mile, as distinct from the land mile, might be said to date from this time. Previously, there had been no distinction between the two, but following the appearance of this booklet mariners gradually began to accept the longer mile, while ashore, where there was less incentive to associate the mile with the size of the earth, the old Roman mile of 5,000 feet persisted. The land or statute mile later became 5280 feet, but this length is by no means universal. In Great-Britain the statute mile is sometimes called the London mile to distinguish it from the old Scotch mile of 1.123 statute miles and the Irish mile of 1.273 statute miles. The various miles used on the continent of Europe have generally given way to the kilometer.

As for the nautical mile, Norwood, after his measurement of an arc of the meridian, proposed that the length be established at 6120. He later changed this to 6,000 feet to preserve the custom that "every man desires to have his reckoning something before the ship, that he fall not in with a place unexpected." His mile was gradually accepted by seamen, but it was not known by the distinctive name *nautical mile* until a century later, the expression first appearing in 1730.

The error in the old Roman mile, which persisted for several centuries, was attributed by Norwood partly to the failure of the Romans to allow for the convergence of the meridians. If a degree of latitude and longitude are considered equal at the 35th parallel, in the Mediterranean south of Italy, the old Roman mile would be about right as a measure of longitude. However, although it is true that early Roman charts considered the earth a plane and did not allow for convergence of the meridians, there appears to be no evidence to indicate that the Roman mile was associated with the size of the degree of latitude or longitude in the minds of early Romans who used the mile of 1,000 paces.

5 Establishing the size of the earth

By 1730 the nautical mile, as a minute of a great circle of the earth, was well established. There remained the problem of determining accurately the size and shape of the earth, that the length of the nautical mile might be accurately defined. As measurements became more accurate and were extended over a greater portion of the earth, the of the earth became established.

We have seen that attempts were made as early as the third century before Christ to establish the size of the earth. Although the earliest methods were somewhat crude, they at least established the order of magnitude. Following the "Peruvian" expedition of 1735–43, the number of measurements of arcs increased and gradually became more accurate. The principal measurements since about the beginning of the 19th century have resulted in the values shown in Table I. Although the original work of most of these investigators was done in meters, all have been reduced to U.S. feet in this table to provide a basis of comparison. Only the equatorial radius and the reciprocal of

Table 1 Size and shape of the earth.

DIMENSIONS ET FORME DE LA TERRE				
Author - *Auteurs*	Date	*Rayon Equatorial* (Mètres)	Equatorial Radius. (Pieds américains) (U.S. Feet).	1/ Flattening. 1/ *Aplatissement*
Commission des Poids et Mesures	1799	6 375 738.7	20,917,737.03	334.29
Biot et Arago	1810	6 376 985.0	20,921,828.23	308.64
Delambre	1810	6 376 428	20,919,997.53	311.5
Delambre	1810	6 376 523	20,920,309.21	308.65
Puissant	—	6 376 951	20,921,713.40	309.61
Beautemps-Beaupré	1816	6 376 522	20,920.305.93	308.65
Walbeck	1819	6 376 895	20,921,529.68	302.78
Schmidt	1828	6 376 959	20,921,739.65	297.65
Airy	1830	6 376 542	20,920,371.54	299.33
Everest	1830	6 377 252.6	20,922,779.67	300.8017
Airy	1837	6 377 541	20.923,650.57	299.32
Francœur	1839	6 377 116	20,922,254.74	305
Plessis	—	6 376 523	20,920,309.21	308.64
Bessel	1841	6 377 397.15	20,923,177.15	299.1528
Kraijenhoff	—	6 376 950	20,921,710.12	309.65
Danish Survey	—	6 377 019	20,921,936.50	300
Everest	1847	6 376 634	20,920,673.38	311.04
Airy	1849	6 377 491	20,923,485.05	299.32
James et Clarke	1856	6 377 936	20,924,945.02	297.72
Clarke	1858	6 378 294	20,926,119.56	294.26
Pratt	1863	6 378 245	20,925,958.80	295.26
Clarke	1863	6 378 288	20,926,099.88	294.36
Clarke	1866	6 378 206.4	20,925,832.16	294.98
Fischer	1868	6 378 338	20,926.263.92	288.50
Schott	1877	6 378 054	20,925,333.15	305.48
Clarke	1880	6 378 249.2	20,925,972.40	293.465
Germain	1882	6 378 284	20,926,086.75	294.30
Harkness	1891	6 377 972	20,925,063.13	300.20
Hayford	1907	6 378 283	20,926,083.47	297.8
Helmert	1907	6 378 200	20,925,811.16	298.3
Hayford	1909	6 378 062	20,925,358.41	298.2
Hayford	1910	6 378 388±35 m.	20,926,427.96	297.0
International	1924	6 378 388	20,926,427.96	297.0

the flattening ( ) are given. The figures in the last column are determined by the ratio *a / (a – b)*, where *a* is the equatorial radius and *b* is the polar radius.

If a standard nautical mile is to be established, based on one minute of a great circle of the earth, it becomes necessary to determine first the size of the earth to be used in the definition. It would seem logical to use the values employed by surveyors and cartographers, so that measurements on the chart would be correct. Unfortunately, however, a number of the "spheroids" of Table 1 have been used and several different ones are in use today. This fact is the basis of one of the problems faced by artillery and it may be an even greater problem when long-range guided missiles are ready for launching.

However, in 1880 the U.S. Coast and Geodetic Survey adopted the Clarke Spheroid of 1866, and since all of North America is mapped on this basis, the choice is not a difficult one for a United States definition.

But this is not the end of the difficulty. In 1866 the values of the units used in the measurements were not well established. Clarke worked in feet and gave his measurements in three units, the foot, toise, and meter. The toise was equal to 6 French feet or nearly 6 feet 5 inches of American measure. This unit has fallen into disuse and can be neglected, since its length was defined in terms of the foot.

The meter was originally (about 1790) intended to be 1 / 10,000,000 of the distance from the equator to the pole. Since various sizes of the earth were accepted, the length of the meter was not everywhere the same. Each country had its own standard. The value used by Clarke in determining the ratio between the meter and the standard British yard was a composite of the various standards in use at the time, The foot was, as now, a third of a yard.

The British standard of length is based upon the British Imperial standard yard, the distance at 62°F between two marks on a bar of bronze kept in the Tower of London. This bar was constructed in 1845 and the length indicated by it was adopted as the fundamental standard ten years later. Clarke's composite meter was defined as 39.370432 inches.

The International Bureau of Weights and Measures was established at the Pavillon de Breteuil at Sevres, in 1877. When a standard meter was established by this body, it was defined as the distance between two marks on a bar of platinum iridium kept in the vaults of the Bureau. The need for a standard length independent of the size of the earth had been recognized as early as 1827. The standard meter is safeguarded by elaborate precautions, and numerous copies supplied to various countries are compared with the original from time to time, Before World War II this comparison was made at intervals of six years. A comparison due in 1939 was cancelled because of the war, and no further comparison was made until October, 1948, the first since 1933. The comparison is made by putting a copy alongside the original under rigorously controlled conditions and examining the marks under microscopes. The maximum error in the determination made in this way is probably about 0.00000001 of a meter (about one part in a hundred million), according to the U.S. Bureau of Standards.

As early as 1889 it was suggested (by S. D. Gill) that the standard length be defined in terms of some natural phenomenon capable of precise measurement and exact duplication. The wave length of light under specified conditions was suggested and by 1906 a standard was tentatively set, based on the red ray of cadmium vapor at 15°C and a pressure of 760 millimeters of mercury. In 1948 the United States proposed a standard based on a wave length of green light emitted by a certain form of mercury made from gold by the Oak Ridge uranium pile of the Atomic Energy Commission. With this the U.S. Bureau of Standards has been able under special laboratory conditions to measure length to an accuracy of 0.000,000,000,000,000,2 inch. The official claim is only a tenth as great, or 0.000,000,000,000,002 inch.

When the British Imperial standard yard was compared with the standard meter by Arago and Kater in 1878, the meter was found to be 39.37079 inches. It was compared again in 1898 by Benoit and Chaney and the ratio was found to be 39.370113, a value adopted as the legal ratio, although a later comparison put the ratio at 39.370147. No one can say with certainty whether the difference is due to inaccura-

https://doi.org/10.58440/ihr-29-a21

cy of the earlier comparison or whether the Imperial standard yard is shrinking, as bronze is known to have done. The latter is generally accepted as the correct explanation.

It may be a surprise to some to learn that the United States standard of length is based on the metric system. This system was legalized in the United States on July 28, 1866, when the length of the meter was defined as 39.37 inches. Since there was no standard U.S. inch or yard, this, in effect, defined the length of the U.S. system of length measurements in terms of the meter. When the United States joined the International Bureau of Weights and Measures, it received copies No. 21 and 27 of the international meter. On April 5, 1893, copy number 27 was declared to be the standard for the United States. It still agrees with the international meter.

Since the international meter legally equals 39.37 U.S. inches and 39.370113 British inches, the length of the foot is not quite the same in the two countries. The U.S. foot is longer, being equal to 1.00000287 English feet. The international meter is equal to 3.28083333 U.S. feet or 3.28084275 English feet. The meter used by Clarke was slightly larger than the international meter, one of the latter being equal to 0.99999190 Clarke meters.

In adopting the Clarke spheroid of 1866, the U.S. Coast and Geodetic Survey used Clarke's figures in meters, but considered them to be international meters. Clarke gave the dimensions as a = 6,378,206.4 meters = 20,926,062 English feet (20,926,002 U.S. feet) and b = 6,356,583.8 meters = 20, 855,121 English feet (20,855,061 U.S. feet). Thus, using the ratio of U.S. feet and the international meter and Clarke's value for the meter, the values are found to be a = 20,925,832 U.S. feet and b = 20,854,892 U.S. feet.

Hence, the spheroid used for mapping in the United States has the same ellipticity as the original Clarke spheroid of 1866, but is slightly smaller (about 170 feet in each radius). However, it is customarily spoken of as the "Clarke spheroid of 1866", and the Coast and Geodetic Survey values are assumed unless the earlier dimensions are specified. The tables used in this country for the construction of charts are based on the dimensions adopted.

Since the difference is generally less than that between different spheroids, and since the ellipticity remains unchanged, the adoption of these values is considered one of definition and of inconsequential significance.

6 Defining the length of the nautical mile

Having selected the figure of the earth upon *which* to base our standard nautical mile, it becomes necessary next to define more exactly which great circle shall be used, since all "great circles" on the earth are not of the same length, due to the flattening at the poles. Various definitions have been suggested, the principal ones being shown in Table 2, with values for both the Clarke spheroid of 1866 and the International ellipsoid, which is based upon Hayford's measurements in 1909–1910.

Again it is a matter of definition, since any value will serve the purpose as long as it is accepted as standard. In the United States the official value is that of one minute of arc of a great circle of a sphere having an area equal to that of the earth. If this is computed using the Clarke spheroid of 1866 in terms of Clarke's dimensions in English feet, the length of the nautical mile is 6080,27 English feet, a value often given in U.S. publications. The value in U.S. feet is 6080.25 U.S. feet, but if the Clarke spheroid is defined in terms of the present relationship of the meter and U.S. yard, the length of the nautical mile is 6080.20 U.S. feet (1853.248 meters) *the official U.S. value*.

Table 2 Nautical mile. Length by various definitions (U.S. feet).

	INTERNATIONAL		CLARKE 1866
	Mètres	U.S. Feet	U.S. Feet
1' of equator	1855.398	6087.25	6087.08
1' of latitude at equator	1842.920	6046.33	6045.88
1' of latitude at poles	1861.675	6107.82	6107.78
1' of latitude at latitude 45°	1852.256	6076.94	6076.70
1' of circle of same length as meridian	1852.276	6077.01	6076.76
1' on sphere of radius 1/2 $(a+b)$	1852.275	6077.00	6076.76
1' on sphere of radius 1/3 $(2a+b)$	1853.315	6080.42	6080.20
1' on sphere having a radius equalling the average radius of curvature of meridian	1852.278	6077.01	6076.76
1' on sphere the area of a great circle of which equals the area of the plane of the meridian	1852.272	6076.99	6076.75
1' on sphere the volume of which equals the volume of the earth	1853.313	6080.41	6080.19
1' on sphere the surface of which equals the surface of the earth	1853.315	6080.42	6080.20
1' on sphere having a great circle 40 000 000 meters long	1851.852	6075.62	
Value recommended by Directing Committee of IHB (1929)	1852.000	(6076.10)	

Table 3 Nautical mile. Values in various countries.

	Mètres	U. S. feet.
Argentina - Argentine	1852	(6076.10)
Belgium - Belgique	1852	(6076.10)
Brazil - Brésil	1852	(6076.10)
Denmark - Danemark	1852	(6076.10)
Finland - Finlande	1852	(6076.10)
France - France	1852	(6076.10)
Germany - Allemagne	1852	(6076.10)
Great Britain - Grande-Bretagne = (6076.8 — 31.1 cos 2 φ) feet	1853.18 =	6080 (Imperial)
Greece - Grèce	1852	(6076.10)
Iceland - Islande	1852	(6076.10)
Italy - Italie	1852	(6076.10)
Japan - Japon	1852	(6076.10)
Netherlands - Pays-Bas	1852	(6076.10)
Norway - Norvège	1852	(6076.10)
Poland - Pologne	1852	(6076.10)
Portugal - Portugal	1852	(6076.10)
Spain - Espagne	1852	(6076.10)
Sweden - Suède	1852	(6076.10)
Turkey - Turquie	1852	(6076.10)
U. S. A. - E. U. A.	1853.248 =	6080.20

The full definition of the official U.S. nautical mile, then, is “the length of a minute of arc of a great circle of a sphere having an area equal to that of the Clarke spheroid of 1866, as used for charts of North America since 1880.”

Neither the United States definition nor the U.S. standard length is universally accepted. Some of the values used in various countries are given in Table 3. It will be seen that several countries have adopted the value suggested by the Directing Committee of the International Hydrographic Bureau in 1929.

Because of the disagreement from country to country, it is necessary in scientific work to use a unit universally recognized, or to carefully define the unit used. But to the seaman, the nautical mile is still a minute of latitude, and who can say he is wrong? After all, by the use of this value and skillful navigation he makes his landfalls as anticipated, maintains schedules, and does not “fall in with a place unexpected”.

https://doi.org/10.58440/ihr-29-a21

IHO International Hydrographic Organization

Hydrographic surveys – The purpose and the choice of scale

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Preamble

This manuscript is a reprint of the original paper previously published in 1955 in The International Hydrographic Review (IHR, https://ihr.iho.int/): Day, A. (1955). Hydrographic surveys – The purpose and the choice of scale. *The International Hydrographic Review, 32*(1), 9–24. https://journals.lib.unb.ca/index.php/ihr/article/view/26749

The main purpose of a navigation chart is to show what lies under the water, in order, first, that a ship shall not take the ground unwittingly, and secondly, that observed changes of depth over identifiable features may be used to assist the determination of her position. The conventional method of showing this information in plan is by a selection of depths reduced to a common datum and they will usually be in greater profusion than the comparable spot heights of the land map. They are supported by contour lines, called fathom lines at sea, using symbols which are strengthened when they surround the shallower areas that need greater emphasis. These depths will invariably have been taken from the final drawing or «fair sheet» of the hydrographic survey of the area and each one will have resulted from an up and down sounding to measure the depth at that particular spot.

There is in fact no known way of determining the depth of a point on the sea floor other than by a vertical measurement from the surface above it; and as far as can be foreseen, the future does not hold any means of seeing through water, at least not in the sense of human vision with its capacity for discrimination and estimation, which is so valuable when more than one dimension is concerned. Even if his was not so, plane-table methods employing the intersection of points of detail on land would seldom be usable, since the sea floor is often covered by sediment which obscures minor detail, as may be observed at low tide at the sea shore especially near a river estuary.

Another type of sea floor may be likened to the Scottish Highlands in which outcropping rocks provide detailed features, although they will often not be recognisable, even when they are visible, from different directions. Such features, when they exist on the sea floor to one side or other of the ship, will be detected, within similar limitations, by Asdics. The Asdic method, which was originally developed for submarine warfare, has, like radar, a beam which is trained in azimuth to give a bearing and distance of an object, provided that it has a surface which will reflect hack a sufficient part of the transmission directed at it. At still shorter ranges there is the new development of under-water television; but these methods have considerable limitations in many of the different conditions encountered under water.

Such a preamble seems unavoidable in any discussion of hydrographic surveying and is particularly important to the present aspect of it. It will sufficiently show why the accepted method of determining the topographical features of the sea floor is by traversing the area with parallel lines of soundings whose distance apart will determine how much is learnt and how much is overlooked. That some detail will be overlooked is inevitable, but it will be the less for the natural processes of smoothing over by sedimentation and the swallowing up of objects in soft sand or mud, or alternatively as a result of the use of Asdics and other methods in addition to systematic sounding.

In the naval surveying service it is standard practice to run the lines of soundings 0.2" apart on paper, as is shown in the bottom right-hand part of Plate I (Fig. 1). This spacing has been adopted since it is convenient for plotting and numbering the fixes of the soundings that have been taken. It is the variation in the distance represented by 0.2" on different scales which is important.

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https://doi.org/10.58440/ihr-29-a19

It will be well next to look at the user's need for varying scales in the charts, which are the end product of the surveys, but it cannot be emphasized too strongly that the purpose of the survey is to find out about the sea floor, whereas the object of the chart is to portray it. The range of scales can be separated into four main divisions of navigation, i.e., ocean, 1/1M to 1/5M or still smaller; offshore, 1/150,000 to 1/500,000; coastal, 1/50,000 to 1/100,000; harbour and approaches, 1/6,000 to 1/25,000. Generally speaking, the closer that a navigator wishes to take his ship to the land, whether below the keel or to one side of the hull, the larger must be the scale of the chart. In harbour work, the outline of the ship, the wharves and the ground tackle of moorings have to be of a size on paper that permits their proper appreciation and a larger scale than 1/6,000 may be needed exceptionally. Large scales are also required when an area has to be dredged and the amount of spoil to be calculated, although such surveys are more for use .by harbour authorities than the navigator with whom this discussion is more concerned.

Clearly a limit to the largeness of the scale is simply and directly set by the size of instruments and chart tables; and a prospective customer may even have to be warned that the advantage of using a blunter pencil on a larger scale may be offset by the need to use a longer parallel ruler with which to lay off his bearings. It must also not be overlooked that the headlands and shore objects which should be included on the chart to give good fixing on it may, on too large a scale, lie outside the limits of the chart table, to which the British standard size of charts, 38" × 25", is conditioned. For example, when the scale is one inch to one mile and the standard dimensions become sea miles, the lengthwise two-thirds of a coastal chart which is likely to be sea area is readily worked with a parallel ruler having a convenient length of 18". Such a ruler will comfortably cover ranges of 12 to 15 miles at which objects at sea are often used.

Having stated that the purpose of the chart and the object of the survey are different, it is necessary to point out that the scale of the survey must not be smaller than that of the chart. By this arrangement, a first principle of chart compilation, which is to work from larger to smaller scales, will be maintained. This could mean that the survey is on an unnecessarily large scale for its main purpose of learning about the sea floor, but on the other hand it will satisfy the need to plot the positions of the under water features with the greater accuracy which the larger scale chart demands. In no other way should the needs of the chart maker, with a projected chart in view, dictate the scale of the survey, nor should they set the limits of the survey, since that might mean stopping short in the delineation of an important feature which extends beyond the limits of the chart. And a last word on charts would be to note that the coastal and larger scales are likely to be directly from surveys, whilst the offshore and ocean scales can be compiled from larger scale charts.

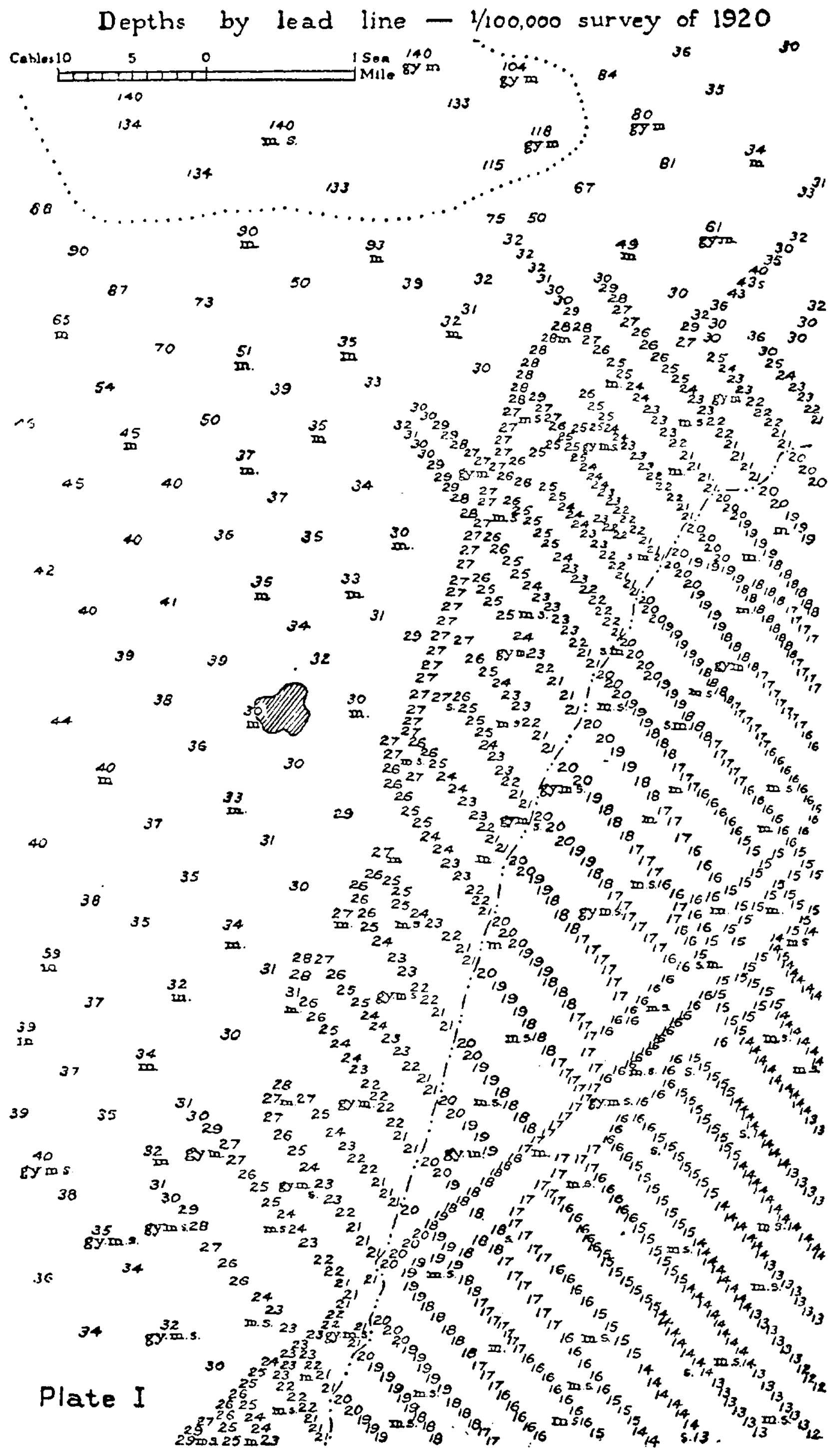

Fig. 1

Turning to surveys, it is convenient to discuss first the effect of instrument and paper sizes on the scale to be used, since this has been referred to in relation to the scale of charts. It will be appreciated that the detail of a survey or, in other words, the position of the surveying ship at frequent intervals along her line of soundings, is plotted by station pointer from sextant angles. The three legs of a station pointer express the two horizontal angles which are observed simultaneously with sextants from the bridge of the moving ship, and the legs are laid alongside the three objects on the plot, a comparable but infinitely quicker operation to that of resection on a plane table ashore by drawing in three lines of sight. The largest station pointer made has a graduated circle 12" in diameter and legs which !have an extended length of 48". It takes two men and a boy to work it, and the length of the rays involved does not make for accuracy unless extreme care is taken. That may be practicable when laying down additional sounding marks on the plot in the quiet of the chart room, but is hardly so on the bridge; where rapid plotting is required so that the ship's course may be adjusted in good time. Consequently the stations pointers more commonly used have either a 6" or 8" circle, and legs from 24" to 32" in length.

It will be patently obvious that it is more accurate to fix on shore marks than on beacons in the sea which are swinging round or between anchors, and a coastal survey can be well within visibility distance of marks on shore when extending only 15 miles to seaward. A survey scale of 3" to a mile may be desirable and it is aggravating to be unable to use shore marks just because rays of 45" on paper cannot be handled. One solution is prior computation and plotting of circles of equal horizontal angle, but this means accepting the use of very few objects when in fact, if others were available, delays owing to the difficulty of taking sextant angles into the sun or a rain squall would be avoided. At the present time a fine radio solution to this problem is in prospect with the continuous wave distance-measuring system of «two range Decca», provided that the trials recently carried out confirm the theoretical accuracy. Any area within its maximum range, which may be as much as 70 miles, can be readily prepared for plotting fixes by drawing, at whatever scale is required, the arcs of distance circles from the two shore transmitting stations; and the latter need not appear on the field plot.

Another factor which must directly exercise some control on the scale is that the smaller the scale, the more space will be taken up by each figure representing a depth; and the more difficult does it become to arrive at the true delineation of an under-water feature. An old textbook used to put it thus:

«If the scale be one inch to a nautical mile and a square inch be divided into a hundred equal areas (suitable for a hundred figures) each sounding will occupy a space equal to about eight acres, i.e., an area a little larger than the Horse Guards Parade and about twice the area of Trafalgar Square.»

Similar reasons will demand that the scale must be large enough to plot clearly the results of Asdic or wire sweeping operations.

Having disposed of considerations which, to say the least, should not be allowed to have too much bearing on the scale of the survey, attention may be turned to the main purpose of the majority of surveys, which is the delineation of the sea floor, having particular regard to features that may provide danger to navigation. To surface navigation a depth of 45 feet on an individual shoal or obstruction is regarded as potentially dangerous, whilst to submarine navigation it is difficult to set any limit. It is, however, reasonable to think in terms of carrying out detailed surveys to include the 100 fathom line. This is often the edge of the Continental Shelf, beyond which there are steep gradients to oceanic depths that are of much less concern either to under-water warfare or surface navigation.

What kinds of feature must be catered for in the, so to speak, blindfold search? What gradients may be expected? How far apart can the lines of soundings be and yet be sum of drawing attention to a need to look more closely? To what extent will this vary with the depth?

Some knowledge of geology will clearly be a help, but there is the usual difficulty of finding the time to acquire it; a hydrographic surveyor must necessarily also be a seaman, and will have a role to fill as a naval officer or alternatively as a harbour master or engineer. Fortunately, it is probably true to say that he can get by if he makes a common-sense appraisal of what he sees of neighbouring land features, especially the run of the valleys or faults. Alternatively, he may use his experience of previous surveys in comparable soundings, and in the fortunate case of the British Naval Surveyor this experience may be of world-wide extent.

He will seldom have found gradients under water to match those on land because there will have been deposits or sediments brought by currents which will have settled in the valleys and at the foot of cliffs, thus smoothing out the original form of such under water features. He will be alive to the effect of tidal streams elongating and maintaining the general shape of sandbanks and the deep channels between them. He is also likely to have encountered coral formation and be able to learn what to expect of them from a study of neighbouring areas.

If precise figures for gradients under water are sought, knowledge seems to be incomplete. In the case of unconsolidated material, the angle of rest may be as little as 5° or as much as 15° depending on whether it is mud, sand, gravel or shingle. If there is clay, gradients may increase to 30° although the latter is not commonly met. Bare rock is encountered comparatively seldom, but when it is, there will be no rules. Canyons with sides nearly vertical or with slopes of at least 60° and a smooth floor running down into deeper water may have held no sediment over the years and thus remain true to original shape. So do steep rocky shores or off-lying rocks, more especially when strong tidal streams keep them washed clean of sediment. Coral atolls in the later centuries of their growth may give gradients near the surface as steep as 40° to 45°, and this gradient may apply to submerged coral heads that are found standing solitarily within the 50 fathom line, meaning that their bases will be of comparatively small extent.

On the one hand then, slopes up to 30° will seem

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less than might be expected and on the other, coral heads and rocky outcrops present a special problem. In the case of the latter, however, their probable presence may often be suspected. Moreover, rocky formations at any appreciable height above the sea floor, are likely to be part of a large feature with slopes of 15° to 20° up to a summit above which there may be outcrops protruding for a few additional feet. Such features are most likely to be ridges having considerable length extending seawards perhaps from an above water headland, and an example is St David's Head in Pembrokeshire which runs out to the Smalls and beyond. Indeed, along this line there is a recent report of an under-water feature which was not found in the previous survey. That survey, however, was nearly 100 years ago and by modem standards would be dubbed as exploratory.

If exceptional cases of needle rocks rising to the surface were to be quoted, there would be Cook Rock in the deep waters of Cook Strait between the North and South islands of New Zealand; Avocet Rock standing in 40 fathoms in the Southern Red Sea; and on the extension of the Peninsula south of Reykjavik in Iceland where the above-water islets are spectacularly sheer, there is a rock found during the last war by a ship which passed so close that the return from the weak sideways transmissions of the echo machine showed more strongly than that from the transmissions directed downwards. Its top is about the size of a card table and it is 11 feet below the surface. Its sides are sheer for at least JOO feet, and thereafter the gradients are very steep for another 80 feet to the sea floor. The venomous picture is completed by the fact that, rather exceptionally, no tide rips, breakers or discoloration betray its presence. However, such rocks provide particularly good Asdic targets and Asdics are being used with very good effect on a current survey off the Borneo Coast where many coral heads are being found.

Having shown reasons why under-water features may, on account of their gradients and shapes as well as their geological likelihood', be less difficult to find than might be supposed, attention is drawn to the illustration in Plates I to III (Fig. 1–3) of a shoal which is totally unexpected geologically and is circular rather than part of a ridge.

