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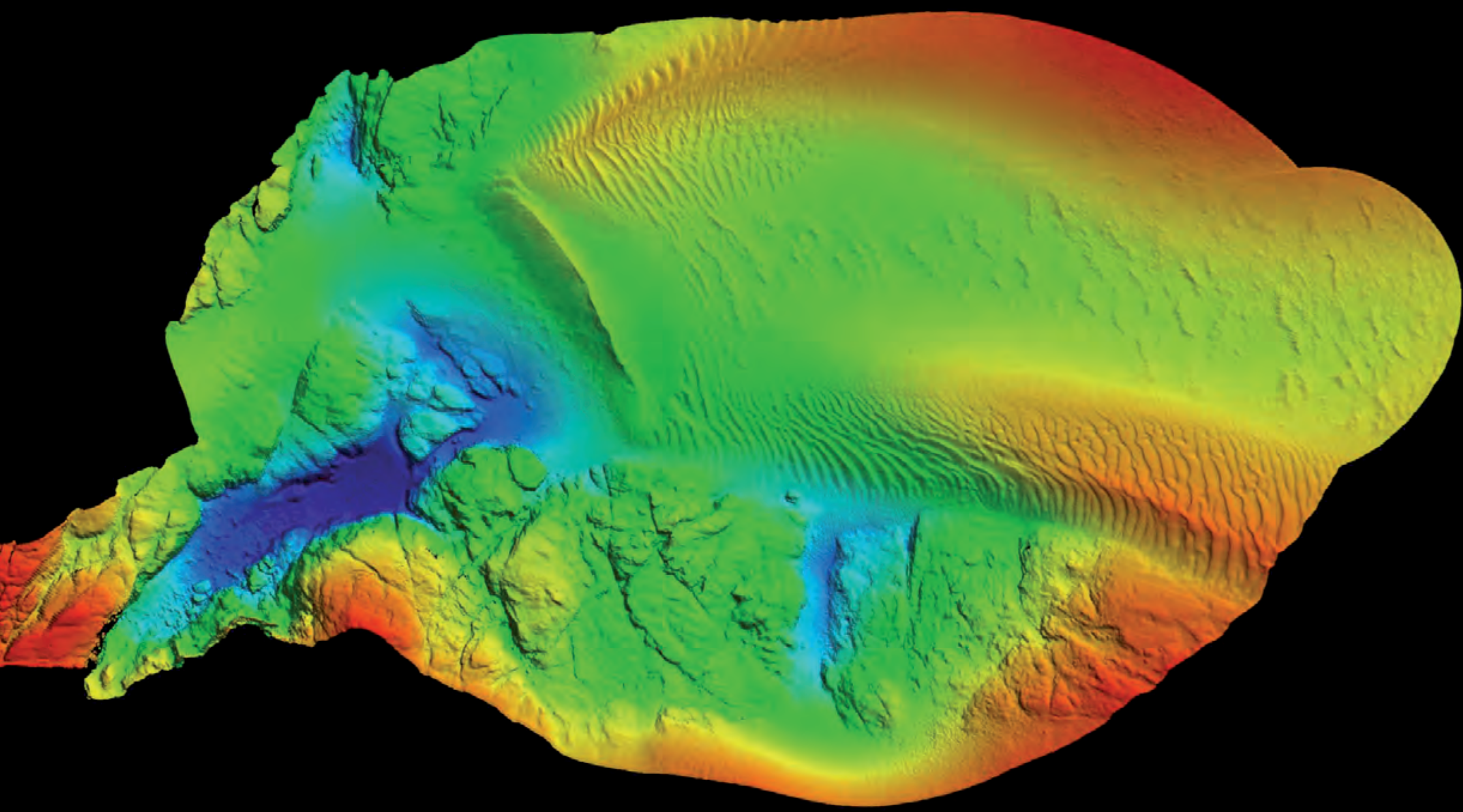

State of the Art in Multibeam Echosounders

Bathymetry from UAV Imagery and Machine Learning

Measuring and 3D Mapping of Sea Ice in the Arctic

Hydro INTERNATIONAL

Hydro International is an independent international magazine published six times a year by Geomares. The magazine and related e-newsletter inform worldwide professional, industrial and governmental readers of the latest news and developments in the hydrographic, surveying, marine cartographic and geomatics world. Hydro International encompasses all aspects, activities and equipment related to the acquisition, processing, presentation, control and management of hydrographic and surveying-related activities.

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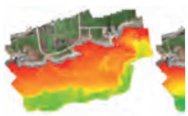
P. 08 **Unlocking the Potential of Marine Geospatial Data**
The Canadian Hydrographic Service, Teledyne CARIS and ECC/PRIMAR are partnering on a pilot project to implement an innovative data service to deliver S-100 products.

P. 12 **State of the Art in Multibeam Echosounders**
Multibeam echosounder technology has gone through an evolution rather than a revolution in recent years. In this article, we focus