Plate I (Fig. 1) shows the method of covering an area by parallel lines of soundings. It will be seen how a spacing of five to the inch became four to the inch, and finally, two to the inch as the depths increase. This will have been on the principle that a feature rising to a dangerous height will be wider at its base as the general depth of the sea floor increases. In those days, sounding up to 18 fathoms was done by a mechanical contrivance for heaving an especially heavy lead so that it was let go forward and the depth line read aft when it came up and down, but the ship's speed had to be greatly reduced. In deeper water there was nothing for it but to stop the ship, and this will have been necessary for every one of

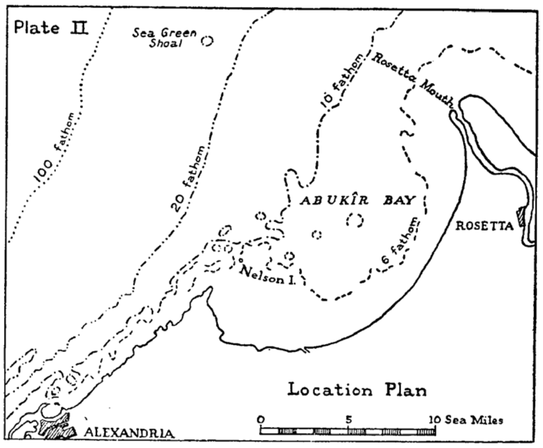

Fig. 2

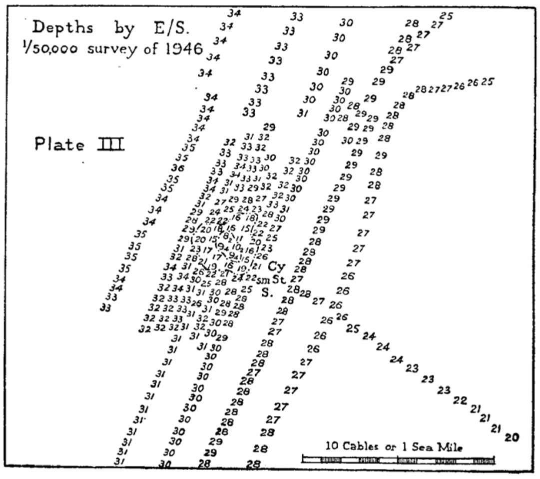

Fig. 3

the spaced-out depths on Plate I (Fig. 1). Nowadays echo sounding, first adopted in 1928, gives a continuous record of depth at high speed, and a closer spacing of lines in deeper water is practicable.

Although no example of it is shown, it will be opportune to add here that additional lines are run whenever the presence of a feature is suspected. It is customary first to run one interline and, at half the standard interval of 0.2", it is possible to show legibly the additional soundings obtained. Thereafter, if the interval is again halved, there is room to plot the ship's track, but depth figures can only be inserted at the expense of previous observations. A further point is that lines of soundings are always oriented so that the general direction of the fathom lines is crossed at right angles and thereby there is less chance of missing the ridge formations which are so commonly encountered.

Plate II (Fig. 2) shows the location of Sea Green Shoal which was reported by a minesweeper fouling her sweeps on it during the war, and which was made the object of an investigation when an opportunity arose in 1946. Using echo sounding, a shoal was quickly found and indeed with the sun high up behind the observer, it could be seen at a distance of

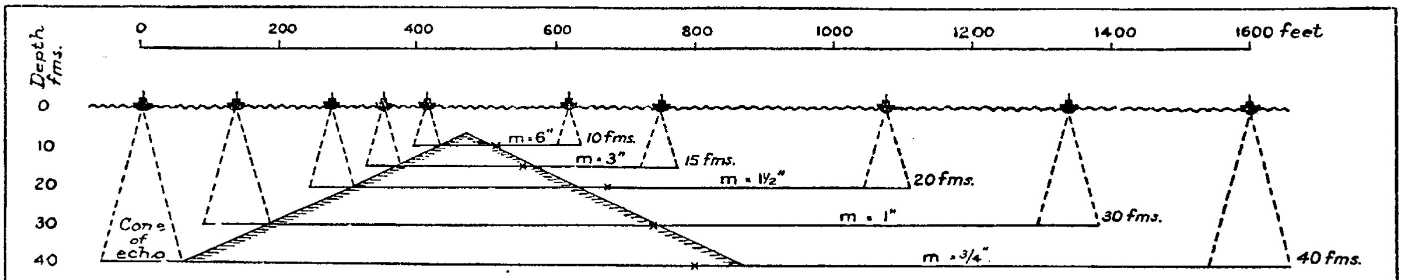

Plate IV Diagram showing at what depth, and at what scale of survey, the base of a 7-fathom shoal with a 25° slope will occupy approximately half the distance (×) between two lines of soundings plotted at a normal interval of 0·2 ins.

Fig. 4

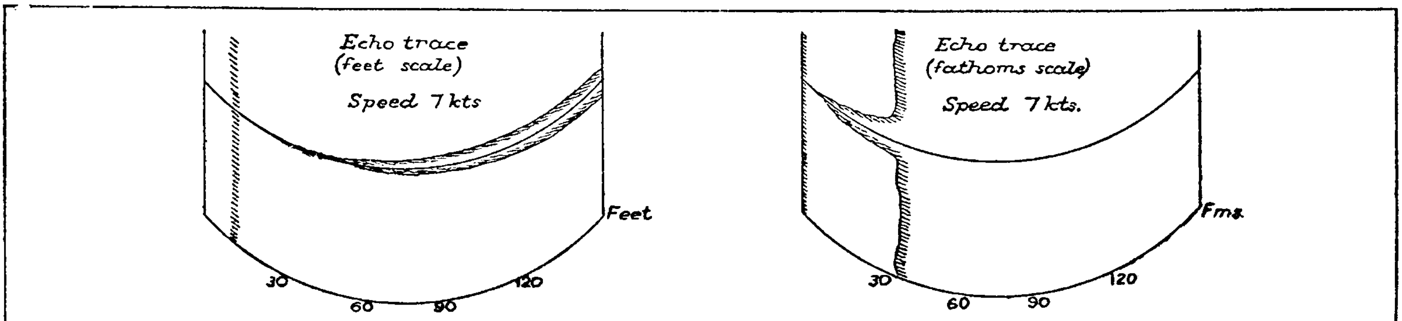

Plate V How a typical E/S recorder would trace the shoal in Plate IV given a speed of 7 Knots across it. (2/5th Scale)

Fig. 5

a quarter of a mile because of a green discoloration of the blue sea, hence the name. It was half a mile in diameter at its base and rose 120 feet to a rounded top, a tenth of a mile across at a depth of 50 feet below the surface. There is no geological reason for a shoal in such a position as for example there might be along the extension of the promontory on which Nelson Island stands, as shown in Plate II (Fig. 2). It accordingly smacks of being wise after the event to draw attention to the seaward of two soundings of 30 fathoms shown in Plate I (Fig. 1) to lie on the edge of the shoal area as shaded in from Plate II (Fig. 2). This sounding would have been 35 fathoms had the slope seawards been uninterrupted, and it may be said with some certainty that had echo sounding been in use in 1920, its continuous trace would have given sufficient indication of a feature to cause its discovery by an interline. Quite probably the trace would in addition have shown the harder material of the shoal extending under the softer mud of the sea floor round its base, thereby demonstrating another advantage of echo sounding.

Using standard methods on a scale of 1/100,000, therefore, an indication of Sea Green Shoal was obtained. That shoal had slopes of only 10°, whereas 25° may be encountered, and accordingly on Plate IV (Fig. 4), an illustration in elevation to show the efficiencies of different survey scales, a shoal with 25° slopes and a least depth of 42 feet has been used. The illustration draws attention to the cone into which the echo transmissions are focussed, so that a line of echo soundings is advantageously a great deal wider than the base of the superseded soundings lead, which was but a few inches across. The advantage is however lessened in deeper water when the cone tends to become pear-shaped. Plate V (Fig. 5) has been added to show that the echo trace can be misleading to the uninitiated in its distortion of the slope, and indeed the writer had not formerly appreciated the extent of the distortion.

In studying Plate IV (Fig. 4) it must be remembered that shoals are more likely to be ridged than circular; that interlines at 0.1" intervals are run in suspect areas; that there are considerable odds against a shoal lying exactly between lines of soundings; and that 25° is a steep slope.

It will be seen, however, that in areas where the sea floor is less than 10 to 12 fathoms down, something quite small rising only, as one might say, a handful of feet off the bottom, can be of importance and likely to escape notice under ordinary methods. If they are infrequent. Asdics find them, but if the floor is generally rugged, Asdics will be insufficiently discriminating. Then, recourse is had to sweeping or dragging a horizontally stretched wire across the area. This is a laborious business, costly in time, and is only used for such a purpose along a channel which valuable ships must navigate with but little water under their keels.

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Having mentioned costs – and time is money – they can at once be dismissed with the accepted conclusion that since scamped work cannot be checked and may lead to disaster, surveys must not be costed at so much a mile, and a hydrographic surveyor's promotion must not be directly related to the number of square miles he covers. Experience shows that there is more than enough incentive to get results, and it is more likely that one of the responsibilities and' anxieties of the surveyor in charge will be to ensure thoroughness.

Nevertheless there are opportunities to save time at the other extreme of surveys; i.e., those covering smooth estuarial sea floors, which moreover may be subject to rapid changes. The Edinburgh Channel is an example and is at present being surveyed twice a year. Because it is narrow, the chart is on a scale of 1/12,500 and so the survey must be to that scale, although 1/24,000 would suffice to delineate the sandbanks. In such case the lines may be run at double the normal interval.

Reverting to the general from the particular, it can be held that surveys of 3" to the mile and larger scales will, in the majority of cases, teach all that matters navigationally about the sea floor by ordinary methods and will be executed to meet a need for a chart of a harbour or its approaches.

Choosing the scale, therefore, becomes the greatest problem in the case of coastal surveys which may have to extend many miles to seaward in order to include the 100 fathom line. There is an immense amount to be done if the old lead line surveys are to be replaced, as they should be, and if sparsely sounded areas are to be covered. The smaller the scale the quicker will the work be done, but the purpose of the survey must be satisfied. In a task of such magnitude priorities must be taken into account, and first will come the safety of shipping wherever it may reasonably expect to navigate. Sometimes it will be economical to include the inshore areas or the shallower parts through which in fact the survey may find safe routes. A t other times, when such secondary areas have been covered by a previous lead line survey, those results may be allowed to suffice for the time being. Taking all things into consideration a scale of 1/72,000 seems most suitable and anything smaller is likely to be inadequate. But if charts on a larger scale than 1" to 1 mile are a navigational requirement, it will usually be wise to go to a yet larger scale for the survey, and especially so in rockbound or coral waters, in order to be sure of matching up to the confidence which users of all kinds will place on the large-scale chart.

And so, references to the chart conclude, as they began, this discussion of scales of surveys, but it is necessary to bring in the surveyor once more, particularly the surveyor-in-charge. He accepts responsibility for the results of his survey. He must have latitude to enlarge the scale which has been ordered should he think it necessary, or report if this is deliberately not done for some reason that he will advance. Alternatively he may open out the lines to save time whenever it can safely be done. If he employs Asdics he has to assess the degree of reliability basing it on the operating conditions and the type of target.

On the surveyor's reports the chart maker is ready to insert explanatory notes for the benefit of the chart users. Chart users are advised in various ways and places how to assess a chart and stress is laid on the date of the survey quoted in its title. This is sound but it increases the responsibility of the chart maker as advised by the surveyor to say so, when, for example, an insufficiently large scale has been used for parts of a modern survey on which the modern chart is based. Captions are then used, as «Unexamined», «Less water may be encountered», etc. On the other hand, a chart may show an important channel through dangerous waters which has been surveyed on a larger scale than that of the chart, and also perhaps than that used for surveying the surrounding waters. In such a case, and there is an example in recent surveys and charts of the Persian Gulf, then an appropriate caption will rightly increase the confidence of the mariner.

Mariners must see a good deal of evidence of out-of-date surveys on their charts, but they may take comfort from the care and devotion brought to their task by the surveyors of the last century. Their soundings were sparse so that their work would be classed as exploratory by modern standards, but their keen powers of observation, supported by masthead lookouts and the cross-examination of local seamen has meant that, on the many coasts they covered, they missed but few shoals dangerous to surface navigation.

My tribute to them I will follow up with my thanks to all those, mostly in the Hydrographic Department, who have helped me in the preparation of this Paper.

Beam identification in multiple-beam echo sounders

Author
M. J. Tucker[1]

Preamble

This manuscript is a reprint of the original paper previously published in 1961 in The International Hydrographic Review (IHR, https://ihr.iho.int/): Tucker, M. J. (1961). Beam identification in multiple-beam echo sounders. *The International Hydrographic Review, 38*(2), 25–32. https://journals.lib.unb.ca/index.php/ihr/article/view/26493

Precis

When using a multiple-beam echo sounder there is some difficulty in distinguishing port and starboard beams, and occasionally even between the first and second beams on one side. By using a transducer with the axial beam stronger than the rest, and tilting the transducer so that this beam points to one side, the corresponding port and starboard beams may be distinguished by their different intensities.

1 Introduction

When examining the sea floor using echo rangers, the information obtained may be considerably increased by using a transducer with several secondary beams, or side-lobes (Chesterman et al., 1958). The application of multiple side-lobes to echo sounding, that is, for determining the bathymetry of the sea floor, has been discussed by Tucker (1960) and by Howson and Dunn (in press). In this application, the transducer is arranged to have a series of beams pointing sideways from the ship as well as vertically (Fig. 1). The echoes from these beams are all received by the same receiver, but will usually have different ranges and can therefore be distinguished on the recording chart, particularly if the beams are narrow compared with the angle between them, which can be achieved by designing special transducers, or by using the multiplicative system described by Howson and Dunn (ibid.). However, with this type of beam pattern there is no means of distinguishing port and starboard beams, and in the simpler systems the beams are comparatively wide and their echo patterns tend to get confused.

On a recent cruise of the Royal Research Ship Discovery II, it occurred to the author that a more easily interpretable pattern could be obtained if the transducer were tilted so that the axial beam of the transducer, which is the strongest, points to one side. Port and starboard beams at similar angles to the vertical now differ in intensity and can be distinguished. Moreover, where the traces from them are superimposed on the recorder chart, the stronger one can be followed and so at least some information is obtained. In practice, using the simple additive system, the echo patterns from the side with the stronger beams usually obscure the pattern from the other side, so that information is only obtained about the sea bed to one side of the ship, except when the bed slopes very steeply.

2 Records

The special sonar installed in R.R.S. Discovery II for fishery and geological research (Tucker & Stubbs, in press) can be pointed vertically downwards and used as an echo sounder. For the records shown here it was tilted slightly off vertical to the starboard by the angles stated in the figure captions. The beam pattern of the transducer in the athwartship's plane is shown in Fig. 2. The fore-and-aft beam width was

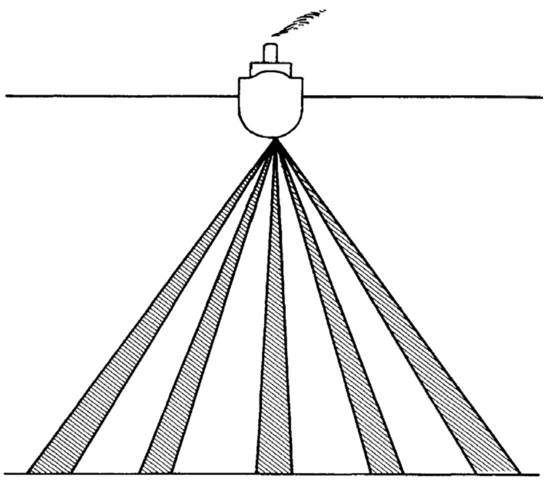

Fig. 1 Diagram of beam arrangement for multiple-beam echo-sounding.

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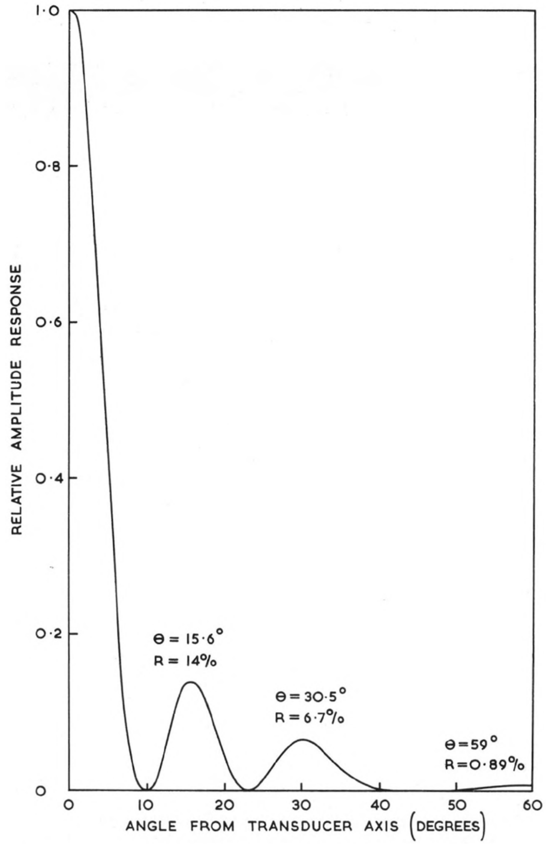

Fig. 2 The beam pattern of the transducer used to obtain the records shown in this paper. The curve has been calculated from the transducer dimensions, and takes account of transmission and reception on the same transducer.

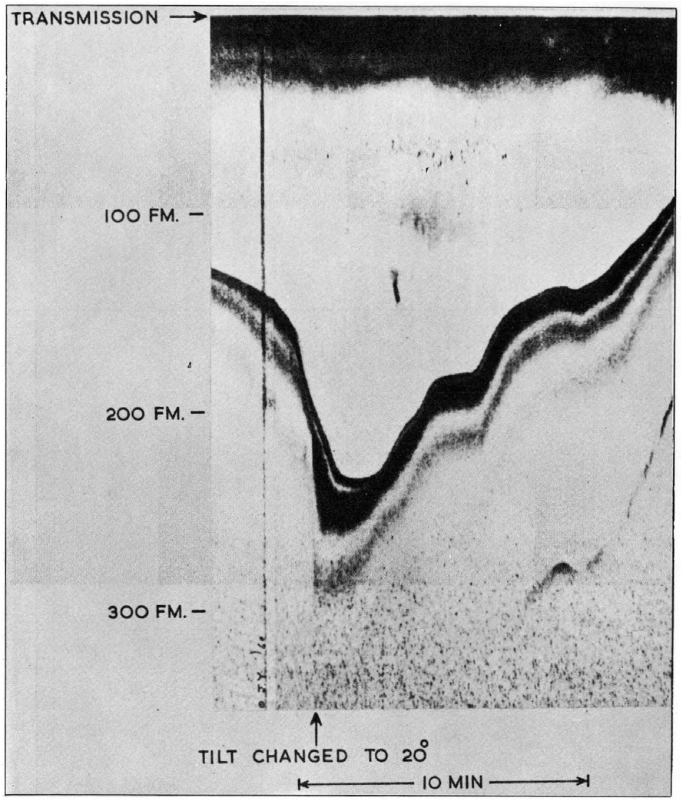

Fig. 3 A record taken steaming north over a canyon off the Spanish coast. The transducer axis was vertical for the left-hand part of the record, and was tilted 20° to starboard at the point marked. (Transducer stabilised against roll).

1.3°, the frequency approximately 36 Kc/s, and the pulse length about 2 m/s. The transducer could be stabilized against roll, but some records were taken with it unstabilized in order to examine the effect.
Some typical records are shown in Fig. 3, 5 and 6. Unfortunately it was not possible to obtain many records on this occasion because the equipment was mainly in use for survey work. However, these records give some idea of the type of result that can be obtained.

The record shown in Fig. 3 was taken approximately 30 miles ESE of Cape St. Vincent on a course of 290° (T), and shows a submarine canyon. Fig. 4 shows the corresponding geometrical construction using the deepest sounding in each track. This shows that the bed of the canyon was sloping downwards at an angle of about 2.5° away from the coast. The transducer was stabilized using a gyroscope as reference, and taking errors of measurement into account, the angle should be accurate to about ± 1.5°. It will be seen that the outside lobe crossed the bed of the canyon before that directly under the ship. The time difference was approximately 25 sec and the ship's speed approximately 9 knots. This allows calculation of the angle of the canyon bed relative to the ship's track, and gives a figure of 110°.

For comparison, Fig. 5 shows a record with the transducer axis vertical. Though this gives quite a graphic picture of the nature of the sea bed, it is more difficult to interpret quantitatively.

Fig. 6 shows a record with the transducer unstabilized. The weather was calm and the ship was rolling only ±5° approximately (max. roll). The beam pattern is still reasonably clear, but could obviously get confused if the rolling were much worse.

3 Discussion

It has been demonstrated that considerable extra information can be obtained using a multiple-beam echo sounder. This information conveniently fills the gap between soundings obtained on normal survey runs. Owing to the finite separation of these runs, and to unavoidable errors of navigation, there is often some difficulty in contouring the charts produced: for example, when humps appear close together on adjacent runs, it is often difficult to decide whether they are isolated, or connect together to form a ridge. The extra information from a multiple-beam sounder could be a great help on such occasions. It also allows a more detailed examination of any interesting features which appear on the records.

It is not, of course, necessary to make a geometrical construction in order to determine the depth at the position where the side-lobe beams hit the sea bed. This, and the horizontal distance from the ship's track, bear a fixed ratio to the range measured from

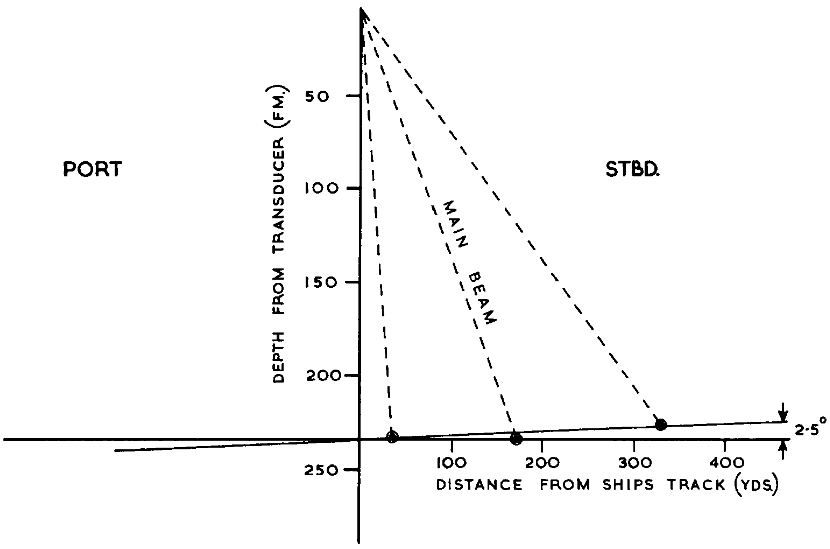

Fig. 4 Geometrical construction corresponding to Fig. 3. The points marked correspond to the deepest part of the canyon on each track.

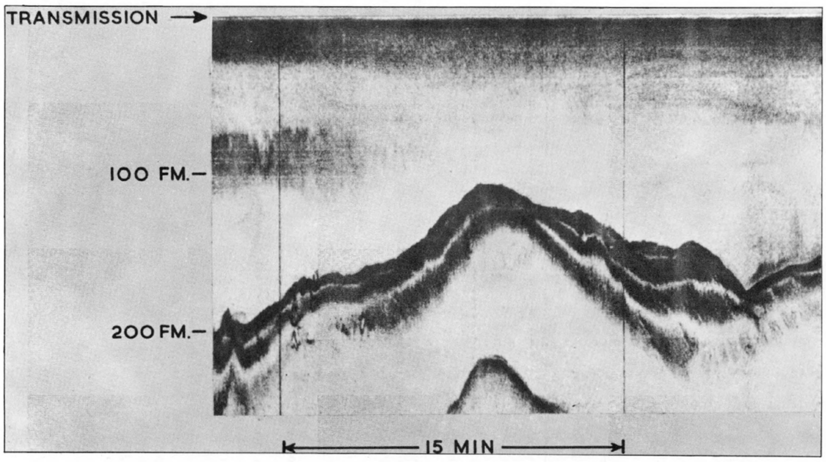

Fig. 5 Record with the transducer axis vertical. The interpretation is considerably more difficult than for the record shown in Fig. 3.

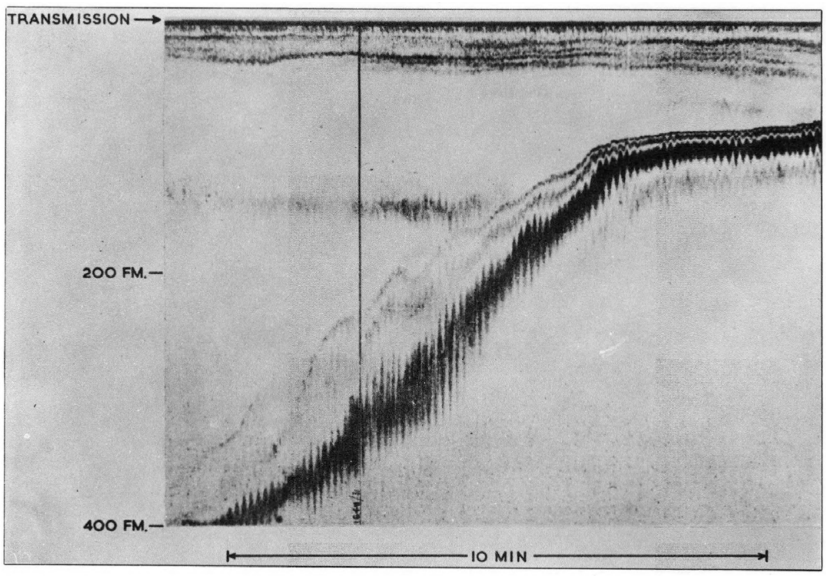

Fig. 6 Record taken with the transducer unstabilized and with the transducer axis tilted 30° to starboard of vertical. Maximum roll angle approx. ±5°.

the recorder chart, and these ratios can be given or the quantities tabulated.

Te beam pattern used on these trials is probably not the optimum. It was arranged for geological work, and for multiple-beam sounding it is probable that the relative sensitivity of the side beams could usefully be increased.

Care must be taken that fore and aft side-lobe beams do not interfere with the picture. In practice it will probably be necessary for the transducer to be at least twice as long as it is wide.

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World bathymetric charts – On the requirement for a world wide bathymetric chart on a scale larger than the General Bathymetric Chart of the Oceans (GEBCO)

Author

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Preamble

This manuscript is a reprint of the original paper previously published in 1972 in The International Hydrographic Review (IHR, https://ihr.iho.int/): Pascoe, L. N. (1972). World bathymetric charts – On the requirement for a world wide bathymetric chart on a scale larger than the General Bathymetric Chart of the Oceans (GEBCO). *The International Hydrographic Review, 49*(1), 153–160. https://journals.lib.unb.ca/index.php/ihr/article/view/23874

At the present time, in spite of criticisms that it is on too small a scale, and therefore cannot show bathymetric information in as much detail as oceanographers require, and also that it is not maintained sufficiently up-to-date, the General Bathymetric Chart of the Oceans (GEBCO) affords the only world-wide Bathymetric Chart.

All Hydrographers and many Oceanographers know of this important series of Bathymetric Charts, its purpose and history have been the subject of frequent articles, the most recent being that in the June 1971 issue of the Journal of the British Cartographic Society. It comprises 16 buttjoining sheets each covering 90° of Longitude, arranged in 4 parallel belts, extending from the Equator to Latitudes 46°40' N and S, and from 46°40' to Latitudes 72° N and S, on Mercator projection, scale 1/10 000 000 at the Equator, 1/6 860 000 at Latitude 46°40' and 1/3 100 000 at Latitude 72°. They are complemented by 8 charts for the Polar Areas on the Lambert Conformal projection, each chart a quadrant, a rolling fit at the same scale at Latitude 72°, the scale decreasing slightly to 1/3 180 000 at the Poles.

These charts are produced by the International Hydrographic Bureau (IHB) with co-operation in the supply of information, co-ordination and cartographic compilation by all the member states of the International Hydrographic Organization (IHO). However, in spite of much international effort and considerable expense, of the 16 Mercator charts of the oceans only those of the Atlantic Ocean have been revised by New Editions since 1955, and only a small proportion of the enormous amount of bathymetric information obtained in the last 20 years is presently available in published form.

The GEBCO series shows bathymetric contours at every 1 000 metres outside the Continental Shelf and Margins enhanced by the customary blue hypsometric layer tints deepening in colour with increasing depth. Whilst this artificial method of representing morphological relief is occasionally subjected to criticism, iso-lines are accepted as the most scientific method of cartographic relief representation and the GEBCO series has been criticised only in that additional depth contours at least at every 500 metres are not shown.

The GEBCO series, although somewhat out-of-date, affords complete worldwide coverage, no other such complete coverage has yet been published at this scale. Bathymetric charts of the separate oceans have been published but no complete worldwide

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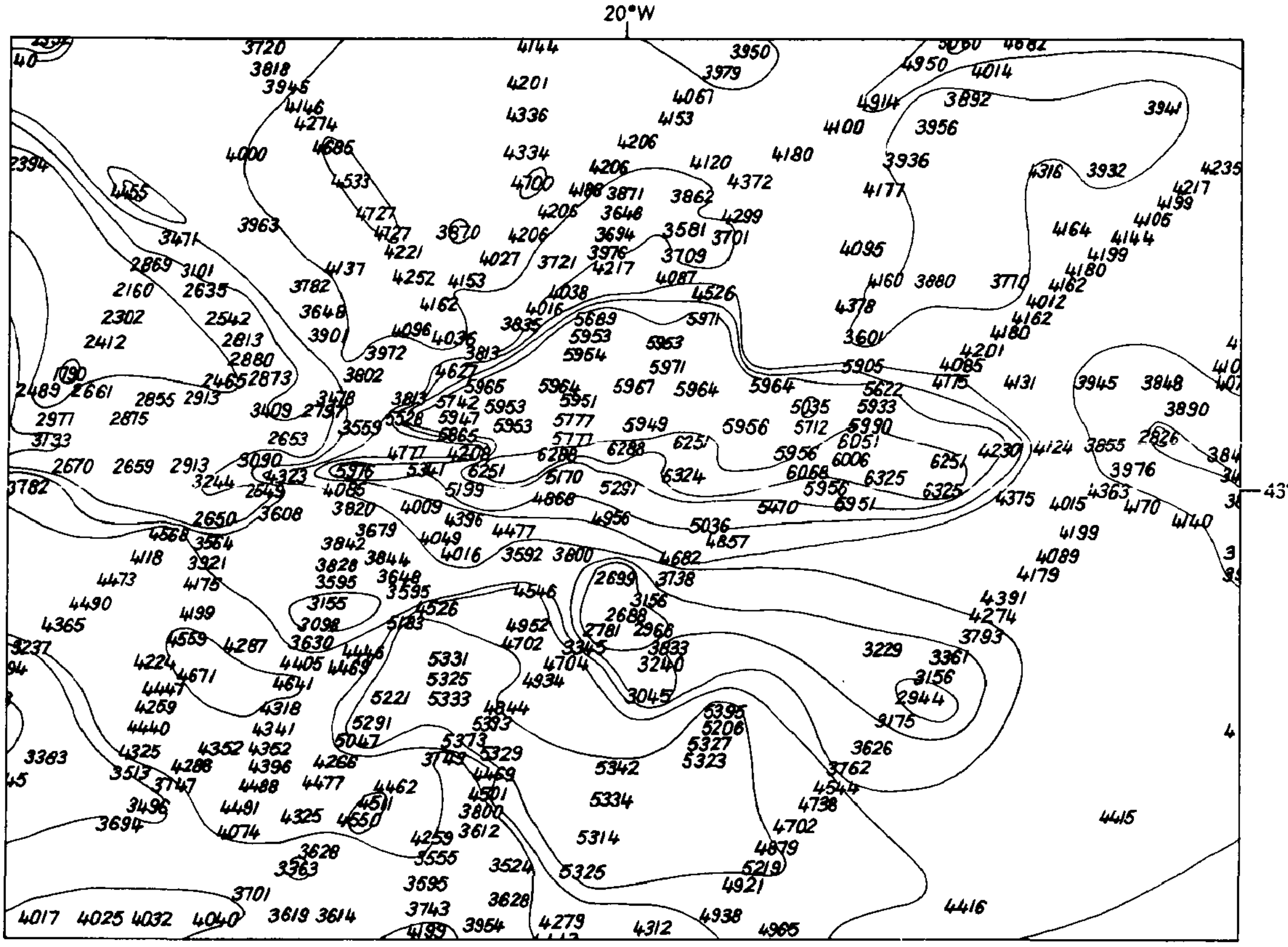

Fig. 1 Ocean Sounding Plotting Sheet. 1:1,000,000.

series. GEBCO has been criticised as being on too small a scale. Charts of certain ocean areas are available in published form on larger scales. The U.S. Naval Oceanographic Office publish Bathymetric Charts (BC charts) of the North Atlantic and North Pacific Oceans and the Mediterranean Sea. These are on Mercator projection, scale 1° Longitude = 4 inches, i.e. 1/1 100 000 at the Equator, 1/950 000 at Latitude 30° N and 1/550 000 at Latitude 60° N with depth contours at every 100 fathoms mostly shown in pecked lines, being interpolated from insufficient information, and most were published in the period 1951 to 1953.

The new, massive World Map on 1/2 500 000 – in reality also a World Chart – now in process of publication by the Socialist nations of Eastern Europe, is still far from complete and the rate of publication of new sheets has decreased in recent years. Of the ocean areas only those fringing the Americas and South Africa are at present available. The sheets of this World Chart are published in 6 zones, from the Equator to Latitude 24° and from Latitude 24° to Latitude 64° on the Conical Equidistant projection, and on a Polar Azimuthal Projection from Latitude 64° to the Poles. Bathymetry outside the Continental Margins is shown by depth contours at every 1 000 metres, i.e., not more closely than those given on the much smaller scale GEBCO charts, supplemented by hypsometric layer tints of 5 gradations of blue.

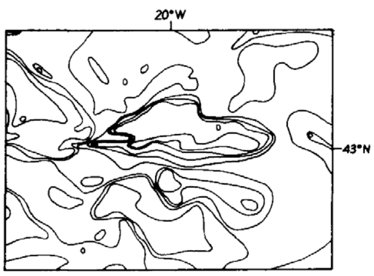

Fig. 2 Bathymetric chart produced by reduction of Fig. 1. 1/2,750,000.

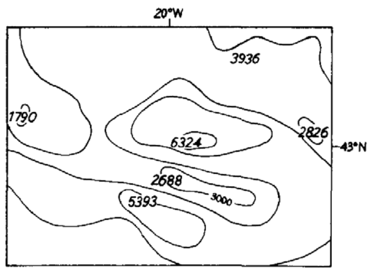

Fig. 3 Portion of Navigational chart. 1:2,750,000.

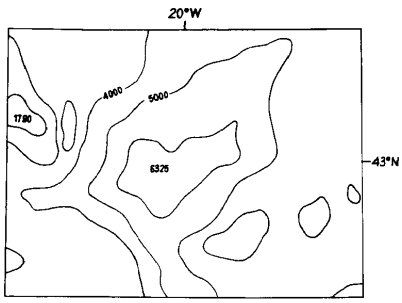

Fig. 4 World Map 1967. 1:2,500,000.

Additional to these, the only other available bathymetric charts are of limited areas, for example those published of "national" areas or from the results of scientific expeditions, e.g., the 1/2 000 000 charts of the North West area of the Indian Ocean. The Japanese Hydrographic Office publishes Bathymetric charts of the ocean areas around Japan and these supplement the United States BC charts.

The total world coverage of contoured Bathymetric charts available in published form, other than the GEBCO series, is thus of limited extent.

However, one other important source of bathymetric information is available. This is the International series of Ocean Sounding Plotting Sheets compiled under the auspices of the International Hydrographic Organisation with the assistance of all member nations. Individual Plotting Sheets are obtainable from several National Hydrographic Offices or from the IHB and give all worldwide original Bathymetric information at present available. This series of 600 sheets is grouped into 8 latitudinal bands each with a common mid-latitude and hence a common longitude scale, the mid-latitude scale of each band being 1/1 000 000. The Hydrographic Offices of 16 nations have accepted national responsibility in agreed ocean areas covering the whole world for the collection of all bathymetric information and for the compilation and maintenance of this information on the master Ocean Sounding Plotting Sheets covering their accepted areas. These master sheets arc compiled in manuscript and show all available depths, to a density limited only by the scale. Some plotting sheets give depths in Fathoms, some are in Metres. These master sheets are maintained in as up-to-date a state as possible, depending on the resources of the national hydrographic office, from information obtained by the nation concerned or supplied from ships of other nations. Copies are made available at a reasonable charge. In recent years certain nations have commenced periodic revision of their master plotting sheets and publish printed copies.

The existence of these Ocean Sounding Plotting Sheets is well known to oceanographers. They are the basis for the GEBCO series of charts.

However, the master plotting sheets show only depth information outside the 200 metre (100 fathom) contour line and on many sheets the coastline of the mainland, and of the islands, is not given, and the continuous compilation in manuscript of dense lines of depth figures, often crossing at narrow angles, makes these important documents somewhat confused and illegible. Until depth contour lines have been added to these crowded plotting sheets they are sometimes unintelligible.

The GEBCO charts are compiled directly from these plotting sheets, contours being first added and compilation made in two stages to accommodate the large scale reduction and with minimum generalisation.

GEBCO has also been criticised in that it is on too small a scale, and a larger scale of about 1/2 000 000 is now desirable. This is the scale of the charts of the new multi-nation International Indian Ocean Expedition, recently published.

Such a larger scale worldwide Bathymetric chart is now possible. The recently agreed International Series of Navigational Charts on Mercator projection, scale 1/3 500 000 at Latitude 22°30', 1/2 000 000 at Latitude 55°, now being produced with International co-operation under the auspices of the IHO now makes this possible. In the early stages of the preparation of this navigational chart, fully detailed bathymetric contours would normally be compiled on the 1/1 000 000 plotting sheets and the availability of this compilation makes the production of a bathymetric version of each International chart a practical proposition.

The usual steps in the preliminary compilation of these charts are shown in Figs. 1, 2, and 3. Fig. 1 shows all the available depths in metres in an area close Northward of the Açores as plotted on the relevant Ocean Plotting Sheet, with depth contours interpolated at every 500 metres. Fig. 2 shows these contours reduced to the scale of the chart, 1/2 750 000 at this latitude, before generalisation. Fig. 3 shows the relevant portion of the navigational chart with generalised depth contours. For comparison the same area as shown on the relevant World Map on 1/2 500 000 is given in Fig. 4 (less the four shades of the blue hypsometric tint).

The compilation stage shown in the Fig. 2 example could thus be the basis of a detailed bathymetric chart, as most of the compilation is complete and only mechanical copying and preparation of any tint plates needs still to be done. When the compilation stage of adding contours on the plotting sheets is carried out by, or in conjunction with, oceanographers no criticisms regarding scientific accuracy can be made. The task of producing a bathy metric version of each sheet of the agreed International Chart series is thus shown to be relatively easy.

The limits of each sheet of this series are given in Fig. 5. These sheets have been schemed only for navigational requirements, with adequate overlaps, and the series does not cover the scientifically interesting central ocean areas. Limits of possible additional charts to cover these areas are shown on Fig. 5 with a distinctive numbering. Three additional charts, for example, would give complete coverage of the North Atlantic.

Again, it is expected that the International Charts will be revised every 5 years, at each Magnetic Epoch, for correction of the isogonals, and this stage should also include an up-dating of bathymetry. So that it is possible that a similar 5 year cyclic revision of any relevant Bathymetric chart could also be anticipated.

It is appreciated that new techniques of mechanical or semi-mechanical methods using line digitisers, computers, and automatic plotters will permit much greater freedom in the production of any bathymetric

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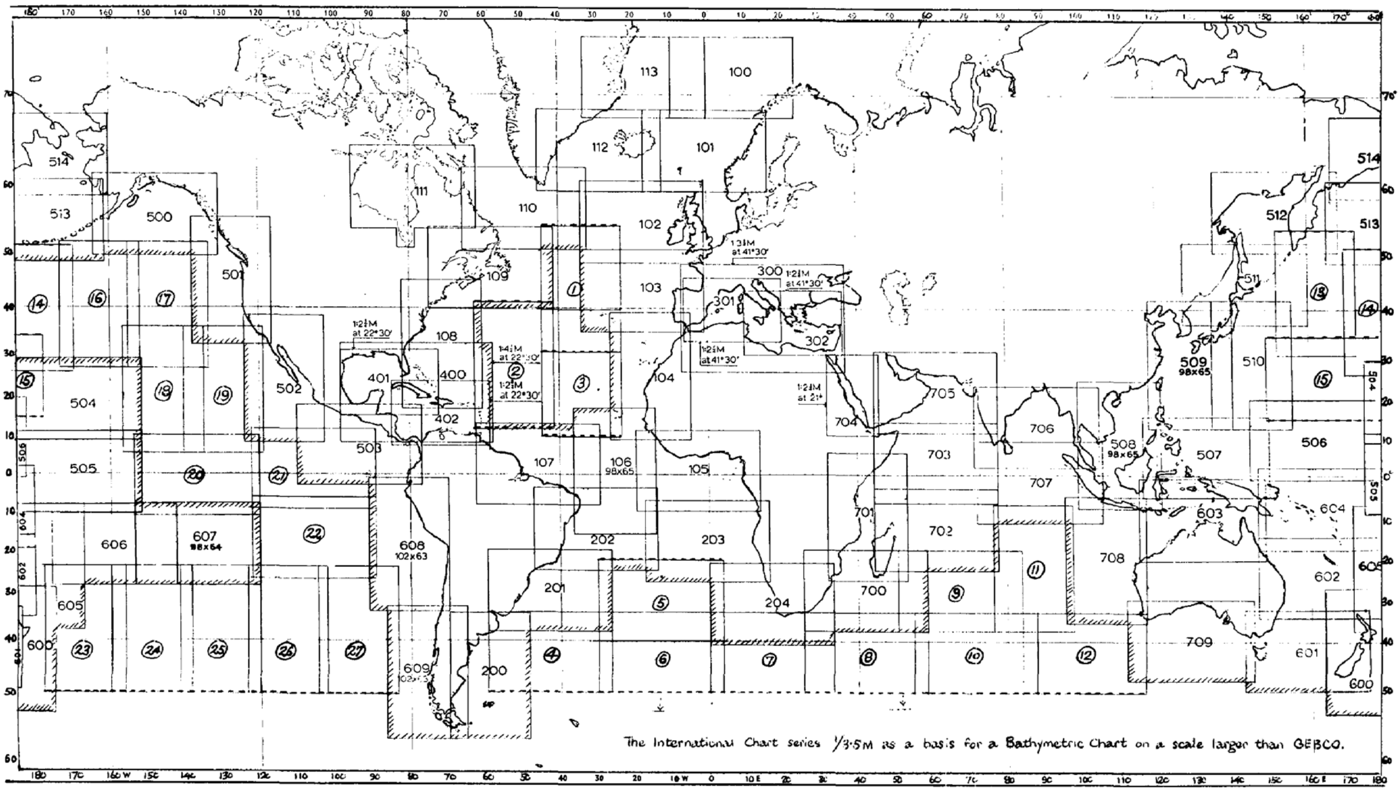

Fig. 5

chart, where most of the detail is in line form, once the relevant contours have been made available from the continuously-updated plotting sheets.

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This article is being written to bring to the notice of World Oceanographers the opportunity that the production of the International Chart series now presents, and it is being published to bring this also to the attention of the compiling Hydrographic Offices, so that the important detailed contoured compilation material, as shown in Fig. 2, is not needlessly destroyed.

It must be mentioned here that any such series of Bathymetric Charts, even with International co-operation, would constitute a major additional undertaking by hard-pressed Hydrographic Offices.

The most important question must now be asked: "What Bathymetric Chart of the World do Oceanographers Require?" i.e., need. Is there a real requirement for a complete worldwide series on a scale of about 1/2 000 000 as has sometimes been stated to the author, or does that need exist only for charts of limited areas of special interest? And what then is the optimum scale? It is possible that Oceanographical Science will be satisfied with such limited area charts, e.g., of some portions of the Atlantic, with detailed larger scale charts to he made when adequate survey position accuracy is available of even more limited areas, e.g., of typical oceanographic features, seamounts, trenches, etc.?

And when these large scale graphics of 'typical examples' are possible, will not they not better appear in Ocean Science text books and thus be unnecessary in any other published form?

But until Cartographers know what are the considered requirements of Oceanographers for Bathymetric Charts, their scale and coverage, it is not possible to discuss in real terms the other important factors of *finance* and *effort*.

The Navigational Chart, whether harbour plan, coastal chart, or ocean passage chart, is a necessity. It is a navigational requirement of the first order. Its production, even excluding the heavy cost of the original surveys, its compilation, printing, and subsequent revision, is a costly business, financed from national resources with only limited re-balance from chart sales.

The Bathymetric Chart, with its layer tints, has hitherto been regarded as not a necessity. Its production has been scientifically important and desirable, and its production has been financed usually only by enlightened Foundations or by International co-operation, in the few series of charts now available. With increasing interest internationally in Oceanography, with the increasing development of the resources of the sea bed in deep and ever-deeper waters, the gathering of bathymetric information is of great practical importance for both scientific and economic purposes. But its communication, in as comprehensive and easily understood a manner as possible, requires presentation in chart form. For multi-user availability, this requires a published Bathymetric chart and the producers and publishers of present small scale navigational charts, the Hydrographic Offices, would appear to be the most efficient publishers of Bathymetric charts.

But this article which demonstrates the overlap between the production of the Navigational small scale chart and a detailed Bathymetric chart, must bring to the notice of Oceanographers the other factors of *finance* and *effort*.

The problem of *finance* needs no re-stating. But *effort*, the compilation effort of trained cartographers, proficient not only in cartographic techniques but in the evaluation and synthesis of source material now being obtained in ever-increasing quantities by ships and research vessels of many nations, is almost as important a problem as finance, in that there is a very limited staff available with such expertise.

However, it could be considered regrettable that much of the large amount of bathymetric information obtained in recent years has not yet been made available in published chart form. It may be that the 600 manuscript Ocean Sounding Plotting Sheets produced with International co-operation under the auspices of the IHO, with copies available from the several participating Hydrographic Offices are sufficient for all scientific and economic purposes.

The attention of Oceanographers is called to the 9th International Cartographic Association (ICA) Congress to be held in Ottawa, Canada, later in 1972. The theme of the morning session on Wednesday, 23 August is Marine Cartography, this theme to exclude Nautical Charting. This article was written for presentation al that conference, hut it was decided to publish it in this volume of the Review, thus ensuring that it will available for advance information, both to those Hydrographic Offices participating in the International Chart Scheme and to International Oceanographers. It is expected that this article will be referred to during the Marine Cartography meeting of the ICA conference and it is hoped that Oceanographers, with possibly a representative from the Intergovernmental Oceanographic Commission, will be able then to state their requirements for Bathymetric Charts.

The purport of this article is to ask, on behalf of International Cartographers for *guidance*, for answers to the questions raised herein, and again to mention the controlling words of *need, finance, effort*.

https://doi.org/10.58440/ihr-29-a12

The value of a nautical chart

Author
L. Oudet

Preamble

This manuscript is a reprint of the original paper previously published in 1973 in The International Hydrographic Review (IHR, https://ihr.iho.int/): Oudet, L. (1973). The value of a nautical chart. *The International Hydrographic Review, 50*(1), 149–161. https://journals.lib.unb.ca/index.php/ihr/article/view/23844

Editor's note

The first half of the present article is reprinted from *The Journal of Navigation* (Volume 25, No. 3, July 1972) with the kind permission of the Royal Institute of Navigation, London.

1 A stranding in the West Indies

In January 1971 the liner *Antilles* sailing among the islands of the same name ran aground in the neighbourhood of the Grenadines, between the islands of Mustique and the Pillories. Nobody was injured but the ship was lost. An inquiry by a maritime court in the following October acquitted the Captain and this came as a great relief to the seafaring fraternity because it was difficult to see how a sailor at the top of his profession could knowingly have navigated with such imprudence. The fatal rock was not shown on the chart and everyone knows that charts are not perfect: the Master had been the victim of the inevitable.

Meanwhile some people, both seamen and laymen, had noted that the passage in which the stranding occurred was not one that would normally have been used by such a ship as the *Antilles*. They felt that her Master had taken an unjustifiable risk in order to show his passengers an enchanting landscape; so first this criticism must be examined.

Cruising is an increasingly important sector of maritime trade and all liners now do cruises; even the big transatlantic ones only operate passenger services at the peak period in summer and for the rest of the year carry the idle rich on the look out for ways to spend money and kill time. Such an employment is certainly not essential and does little credit to a society that finds such an outlet for its capital, but one cannot blame a master for taking command of a cruising ship; it is not he who is responsible for the system. In the long run it has the merit of finding work for crews who would otherwise he laid off. The trade unions, with no love for capitalism, have helped by their demands lo perpetuate and even to foster the profitable undertaking of cruising. It may he added that even the USSR fits out cruise liners.

Cruising is thus a widespread enterprise; since it is profitable it is accepted, and every company tries to attract custom. On French ships the ambition is to surpass other nations in the pleasures of the table. But naturally in a floating hotel like a liner the attractions are not confined to good eating and the ports of call; a captain aware of his responsibilities usually tries to make the voyage itself as interesting as possible. The company did not leave this point entirely to the initiative of the Master of the *Antilles*, but actually encouraged him by allowing extra time en route.
Had he used the extra time in detours out of sight of land he would certainly have been acting contrary to his employers' intentions.

One cannot however press this point too far for the Captain is 'master under God' and the company cannot dictate his course; he was free to choose a course that would make the voyage as interesting as possible and that was his job. One might say that that was what he was there for, and one might add that he would never have dreamed of taking a cargo where he lost his liner.

Thus it was in carrying out his assignment that the Captain decided on a bold piece of seamanship. But boldness is not rashness and whatever the assignment may be it does not justify risks that might prejudice its execution. We must see whether the Captain of the *Antilles* did in fact navigate rashly. From his own statements, he was fully aware that the passage he was taking was an unusual one and did everything he could to make sure that it was not dangerous. He took continuous soundings whenever close inshore or in the vicinity of danger. He had on previous occasions sailed in the neighbourhood of the channel in which the accident occurred and his soundings had not shown any discrepancy with the indications of the chart. In attempting the channel that was to lead to disaster he thought that he was only making a reasonable extrapolation. It was a reasonable extrapolation but it was based on false premises. What took place to the north of Mustique could equally well have happened on the other experimental passages

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she had already made; the *Antilles* had in fact been sailing dangerously for a long while and in the long run the unappreciated risk could not fail to become an actuality.

We must now clinch the matter and see how an experienced master, one of the best in his company, could have thought himself justified in making a passage which was in fact dangerous. Two explanations have been put forward but neither of these is valid. The first suggestion was that he had ventured close inshore with a chart that was a hundred years old, and should have mistrusted so old and necessarily defective a survey. But this does not accord with the development of hydrography; precise methods of survey had been in use since the end of the eighteenth century, thanks to the perfecting of the sextant and instruments associated with it like the station pointer; so that in a narrow channel like that off Mustique it was easy to make a close and accurate survey. An examination of the chart shows that it was based on surveys the scientific character of which remains valid today. In fact it shows the regular lines of soundings that are recognized in the nautical literature as evidence of careful hydrographic work. This does not of course exclude the possibility that a dangerous rock has escaped detection in these regular soundings, but that is another matter and we shall consider it presently.

It was also suggested that the *Antilles* might have struck a coral reef. If so, such a reef could well have grown by 1971 to become a danger to navigation which did not exist a hundred years earlier and, if he was in an area of coral, the Captain was wrong to ignore this possibility; everybody knows that while the sea wears away even the hardest of rocks it does not stop corals from growing. But the chart indicates no coral anywhere in the vicinity and the investigations carried out after the accident show that the *Antilles* struck an uncharted rock, which must have already been there a hundred years ago, and which had escaped the survey of that date.

Such defects are inherent in the methods employed before the middle of the present century and can only now be eliminated by the most modern methods of underwater search. If one is to be certain of detecting all the irregularities on a bottom whose general features have been established by lines of soundings, an ultrasonic transmitter is towed just clear of the bottom so that its beam sweeps over the surface to be examined; any object that it encounters gives an echo in the receiver. It then only remains to proceed to the point above the obstacle and determine its depth and extent by sounding or by sending down a diver.

There was no such method a hundred years ago and even if one were revising the chart of the Grenadines today it would possibly not be employed, and that brings us to the root of the problem which is the scale of the chart. To construct a chart at any given scale the survey is carried out at a similar scale, and the use to which the chart can subsequently be put depends on this. It is a point which Sailing Directions still barely touch on, so that the Captain of the *Antilles* was insufficiently informed as to the use he could make of his chart.

The French chart of the Grenadines, like the British chart from which it is derived, is on a scale of about 1/75 000 which means that the surveys on which it is based were on a scale not less than this. Parts of the survey may been on some larger scale, 1/50 000 perhaps or 1/25 000 and therefore in greater detail, but this is immaterial because the navigator cannot know it. A survey at 1/75 000 means that on the plotting sheets from which the chart is compiled the lines of soundings are represented by lines drawn not more than one centimetre apart, the equivalent at that scale of 750 m. Soundings at that interval are therefore appropriate for a survey of that scale and for the chart compiled from them. Thus to read on a chart that its scale is 1/75 000 means that the lines of soundings on which it is based could be 750 m apart.

Naturally the soundings are much closer together along the tracks followed by the surveying vessel or her boats. In 1860 the only apparatus for sounding was the lead and line and at depths between 10 and 20 m, as in the case with which we are concerned, the distance between successive soundings would be the distance made good by a boat under oars in the time needed to heave and recover the lead, some tens of metres. Nowadays surveying ships and their boats are equipped with echo sounders of a type similar to those found on every ship's bridge which provide a sounding, say every three seconds. At 5 knots this gives a sounding interval of 7.5 m, but at a scale of 1/75 000 this still does not mean that the lines of soundings are less than 750 m apart. Such a pattern cannot claim to cover the bottom with a fine tooth-comb the teeth may be 750 m apart. Even in a large-scale survey of 1/10 000 the guaranteed interval is as much as 100 m and dangerous obstructions can occur between two lines at that separation. Detection by sonic beam, of which we have already spoken, is the infallible method for discovering such obstructions, and since the effective range of the beam is upwards of 1000 m, surveys at 1/100 000 carried out since the method came into use can provide a degree of certainty hitherto unattainable. One may say in fact that any chart based on surveys before 1970 carries with it a risk that the surveyors may have missed some dangerous wreck or other obstacle to navigation.

The risk certainly varies in different areas. Thus the largest scale of charts covering the English Channel is about the same as the scale of the chart of the Grenadines, but one would not therefore say that it is dangerous to approach within 750 m of every marked danger on the Channel charts, nor that the navigator is anywhere in danger of striking an uncharted wreck or obstruction. It must however be recognized that this security is due as much to the presence of

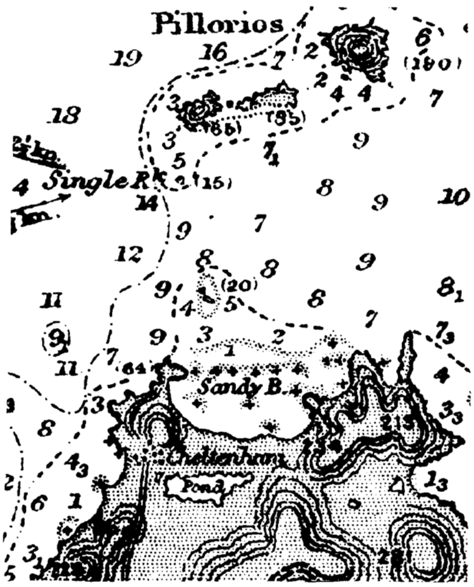

Fig. 1 The British chart (No. 2872) × 4.

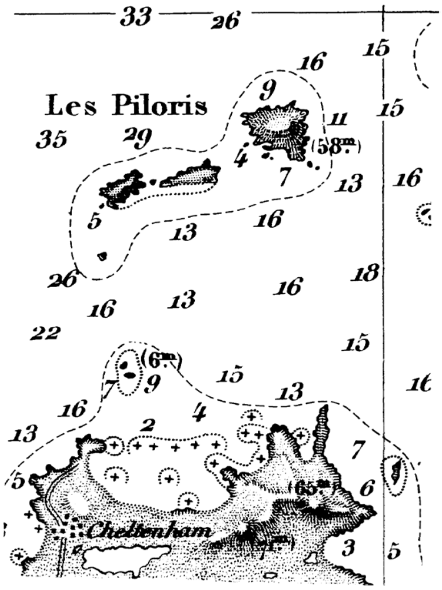

Fig. 2 French chart (No. 3206) × 4.

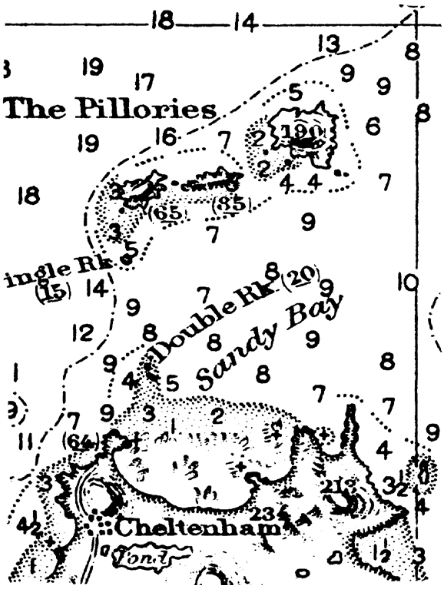

Fig. 3 The American chart (No. 1640) (No. 3206) × 4.

buoys, the volume of traffic, and soundings taken by ships that frequent this seaway, as to systematic hydrographic surveys. Even so the same degree of safety does not apply everywhere, among the shifting sands of the Goodwins for example it is the buoyage that contributes most to safety. Besides, in areas where navigation is infrequent the possibility cannot be excluded that there are submerged rocks not marked on the charts in the neighbourhood of those that are marked. In this respect the 'crab catchers' who like to skirt dangers would be well advised to temper their appetites by the larger scale charts of the French and English coasts. In any case navigators know that the largest scale chart available for any area should always be used.

For the Grenadines there is no chart on a larger scale than 1/75 000 and it seems clear that the Captain of the *Antilles* would not have attempted the Mustique channel had he realized the qualifications as to the reliability of his chart that we have stated above. This channel, some 400 m wide, was not adequately covered by a survey in which the gaps between lines of soundings might be as much as 750 m.

It is true that the representation of the area on the British and French charts gives an impression of accuracy in this respect which might mislead a mariner unfamiliar with hydrographic procedures. To illustrate this other important aspect of the problem parts of the British chart (No. 2872; Fig. 1), the French chart (No. 3206; Fig. 2) and the American chart (No. 1640; Fig. 3) are here reproduced at four times the scale of publication. Of course this enlargement of charts is not to be recommended to the navigator since it does not alter the scale of the original survey; it is only to make the topographical details clearer and to show the part that a draughtsman plays in interpreting survey data.

On the original British chart (depths in fathoms) one finds a continuous 5-fathom contour on both sides of the channel except to the north-east of Cheltenham, westwards of a narrow point of land. On the French chart (depths in metres) the 10-m contour replaces the 5-fathom contour and shows no discontinuity at this point. This chart also stands up to enlargement better than the British chart; the topography, bottom contours and lettering are so clear that it is hard to believe that it is an enlargement, only the size of the figures showing depths reveal to anyone familiar with charts that it is so.

But we must turn to the American chart to find a style of interpretation different from the original. While there is an extreme simplification of such details as the topography everything that concerns dangers to navigation, awash or submerged, is more conspicuously shown than on the other two charts. It seems that to some extent the Americans have incorporated information of their own; the entire area of dangers awash or barely submerged is shown by a stipple, which is particularly close along the perimeter and emphasizes its dangerous aspect. Besides, the 5-fathom contour is shown by a discontinuous pecked line which gives the impression that the dangers may extend as far as that. Above all, this contour is completely absent to the north of Mustique where the inscriptions 'Double Rk. (20)' and 'Sandy Bay' take its place. The general impression is that to the north of the island the limits of the danger are ill defined and that it may well extend as far as the middle of what is shown as a channel on the other charts.

All this shows how difficult it is for a navigator to make an appraisal of the chart, yet it is something he has to do whenever he is in unfamiliar waters. This is too large a subject to deal with in a short paper and would require the collaboration of hydrographers and navigation instructors. Short of that it is worth repeat-

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ing the advice given by a hydrographer many years ago. This 'rule of thumb ' is that whatever chart he may be using a mariner should not approach nearer to charted dangers than the width of his own thumb. Taking this as 2.5 cm, the equivalent of the English inch, it will he seen that it represents two and a half times the maximum interval between lines of soundings, or 1875 m for a chart at the scale of 1/75 000. The rule of thumb is in fact an application of the seafaring proverb 'too strong never breaks'.

It may not always be possible to allow so wide a margin, but it is wise to keep this order of magnitude always in mind and, in particular, lo apply it when sailing in unfrequented waters. The Captain of the *Antilles* ignored the rule and this led him to overestimate, as doubtless many sailors do, the degree of confidence which should be placed even in a good modern chart where there is always the possibility that submerged dangers may have escaped the surveyor's notice. As we have shown, this risk is only averted by the most modern methods of survey and it will be many decades before they will have been applied to all existing charts. Channels like that in which the *Antilles* was lost will certainly not have a high priority. That is why there should be no delay in making mariners aware of the lesson which cost the life of one unfortunate ship. The 'rule of thumb' will long retain its value in counselling prudence to those who are tempted to sail in waters where some uncharted rock may have escaped even a relatively recent survey.

2 The concept of cartographic interpretation

I have showed that identical original data when cartographically interpreted can nevertheless result in varied cartographic representations. All cartographers, as indeed all men, have individual personalities and consequently an individual character tends to be stamped on the picture of the reality as seen by each cartographer. Thus we see that the French cartographer, using the British chart as original, has delineated a more attractive picture of the facts, whereas the American has depicted a more menacing aspect.

What then is the relation of these pictures to the surveys on which they are based. A full scale photograph of an original survey (No. D 5931, Sheet 5) carried out in 1861–1862 by a British survey party demonstrates this relationship (Fig. 4). Here, as will shortly be shown, enlargement would lead to a faulty analysis of the document.

The authors of the 1861–62 survey are today succeeded by others whom I would like to thank for permitting me to publish this document. They are thereby doing me the honour of making me their advocate at the bar of public opinion, an opinion which, roused to indignation by the loss of a splendid and well commanded ship, suspected inadequacy of the chart in question. Although the document was in effect inadequate for the use to which it was put, this does not in any way prevent it giving a far fuller degree of security to the navigator than at first appears. If in point of fact the arguments were always as good, advocates would have no difficulty in securing acquittal for their clients.

Close to the exact position of the stranding the maximum spacing between soundings is a third of that acceptable for the scale, i.e. 250 m instead of 750 m. This has been brought out by superimposing a dotted line through adjacent soundings which serves to render their small interval more apparent. We may be certain that soundings were in fact made at closer intervals all along these dotted lines for, as mentioned above, this was an easy matter at that period.

As it was naturally not possible to plot all these soundings on the sheet the cartographer had to limit himself to the minimum interval necessary for separation of two adjacent soundings where obviously the figures have to be as small as possible consistent with legibility. When selecting his soundings for the final chart he has naturally systematically chosen the shoalest.

A second addition has been made to this same document. In the area around the scene of the stranding circles have been added to highlight "blanks" in the survey, areas where no soundings exist. We can see that here these blank areas have a maximum diameter of 500 m, whereas further from shore their diameter reaches, although never rises to more than, the 750 m acceptable for the scale. The

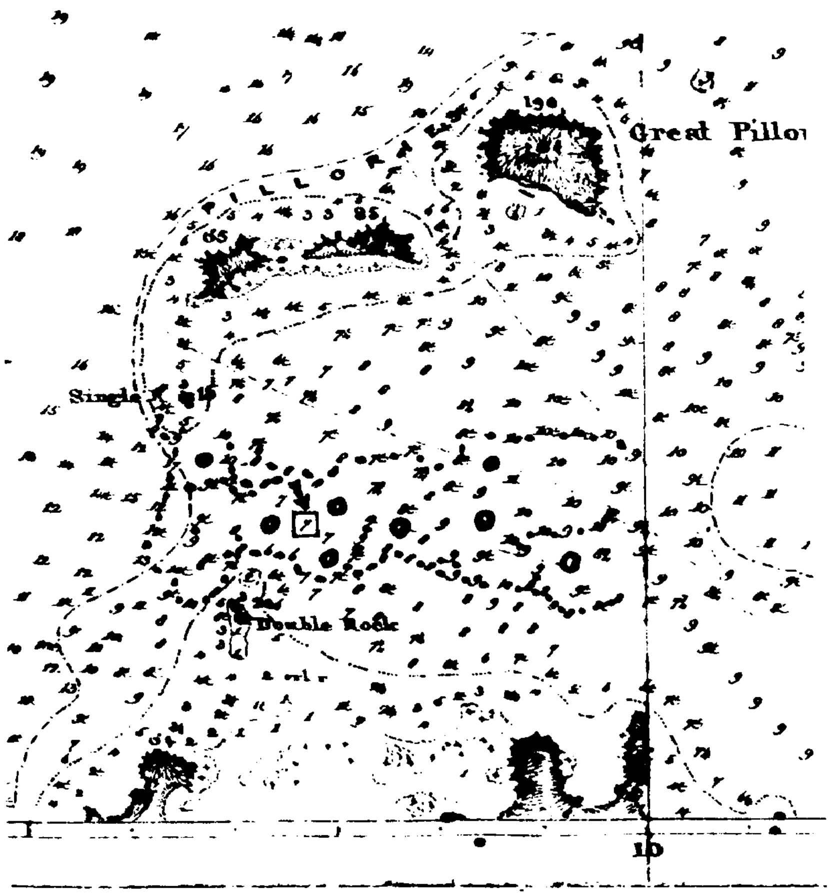

Fig. 4 Extract from the original British survey. Approximate position of wreck indicated by the arrow.

rock on which the *Antilles* stranded is within the area of these blanks (see Fig. 4).

The foregoing analytical appraisal shows that in this survey both its execution and its portrayal – and the two are not interdependent – meet very adequately the survey's requirements within the limits of its scale. A hydrographer's professional conscience can take him no further than the limits which figure size imposes, for the whole must remain legible, however small and densely packed these figures may be.

The rule of thumb is self-evident on a plotting sheet. We can be sure that the width of a thumb mark will cover any blank, even the largest permitted by the chart scale.

However, it must never be thought that the broad application of this rule will provide the easy solution to all problems of interpretation. Following the example of biblical scholars who have provided us with scriptural exegeses, I venture to suggest that the cartographer in his turn would do well to provide a critical estimate of each chart's worth – a cartographic exegesis in fact, a word conjuring up patient and careful work carried out by experts – and that this information should he included in Sailing Directions.

It was to show the extent of the problem of interpretation on one particular chart that I wrote my article "A stranding in the West Indies", reproduced here. An extensive analytical appraisal of the chart in question led me to include a short paragraph reducing everything lo be learned from the appraisal to a single simple rule.

We may note in passing that the appraisal of a similar scale chart in the English Channel has led to results which are at first sight considerably different, but in reality to the discovery that the two have certain common points. One is that each chart must he used for its own specific kind of navigation, and another that its degree of dependability is not even uniform all over the chart. Thus, the cartographic reliability of a depthreferenced rock is certain, provided of course that a check has been made for other peaks at lesser depths, using divers if necessary. On the other hand a sandbank or a coral reef may vary. Some sandbanks pile up, others disappear, others again have seasonal mean levels, and yet others have surfaces with wave-like undulations. In the north of France we call these sand-waves "ridens" (ripples). As a result of the perpetual movement of swell and currents the size and location of these sand-waves changes continually. This aspect of hydrography is still poorly understood. We knew that these sand-waves existed in waterways, but in the Channel they remained undiscovered until the day the keels of supertankers came near to grazing their crests. When measuring an actual clearance in order to fix a maximum acceptable draught the depth values began to fluctuate and never remained twice the same.

The ultimate reason for this cartographic appraisal is perhaps when the hydrographer discovers that there is a capital deficiency in the chart he is selling to the public. In 1970 Captain J. D. Winstanley, R. N. made a remarkable analysis of both the extent of the sandwave problem and the means of solving it (Journal of Navigation, Vol. 23, No. 4). The question was so new that there existed no specialized survey equipment suitable for the work. Up until then there had never been any need for such high measuring and positioning accuracies when sounding so far from the coast. It became a necessity to position these sand-waves month after month and to plot their various profiles – and all this in an area fifty miles or so out sea! Let it be remembered to that this was vital for the navigational needs of the ships bringing in to Europe her vital lifeblood, as well as for the chart that is so vital to these ships from whatever quarter they come. It is thus a far cry to the chart of the Caribbean.

What does all this signify. Astoundingly, but quite simply, that our charts are both incomplete and insufficiently documented, and that we are ignorant of the fact. In order to comprehend its significance we should perhaps go back several centuries to those handsome old parchments embellished with marine monsters that are the glory of our museums. Doubtless modern hydrographers, well up in such things as electronics and artificial satellites, will say "Those were works of art. Our charts in 1972 are the fruits of science".

But this is not the case, and at heart hydrographers well know it. They are perfectly aware that they only possess absurdly inadequate means to satisfy the mariner's needs, needs that are moreover invariably underestimated by those who control their budget. They are well aware that they do not yet have the cameras to take to sea to chart the bottom. A great deal more science enters into the charts of 1972 than on those medieval charts - but there is still not enough, since science has not pronounced the last word and will in fact never do so. How then should those blanks in the survey be interpreted on our charts, blanks which will have to be filled in by succeeding generations. We should use the art of today of course, but a subtle art containing something of both Raphael and Picasso.

From this aspect, we could classify the three national charts of the region where the liner *Antilles* was lost as follows.

- The original British chart. Here we can discern the pleasing quality of those expressive primitive painters of the Middle Ages who with great simplicity of means were able to express virile force, feminine grace and the whole gamut of feelings to he read on a human face.
- The French chart. This can be likened to Raphael, and to the Renaissance in all its beauty. Here Nature is not quite handsome enough, and so the artist embellishes her.
- The American chart. And here we come to Picasso. On a single canvas the painter gives us an object's front, back, and even interior! The result may sometimes he hideous, but he cares little. Is there

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not a saying-exaggerate to make yourself better understood!

It is nevertheless the Americans who were right to show the fads in their worst light. It is probable that if he had been using an American chart the *Antilles*' Captain would have abandoned the idea of entering this particular channel, for a skilful presentation of visible dangers already foreshadowed the existence of invisible ones.

All this is merely an attempt to enter into the subtleties of cartographic interpretation, and such considerations would no doubt be most useful when working out the fundamentals of a philosophy for cartography. However, when a ship's captain takes up a chart he has no time to philosophize. He has need of concrete facts and, as we have now seen, the figures and symbols taken in their aggregate may well prove misleading to him. The error committed by the Captain of the *Antilles* is enough to prove this, but we have now produced further evidence to show that cartographers themselves are not always of like mind in the interpretation of a survey. in these circumstances, what chance has the mariner of interpreting the chart before him without risk of mistake?

The remedy is now clear. During my twenty-three years with the French Hydrographic Office I used vaguely to seek this remedy, feeling subconsciously that it must exist. I had noted that in the British Admiralty Pilots published during the first half of the present century density of soundings was considered as one of the criteria for determining the value of a chart, but that this notion has disappeared in more recent editions. I also noted that French hydrographers were tending to reduce the number of soundings and to increase contour lines. The result seemed to me to lead to a more intelligible picture of the submarine topography, but nevertheless I continued to be dissatisfied when pondering over such charts as the one for the Approaches to the English Channel, from the South of Ireland to Penmarch. What was the exact worth of all those soundings and of all those contour lines? On this very wide continental shelf all the important banks carry names – a fact that demonstrates their existence better than anything. But what exactly were the merits of each of these soundings measured and positioned in the last century, or in an even earlier age?

Now that I know the remedy, am not at all proud of having taken so long to perceive what was staring me in the face all the time. For 23 years I used to write Sailing Directions, the object of which is to supply all that cannot be shown on a chart, yet it was not until 18 months after the loss of the *Antilles* that I was to realize that what these Sailing Directions lacked was an appraisal of the value of each chart. These volumes enumerate the relevant charts at the head of each chapter or sub-section; to these details we should now add evaluations, drawn up by hydrographers themselves, regarding the degree of reliability of their work, its limitations, and the uses to which mariners have a right to put it.

This evaluation would have to be revised with each succeeding edition and for each block correction. The mariner should be made aware that a particular edition has been pulled from an already worn plate used for an earlier edition, and that another includes data from a survey on a given date concerning one particular part of the chart and not its other portions. It seems strange that when new editions are exchanged between Hydrographic Offices in the form of the actual charts annotated with these very indications none of us has realized until now that these are of even more concern to the mariner than to the chartmaker.

However it is never too late to mend our ways! It is therefore with a somewhat malicious pleasure that I wish those who have followed me every success, for the critical evaluation of certain charts will be an unremitting task that will sometimes lead to curious discoveries. At least ten years will be needed to complete a first evaluation, and what is more, the need for fresh ones will no doubt arise, and they in their turn will destroy, modify and reveal.

Such is man's lot. Three centuries ago Boileau had this advice to give about taking up a work only just completed: "Polish it unceasingly, and then polish it all over again". In the French Navy there is a caustic and somewhat disillusioned saying: "To do a job and then to undo it – both arc still work", although I cannot say that I myself approve of this dictum.

The exegesis I am advocating is at one and the same time a science and an art: the task should be allotted to those same patient, careful and disinterested cartographers who must be relentless in their probings of the depths of the human mind. There are already scriptural, juridical and literary exegeses: it is an honour for the nautical cartographer to join this company.

IHO International Hydrographic Organization

Satellite navigation in hydrography

Authors
R. M. Eaton, D. E. Wells, and N. Stuifbergen

Preamble

This manuscript is a reprint of the original paper previously published in 1976 in The International Hydrographic Review (IHR, https://ihr.iho.int/): Eaton, R. M., Wells, D. E., and Stuifbergen, N. (1973). Satellite navigation in hydrography. *The International Hydrographic Review, 53*(1), 99–116. https://journals.lib.unb.ca/index.php/ihr/article/view/23736

"I'll put a girdle round about the earth in forty minutes."
(Puck in "Midsummer Night's Dream" by William Shakespeare).

1 Introduction

Satellite Navigation ("Navsat") is a remarkable development in positioning that gives a dozen or more good fixes per day, anywhere in the world. The accuracy of the ship's position from a good pass is from 60–600 m, depending on how well the ship's course and speed is measured. For stationary receivers, this positioning accuracy improves to about 20 m.

Navsat's great value to hydrography is that the fix is virtually free of systematic position errors. Navsat is extremely useful in offshore surveys as a complementary partner to a high resolution, continuous system which has systematic biasses or which accumulates error with time; we describe integration with rho-rho (range measuring) Loran-C, and Doppler Sonar. The continuous system feeds accurate course and speed to Navsat, which in turn provides a control network of intermittent, bias-free fixes. By bridging a number of satellite fixes the combined system means out random errors and improves on the single-pass accuracy of Navsat.

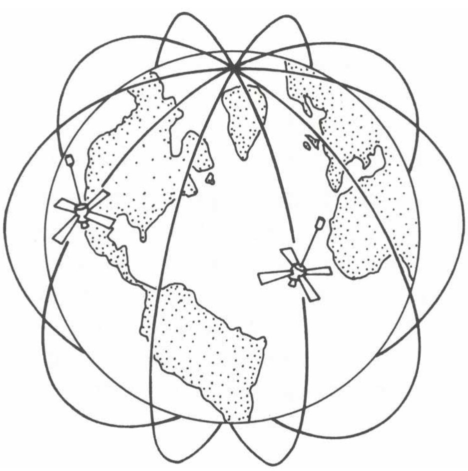

Fig. 1 The polar orbits of six navigation satellites form a birdcage of irregularly spaced hoops around the rotating earth.

Navsat has many auxiliary applications. It is used to resolve the cycle ambiguity in low frequency radio aids; to calibrate both marine survey positioning systems and radio aids to navigation; to position the transmitters for the radio aids; to position offshore drilling rigs; and as a geodetic instrument capable of establishing shore control to 1 m accuracy.

The "Datum Shift" between a Navsat position and a position from the local geodetic control often causes confusion. We outline the reason for the difference, and give algorithms for computing it.

2 The Navy Navigation Satellite System (NNSS)

"Transit" (i.e. satellites that pass overhead) is the specific name for this type of satellite system, but we will use the more usual term "Navigation Satellite" abbreviated to "Navsat". Those who are not familiar with it should read Stansell (1968).

To recapitulate briefly, the satellites broadcast two stable, harmonically related carrier frequencies at 150 MHz and 400 MHz; as the satellite passes the ship, at 7.3 km/sec., the receiver measures the amount by which these stable frequencies are Doppler shifted. The satellites also transmit a series of digital signals, by imposing balanced phase modulations on the carriers. These signals can be used as time marks, and they contain parameters describing the satellite orbit. The parameters are computed by fitting orbital arcs to Doppler measurements from four tracking stations in Maine, Minnesota, California and Hawaii, and extrapolating the arc for 16 hours beyond the time of the last data used. These orbit predictions are injected into each satellite's memory twice a day. There are at present six operational satellites in almost circular polar orbits having heights of 1100 km (compare with the earth's radius of 6400 km) and

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periods of one hour and forty minutes (not forty minutes, as predicted by Puck; Shakespeare must have been using poetic licence!). Fig. 1 illustrates the configuration.

At 1100 km height the satellite can be received over a circle on the earth's surface of radius 30°. All satellites transmit the same frequency, but because the Doppler shift is large (about 8 kHz) compared with receiver bandwidth, the transmissions from two satellites interfere only if the passes are nearly simultaneous. The satellites all pass over the pole, and so at the equator their orbits are well separated; simultaneous passes are rare at low latitudes, and there can be gaps of four hours between passes. At high latitudes simultaneous passes occur more frequently, but there are more passes available.

3 How the measurements are made

As in any other radio positioning method, the Navsat receiver makes measurements on transmissions from known points (in this case the known position of the satellite at given time intervals along the orbit) and translates these into position lines whose intersection defines the ship's position. In Navsat the receiver measures Doppler counts by integrating the changing frequency as the satellite's velocity relative to the receiver changes, and transforms these into differences of distance that define hyperboloids in space. These intersect each other and the earth's surface at the ship (Fig. 2). Satnav is a hyperbolic radio aid in the sky.

Fig. 3 shows a satellite travelling at a speed of about 7.3 km/sec., continuously transmitting the frequency f_S, a sequence of time marks represented by t_1, t_2, … t_i, … and orbital data establishing its position at these times. The receiver has an oscillator generating the frequency f_g.

Each time mark transmitted by the satellite at t_i arrives at the ship after travel time S_i/c, where for the moment we assume the signals propagate in a vacuum. For example, between $(t_1 + S_1/c)$ and $(t_2 + S_2/c)$, the number of "satellite clock ticks" (or cycles of f_g arriving at the receiver must equal the number transmitted by the satellite, that is

$$N_r = f_s\,(t_2 - t_1) \qquad (1)$$

However the number of "receiver clock ticks" (or cycles of f_g) occurring during this same period is

$$\left(N_g = f_g\left[\left(t_2 + \frac{S_2}{c}\right) - \left(t_1 + \frac{S_1}{c}\right)\right] = f_g\,(t_2 - t_1) + \frac{f_g}{c}\,(S_2 - S_1)\right) \qquad (2)$$

The receiver actually measures "ticks" of the beat frequency between f_g and f_S (f_S being deliberately offset 80 parts per million below f_g to avoid negative cycle counting), so that the measured Doppler count is

$$N = N_g - N_r = (f_g - f_s)\,(t_2 - t_1) + \frac{f_g}{c}\,(S_2 - S_1) \qquad (3)$$

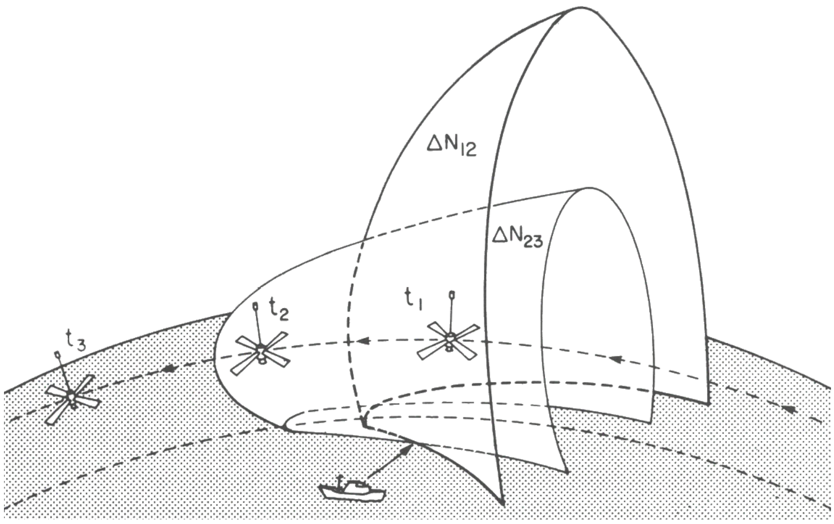

Fig. 2 Diagram of a "pass", showing the satellite's position at times t_1, t_2, t_3. A receiver anywhere on the surface of the taller space hyperboloid would measure the *same* Doppler count Δ*N*12 in the interval between t_1 and t_2. The intersection of the hyperboloids with the earth's surface defines terrestrial position lines, as shown on Fig. 7, and the point at which these cross gives the ship's position.

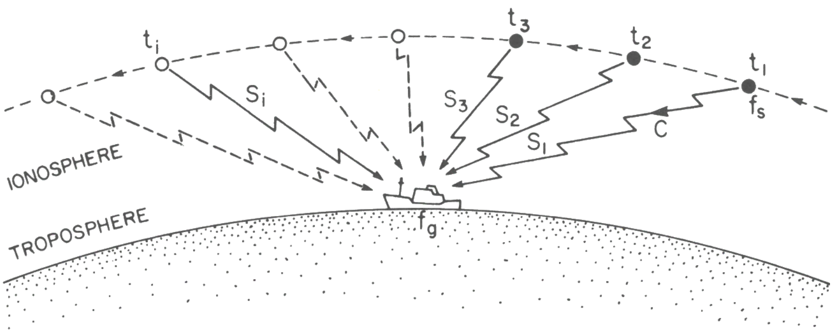

Fig. 3 The satellite passes the ship at about 7.3 km/s continuously transmitting a measuring frequency f_g, which travels the distance *S* to the ship at velocity *c*. Separate refraction corrections to velocity are calculated for the ionosphere and the troposphere. The frequency actually received is Doppler shifted due to the high relative velocity between ship and satellite, and the receiver compares it against a reference frequency f_g to measure the "Doppler Counts".

In this equation we know the counting period $(t_2 - t_1)$, the vacuum velocity *c*, and the satellite frequency f_S, which is included with the orbital data, but we don't know f_g. The slant ranges *Si* depend on the known satellite positions and the unknown ship's positions, at time $(t_i + S_i/c)$.

Several assumptions buried in the derivation of Eq. 3 are:

- Signals propagate as in a vacuum.
- The orbital data establishes true satellite position at time t_i.
- Doppler counting starts precisely when a time mark arrives at the receiver's antenna.
- Both f_g and f_S are constant during a pass.
- Relativistic effects are negligible.

For some applications, such as general navigation, all these assumptions are valid. For other applications, such as geodetic surveying, none of them are,

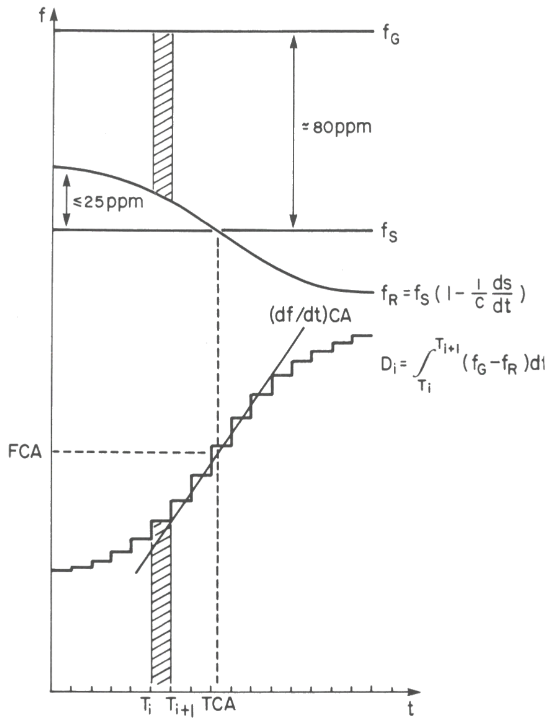

Fig. 4 The satellite oscillator frequency f_S, is offset approximately 80 ppm below the receiver oscillator frequency f_G, and the Doppler shifted satellite signal f_R is offset up to 25 ppm above and below f_S, coinciding with f_S at closest approach (where the relative velocity between satellite and receiver is zero). Because f_S is a lower frequency than f_G, the integrated Doppler counts D_i form a curve inverted with respect to the f_R curve. The three parameters most fully representing the characteristics of a set of Doppler measurements are the closest approach time TCA, frequency FCA, and slope (d*f*/d*t*)CA.

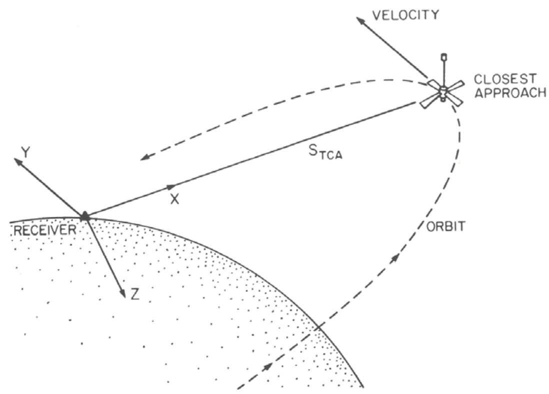

Fig. 5 The natural coordinate system for Navsat is the Guier plane, defined by the estimated receiver position and satellite velocity vector at closest approach. In this coordinate system the computed receiver position is allowed to move in the XY plane, but the receiver Z coordinate is kept fixed at zero. Correspondingly, when the latitude, longitude, height coordinate system is used, he receiver position is allowed to move in latitude and longitude, but the receiver height is kept fixed at the estimated value.

and corrections must be made for each assumption. Currently for hydrographic surveying only the first assumption is corrected for.

4 How the fix is obtained

The satellite generates time marks every 20 ms, so that in principle a maximum of 45 000 Doppler counts could be measured during one pass (equivalent to 45 000 hyperbolic lines of position per fix). In practice, so much data would vastly increase computational problems without improving the results. In general we need only make enough measurements to ensure good redundance, and Doppler counts of 20 seconds (maximum 54 counts per pass) are generally measured, depending on the hardware and software being used.

In any case we end up with many more lines of position than we would need to fix a single ship's position. However, the ship occupies a different position for each slant range S_i in Eq. (3), so the paradox is that no matter how much data we collect during a pass it will not be sufficient to solve for all the ship's positions, To overcome this problem, we must use an independent navigation system to construct a table of ship's positions for each S_i. This table of positions is then adjusted as a whole, together with the unknown f_g, in a series of iterations, until the slant ranges calculated between ship's position and satellite positions fit the slant range differences measured by the Doppler counts as well as possible. If the table of relative ship's positions is distorted then this fit may be poor, and the adjusted table wrong. In fact, most often the table is constructed on the assumption that the ship's course and speed are constant during the pass, limiting the usefulness of Navsat to passes during which these conditions are met. No matter how carefully constructed, error in the table of relative ship's positions is the predominant factor in determining fix accuracy from moving ships.

5 Coordinate systems

In contrast to other radio positioning systems, Navsat operates in three dimensions rather than two dimensions. However it remains a two dimensional positioning system; only two coordinates can be obtained from a single pass. (Three dimensions can be obtained by combining data from several passes at a motionless receiver). Since we can determine only two coordinates from Navsat we must choose a value for the third coordinate ourselves. Usually the two

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coordinates we compute are latitude and longitude and the coordinate we specify is ellipsoid height. Errors in the choice of height will mainly affect the longitudes computed.

Some insight into the nature of a Navsat fix and how different errors affect fix accuracy can be gained by considering another two dimensional coordinate system, the Guier plane (Guier, 1965). To discover this coordinate system, we first look at the characteristics of a set of Doppler measurements (Fig. 4 and 5). The three parameters which most fully represent the information contained in such a set of measurements are the time at which the satellite most closely approaches the receiver t_{ca}, the frequency at closest approach fca, and the Doppler curve slope at closest approach $(df/dt)_{ca}$. t_{ca} measures the receiver position along the satellite track (since Transit satellites are in polar orbits, this along-track coordinate is equivalent to latitude). At closest approach the Doppler shift is zero and f_{ca} measures the frequency offset $(f_g - f_S)$. A less obvious relationship exists between the slope of the Doppler curve at closest approach $(df/dt)_{ca}$ and the minimum range Stca between satellite and receiver at that instant. Since the Doppler shift measures the relative velocity between satellite and receiver, then the slope of the Doppler curve measures relative acceleration. The closer the satellite trajectory is to the receiver (that is the smaller the closest approach range), then the greater the relative acceleration, and the steeper is $(df/dt)_{ca}$.

Thus there are two geometrical properties of each pass, the along-track and cross-track (slant range) coordinate at closest approach, which, together with the frequency offset, best characterize the observed data. The Guier plane is the two dimensional coordinate system whose axes are the alongtrack and cross-track coordinates at the point of closest approach. It is unique to each satellite pass, and is tilted with respect to the receiver's horizon plane by the closest approach pass elevation angle.

6 Accuracy of the fix

Let us consider the effects various errors will have on the Doppler curve, and hence the Guier plane coordinates.

Part of the signal path from the satellite lies through the ionosphere, part through the troposphere (Fig. 3).

Uncorrected ionospheric refraction shortens satellite-to-receiver slant ranges, the net effect of which is to reduce the closest approach slant range (cross-track coordinate) by about 50 m.

Ionospheric refraction is frequency-dependent, and so can be corrected by combining Doppler measurements at the two measuring frequencies of 150 and 400 MHz, with residual errors of no more than a few metres.

Uncorrected tropospheric refraction increases the closest approach slant range by about 20 m. We can correct for tropospheric refraction using a model of the vertical profile of refractivity, and average or observed

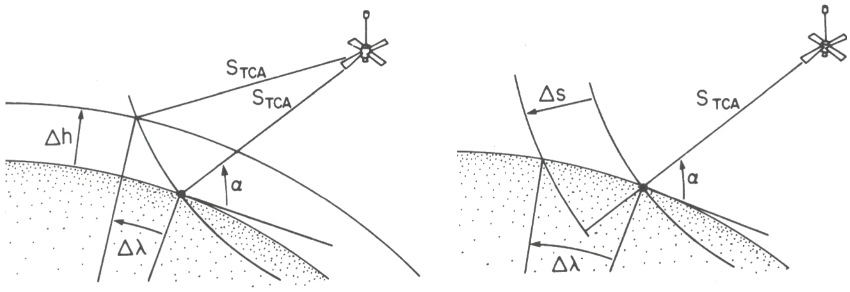

Fig. 6 Both diagrams show the Guier cross-track coordinate as a slant range at closest approach STCA. (The satellite's track is into the page). Left diagram: Effect of height error. On transformation to latitude-longitude coordinates, an error Δh in the assumed height will give rise to a longitude error Δλ whose size depends strongly on the pass elevation angle α. Right diagram: Effect of a cross-track error. An error Δ*S* in the range at closest approach will also cause a longitude error, whose size again depends strongly on satellite elevation.

surface weather conditions. The residual range errors are 5 cm above 20° satellite elevation and 45 cm at 5° elevation. (Hopfield & Utterback, 1973). This tropospheric correction is not made by most Navsat fix programs, however they usually automatically eliminate measurements made below 7½° elevation, where the tropospheric effect is most serious.

Errors in satellite orbit coordinates affect both along-track and crosstrack coordinates. However, the main source of orbit errors is unpredictable atmospheric drag effects, so the along-track effect (30 m) predominates. Signal delays in the receiver affect the along-track coordinate by 10 m. Oscillator drift affects the Doppler curve slope, and thus the cross-track coordinate by about 1 m. An error in along-track (North-South) ship's velocity affects the Doppler curve slope and thus the cross-track coordinate. The time of closest approach is midway between the two "shoulders" of the Doppler curve; asymmetric data which does not contain equal portions of both shoulders weakens the determination of t_{ca}, and hence the alongtrack coordinate.

While we do not usually compute our position in the Guier plane, the results we obtain are equivalent to navigating in the Guier plane (extracting the essential information from the pass), and then transforming lo a more conventional coordinate system, such as latitude, longitude and height. This transformation would simply consist of rotating the Guier plane through the pass elevation angle into the horizon plane. Latitude corresponds to the along track coordinate. Longitude and height are both functions of the Guier plane cross-track coordinate and the pass elevation angle, and are therefore not independent. Navigating in the horizon plane, we must hold the height fixed, and consequently height errors will affect longitude. The cross-track errors are not strongly dependent on pass elevation, however on transformation to Latitude and Longitude coordinates a small cross-track error becomes a large longitude error for high elevation passes. Fig. 6 illustrates this.

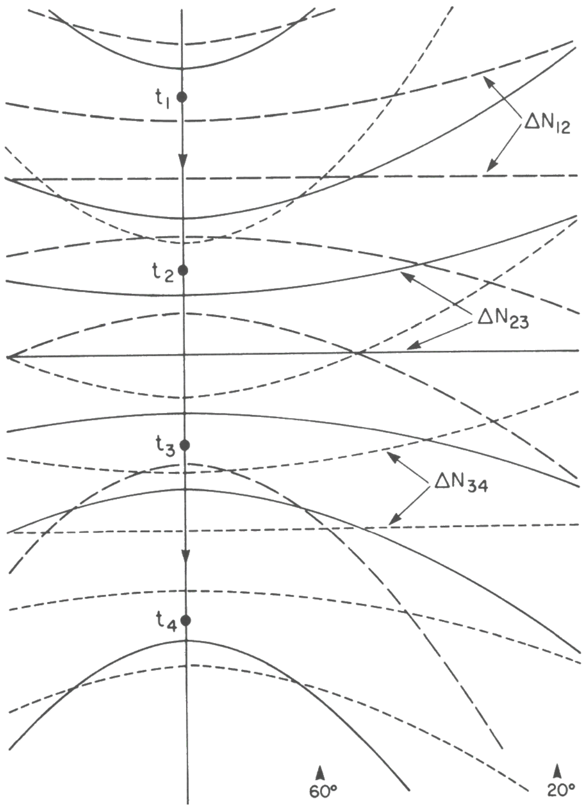

Fig. 7 A space observer's view of satellite positions at t_1, t_2, t_3, t_4, and the corresponding position lines generated on the earth's surface by Doppler counts ΔN_{12}, ΔN_{23}, ΔN_{34}. The projection is orthographic, and a strip extending 2000 km from the satellite sub-track is shown. The satellite's track is nearly N-S so that the position lines run predominantly E-W, defining latitude better than longitude throughout the lattice. Longitude is particularly badly defined for high elevation passes, when the ship is nearly underneath the satellite. The best fixes are obtained at pass elevations from 60°–20°. At low elevation angles, when the ship is a long way from the satellite, both the fix geometry and the quality of measurements deteriorate. The effect on fix geometry of asymmetry in Doppler counts (represented by a fix at the top or bottom of the lattice) is very evident.

Fig. 7 shows a different approach to Navsat error analysis, by looking at the position lines generated on the earth's surface by a series of Doppler counts.

7 Fix accuracy diagnostics

A number of diagnostics can be used to indicate the quality of a particular satellite fix. Most important is that enough Doppler measurements be made. Using 30-second Dopplers as an example, if less than 20 counts are measured (after rejecting the low elevation data) the reason may be any one of low elevation pass, low signal level, interference, poor antenna site, or poor receiver performance. Regardless of the reason, the resulting fix will probably be poor.

As mentioned above, the accuracy of a fix in latitude and longitude coordinates depends strongly on the pass elevation angle. For high elevation passes (greater than 60°) the longitude is poorly determined. For low elevation passes (less than 20°) refraction and the shallowness of the Doppler curve degrade the fix accuracy.

Maintaining a plot of the computed values for the local oscillator frequency, f_g, as a function of time provides a sensitive indicator of potential fix errors. The frequency f_g should change slowly and linearly with time (a few parts in 10^{10} per day for the best oscillators). An outlying value of f_g indicates that something is wrong (very often the ship's relative motion input) and the probability of a poor fix is high. However maintaining a record of f_g is difficult with most current fix programs, since they compute ($f_g - f_S$), not f_g; and f_S is different for each satellite. Separate plots for each satellite can be maintained, or the value for f_S can be located in the orbital message data and f_g computed manually.

A fourth diagnostic is the "residual" value provided by many fix programs. The residual expresses the fit between the computed slant range difference (based on the final ship's coordinates) and the measured slant range differences (based on the measured Doppler counts); the lower the residual the better the fit. A poor fit is unlikely to give a good fix, but the converse is not necessarily true. Caution should be used in comparing residuals between different programs. Every measurement provides a residual, which can be expressed either in metres (slant range difference) or Doppler counts. The single "residual" value printed out may be the largest residual, or the RMS value of the residuals, or the mean of the absolute values of the residuals.

Other diagnostics are the number of iterations a pass required to converge, the symmetry of the data about closest approach, and, for some receivers, a digital representation of the signal strength.

Despite all these diagnostics, an undetectable "wild" fix will occasionally occur which satisfies all the diagnostic criteria, except that the position is very much in error. For this reason it is never safe to blindly force other navigational systems to agree with Navsat positions.

8 Accuracy at sea

We have outlined the size of errors that can be contributed to the Navsat position by various individual sources. Their combined effect on a stationary receiver is to produce the scatter of about 20 m observed in a series of fixes on land. What is the accuracy of a fix in a moving ship at sea? There is surprisingly little direct evidence, probably because it is difficult to find a system that matches Navsat accuracy at the distances offshore at which it is used. Most information comes from how well Navsat agrees with a partner system with which it is integrated; Fig. 9 shows an example. However we made a more direct test in 1973 when Navsat was used for lane identification on a calibrated range-range Decca survey system east of Newfoundland. The course and speed given by Decca were used to compute the Navsat fix, and the range from the Navsat position to the Decca transmitters on shore was then calculated. This was compared with the Decca range, which had been rigorously corrected by the phase lag method (Johler, 1956; Brunavs, 1971) and had an estimated accuracy of ± 30 m (1σ).

https://doi.org/10.58440/ihr-29-a15

Table 1 Some common datum parameters.

Local geodetic datum	Reference ellipsoid		Datum translation components		
	a (m)	*f*	x_0 (m)	y_0 (m)	z_0 (m)
Australian Geodetic	6378160	1 /298.25	-122	-41	146
European	6378388	1/297	-84	-103	-127
North American 1927	6378206.4	1/294.9786982	-22	157	176
South American 1969	6178160	1/298.25	-77	3	45

Comparisons were restricted to daylight hours, to avoid skywave contamination of Decca at the 500 km distances of the test. Satellite fixes were restricted to the passes of 20°–60° elevation, having at least 10 minutes of good data. The transmitters were to the westward of the ship, so that we were looking at longitude errors, the weaker component of the satellite fix. The standard deviation (1σ) for 113 comparisons was ± 120 m. This should be a good indication of single pass accuracy; a combined system that bridges a number of passes will improve on it, particularly if it uses improved methods of inputting the table of ship's coordinates. In the above case the ship was assumed to travel the straight line path given by the best fit velocity from a set of Decca fixes. It would have been better to have input Decca fixes at each Doppler count interval, so long as the Decca was stable enough to define the ship's track accurately.

9 Datum transformations

One of the most misunderstood aspects of using the Transit system is the matter of datum transformations. The problem arises because the coordinates of most control points are referred to a different kind of coordinate system (which we call a local geodetic datum) than are the coordinates we get from Navsat. First let us find out why this is so, and then look at what we can do about it.

The motion of an artificial near-earth satellite depends almost entirely on the effect of the earth's gravity field. Therefore, by tracking a satellite or satellites from several points on the earth's surface (terrain points), we can obtain enough data to locate the earth's centre of gravity (the geocentre) within a few metres relative both to terrain points and satellite orbit. A significant aspect of using satellites is that they are a link which can be used to connect observations from different continents and thus establish one world-wide coordinate system.

Local geodetic datums, on the other hand, were established long before the dawn of the satellite age. Lacking satellites to locate the geocentre, the stars were used. In the earliest and crudest method, arcs on the terrain were accurately surveyed to find their lengths, and precise astronomic observations were made to find the angles the arcs subtended at the geocentre. The size (semi-major axis *a*) and shape (semi-minor axis *b*, or flattening $f = (a - b) / a)$ of a reference ellipsoid could then be computed by comparing the linear and angular lengths of two or more meridian arcs at different latitudes. A reference ellipsoid was chosen because it is the simplest figure which reasonably approximates the shape of the mean sea level surface (which we call the geoid). Having chosen an ellipsoid, it was positioned relative to the earth by specifying the geodetic coordinates (latitude Φ, longitude Λ, and height *h*) of a single terrain point, and an initial azimuth to a second terrain point. It was then assumed that the centre of the ellipsoid coincided with the geocentre, whereas in fact the difference was usually several hundred metres. More sophisticated techniques of choosing the ellipsoid size and shape, and positioning it relative lo the earth, have been developed; but the primary limitation (lacking satellites) is that only data from interconnected geodetic networks, that is from a single continent, can be used for each such determination. As a consequence, each continent, and in some cases each country, presently has its own local geodetic datum, reference ellipsoid and implied geocentre location. Table 1 lists the ellipsoid sizes and shapes used with several local geodetic datums, together with the coordinates of the ellipsoid centres expressed in a particular geocentric (satellite) coordinate system called WGS72 (Seppelin, 1974). These datum translation components, as they are called, are Cartesian coordinates in a right handed coordinate system whose *Z*-axis passes through the north pole and *X*-axis passes through the intersection of the equator and the Greenwich meridian. (The actual definition of this coordinate system uses more precise language).

Given the local geodetic coordinates of a terrain point, and values for *a, f,* x_0, y_0, z_0 such as from Table 1, the geocentric Cartesian coordinates of the terrain point can he computed from:

$$\begin{aligned} X &= x_0 + (N + h) \cos \phi \cos \lambda) \\ Y &= y_0 + (N + h) \cos \phi \sin \lambda) \\ Z &= z_0 + (N (1 - f)^2 + h) \sin \phi) \end{aligned} \quad (4)$$

where the prime vertical radius of curvature is

$$N = a\,(\sin^2\phi + (1-f)^2\cos^2\phi)^{-1/2} \qquad (5)$$

Unfortunately, given *XYZ* it is not so easy to invert Eq. (4) to obtain *Φλh*. However there are three ways of doing this; the direct method (Paul, 1973); the differential method (Heiskanen & Moritz, 1967); and the iterative method, which we shall now describe.

9.1 Iterative method

Given *X*, *Y*, *Z*, x_0, y_0, z_0, *a* and *f*, we first compute, in order:

$$x = X - x_0$$
$$y = Y - y_0$$
$$z = Z - z_0$$
$$\lambda = \arctan\left(\frac{y}{x}\right)$$
$$p = (x^2 + y^2)^{1/2}$$
$$N_0 = a$$
$$h_0 = (x^2 + y^2 + z^2)^{1/2} - a\,(1-f)^{1/2}$$
$$\phi_0 = \arctan\left[\frac{z}{p}\cdot\frac{N_0 + h_0}{N_0\,(1-f)^2 + h_0}\right]$$

Then for the iterations *i* = 1, 2, 3… we compute, in order:

$$N_i = a\;[\cos^2\phi_{i-1} + (1-f)^2\sin^2\phi_{i-1}]^{-1/2}$$
$$h_i = \frac{p}{\cos\phi_{i-1}} - N_i$$
$$\phi_i = \arctan\left[\frac{Z}{p}\cdot\frac{N_i + h_i}{N_i\,(1-f)^2 + h_i}\right] \qquad (6)$$
$$|h_i - h_{i-1}| < a\epsilon$$
$$|\phi_i = \phi_{i-1}| < \epsilon$$

for some appropriately chosen value of ε (for example $\varepsilon = 10^{-7}$ radians for convergence to one metre or less).

Returning to the problem at hand, we obtain a Navsat position in a geocentric coordinate system (that is $x_0 = y_0 = z_0 = 0$), but we are interested in trying our Navsat coordinates to the geodetic coordinate system of the closest country or continent. The solution is to first convert Navsat *Φλh* to geocentric *XYZ* using equation (4) with $x_0 = y_0 = z_0 = 0$, and whatever ellipsoid dimensions a and f have been built in to the Navsat computer program used; and then convert the geocentric *XYZ* thus obtained into geodetic *Φλh* iteratively using Eq. 6 with the values for x_0, y_0, z_0, *a*, *f* given for the local geodetic datum.

Note that in both Eq. 4 and 6 the third geodetic coordinate h is the height of the terrain point above the reference ellipsoid, not the height above sea level. Therefore we need to know the height of mean sea level (the geoid) above the ellipsoid used for Navsat computations, so that we can obtain the correct value of *h* to use in Eq. 4. Maps of geoid heights above the Navsat reference ellipsoid are usually supplied with computer software. One can be found in Moffett (1973).

10 Applications

10.1 A bias-free control for integrated offshore positioning

The great power of Navsat for precise surveying offshore lies in the fact that the position errors, though sizeable, are generally random from one pass to the next. For instance, the effect on the fix of an error in measuring ship's velocity is equal and opposite for north-going and so uth going satellites. In contrast, most other electronic positioning methods have high short-term repeatability but suffer from large offsets, or accumulate error with time. The two types complement each other neatly. Good repeatability produces accurate course and speed measurement for computing the satellite fix, and bridges between a number of passes to mean out random Navsat errors. In return, Navsat provides a bias-free control network. Fig. 8 illustrates this symbiosis.

10.2 Navsat combined with rho-rho Loran-C

In the last decade, portable atomic frequency standards have been developed that are capable of keeping time (which is simply a matter of counting cycles at a known frequency) with an accuracy of a few parts in 10^{13}. If two such clocks had been rated against each other and then sealed in Tutankhamen's tomb in 1352 B.C., they would have differed by about 1/100 s when re-discovered in the last century.

Precise timing can be used with any radio aid to measure ranges, and hence position the ship. One atomic clock controls the transmitter, while a second operates the receiver, feeding to it a replica of the transmitted signal, at the time it is actually transmitted. The interval between the replica and the arrival of the real signal from the transmitter is the radio wave travel time; given accurate knowledge of propagation this can be converted to range.

The first stage in this so-called "rho-rho" mode of operation is to synchronise the two atomic clocks. It is not necessary to take the receiver physically to the transmitter to do this; entering a known signal travel time is equivalent. To determine travel time, both the distance to the transmitter and the propagation velocity must he known, and since the propagation velocity can only be predicted accurately over water, a good fix at sea is preferred for initial synchronisation. In practice, we use the mean of several days of "good" satellite passes to synchronise to ± 0.1 μs, or ± 30 m (1σ) (Grant, 1973).

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Thereafter, continuous comparison with satellite navigation keeps control over the other small systematic errors that can creep into rho-rho positioning. An error of about 5 parts in 10^{13} is likely in rating the receiver clock alongside the dock before sailing (which is done simply by recording how the range changes with time over at least 24 hours); this introduces range error at the rate of ± 0.05 μs, (± 15 m) per day, and the accumulation will be detected by Navsat after four or five days. Overland errors, station position errors, etc., are also eliminated by a long series of comparisons with Nanat. In fact, one approach to this combination looks on Loran-C purely as a relative motion sensor to track the ship in between satellite passes (Hatch, 1974).

10.3 Navsat and Doppler Sonar

The return echo from an oblique sonar transmission aimed at the seabed ahead of the ship will be Doppler shifted in proportion to the ship's speed. Matching this with a second transmission aimed astern eliminates errors due to ship's trim. If another pair of port/starboard transmissions are added, and the whole integrated with a good gyro compass, the resulting system gives very sensitive relative navigation, so long as water depth is less than about 200 m and sea conditions are moderate. Our limited experience of calibrating Doppler Sonar in a harbour against horizontal sextant angle fixes showed an accuracy of better than 0.5 % of distance run.

At sea, Navsat is used to calibrate fixed errors in the gyro, and scale errors in the Doppler measurement, and also to provide the framework of control positions on which to hang the dead reckoning. The measurement of ship's track during the pass is smooth, and the response to alterations in course and speed immediate. This makes Doppler sonar better at providing velocity for the calculation of satellite fixes than most radio navaids, which are relatively "noisy".

When using Doppler sonar, the ship's track can justifiably be broken into 20 s intervals for computing the Navsat fix. This refinement is probably not obtainable from very-long-range radio positioning methods, such as Loran-C, because they are too noisy to define a short track segment. Stansell (1973) estimates that the use of 20 s Doppler intervals improves Navsat accuracy from ± 100 m to ± 60 m.

10.4 Cycle identification by Navsat

All phase comparison and cycle matching radio aids resolve only the fraction of a cycle; they rely on auxiliary measurements to determine the whole number of cycles in the reading. These "coarse" measurements tend to become ambiguous just when they are needed most: at long range or under adverse radio conditions. The traditional solution of the surveyor has been to lay buoys as "lane markers". In order to give the resolution required, these must be laid in shallow water, to restrict their radius of swing, and they are often lost in storms or to trawlers. Many valuable survey

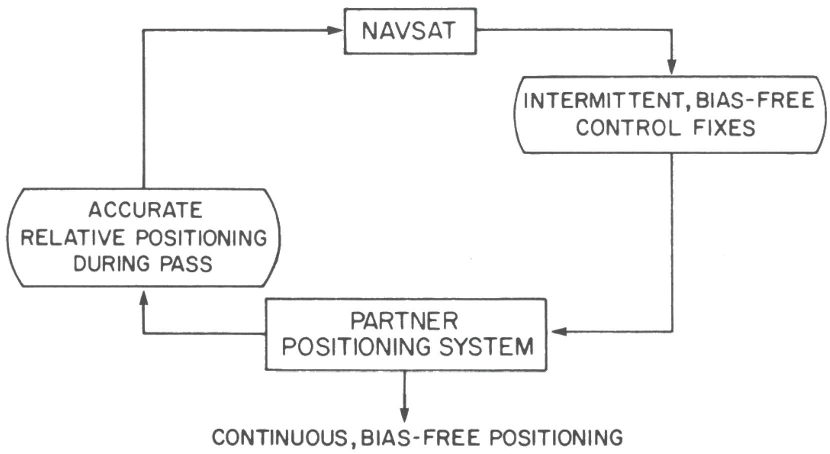

Fig. 8 Feedback loop in a combined Navsat system. The partner may suffer from large systematic errors, but it can still provide the accurate course and speed needed over the 20 minutes of a satellite pass. A series of bias-free Navsat fixes provides a control framework for the partner system, which then produces continuous, bias-free, positioning.

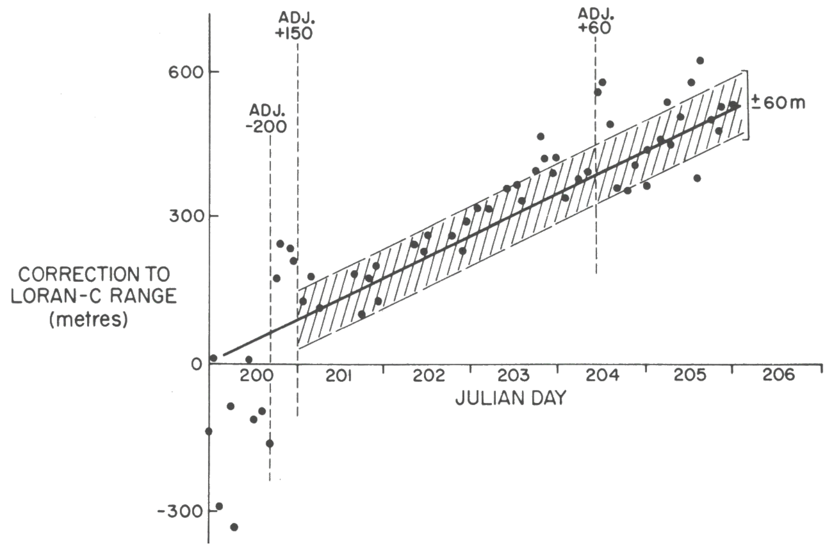

Fig. 9 Control graph used to synchronise rho-rho Loran-C by Kavsat (on day 200), and then to keep a continuous check on the accumulated clock drift correction. Points represent the difference between range to the transmitter by Loran-C, and range computed from the Navsat fix.

hours have been lost in the past steaming to a buoy to re-set lost lanes.

The Navsat accuracy of ± 120 m from about two thirds of all good passes means that Decca lane identification (± 180 m required) is usually acquired on the first pass, and rho-rho Loran-C cycle identification (± 1500 m required) is assured. Even for medium frequency radio aids with a half lanewidth of around 40 m, there is about 50 % probability of being within ± 1 lane; this means that useful work can often be done on the run in to the marker buoy, even if positions must be adjusted by one lane afterwards.

10.5 Calibrating radio aids

Long range survey positioning systems are usually calibrated within line of sight of the transmitter (when safe navigation permits) but are used at much greater ranges. The Surveyor assumes that short range calibration, plus knowledge of the radio wave propagation velocity, is valid in the distant survey area. Now these calibrations and velocity assumptions can he checked by making a large number of Navsat comparisons during the survey.

Overland signal path, with its unpredictable propagation velocity, may sometimes be unavoidable. Navsat can be used to give a first approximation to the overland phase lag corrections, although the accuracy will be lower than for an all-over-water path because the corrections will usually vary rapidly with location as the proportion of land path changes. If a good model for the phase lag corrections is available, Navsat will give spot checks on the model to validate or adjust the predictions.

"Main Chain" aids to commercial navigation can also be calibrated very economically for latticing small scale charts. We recently ran a Decca and Loran-C test calibration in the Gulf of Maine; the agreement between calibrations and comparisons with previous fixed-error corrections indicated a calibration accuracy of ± 300 m (2σ). We had no need to set up a local high accuracy radio system to do the calibration, nor did we have to depend on seeing the land for visual fixes.

10.6 Shore control and geodesy

Navsat was designed for navigating submarines. It is a striking testimony to the powerful technique of meaning out random errors by accumulating a large number of satellite passes, that one of its major applications has been in geodesy. The results of five days' observations at one point will give a position consistent with other Navsat positions within a very few metres; "consistent" because it will differ from positions on the local survey network by the datum shift. At this level of accuracy, small systematic errors, such as residual refraction errors, become noticeable, and precision is further improved by the "translocation" technique of measuring interstation distances by making measurements on the same satellite simultaneously at two or more stations. Doppler satellite distances observed this way agree with geodetic triangulation within 1–3 metres over both short lines (less than 200 km) and long lines (1000 km). (See for example Anderle, 1974; Khakiwsky, 1973; and Kouba, 1974).

Fixed site surveys by Navsat require none of the precise and laborious observations of high order control surveys. All one needs is a portable receiver, an attendant to change tapes, and a good 3-D computer program to process the results afterwards.

Navsat is also used for fixing the position of long range navaid transmitters, and to provide geographic position for shore control for hydrographic surveys (Finnegan, 1971). It has recently become the standard method of positioning offshore oil drilling rigs in Canadian waters, satisfying both legal and operational requirements, with an accuracy of ± 15 m (Hittel, 1971).

Acknowledgements

Satnav was, to our knowledge, first used for Decca Jane identification by Shell (Canada) Ltd., in 1970.

We thank Mobil (Canada) Ltd. and Dabbs Control Surveys Ltd. for the opportunity to test Doppler Sonar.

 https://doi.org/10.58440/ihr-29-a15

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The electronic chart – Present status and future problems

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Preamble

This manuscript is a reprint of the original paper previously published in 1986 in The International Hydrographic Review (IHR, https://ihr.iho.int/): Kerr, A. J., Eaton, R. M., and Anderson, N. M. (1986). The electronic chart – Present status and future problems. *The International Hydrographic Review, 63*(1), 97–105. https://journals.lib.unb.ca/index.php/ihr/article/view/23424

This paper was presented at the Fifth International Congress of the International Association of Institutes of Navigation, Tokyo, Japan, October 1985. It is published in the *Journal of Navigation* (U.K.), Vol. *39*, No. I, 1986 and reproduced here with permission.

1 Introduction

Interest in the use of video displays for nautical chart presentation has increased rapidly during the last two years. Eaton et al. (1984) at the Second International Hydrographic Technical Conference provided a list of ten different systems already in production. Oshima (1985) speaking at a Workshop on the subject in Canada, earlier this year, mentioned that some 4000 Japanese fishing boats and 150 merchant vessels now carry electronic charts of varying degrees of complexity.

The electronic chart is in reality simply the output end of an integrated navigation system which brings together different navigation sensors, in particular the combination of radar imagery, with the digitized chart data. The idea of integrating chart and radar data goes back to the 1950's (Dickson, 1952) and was one of the objectives of the "Manav" Integrated Navigation System (Millar & Hansford, 1983). However, at that time the technology had not reached a state by which digital data could be handled so easily.

Outside the marine field, video display technology has been developing even faster in the aviation industry (Bernard, 1983) where crowded airways and the speed of modern aircraft, particularly military aircraft, make fast and accurate navigation decisions an urgent necessity. Electronic map displays are now being seriously considered for automobile navigation (Shuldiner, 1985) although it is contended that, for navigating ground vehicles, recorded voice instructions are more effective than a map display (Streeter & Vitello, 1985).

At present it appears that the marine developments are being pursued most actively in Japan (Oshima, 1985) and the United States where electronic charts have been developed for harbour navigation (Rogof, 1985) and for the navigation of naval hydrofoil vessels (Puckett, 1983). There is also considerable activity in Canada where one company has used electronic charts for navigating oil industry vessels in the Arctic and is now actively engaged in developing systems for ferries (Ridgewell, 1985). In the United Kingdom an experimental system for the use of fishing vessels has been developed (Coates et al., 1984) and an interesting and futuristic approach is being taken in the Netherlands in the design of the "ship 90" complete with a "bridge 90" (van Opstal, 1985). Aside from these primarily government efforts, several commercial developments are also underway in Europe. These include a market research study by the International Management Institute in Geneva to examine the future of the electronic chart as a product.

Although navigators and hydrographers may be fascinated by the display technology of the electronic chart, it is becoming increasingly clear that this may be less difficult than the development of the data bases and questions of legality and finance. The development of suitable data bases of chart information is far from simple and the matter of the smooth exchange of digital data is now being actively ad-

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dressed by the International Hydrographic Organization (IHO) through its CEDD (Committee on Exchange of Digital Data) Committee (IHB, 1984). At this stage, some manufacturers of electronic charts are simply digitizing information directly from the paper charts and this brings into question legal matters such as copyright and the overall responsibility for the quality of the data that will be presented to the navigator. Hydrographic offices are concerned about the impact of the electronic chart on their future activities, and the North Sea Hydrographic Commission has established a working group to examine the issues. It is evident that the approach to the provision of digital data is not uniform. It is reported that the Japanese Hydrographic Office plans to provide the private sector with digital chart data from May 1985 (Oshima, 1985) and that in the United Kingdom the Hydrographic Office is digitizing charts of the south coast of England as a test set. Apparently, in Sweden, a commercial firm is providing digital data by digitizing the government charts itself. Obviously, some policies for international standardization, quality and marketing must be developed very soon.

The updating of electronic charts has been recognized by Hammer (1984), Eaton et al. (1983) and others from the start as an important matter to be resolved. Obviously, if a commercial company digitizes a chart and does not simultaneously develop a system to continuously update it, the product will not be acceptable to the navigator. Various approaches to the matter have been proposed, from transmitting Notices to Mariners to be manually inserted into the chart file aboard, to the prophecy of Rear Admiral R. Morris, now being actively examined in Canada, that the entire updated chart will be transmitted directly to the navigator by satellite (Mukherjee & Anderson, 1985).

Fundamental to all thought on the electronic chart is whether or not it will partially or completely replace the paper chart. At this stage, there are some who will argue that the electronic chart is but a diagram providing only essential tactical information for the navigator, while there are others who argue that once the navigator has started using the electronic chart, the paper one will be left to gather dust in the chart drawer.

2 Technology

The technology central to the electronic chart has already been described in detail by Eaton et al. (1983) and elsewhere and need only be summarized here. In the first place the navigator must be precisely positioned relative to the charted information. Various electronic systems, such as Loran C, are available for this. It is expected that GPS may be used at some future date. Processing of navigational data and presenting it in the form of off course corrections and way point navigation is already commonly available for many electronic receivers. The charted data must be provided in digital form and then displayed. This introduces the matter of the density and type of information needed.

One problem of the paper chart today is its increasing clutter (Kerr, 1985) and the electronic chart provides a way to avoid this by being selective in the data required. For instance, a supertanker will be primarily interested in depths greater than 20 metres whereas a small yacht will be interested in depths less than 5 metres. Ideally, the electronic chart should have available a complete hydrographic data base from which selected data, such as depth contours, may be drawn, but at present limitations in data base management and memory capacity have inhibited this total flexibility. Present examples of electronic charts have been designed for specific classes of users. The ability to change scale and projection at will is a potential feature of the electronic chart, so that as a vessel approaches a port from seaward, the navigator can call up an increasingly larger scale and more detailed display. This zoom capability may be provided, at its least sophisticated, as a set of specific frames or, in a more elaborate manner, as a continuous change of scale.

There has been considerable interest in the cartographic presentation of the new medium. The video game industry has demonstrated the amazing capabilities of symbolization and animation. This capability is available to the electronic chart manufacturer and a decision to be made is whether to copy precisely the existing paper chart or to branch out into new symbols. At present, work is going on in the Deutsches Hydrographisches Institut (DHI) to study the simulation of electronically drawn symbols as near copies of the paper chart symbols. Certainly the electronic medium offers capabilities, such as flashing symbols, to direct the navigator's attention which are not possible on a paper chart. The ability to select colour has proved a particularly fascinating subject to persons involved with the electronic chart. Theoretically, the active presentation of colours on a video display offers a great choice of options and cartographers have often noted the psychological implications of colour (Samson & Poiker, 1985) such as red as a danger signal. In spite of these theories, it appears that experienced mariners tend to prefer the colours that they are used to on the paper chart. Electronic chart manufacturers to date have exercised a free choice in colour selection and interesting designs have developed. However, it is important that the designs be standardized soon, as without doubt there is a danger in having no uniformity.

The superposition of the radar display is a key feature of the electronic chart. The ability to provide the navigator with a single display showing both static chart data and mobile targets, such as other ships, was recognized as essential under the economic studies of the "Manav" project (Millar & Hansford, 1983). The ability to do it elegantly has only been allowed by the development of video systems and greatly facilitated by the advent of raster scan converters and the availability of digital radar displays in matrix format. True motion displays have been used in many of the electronic charts to date with which the observer's vessel moves across the display, but as the vessel approaches the edge of the chart the frame automatically moves forward. However, alternative displays such as centering the display on the ship are equally possible. The manner in which the radar returns have been displayed on the electronic chart, with respect to colour and suppression, has varied in the designs.

The International Hydrographic Organization has now spent many years in reaching a uniform standard of paper chart presentation (Newson, 1983) and it is clear to many that the development of standards for the electronic chart, both in its display and data exchange format, must be given high priority. At the same time, it must be recognized that we are dealing with a new medium with exciting possibilities and its potential should be explored before we tie ourselves firmly to set standards (Luder & Barber, 1984). As an approach to examining these possibilities and other aspects of the electronic chart, the Canadian Hydrographic Service has contracted a commercial company (Universal Systems Ltd., Fredericton, New Brunswick) to develop an Electronic Chart Test Bed with which to examine the options. The company, which has expertise in developing interactive cartographic systems, will utilize a large electronic display controlled by a MicroVax II computer. While this system may be more powerful than those that will actually be needed in future electronic charts, it will allow the process to be modelled by testing different approaches to chart framing, to scale zooming, to colour choice, and to the design of symbols. It will also permit experiments to be made with different approaches to data bases.

3 Data bases

It is nearly twenty years since some national hydrographic offices started developing computer assisted chart production systems, although it is less than five years since the majority of these offices have been confident enough in their system to use them on a production basis. It is now clear that the digital era has arrived and the digital chart files are growing daily. In some countries, hydrographic data is also being regularly collected in digital form. There is an increasing awareness that some form of data base management is urgently required and that, since there is a need to exchange this data internationally, some common formats are needed.

To date, the digital data required for the electronic charts has been obtained by digitizing the paper charts, but it should be recognized that a paper chart includes only a fraction of the total survey data collected. It is a fairly general rule of hydrography that charts are always published on a smaller scale than the scale of the survey from which they are derived. This means that an electronic chart should only be permitted to enlarge the scale up to a maximum of the scale from which the data base is drawn, which at present is the largest scale chart. This presents a difficulty for those companies which might wish to display very large scale charts of ferry terminals and other critical areas. Since a strength of electronic charts is that they can provide special versions for different types of users such as fishermen, yachtsmen or VLCCs, it is necessary that the data base includes all the data from which to make the selection. For instance, a chart for a fisherman engaged in trawling will require the full detail of the bathymetry and not the selection of soundings required for normal commercial navigation.

The simple and straightforward approach is obviously to digitize the largest scale paper charts, but a better and more flexible approach, if the data base management system can handle it, is to provide some carefully assembled collection of all the data available. In the Canadian Hydrographic Service experimental work is being carried out to develop what is termed a digital Qualified Data Base (QDB). This is the development of a unique set of digital data, based upon the largest scale charts, but includes all the survey data available for that area but with all overlaps reconciled. The present approach has been to contour the areas in detail and then to digitize this very dense selection of contours. However, this dependence upon contours may inhibit one potential of the electronic chart which is to add tidal height to the soundings in real time to provide actual depth to the navigator. The significance of the QDB, as opposed to providing digital records of all data, is that the data has already been qualified and is therefore more amenable to selection and presentation to the navigator.

4 Legal aspects

Considerable attention has already been given to the legal consequences of introducing this new product. Developments to date, in which the electronic chart is being provided by a commercial manufacturer from digital data that they have obtained from national hydrographic offices, promise to change the legal responsibilities significantly. In some countries, where special charts for yachtsmen and fishermen have been produced commercially from data derived from government sources, the national hydrographic offices appear to have abdicated any legal responsibility. However, as far as is known, this has yet to be tested in the courts. In meetings of the North Sea Hydrographic Commission Working Group it was a general first opinion that, both morally and to meet the stated expectations of the users, the hydrographic offices should remain responsible for the data which they provided.

Mukherjee and Anderson (1985) have discussed some of the legal issues associated with the electronic chart. Of particular importance is the subject of copyright. Some national hydrographic offices have copyrighted their charts while others have not. The

https://doi.org/10.58440/ihr-29-a16

purpose of copyrighting and its effectiveness need to be examined. Mukherjee (1985) has noted that copyright has a moral and a commercial aspect. Copyrighting is essentially the right to prevent others copying one's creative work and, in Canada, at least, a chart is interpreted as a creative work. The reasons for exercising this right in terms of the chart may be to prevent the production of inferior products and thus the tarnishing of the reputations of a hydrographic office, or associated with this, a means to prevent the release of an unsafe product which might result in the producer of the original chart being held legally responsible. Yet another reason, and certainly the one of concern to commercial organizations, is the loss of revenue when a product is copied and sold. The revenue available from the sale of charts can be considerable, although most national hydrographic offices wil1 point out that these revenues do not even approach the overall cost of surveys and cartography. Nevertheless, if these revenues were lost there would be concern by national governments, particularly in these days of interest in cost recovery.

The introduction of the electronic chart poses some new questions on the matter of copyright. First of all, it has been suggested that the electronic chart is simply software and there is considerable general interest in the copyrighting of software. The copyrighting of software has been through considerable examination in the courts and arguments have been presented and refuted that software must be in human readable form and that source and object codes may not be covered. The distinction between programs which control a process and the actual data does not seem to have been made, but going back to the basic definitions it cannot be argued that data is a creative work but rather it is something, in our case a chart, that has been produced from the data that is subject to copyright. These fine distinctions must clearly be left to the lawyers, but it must be argued here that if hydrographic offices are to control the use of their data or their charts, they must insist on copyrighting.

Another legal matter which is becoming of increasing concern to hydrographers is their liability for the products for which they are responsible. The situation regarding the paper chart has a considerable history in the courts and is reasonably well established, but the increasing use of commercial contracts for both survey and cartographic work by national hydrographic offices promises some changes in the legal position. Essentially, even if the work is carried out under contract, provided it is properly supervised, the hydrographic office remains responsible. While the manner in which the contract is described may have a bearing, if the contractor does something in an unsupervised fashion, then he will find himself legally liable. The manner in which the data is provided by the hydrographic office to a commercial manufacturer of an electronic chart is presumably, therefore, the causative factor in the matter of legal liability. If a manufacturer simply digitizes data off a chart without permission and produces an electronic chart, then the manufacturer rather than the hydrographic office will presumably be responsible for any errors that are made. If, on the other hand, the hydrographic office digitizes the data itself, and this is faithfully displayed by the electronic chart manufacturer, then the former will remain legally liable. It can be appreciated from these assumptions, if they are correct, that if a hydrographic office feels that it has a moral responsibility for its data, and to meet the stated expectations of users, it must ensure that it can supervise every step of the production of the electronic chart. It is this concern which turns us back again to the importance of copyright.

5 Administration

Hammer (1984) has observed that there are three communities of interest associated with the production and use of electronic charts. The first of these are the government hydrographic offices, which provide the data and normally digest this into the paper chart form. Then there are the "value-added" producers which take the data or digitize the charts and turn them into the electronic chart and, finally, there are the navigators who use the charts. To date, in the case of paper charts, the governments have served as regulators and have accordingly been responsible for the product throughout. It appears that there are several approaches that can be taken for the centre link. In Japan, the Hydrographic Office has taken up the responsibility of digitizing its own charts. It may be noted that this has not been the total chart, but selected information from it. It is their plan that these data will be sold through the Japanese Hydrographic Association, at the very modest cost of $20 per chart. It is not known how the Hydrographic Office provides updates to the digital chart files or how it assures itself that the presentation of the data is without error or distortion. At least one American company makes its own digital tapes from the government charts, which are not copyrighted. The company has proposed that it could produce hard copy overlays to give the National Ocean Survey in order that it could check the accuracy of the electronic chart.

At present, the manufacturers of the electronic chart hardware must either digitize their own data tapes or, in the case of Japan and possibly now the United Kingdom, obtain the tapes directly from the hydrographic offices. There is another scenario that has been proposed by the Norwegian Hydrographer, in which an organization be established to obtain and sell the digital data, acting as an additional middleman. These organizations could be commercial or part govern mental. It has been suggested that such organizations could be licensed by the hydrographic offices to carry out this function. They would be financially self-supporting, buying the rights to digitize charts from different national hydrographic offices and then selling the chart tapes to the electronic chart manufacturers. These bureaux have been proposed on a regional basis and would be more readily controlled than all the hardware manufacturers, which appear to be proliferating. Arrangements could be made between the bureaux and national hydrographic offices to ensure the quality of the digital data. The bureaux would also relieve the latter of the digitizing task. If the electronic chart develops to such an extent that it replaces the paper chart, the royalties paid by the bureaux to the hydrographic offices would provide some compensation for this lack of revenue. It is far from clear how data from a more raw state could be accessed and at this time it is perhaps realistic only to consider the digitization of the largest scale charts.

Supervision of the actual output of the electronic chart may still present a problem as there is no guarantee that the manufacturer will choose to display all the data or that the resolution of the display will permit a clear depiction of the data. Hydrographic offices would, for instance, not be happy to see their charts displayed at a larger scale than they were drawn. It may be necessary for electronic chart systems to be accredited in some way either directly by the hydrographic offices or by the bureaux and to advise mariners that they were at their own risk unless they used a properly licensed system. However, in this it must be surmised that the manufacturers are as anxious to sell a good product as are the hydrographic offices.

Finally it may be asked what part the International Hydrographic Organization has to play in these developments. Over many years it has advocated a free exchange of chart data between countries. It has also advocated international standards. Does it now have a part to play in the establishment of digital chart bureaux? Possibly the Regional Commissions of the IHO might be responsible for setting the standards and licensing the bureaux. Certainly the IHO has already shown its concern for the legal questions concerning the electronic chart by going to the International Maritime Organization (IMO) to ask its opinion.

6 Conclusion

While we are already well launched on the technical road to producing electronic charts, there are still some important issues to be faced at an administrative level. First is the question of updating and how this can be achieved; there is then a question for standards: then there is a question of legal responsibility and. finally, there is the matter of how the data will be administered. Are we to see the demise of national hydrographic offices as producers and sellers of nautical charts or will they become managers of hydrographic data bases only with the data being converted into digital form and kept updated by special bureaux and the charts in electronic form by commercial companies? At this stage the majority probably believe that there will always be a requirement for the paper chart and that electronic charts are but a diagrammatic presentation forming part of an integrated system. However, the business aspects of the electronic chart bear as much watching as the technological advances.

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https://doi.org/10.58440/ihr-29-a16

International hydrographic survey standards

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Preamble

This manuscript is a reprint of the original paper previously published in 1998 in The International Hydrographic Review (IHR, https://ihr.iho.int/): Mills, G. B. (1998). International hydrographic survey standards. *The International Hydrographic Review, 75*(2), 97–105. https://journals.lib.unb.ca/index.php/ihr/article/view/22954

1 Background

The International Hydrographic Organization (IHO) traces its origin to the establishment of the International Hydrographic Bureau (IHB) in 1921 which was formed to consider adopting similar methods and procedures in hydrographic data acquisition and nautical chart publication. In September 1970, the Member States formally adopted the IHO name and narrowed the meaning of the IHB to refer only to the Organization's Headquarters in Monaco. The stated objectives of the IHO include, among others, the coordination of the activities of national Hydrographic Offices and the adoption of reliable and efficient methods of conducting hydrographic surveys. To accomplish these objectives several committees and working groups have been periodically established to draft standards and specifications which are then submitted to the Member States for ratification.

The "IHO Standards for Hydrographic Surveys" are promulgated in Special Publication 44, otherwise referred to as S-44. The first edition of these Standards were published in 1968 with subsequent editions in 1982 and 1987. It should be noted that the IHO Standards are voluntary and are provided as guidance to Member States and others in their conduct of hydrographic surveys. The first three editions of the Standards were philosophically similar in that they applied to surveys conducted for the purpose of compiling nautical charts generally used for marine navigation. Survey scales were specified based on marine traffic usage and water depth and positioning accuracy standards were then based on survey scale due to the practical limitations of draftsmanship.

A Working Group, comprised of experts from 13 Member States, was established in 1993 to review the existing Standards and develop recommendations for changes to S-44 that were relevant to newly developing technology in satellite positioning, wide swath sonar and increased shipboard computer capability. The resulting proposal for the Fourth Edition of the Standards was approved in January 1998 by the IHO Member States and published in April 1998 (IHO, 1998).

As a result of advances in precise positioning from satellite systems (GPS – Global Positioning System and GLONASS) and the ability to accurately plot digital spatial data, S-44 has been modified to utilize real-world metric positioning accuracy standards. Shallow water multibeam echosounder systems and side scan sonars with dramatically increased data density have resulted in changes to the Standards to describe adequate bottom coverage in lieu of specified line spacing based on scale. With the development of Geographic Information Systems (GIS), hydrographic survey data is being used by a much more diverse group than previously. This not only increases the demand for data in digital form but also for metadata about the quality of the data and the methods and procedures used for acquisition and processing.

A brief review of measurement errors is needed to understand the meaning of the 95 % confidence levels specified for position and depth accuracies in the new Standards. An error is the difference between a measured value and the correct or true value and can be categorized as a blunder, systematic error or random error. Blunders are generally large errors

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https://doi.org/10.58440/ihr-29-a17

caused by inattentiveness or lack of skill on the part of the observer. Systematic errors are those that follow some physical law or rule by which they can be predicted. Random errors are generally small errors resulting from the limitations of measuring devices and processes, are equally likely to be negative or positive, and are governed by the laws of probability. Blunders must be eliminated by the establishment of adequate "checking" procedures and are assumed to not be present in quality hydrographic survey data sets. Systematic errors are measured or modeled using calibration techniques and must be removed from survey data prior to evaluating them against the IHO Standards. Random errors result from the inability to perfectly measure any quantity or to perfectly model any systematic error.

In practice, random errors of hydrographic measurements are assumed to be normally distributed (otherwise referred to as a Gaussian distribution). If one were to graph an infinitely large number of normally distributed random errors, the resulting "probability density function" would be a "bell-shaped" curve. The plus/minus distance from the mean that encompasses 68.3 % of the area under the curve is referred to as the standard deviation and symbolized by sigma (σ). The area under the curve between ±2σ from the mean is 95.4 % of the total area under the curve. In the strictest definition, the usage of standard deviation, or probability percentage, in describing the quality of data refers to precision or the repeatability of a measurement. The closeness of the mean of a series of measurements to the true value defines the accuracy.

2 New survey "orders"

The S-44 Working Group proposed a classification scheme for hydrographic surveys based on an area's importance for the safety of surface navigation. The variation in accuracy standards for each survey "order" reflects this variable importance and effectively replaces the scale-based positioning and data density standards of previous editions of the Standards.

Special Order hydrographic surveys cover areas where ships may need to navigate with minimum underkeel clearance and where the bottom characteristics are potentially hazardous to vessels such as boulders or rock outcroppings. This Order survey requires higher accuracies than those previously specified and for that reason has been particularly controversial. Special Order surveys are only applicable to those areas specifically designated by the Member State's agency responsible for the survey quality. Inherent in the requirements are closely spaced survey lines with side-scan sonar, multi-transducer arrays or multibeam echo sounder arrays to obtain "100 % bottom search". This term was adopted after numerous discussions on the impreciseness of the previously proposed term "100 % ensonification".

Order 1 surveys are intended for harbours and general intercoastal and inland navigation channels including those approaching harbours where vessel drafts have a greater clearance above the seafloor or where the bottom characteristics are less hazardous (e.g. silt or sand) than for Special Order survey areas. The standards for this order are very similar to the general standard of previous editions of S-44.

Order 2 surveys are applicable for those areas with depths less than 200 metres which are not covered by the criteria for Orders 1 or 2. Specifications for Order 3 surveys are applicable in water depths greater than 200 metres.

3 Positioning standards for soundings

The Third Edition of the S-44 IHO Standards specified that soundings should be determined, relative to shore control, such that there is a 95 % probability that the true position lies within a circle of radius 1.5 mm, at the scale of the survey, of the determined position. Therefore, for a 1:10,000-scale survey, soundings were to be located within 15 metres of their true position with a confidence of 95 % probability. In addition to all of the equipment and measurement errors associated with positioning systems, random errors associated with plotting soundings, either manually or by plotter, had to be included. Hence, the allowable error in positioning systems and their measurements in the U.S. were restricted to 1.0 mm at the scale of the survey.

The new Fourth Edition of the Standards specifies varying horizontal accuracy, in metres at the 95 % confidence level, for the four survey orders. One new aspect of the positioning standard is the inclusion of a depth-dependent factor which takes into account the added uncertainty of the positions of soundings from multibeam sonar systems as depth increases:

- 2 metres for Special Order
- 5 metres + 5 % of depth for Order 1
- 20 metres + 5 % of depth for Order 2
- 150 metres + 5 % of depth for Order 3

Because the term accuracy is used in these specifications, it is incumbent on the data acquisition unit to minimize all systematic errors and use appropriate equipment and techniques with sufficiently small random errors.

4 Depth standards

The total error in measuring depths, according to the Third Edition of the IHO Standards, should not exceed, with a probability of 90 %, 0.3 metres for depths less than 30 metres or 1 % of depths greater than 30 metres. This did not include the errors associated with the measurement of tides, determination of a sounding datum and the transfer of the sounding datum from an appropriate tide gauge to the survey area. The combination of such tide-related errors was not to exceed the error allowed for depth measurement.

The Working Group decided during the drafting of the Fourth Edition of the Standards to adopt three major changes regarding depth accuracy in addition to the introduction of the four survey orders:

(1) the probability or confidence level should be increased from 90 % to 95 % which is a more widely used value for survey measurements.
(2) depth accuracy standards should allow for fixed errors as well as depth dependent errors and these should vary according to survey order.
(3) errors due to tidal measurements, datum determination and sounding datum transfer should be included.

The below listed values a and b should be introduced into the following equation to calculate the error limits for depth accuracy:

$$\pm\sqrt{a^2 + (b \cdot d)^2}$$

Special Order	*a* = 0.25 metres	*b* = 0.0075
Order 1	*a* = 0.5 metres	*b* = 0.013
Order 2	*a* = 1.0 metres	*b* = 0.023
Order 3	*a* = 1.0 metres	*b* = 0.023

In the above expressions:

- *a* is the depth independent error, i.e. the sum of all constant errors
- *b* is the factor of depth dependent error
- *d* is the depth
- *b·d* is the depth dependent error, i.e. sum of all depth dependent errors

Fig. 1 below compares the depth error limits for the four orders to the comparable allowable error from the Third Edition of the Standards. The latter was obtained by calculating the root-sum-square of the allowable error for depth measurements (0.3 metres for 0 to 30 metres depth, 1 % of depth deeper than 30 metres) plus the allowable error for errors due to tides (also 0.3 metres for 0 to 30 metres depth, 1 % of depth beyond 30 metres) and converting the result from 90 % probability to 95 % probability. By comparing the curve for Order 1 to that of the Third Edition, one can see general agreement between O and 10 metres, a relaxation of the standard for Order 1 between 10 and 45 metres, and a more stringent standard deeper than 45 metres. As most Order 1 surveys will generally be conducted in depths less than 45 metres, this more restrictive standard in deeper water should not be viewed with concern.

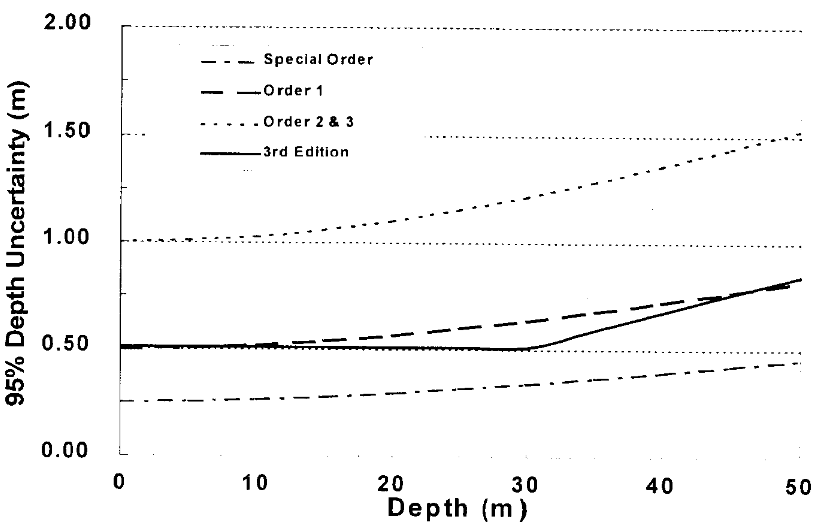

Fig. 1 Comparison of Depth Accuracy Standards.

5 Data density standards and feature detection

Previous editions of the Standards included recommended sounding line spacing and sounding interval based on the scale of the survey. It was anticipated that these "data density" standards would provide a reasonable probability that features potentially hazardous to navigation would be detected. The Third Edition of the Standards stated that sounding lines should not be more than one centimetre apart at the scale of the survey and the sounding interval should not exceed 4 to 6 centimetres at survey scale except in areas of quite flat or smooth seabed. It was decided that a more "scientific" approach should be taken using increased computer capabilities and/or side scan and multibeam sonar systems.

The Working Group initially considered the use of geostatistics to determine the best estimate of the depth of the seafloor, called a bathymetric model, and an error estimation of that modeled surface using bottom roughness and the proximity of the soundings to one another. The acceptability of the survey data could be judged by comparing the resulting error model to values based on the above equation for depth accuracy where the values for a and b are as follows:

Special Order	Not applicable since 100% bottom search is compulsory	
Order 1	*a* = 1.0 metres	*b* = 0.026
Order 2	*a* = 2.0 metres	*b* = 0.05
Order 3	*a* = 5.0 metres	*b* = 0.05

The error model could be used to identify areas of high probability of the occurrence of shoals due to geological processes. Obviously, it could not provide any statistical model for the occurrence of man made features. This latter characteristic plus the lack of widespread familiarity and use of geostatistics rendered it unsuitable as the primary international standard. However, it was retained as an option in a later section of the new Standards.

Eventually a combination of maximum line spacing, sonar system detection capability and the concept of 100 % bottom search were adopted. While the Third Edition of the Standards prescribed line spac-

 https://doi.org/10.58440/ihr-29-a17

ing that was dependent on the scale of the survey, the new Standards are generally dependent on the average water depth (Order 1–3 times average depth or 25 metres, whichever is greater; Order 2–3 to 4 times average water depth or 200 metres, whichever is greater; and Order 3–4 times water depth). This line spacing does not apply to Special Order surveys which require 100 % bottom search, a new term that implies a full search of the seafloor has been conducted. Some relaxation in the line spacing standard is permissible if appropriate procedures are adopted to ensure adequate detection of hazards for navigation. Sonar systems used for Special Order surveys must be capable of detecting features greater than 1 metre in size whereas the detection capability of systems for Orders 1 and 2 is for features 2 metres in size in depths up to 40 metres and 10 % of the depth beyond that depth. Some considerations about the feature detectability of side scan sonars and multibeam systems are presented by Clarke (1998).

6 Other items of interest

Under the new Standards, primary shore control points should be located to a relative accuracy of 1:100,000 if ground survey methods are used and errors should not exceed 10 centimetres at the 95 % confidence level when using satellite positioning. Standards for the positioning of navigation aids and other important features have also been modified in accordance with the four orders of hydrographic surveys. Fixed aids should be positioned within 2 metres for Special Order and Order 1 surveys and 5 metres for Orders 2 and 3 whereas the standards for floating aids are 10 metres for Special Order and Order 1 and 20 metres for Orders 2 and 3. The location of other topographical features, including natural coastline, should be located within 10 metres for Special Order surveys and 20 metres for Orders 1, 2 and 3.

A new requirement pertaining to the measurement of tidal heights has been adopted. The total measurement error should not exceed ±5 centimetres at the 95 % confidence level for Special Order surveys and ±10 centimetres for other surveys. These measurement errors plus those introduced from the sounding datum determination process and the transfer of that datum from the tide gauge to the survey area must then be combined with the other depth measurement errors to determine the depth accuracy of soundings.

Digital metadata should now be included with all hydrographic surveys to facilitate the usage of the data by an increasingly diverse population of users. Information should be included not only about the survey vessel, area, date and equipment used but also about the calibration procedures, sound velocity determination and tidal reduction methods. Estimates about the data accuracy and associated confidence levels should also be included.

7 Summary

The development of this new edition of the IHO Standards took nearly four years. During that time the Working Group considered a wide range of views from the various Member States, each of which had concerns about the implications of these Standards for not only the profession of hydrography but for their nation.

The effect of this Fourth Edition of the Standards on NOAA hydrographic surveys, both in-house and contracted, has not yet been fully determined. Given that most surveys will fall into the Order 1 category, particular care will be necessary to meet the horizontal accuracy requirements. It is also likely that renewed attention will be given to quantifying the errors associated with tidal height measurements, datum determination and related errors.

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Hydrographic GIS

Author
Horst Hecht

Preamble

This manuscript is a reprint of the original paper previously published in 2000 in The International Hydrographic Review (IHR, https://ihr.iho.int/): Hecht, H. (2000). Hydrographic GIS. *The International Hydrographic Review*, *1*(2), new series, 71–76. https://journals.lib.unb.ca/index.php/ihr/article/view/20499/23662

1 Introduction

Geographic information has been the basic information for navigation at land and at sea as well as for military and administrative purposes since the early beginnings of our culture. Since these early days maps and charts have been used both for displaying the information and as analogue databases, containing the geo referenced data in a graphically fixed form.

Geographic Information (GI) may be defined as an information entity providing a qualitative description of a location together with a quantitative, measurable geo graphic reference containing positional and topological information, and its relationships to other geographic information entities (Fig. 1). The development of information technology, together with the tremendous increase of computer power have, for the first time in history, now allowed a new, direct access to geographic information by means of digital databases. Geographic information can be retrieved, evaluated and presented today in a very diverse, flexible manner without being restricted by graphical symbols and their need of translation through cartographic legends. At the same time the real-time positioning possible with the Global Positioning System (GPS), together with digital survey methods (remote sensing, digital sounding) have tremendously increased efficiency of information collection. Correspondingly, new applications have emerged in the use of geographic information, particularly in conjunction with GPS for real-time navigation. Technological progress and the increasing requirements of navigation and administration lead to a development where, as a vision, *'accurate and up-t o-date, high resolution geographic information will be readily available from anywhere (land, sea, air) and for any purpose'*.

This will require:

- Completing / updating geographic data coverage on a global scale
- Availability of data as digital vector source data (as opposed to analogue raster data or data digitised from analogue sources)
- Interoperability between GI data of various sources (land, atmospheric, hydrographic and oceanographic data)
- Networking between geographic information providers

2 The position of hydrography in geographic information

Hydrography traditionally has been a service for navies and merchant fleets. In this function hydrogra-

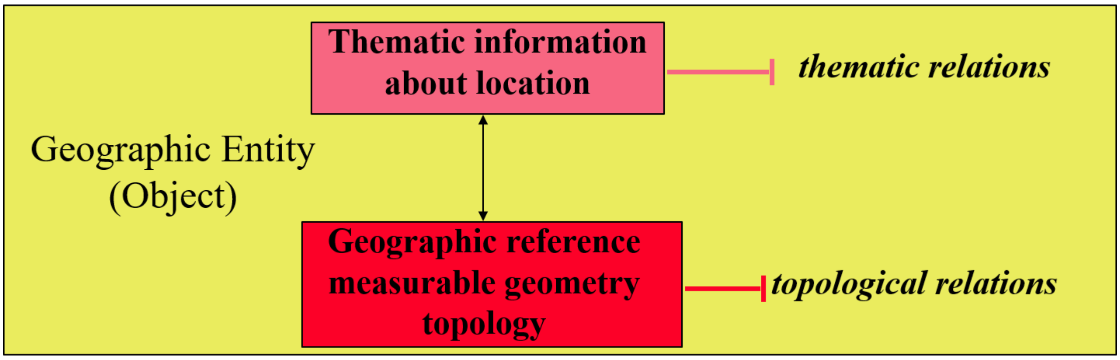

Fig. 1 Schematic Structure of Geographic information.

https://doi.org/10.58440/ihr-29-a11

phy has helped mankind to establish and secure a global transportation network which is the basis for our modern economy. It also helped to explore the hydrosphere both scientifically and economically. As a natural consequence it became necessary to agree on common rules for administering the marine space. This has been accomplished through the UN Convention on the Law of the Sea (UNCLOS) where hydrography has been given an additional function in:

- Claims of maritime boundaries
- Marine environmental monitoring
- Use of the Exclusive Economic Zone (EEZ)
- Management of living and non-living marine resources

Hydrography, together with the related science of oceanography, has natural interfaces with topography on the land, and with the atmospheric sciences. Hydrograph y at present, however, seems still being pretty isolated from these other types of geographic information. This may be illustrated in the following example.

3 The Baltic Sea Region project

The Baltic Sea Region (BSR) interestingly is defined in hydrological terms as the Baltic drainage area, i.e. those countries having rivers flowing into the Baltic Sea. Thus, not only the coastal states surrounding the Baltic Sea are considered to belong to the Baltic Sea Region but also more distant countries like Belarus belong to it (Fig. 2). As the result of the dramatical political changes, governments of this region in 1994 set up a joint programme to intensify mutual cooperation, and to speed up economical and environmental development. Spatial planning and administration has soon been recognised as crucial for this purpose.

This resulted in the so-called Stockholm Declaration[1] of 21 October 1996:

- Outlining a policy of sustainable development for 'coupling of economic development needed in cities and regions with the cautious use of the coastal zone and landscape in the hinterland'
- Launching a Baltic Region-wide GIS initiative involving:
    - The Helsinki Commission (marine environmental protection)
    - The MAP Baltic Sea Region (MAP BSR) Project of national mapping authorities
    - The University GIS Network of Upsala University

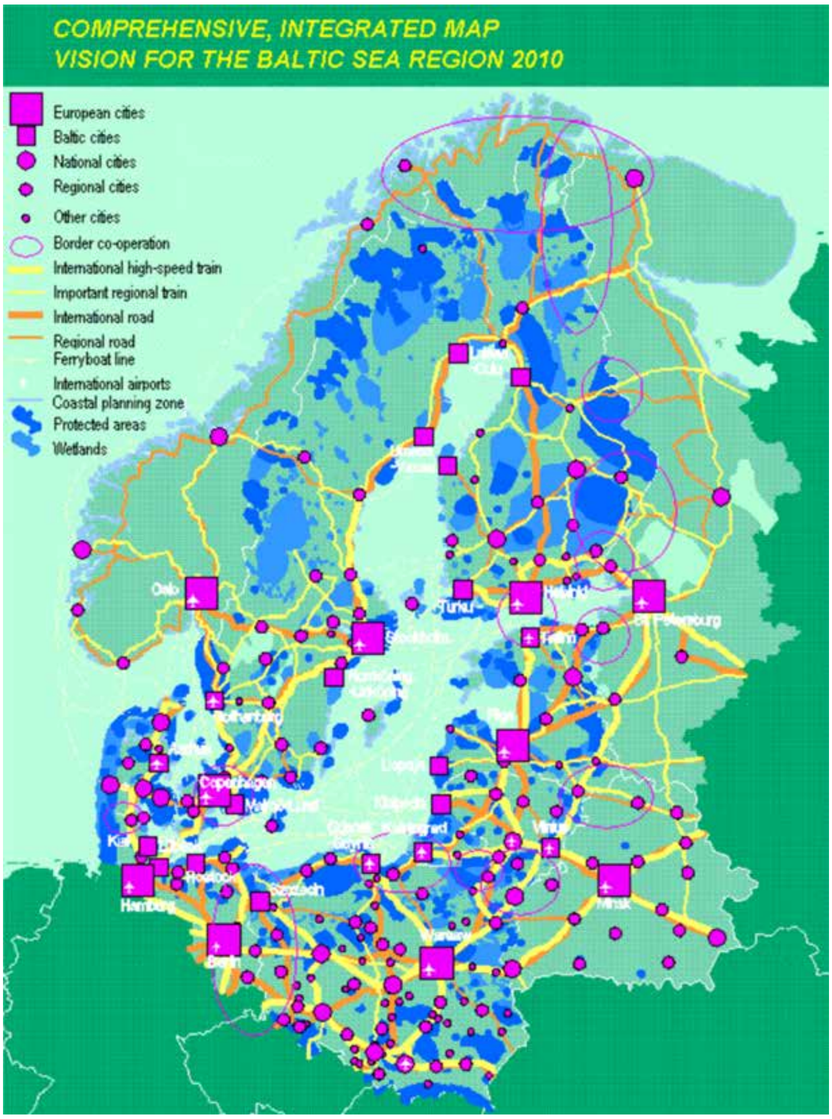

Fig. 2 The Baltic Sea Region

Funding was provided by the European Union under the Baltic Sea Region Initiative.

Although sea-borne traffic plays a very important role in the Baltic Sea[2] – approximately 60 million passengers are ferried annually across the Baltic Sea – hydrography has not been taken into account in the Baltic Sea Region Project. On the other hand, the third conference of the Ministers of Transport of the Baltic Sea States, at a conference in Berlin on 21 April 1997, has stated the goals for the Baltic Sea to:

- Promote maritime transport as environmentally friendly means of transport

[1] Stockholm Declaration on Sustainable Spatial Development Policy in the Baltic Sea Region. Internet URL: https://vasab.org/home/about/ministerial-conferences/stockholm-1996/ (accessed 23 Feb. 2023).

[2] Laue, U. (1998). Ostseeschiffahrt – Besonderheiten und Entwicklungen (Baltic Sea shipping – peculiarities and developments). *Schiff & Hafen 3/98*, p. 10–13.

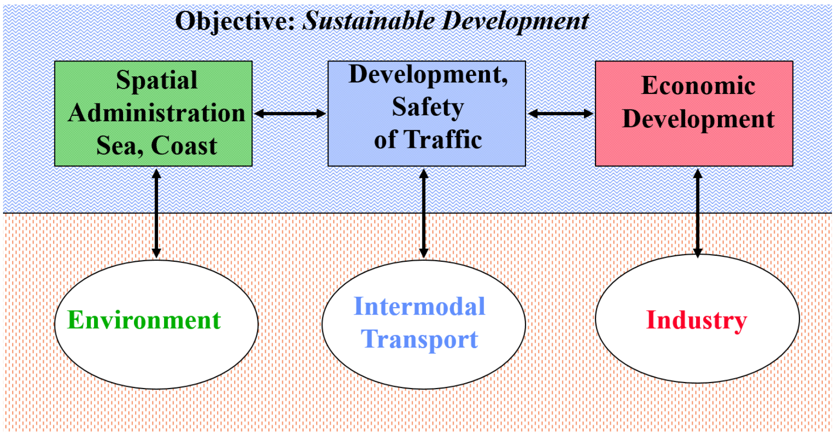

Fig. 3 Schema of Coastal Zone Management.

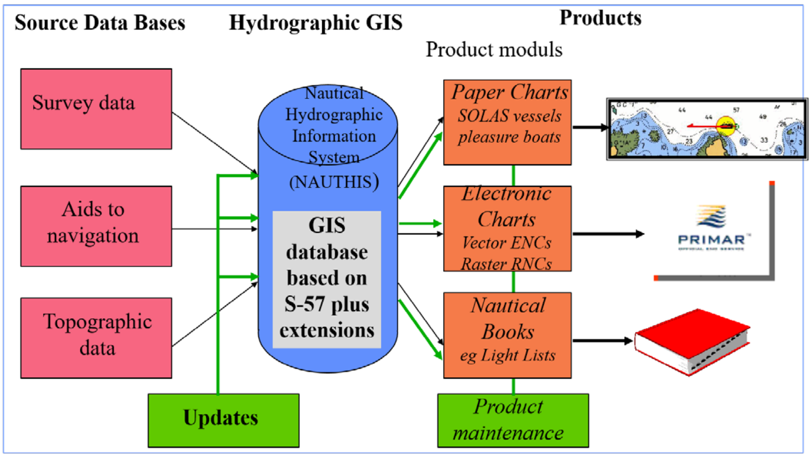

Fig. 4 Overview of a hydrographic GIS.

- Providing 'continuous transport systems, by integration of all modes of transport'
- 'Provide European-wide logistic systems and interoperable information and communication systems for electronic data exchange along the transport chain'

The fact that hydrography has been ignored in the set-up of both projects seems to illustrate that the provision of marine safety information is considered a separate issue not related to spatial administration, or to the integration of transport systems. In other words, hydrography has not yet been made visible as the prime source of marine information having a potential impact on sustainable development, especially in the coastal zone area (coastal zone management), as well as on the efficiency of intermodal trans-port, e.g. by increasing safety and efficiency of the maritime transport.

It is a trivial fact that the coastline links seaside and landside. Thereby spatial administration traffic management and economic development are closely related and form the objective of Coastal Zone Management (Fig. 3).

4 Vessel Traffic Management and Information Services

Vessel traffic services have been established world-wide as an efficient means of securing safety of navigation especially in congested and narrow waters. This concept has recently been broadened towards vessel traffic management and information systems in order to increase efficiency of navigation.

Vessel traffic management, the essential function of vessel traffic services, is defined as follows: 'The set of efforts (measures, provisions, services and related functions) which, within a given area and under specified circumstances intend to minimise risks for safety and the environment, whilst maximising the efficiency of water-borne and connecting modes of transport'.

In its broadened meaning 'Vessel Traffic Management and Information Services' intend to respond to public and private demand for facilitating vessel traffic management. Vessel traffic management and information services include services distributing in given areas (at regional, national or transnational level) the pertinent information to be used both in real-time and in retrieval modes by actors involved.

Hydrographic information is, to a limited extent, already part of VTS today, e.g. Navigational Warnings. More, however, is being needed such as, e.g., real-time surface current data at the approaches of ports where cross currents are known to be dangerous, digital navigational warnings or temporary updates of electronic chart data, latest ice information etc. In addition, it has proven to be very useful if both VTS Centres and ships at sea have the same and up-to-date level of electronic chart data both for navigation and geographic reference.

In principle, VTMIS is conceived as a system linking:

- Logistic information
- Traffic information (land/sea) Navigational information and warnings
- Meteorological and current data, ice information

The European Union, in a Concerted Action, has studied the potential of VTMIS to enhance maritime transport, and potential measures for their implementation. One important aspect is networking together the various information to facilitate access by ship operators, maritime administrations and ships at sea to obtain the relevant latest information. The European Union within the Fourth Frame Work Programme currently has established a project on information of a VTMIS Information Network.3

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5 Implementation of GIS at Hydrographic Offices

With its 'Transfer Standard for Digital Hydrographjc Data# (Special Publication S-57) IHO has established a flexible, powerful, modern GI data standard for digital hydrographic data. It has been already accepted as a world-wide transfer standard for the Electronic Chart Display and Information System (ECDIS) which itself is a real-time navigation information system. ECDIS, however, currently is the only realisation (application profile) of this standard for particular purpose. In principle, S-57 represents an excellent basis for a wide range of hydrographic information systems.

Many hydrographic offices today are already working on establishing hydrographic information systems allowing the integration of different product lines, such as:

- Production of ECDIS data
- Storing the results of hydrographic surveys
- Production of paper charts and nautical publications

With the necessary extensions to the Object and Attribute Catalogues of S-57, it is easy to extend the capability of S-57 to many other applications, for instance in oceanography. As an object-based standard it provides the potential for linking the GIS systems of HOs to other external GIS of land mapping authorities, maritime and port authorities, universities and other scientific institutions.

6 Extended information services planned at BSH

The following is a description of developments planned at the Federal Maritime and Hydrographic Agency (BSH), Germany, as an example.

Like many other (currently 10) hydrographic offices, BSH is co-operating with the Regional Electronic Navigational Chart Co-ordinating Centre Northern Europe, PRIMAR, on the distribution of electronic chart data and provision of respective updating services.

In order to integrate their production lines for the traditional paper products and the electronic chart data, BSH has set up a project to develop a 'Nautical Hydrographic Information System' (NAUTHIS, see schematic overview in Fig. 4).

Experiences from seagoing tests of ECDIS have shown that ECDIS as a navigation system is used in a different manner than the traditional paper chart. In particular, in narrow waters the virtually unlimited zooming capabilities of ECDIS are stretched to their limits. It has turned out that it would be unsatisfactory, and in the long run even unsafe, if ECDIS data would only be based on digitised paper chart products. Rather ECDIS data must reflect the full data accuracy of the regional source data. As the ECDIS database is a combination of hydrographic and relevant topographic data where data from different authorities are being compiled into a single database, it is seen essential to develop any hydrographic information systems of HOs into a source database for hydrographic data networked wit11 source databases of other relevant authorities. This is a goal pursued in the medium term for NAUTHIS where links will be established to topographic data bases of federal coastal states of Germany, and databases operated by local water and shipping off ices.

7 Conclusions

Hydrographic data are essential geographic base data increasingly needed beyond navigation, for EEZ administration. Vector geographic information data offer a huge synergy potential when networked with other databases.

The technological progress with computer power and telecommunication will put HOs under pressure to incorporate the data with larger national geographic information networks. The VTMIS project of the European Commission is an example and part of the policy of EU forming trans-European geographic information data networks to facilitate administration (multi-modal transport, economic development and environmental protection).

Hydrographic Offices will have to adjust soon to the widening scope of geographic information in a net worked world.

8 Note

This article is a text version of a lecture presented at the 'Workshop on the modern management of a hydrographic service' on 23 September 1999 at the International Maritime Academy in Trieste, Italy.

Author's biography

Horst Hecht

Horst Hecht, born 1943, received a master's degree in meteorology in 1969 at the Free University Berlin. From 1970 to 1988 he was serving as IT manager at the German Hydrographic Institute, which 1990 became the German Federal Maritime and Hydrographic Agency (BSH). From 1988 to his retirement in 2008 he was Director of the Hydrographic Department, acting also as head of the Rostock office of BSH from 2003 to 2008. For many years, he was involved with ECDIS standardisation in various bodies of IHO and IMO, and he is co-author of the textbook "The Electronic Chart". After his retirement, he was active until 2017 as freelancer and senior scientific advisor on marine GIS issues to a major geospatial software company.

https://doi.org/10.58440/ihr-29-a11

Development of IHO S-100 – The new IHO geospatial standard for hydrographic data

Authors

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Preamble

This manuscript is a reprint of the original paper previously published in 2007 in The International Hydrographic Review (IHR, https://ihr.iho.int/): Alexander, L., Brown, M., Greenslade, B., and Pharaoh, A. (2007). Development of IHO S-100 – The new IHO geospatial standard for hydrographic data. *The International Hydrographic Review, 8*(1), 56–162. https://journals.lib.unb.ca/index.php/ihr/article/view/20782

1 Introduction

The International Hydrographic Organization (IHO) is an intergovernmental consultative and technical organization established in 1921 to support the safety of navigation, and to contribute to the protection of the marine environment. IHO Special Publication 57 (IHO S-57) is the IHO Transfer Standard for Digital Hydrographic Data. It is the standard intended to be used for the exchange of digital hydrographic data between hydrographic offices, and for the distribution of hydrographic data to manufacturers, mariners and other data users (e.g., environmental management organisations). It was developed so that the transfer of all forms of hydrographic data would take place in a consistent and uniform manner. To date, S-57 Edition 3.0/3.1 has been used almost exclusively for encoding Electronic Navigational Charts (ENCs) for use in Electronic Chart Display and Information Systems (ECDIS). However, there are changing requirements, customers and technology for hydrographic data and as S-57 is intended to support all types of hydrographic data, not solely ENCs, it needs to be expanded in order to accommodate these new requirements.

This information paper explains what is planned in regard to the next edition of the standard. In particular, it provides a brief description of how the standard will be aligned with geospatial standards under development by the International Organisation for Standardisation (ISO) and the benefits to be gained for IHO and its stakeholders.

2 History of S-57

IHO S-57 was formally adopted as an official IHO standard at the XIVth International Hydrographic Conference in May 1992. It includes:

- A general introduction with list of references and definitions
- A theoretical data model on which the standard is based
- The data structure and format that are used to implement the data model General rules for encoding data into the ISO 8211 encapsulation

In addition to the main document, there are two appendices:

Appendix A is the Object Catalogue. It provides the official, IHO-approved data schema that can be used within an exchange set to describe real-world entities.

Appendix B contains the IHO-approved Product Specifications. These contain additional sets of rules for specific applications. Currently, the only product

[1] CCOM-JHC, University of New Hampshire, Durham, New Hampshire USA

[2] Office of Coast Survey – NOAA, National Ocean Service, Silver Spring, Maryland, USA

[3] United Kingdom Hydrographic Office, Taunton, UK

[4] International Hydrographic Bureau, Monaco

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specification in S-57 that is in wide use is for an Electronic Navigational Chart (ENC). A product specification for an IHO Object Catalog Data Dictionary was also included but for all practical purposes has never been implemented.

Edition 3.0 was released in November 1996. Edition 3.1 containing minor revisions/additional attribute values was issued in November 2000. Currently, S-57 3.1 is "frozen". It will remain valid – in perpetuity – until no longer required.

3 Current limitations of S-57 Edition 3.1

Although S-57 Edition 3.1 has many good aspects, it does have certain limitations:

- It was primarily developed to meet the ENC requirement called for in an IMO-compliant ECDIS.
- It has an inflexible maintenance regime. Freezing standards for lengthy periods is counter-productive.
- As presently structured, it cannot support future requirements (e.g., gridded bathymetry or time-varying information).
- Embedding the data model within the encapsulation (i.e., file format) restricts the flexibility and capability of using a wider range of transfer mechanisms.
- It is regarded by some as a limited standard focused exclusively for the production and exchange of ENC data.

In order to address these and other limitations, the IHO Committee on Hydrographic Requirements for Information Systems (CHRIS) authorised work to begin on a major revision of Edition 3.1. This revision will result in a new standard that includes both additional content and a new data exchange format. The present intention is to publish a new standard in late 2007 and gain ratification by CHRIS in 2008.

4 New name

During the years that S-57 has been in use, many people have come to regard the IHO S-57 standard and the ENC Product Specification as the same thing. In reality, the ENC Product Specification is actually based on S-57. This resulted in the impression by many within the ENC community that the work on a new standard to support other hydrographic products would radically change the ENC, thus affecting ENC production and ECDIS implementation. This is not the intention.

At the 17th Meeting of CHRIS (September 2005), it was decided that the S-57 Edition 4.0 that was currently under development would henceforth be designated as S-100 (IHO Geospatial Standard for Hydrographic Data). Any product specifications developed using S-100 would follow in an S-10x series as they are produced. Thus, at some future date when an ENC Product Specification based on S-100 is developed, it will be designated S-101.

Fig. 1 S-100 will support a far greater variety of data sources, products and services.

5 Goal / objectives

The primary goal for S-100 is to be able to support a greater variety of hydrographic-related digital data sources, products, and customers (see Fig. 1). This includes imagery and gridded data, 3-D and time-varying data (*x, y, z*, and time), and new applications that go beyond the scope of traditional hydrography (for example, high-density bathymetry, seafloor classification, marine GIS, etc.). It will also enable the use of Web-based services for acquiring, processing, analysing, accessing, and presenting data.

Other goals include:

- Separating the data content from the carrier (file format). In this way, data can be manipulated and encoded without being permanently tied to a single exchange mechanism.
- Manageable flexibility that can accommodate change. Future product specifications will be based on a core data model that may be extended to meet the needs of different hydrographic information communities. This will allow the core standard to evolve (through extension) without the need for producing new versions of existing product specifications.
- An ISO-conforming registry on the IHO Web site containing feature data dictionaries (as registers) and product feature catalogues that are more flexible and capable of being expanded.
- Providing separate registers for other user communities. These will include new features and attributes and additional product specifications that may be created (for example, Nautical Publications, Inland ENC Product Specification, etc).

6 ISO standards for geographic information

The International Organisation for Standardisation (ISO) is a non-governmental international standards organisation comprising a worldwide federation of national standards bodies from over 130 countries. In response to a growing demand for geographic information standards, ISO established Technical Committee 211 (ISO/TC211) in 1994. The aim of ISO/ TC211 is to establish a structured set of standards for information concerning geographic objects or phenomena. IHO, together with many other geographic standards development organizations, is a Class A Liaison Organization to ISO/TC211. Currently, there are over 22 Class A members, including:

- Digital Geographic Information Working Group (DGIWG),
- Global Spatial Data Infrastructure (GSDI),
- Open Geospatial Consortium {OGC),
- United Nations Geographic Information Working Group (UNGIWG).

7 ISO 19100 Standards

The standards developed by ISO/TC211 are contained in the ISO 19100 series of geographic information standards. For all forms of geographic data, these standards specify the methods, tools, and services for:

- Data management (including definition and description),
- Acquiring, processing, analysing, accessing, and presenting data,
- Transferring data in digital electronic form between different users, systems and locations.

In the most general sense, these standards fall into one of the following categories:

- Framework and Reference Model,
- Profiles and Functional Standards,
- Data Models and Operators,
- Data Administration,
- Geographic Information Services.

Currently, there are over 40 standards in the ISO 19100 series. These include both formally adopted and draft International Standards for spatial and temporal schema, metadata, imagery and gridded data, profiles, portrayal, encoding, and so forth.

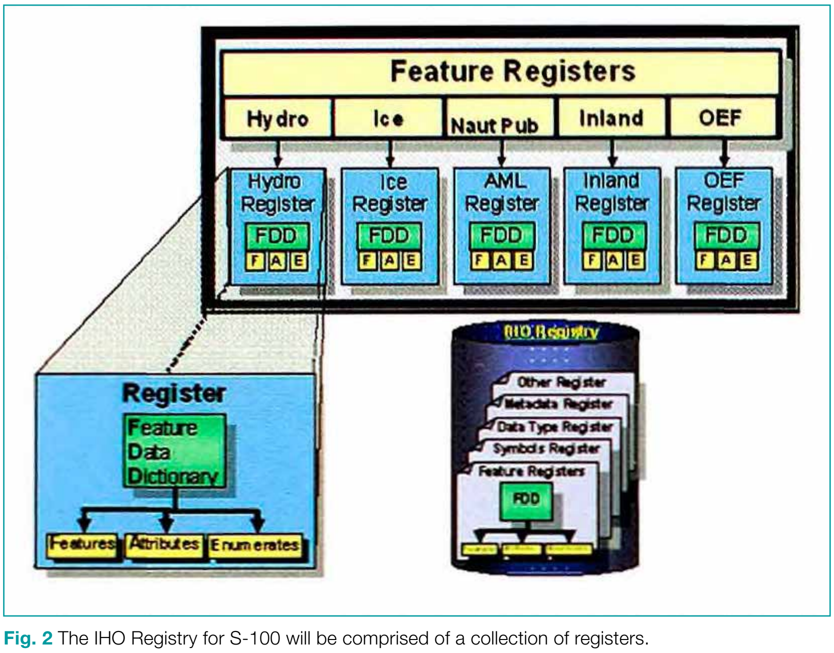

Fig. 2 The IHO Registry for S-100 will be comprised of a collection of registers.

8 Alignment with ISO/TC211

Given the prominence of ISO standards and their worldwide recognition and use, it makes sense for IHO to adopt the IS0/TC211 suite of standards for S-100.

In 1999, ISO/TC211 invited the IHO and the NATO Digital Geographic Information Working Group (DGIWG) to enter into a cooperative agreement for future standards development. Rather than work at cross-purposes, it was considered prudent to harmonise the data content contained in IHO S-57 (i.e., the Object Catalogue) with that of NATO DIGEST (the DGIWG Feature Data Dictionary – formerly called Feature Attribute Coding Catalog or FACC). Further, the intent was to develop hydrographic standards that were compatible with a broad range of other ISO geospatial standards. This was agreed by the 12th CHRIS meeting in October 2000. Currently members of both organizations attend each other's meetings and have played important roles in the harmonisation process.

9 New framework

Alignment with the ISO 19100 series of geographic standards will require a different way of organising and defining S-100, compared to S-57. More specifically, it will require a new framework or structure, and a revised set of terms used to describe the components of S-100.

S-100 will consist of a wider range of components than S-57 from which product specifications will be built. These specifications will need to be inclusive and comprehensive in order to enable a more flexible maintenance regime for S-100.

10 Registry component

Perhaps the most significant aspect in terms of alignment with the ISO TC/211 standards is the employment of a “registry” containing one or more “registers” (see Fig. 2).

A “registry” is the entire information system (or location) in which a collection of registers is located. In the case of S-100, IHO will host a registry that will provide a facility to store various registers of hydrographic-related information such as feature data dictionaries, data types, and metadata.

Unlike S-57, the feature dictionaries will only consist of the definitions for features, attributes and enumerations. Binding between these definitions, units of measure, format and the like, will be included in a feature catalogue which will be specific to each product specification. Initially there will be registers for Hydrographic Information (based on the existing S-57 feature and attribute catalogues), Dynamic Ice Coverage, Nautical Publications and Inland ENCs. Other types of information that do not fit into these categories can be included in the Open ECDIS Forum (OEF)

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register. For each register there is an organisation that will be responsible for its content and management. A major benefit of the registry concept is its flexibility. Multiple versions of similar entries in a data dictionary can be maintained using unique identification and classification. For instance, an entry can be classified as being either:

- valid (latest version),
- superseded (previous version/s),
- retired (no longer recommended for use),
- non valid (proposed but not accepted or no longer acceptable).

In this way product feature catalogues can reference an item that will remain valid even if a newer version is registered at a later date. Thus, if a new item is registered, a new version of a current product specification is not required. Non valid items will remain public in order to ensure that any future proposals for similar items have not been previously rejected. An operational registry is planned for early 2007.

11 Framework Component

The framework component will be similar to a "cookbook" or "recipe book" demonstrating how different parts of S-100 are selected and used together in the development of product specifications.

The three most important parts of any product specification are the content model, application schema and encoding model. The content model consists of features, spatial metadata, quality and so forth. The application schema (see Fig. 3) specifies the rules for how the various pieces of the content model are assembled (that is; a feature and its spatial component). These rules can then be applied to develop a product specific application schema that in turn forms the basis of the product specification. Individual product specifications consist of a feature catalogue, an application schema, an encoding (for example, Geographic Markup Language – GML), and so forth, (see Fig. 4).

12 Geometry Component

The one and two-dimensional geometry of S-57 is updated in S-100 to accommodate the use of a wider range of database and encoding applications. For example, the use of a composite curve to amalgamate the individual curve components of a feature will simplify operations on such a feature in the software environment. A new three-dimensional model has also been added.

13 Imagery and Gridded Component

This component defines specific grid organisations to be used for hydrographic data and images associated with hydrographic data. Both simple grids and complex multi-dimensional grids are defined.

Hydrographic soundings are by their nature a set of measured data points. These data points can be represented in a grid structure in several different ways, including elevation models, using a regular grid spacing, and irregular grids with variable size cells or picture elements (pixels) that closely correspond to the handling of soundings as point sets.

Images are also of great importance for hydrographic data. This includes images from sensors such as aerial photography or LiDAR, photographs that can be associated with vector based feature oriented data and scanned paper chart products, commonly known as "Raster Charts". All of these applications of imagery and gridded data are covered by S-100.

14 Metadata Component

The metadata component is a community profile that provides a specification for describing, validating and exchanging metadata about geographic datasets commonly produced by hydrographic organisations. It is based on ISO 19115 and also takes account of ISO 19139 for the XML implementation.

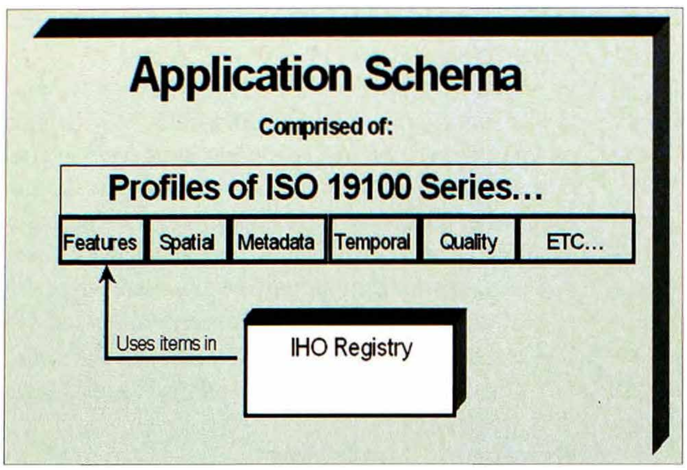

Fig. 3 Application schema.

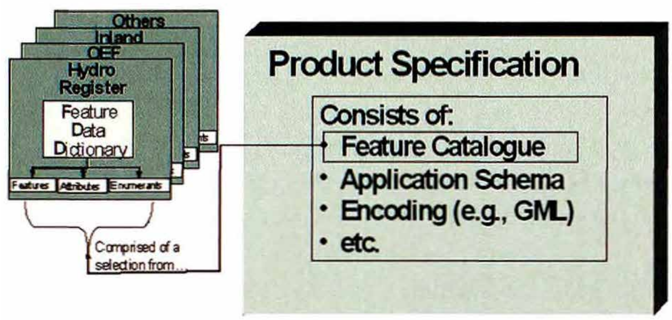

Fig. 4 Individual product specifications will be comprised of several components.

The profile contains two parts:

Part 1 supports cataloging and discovery metadata and contains the minimum specification for descriptive elements required for hydrographic metadata capture.

Part 2 makes provision for the documentation of more detailed feature and attribute level metadata.

15 New Terminology (IHO S-57 → IHO S-100)

Some of the terms and definitions currently used in S-57 Ed. 3.1 will no longer be used. They will be re-defined or will be modified into what some have described as the new language of "ISO-ese". While this transition may be difficult at first, in the longer term it will be beneficial since IHO S-100 will be using the same language as the ISO TC/211 series of standards.

Some examples of this change in terminology are mentioned in the following table.

S-57 Ed. 3.1 → IHO S-100

[none]*	a registry for a standard contains a number of registers
object	feature
attribute	feature attribute
attribute values	enumerated values
object catalogue	a feature data dictionary contains features and attributes but without any mandatory relationship. Using this, a specific feature catalogue (mandating relationships between features and attributes) can be specified for a variety of requirements (e.g., a product specification).

*The closest thing to a registry/registers that currently exists are the arrangements on the Open ECDIS Forum (OEF). During the past six years, it has served as a useful mechanism/database for registering additional objects/attributes that were not contained in S-57 Edition 3.0/3.1.

16 Benefits

There will be numerous benefits gained from adopting S-100:

- Using ISO-developed components and terminology will help ensure that S-100 and future extensions are in the mainstream of the geospatial information industry. This should also help to facilitate a greater use and lower cost implementation of S-100 for hydrographic and other types of geospatial applications (for example, Marine GIS).
- Conformance with the ISO/TC211 standards will maximize the use of commercial-off-the-shelf (COTS) software applications and development.
- New components of S-100 will not be developed in isolation from the rest of the geospatial information technology community.
- Any new requirements can be incorporated within the established framework of ISO/TC211 based standards.
- Rather than being regarded as simply a standard for hydrography, S-100 will be interoperable with other ISO/TC211 standards and profiles such as NATO DIGEST.
- There are many national standards bodies that will take full advantage of S-100 being aligned with ISO/TC211 standards.
- More than just hydrographic offices and ECDIS equipment will be able to use S-100 based hydrographic data.
- It will facilitate the ability of hydrographic offices to use other sources of geospatial data, for example combining topography and hydrography to create a coastal zone map.

Another improvement will be the way in which ENC data will be encapsulated. In simple terms, encapsulation means the form of data structure used for the exchange of ENC data. The current edition of S-57 uses an out-dated ISO standard referred to as ISO/IEC 8211, "Specification for a data descriptive file for information interchange". First published in 1985, ISO/IEC 8211 was developed when the state-of-the-art was the 3.5" floppy disk. ISO/IEC 8211 is no longer widely used, and it would not be possible to efficiently encapsulate some of the new data functionality using this legacy standard. The GIS industry has provided a standards-based format that provides a good replacement for ISO/IEC 8211. The Geography Markup Language (GML) has been developed by the Open Geospatial Consortium, and the current version is progressing to become an ISO standard. Using GML as one method of encapsulating S-100 data fits in well with the overall strategy of using existing standards in order to facilitate acceptance.

17 Migrating from S-57 Edition 3.1 to S-100

ENC data conforming to S-57 Edition 3.1 will continue to be a requirement for type-approved, IMO-compliant ECDIS for the foreseeable future - even after S-100 has been released. As a consequence, hydrographic offices will continue, as at present, to produce Edition 3.1 ENC data to support this.

18 Implications for the ENC Product Specification

It goes without saying that if any improved ENC Product Specification (such as S-101) is to be adopted in the future, it must provide mariners with useful new functionality. This could include such things as "plug and play" updating of data, symbology and software enhancements as well as the more efficient use of additional data created under S-100. Also, any development of S-101 will be undertaken over several years, and will involve the active participation of all stakeholders, including hydrographic offices, ENC software producers, ECDIS manufacturers, mariners,

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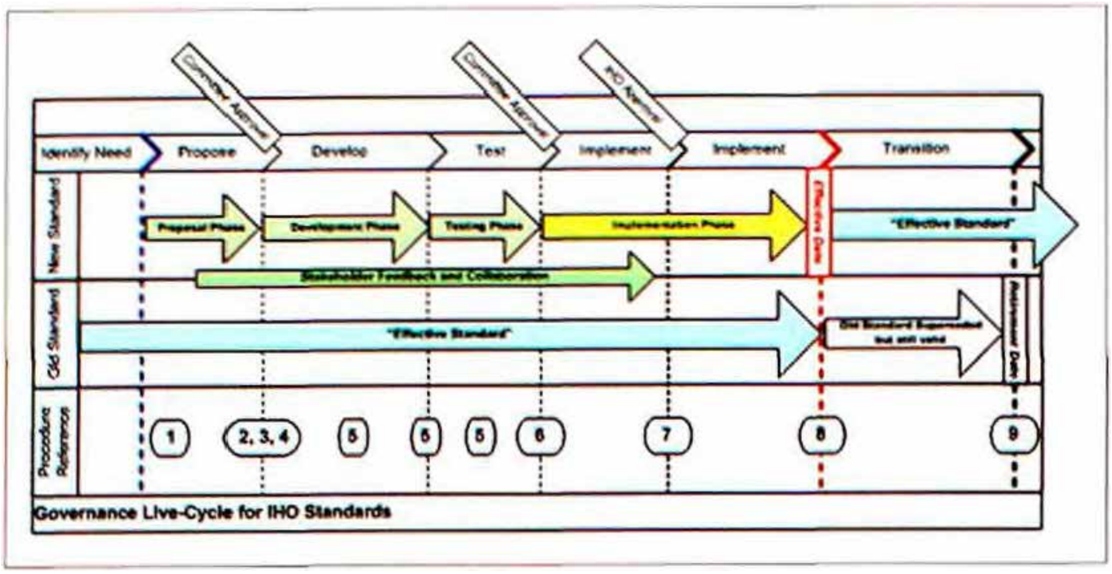

Fig. 5 Typical Lifecycle of an IHO Standard.

and other maritime users. The development, implementation and transition into force must also follow the IHO CHRIS governance model for IHO technical standards as illustrated in Fig. 5.

The IHO CHRIS agreed at its meeting in September 2006 that an S-101 Information Paper should be published late in 2007/early 2008 which will explain in detail the proposed content and structure of any future ENC product specification.

As a consequence of the extensive development process, any improved ENC Product Specification (S-101) could not come into force before at least 2012 and even then, the standard would sit alongside the existing S-57 Edition 3.1 Product Specification for some time. Furthermore, it is intended that any ECDIS which are upgraded to use S-101 ENCs will continue to be able to use S-57 Edition 3.1 ENCs as well.

19 In Summary

The primary goal for S-100 is to support a greater variety of hydrographic-related digital data sources, products, and customers. This includes matrix and raster data, 3-D and time-varying data (*x, y, z*, and time), and new applications that go beyond the scope of traditional hydrography (for example, high-density bathymetry, seafloor classification, marine GIS). It will also enable the use of web-based services for acquiring, processing, analysing, accessing, and presenting data. S-100 is not an incremental revision of Edition 3.1. S-100 will be a new standard that includes both additional content and support of a new data exchange formats.

Due to the worldwide prominence of ISO standards, IHO S-100 will be based on the ISO suite of standards. However, alignment with the ISO 19100 series of geographic standards will require a different structure for S-100 compared to S-57. More specifically, this will involve a new framework, and new/revised terms to describe the components of S-100.

The present intention is to release S-100 in late 2007. IHO S-57 Edition 3.1 will continue to be used for many years to come – even after S-100 has been released. As such, Hydrographic Offices will continue to produce S-57 ENC data to meet IMO ECDIS Performance Standard requirements, and to maintain world-wide ENC coverage. Any future ENC Product Specification will take several years to develop after publication of the S-100 base standard, and will involve the active participation of all IHO stakeholders.

Thirty years of satellite derived bathymetry – The charting tool that hydrographers can no longer ignore

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Preamble

This manuscript is a reprint of the original paper previously published in 2020 in The International Hydrographic Review (IHR, https://ihr.iho.int/): Laporte, J., Dolou, H., Avis, J., and Arino, O. (2000). Thirty years of satellite derived bathymetry – The charting tool that hydrographers can no longer ignore. *The International Hydrographic Review, 24*, 129–154.
https://ihr.iho.int/articles/thirty-years-of-satellite-derived-bathymetry-the-charting-tool-that-hydrographers-can-no-longer-ignore/

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.

The advent of new generation satellite constellations, such as Sentinel-2*, 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 (Fig. 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.

*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.

Resumé

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).

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https://doi.org/10.58440/ihr-29-a20

Or, l'avènement d'une nouvelle génération de constellations satellitaires telles que Sentinel-2*, 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 (Fig. 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.

*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.

La llegada de las constelaciones de satélites de nueva generación, como Sentinel-2*, 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 antecedents 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 (Fig. 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.

* 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.

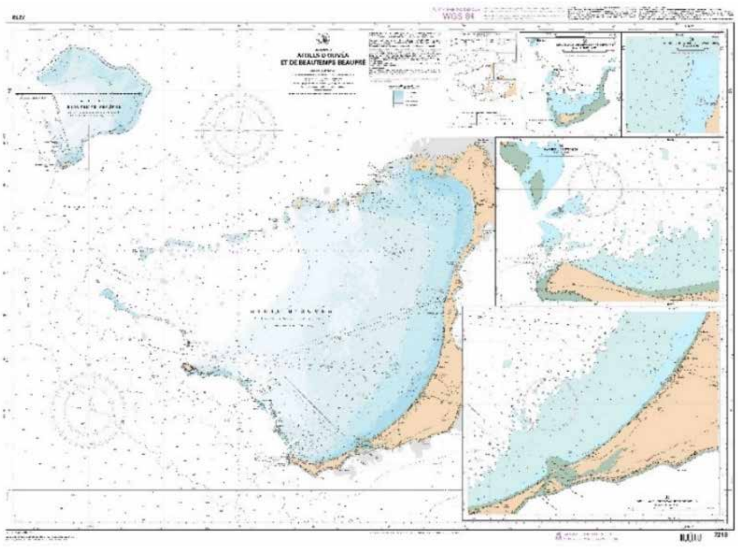

Fig. 1 The first SDB official chart. Source: 2010 SHOM, publication 1990 based on a 1988 SPOT image.

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[1], 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 fulfil 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.

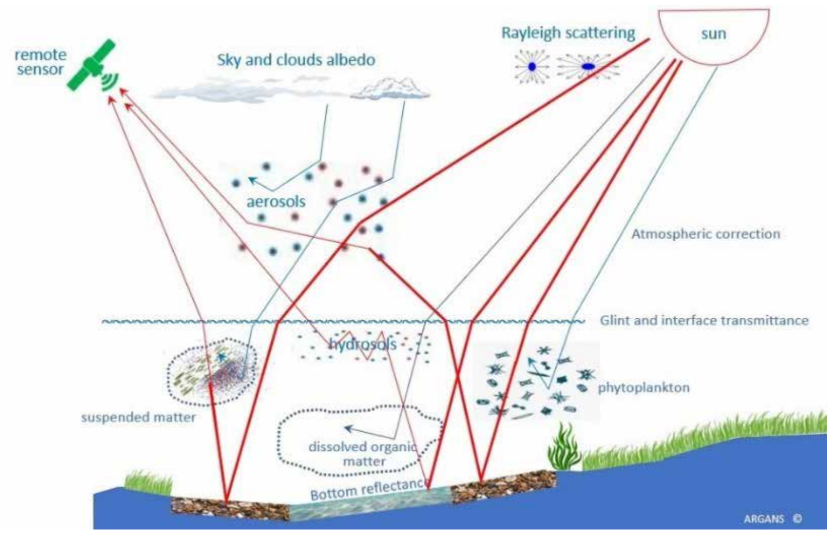

Fig. 2 SDB fundamentals: only red paths may contain attenuated depth information.

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 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;

[1] About the real cost of free satellite images, please refer to the footnote at the end of paragraph 4.

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- 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 (Fig. 2), categorises SDB as an applied science.

To solve the simple depth equality (Z is 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 Rrs observed by the satellite after travelling though the water column, across the surface, and through the atmosphere.

For the record, the remote sensing reflectance Rrs above the surface, which is provided by satellite missions' L2A products , is linked to the reflectance in the water by:

$$R_{rs}\left(0^{+}, \Theta_{obs}^{air}, \Theta_{sun}^{air}, \Phi\right) = \frac{t}{n^{2}} \frac{E_{0}(0^{-})}{E_{0}(0^{+})} r_{\infty}\left(0^{-}, \Theta_{obs}^{w}, \Theta_{sun}^{w}, \Phi\right)$$

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 $E_0(0^-)/E_0(0^+)$ 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 (Fig. 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 (Breiman, 2001), trained to generate optimal solutions amongst numerical models.

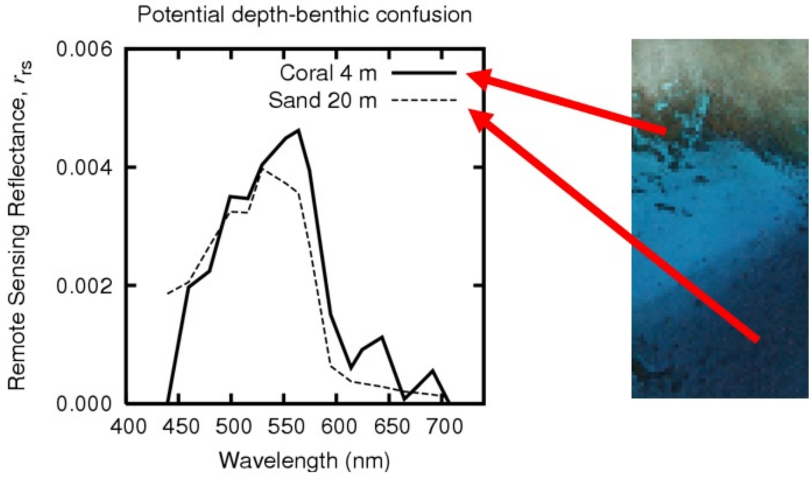

Fig. 3 SDB Fundamental Uncertainty: Only the analyst can decide whether the same dark pixel corresponds to a deep sandy bottom or a shallow dark bedrock. Source: Dr Hedley's IDA tutorial 2019.

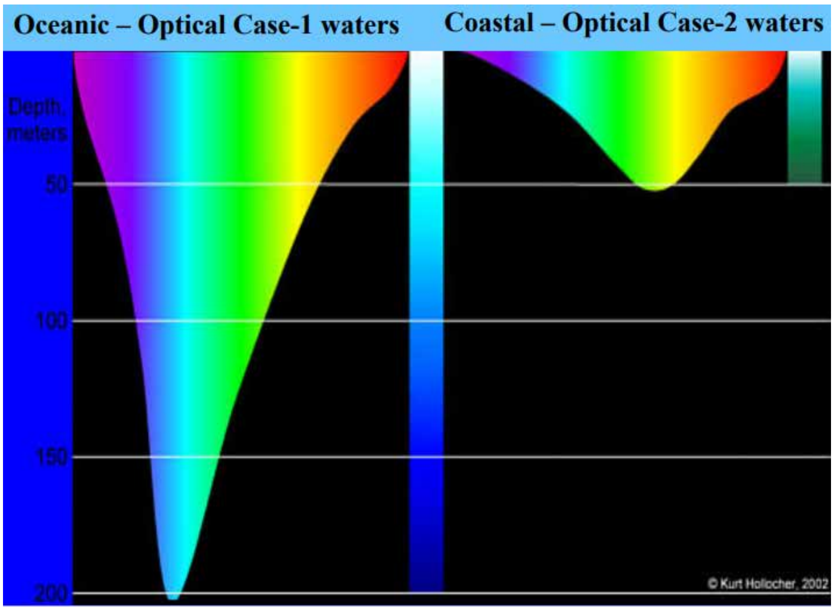

Fig. 4 SDB fundamentals: Light penetration in Cases 1 and 2 waters. Image courtesy of Kyle Carothers, NOAA-OE.

[2] The reflectance *R(z,λ)* of the surface of a material is the fraction of incident radiant flux reflected by that surface.

[3] Sentinel-2 L2A: Bottom-Of-Atmosphere (BOA) reflectances in cartographic geometry.

[4] 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.

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Table 1 A selection of common RTE symbols and abbreviations (Miller et al., 2005).

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
$E_d^{0+}(S_{ky}\Theta_S)$	Irradiance measured on the sea-surface, combining skylight (S_{ky}) and sunlight (Θ_S)
$E_d(z,\lambda)$	Downwelling irradiance
$K_d(z,\lambda)$	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
0^+	A position of observation just above the sea-surface
0^-	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

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 (Fig. 4).

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** (Mobley, 2001).

$$\cos\theta \frac{dL(z,\theta,\varphi,\lambda)}{dZ} = -c(z,\lambda)L(z,\theta,\varphi,\lambda) + \int_{4\pi} L(z,\theta',\varphi',\lambda') \times \beta(z,\theta',\varphi',\theta,\Phi,\lambda)d\Omega' + S(z,\theta,\varphi,\lambda)$$

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.

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 Fig. 2.

SDB's basic assumption is that all power fluxes, i.e. the various radiances and irradiances, decrease exponentially with depth in homogenous water, free of local boundaries effects. 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 $K_d(z,\lambda)$, 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.

Bottom 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 $L_b(\vec{x}_0)$ where $V(\vec{x}_0)$ is a vicinity of $\vec{x}_0$. Bottom detection occurs when $\text{mes}\{\delta L_b(\vec{x})\} \geq \Delta^{\text{trh}}_{\text{mes}(L)}$ where mes is a measure of the water leaving radiance L_w, and $\Delta^{\text{trh}}_{\text{mes}(L)}$ 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 and 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:

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

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 (Miller et al., 2005) as the signal to noise ratio would 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.

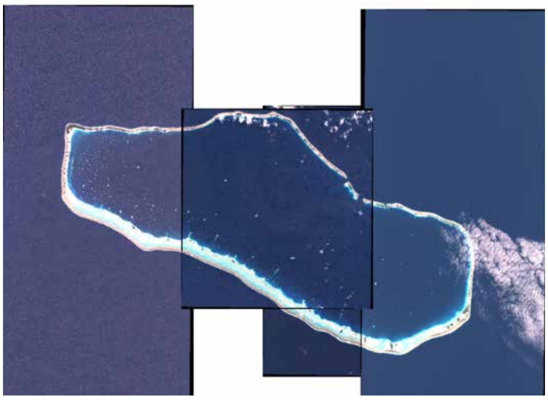

Fig. 5 A Pleiades 4-images mosaic: In spite of appearances, the two left scenes are worthless because of glint.

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 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:

$$R_{\mathrm{rs}}(\lambda) \approx B + A^{\exp(-k\cdot\mathrm{depth})}$$

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 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 (ARGANS internal R&D; Zoffoli et al., 2014).

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 (Fig. 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.

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, images 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 × 10 metre pixel receives more photons than a VHR 0.5 × 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

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Table 2 A selection of twenty SDB models.

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.
Conger et al.	Band combination	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 reflectance.
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[5]	Optimized matching	Hyperspectral	Bottom types, Z and OAC	Requires careful preparation of spectral library. Useful in low diversity areas.
SAMBUCA[6]	Algebraic	Hyperspectral	Bottom types, Z and OAC	Assumes that bottom is a linear combination of two substrates. Derived adaptation of Lee et al inversion scheme to optimise depth retrieval.
SWAM[7]	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.

[5] Bottom Reflectance Un-mixing Computation of the Environment model, an inversion method derived from the algorithm (Klonowski et al., 2007).

[6] Semi-Analytical Model for Bathymetry, Un-mixing and Concentration Assessment, an inversion method derived from the algorithm by Brando et al. (2009).

[7] Software User Manual (SUM) of the SEOM S2-4Sci Land and Water: Coral Reefs (Sen2Coral) project funded by the European Space Agency (ESA).

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 hyperspectral	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 hyper-spectral	Maps of bottom types	Suitable to reefs of consistent bottoms and environment.

Table 3 Comparison of HR and VHR assets.

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	Computing time 30 times faster
SDB Value-for-money	✓		VHR minimum charge ≈ € 20/km2

0.5 × 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

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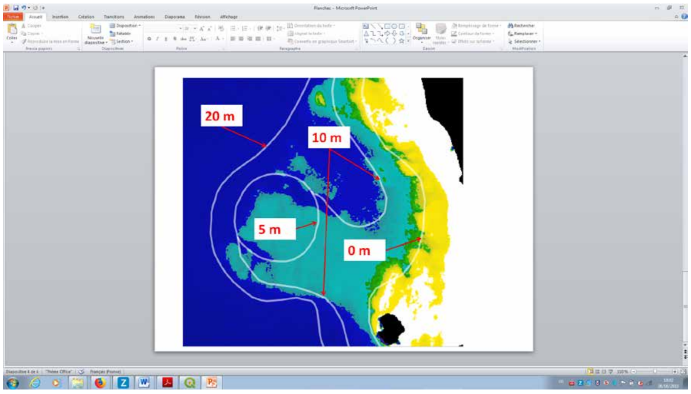

Fig. 6 Rehabilitation of a vintage chart: The "Perfect Image" on the left confirms and completes the ancient chart on the right with an almost 100 % guarantee of shoal detection and surface coverage.

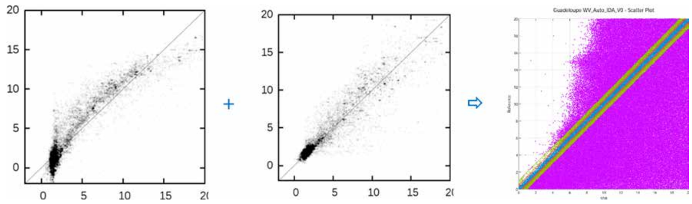

Fig. 7 SDB depths TVU Scatter plot: Merging too many S-44 compliant areas usually ends-up with a larger non-compliant zone.

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.

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 human-made structures. (Fig. 6).

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 (Sagawa et al., 2019) 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 (Fig. 7) consisting of merging areas characterised by different environments.

…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 re-

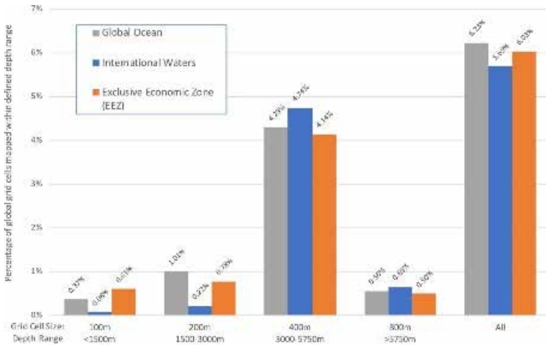

Fig. 8 GEBCO Histogram of the World ocean percentage covered.

flectance. 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 (Fig. 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.

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 (Hamylton et al., 2015) to the exploration of future Marine Highways in uncharted waters[8] and determination of precise UNCLOS baselines[9].

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 leadline 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 in-

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

[9] 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.

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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

famous 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

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.

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 (Fig. 9) selected with care.

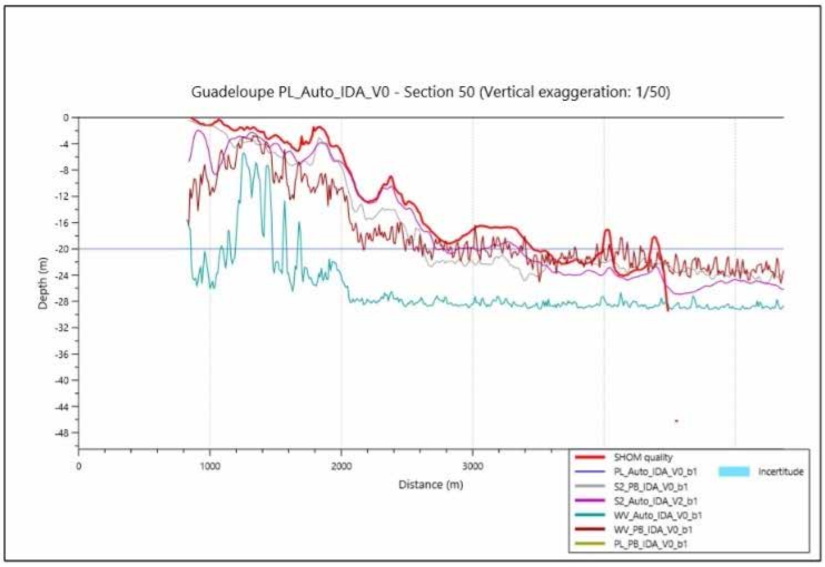

Fig. 9 Comparison of a Sentinel-2 "Perfect Image", with Ground Truth, Pleiades, and World View cross sections: The purple trace (S2_Auto_IDA_V2_b1) follows better the red sonar profile than single VHR images WW_Auto and PL_PB.

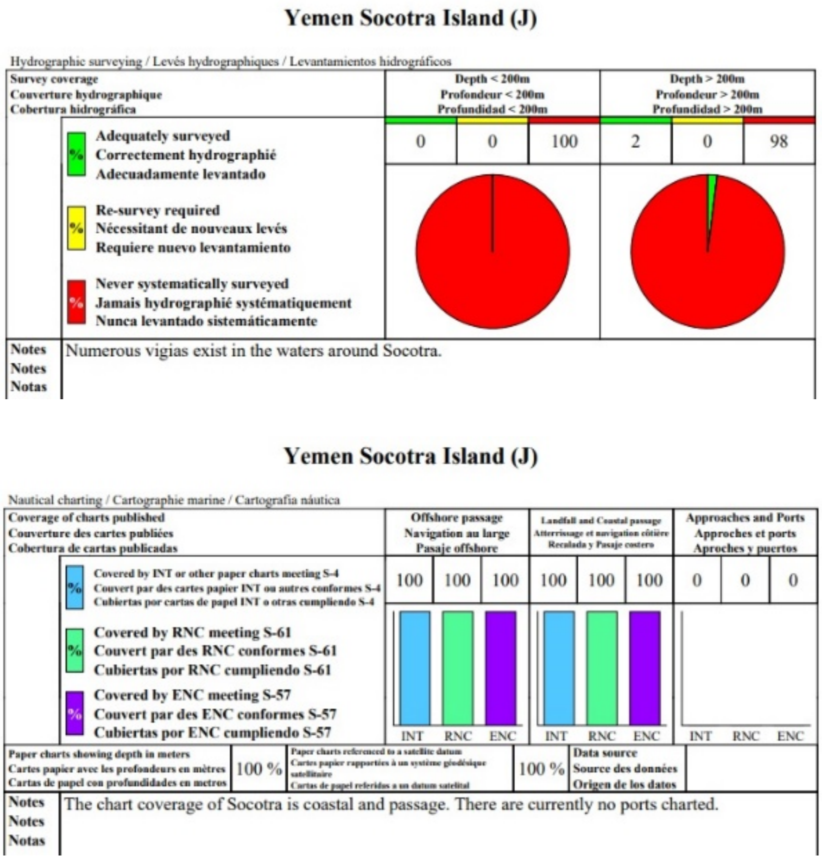

Fig. 10 One of the two hundred and sixty-three C-55 world areas displaying the state of surveys (top) and charting (bottom).

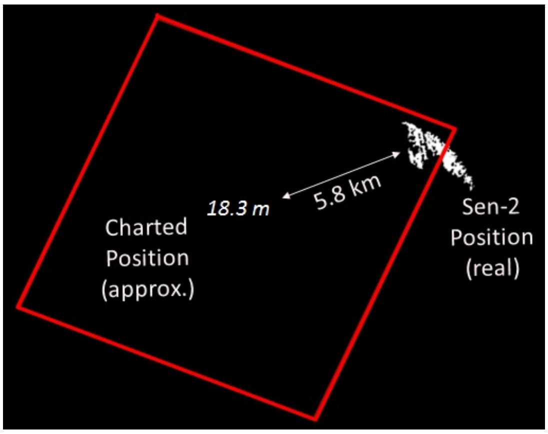

Fig. 11 Sentinel-2 conformation of a misplaced shoal: By peering at blue spectral bands, this shoal was found on three out of five Sentinel-2 images carefully selected from a large time series of over 50 scenes spread over several months.

3.3 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[10] 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 (Fig. 10).

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 (Fig. 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.

3.5 SDB costs considerations

Be they powerful oil and 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"

[10] 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)".

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Table 5 Sentinel-2 Pros & Cons.

Pros	Cons	Comments
Value-for money[11]		Sentinel-2 offers an open and free access to its imagery compared to an average 20€/km^2 for VHR commercial images.
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.

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.

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 (Hedley et al., 2018).

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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[11] 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."*

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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

A FIG/IHO/Cat A Hydrographer, Henri Dolou 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.

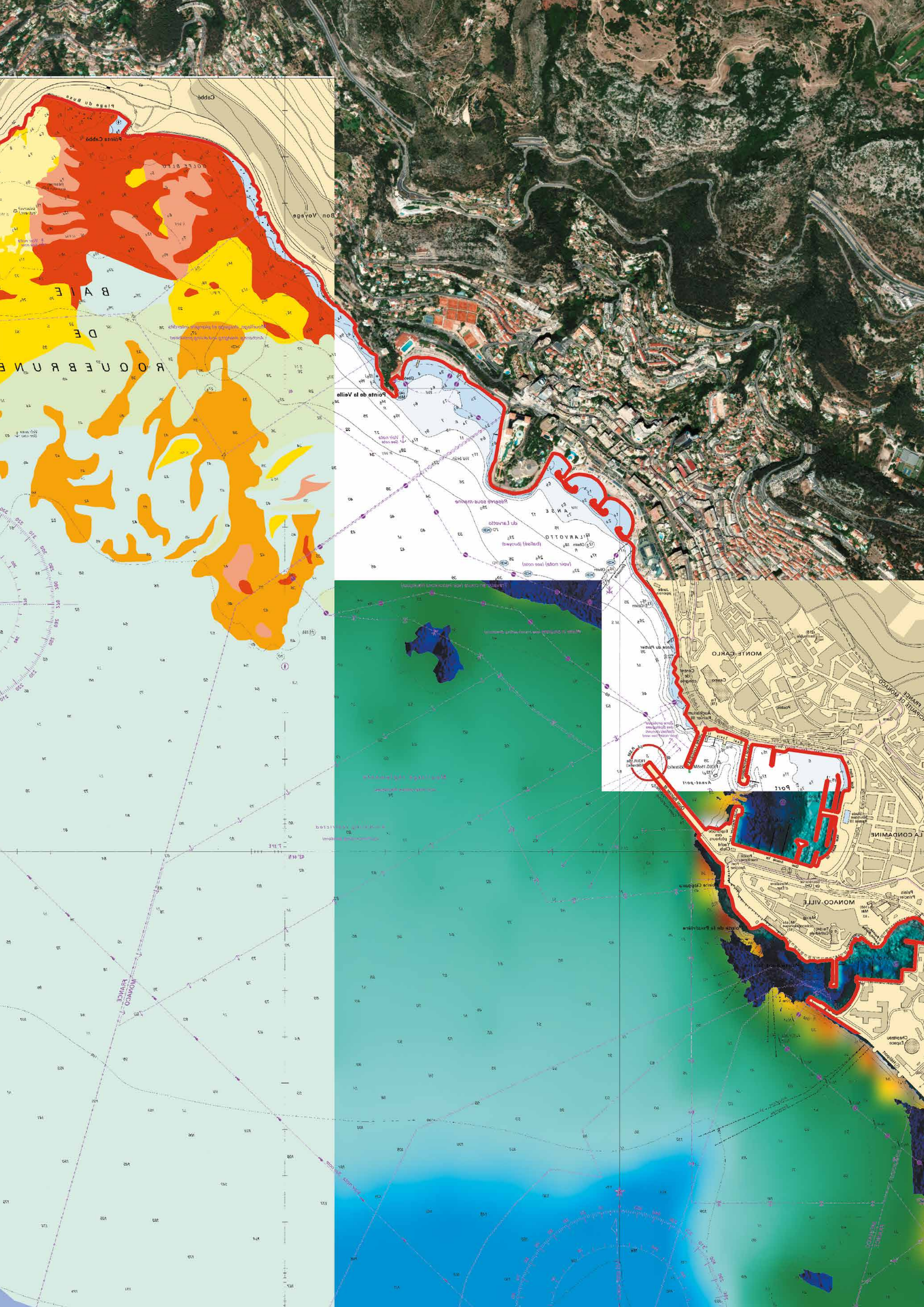
Joseph Avis

Joseph Avis 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. In 2018 Joseph joined ARGANS as an Earth Observation Scientist where he applied his expertise in hydrological and geomorphology applications on a range of Earth Observation projects. Joseph has since taken on the role as Technical Lead of ARGANS Satellite Derived Bathymetry projects working with ESA and a national hydrographic agency where he manages a team split between UK and France.

Olivier Arino

Dr Olivier Arino 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.

https://doi.org/10.58440/ihr-29-a20



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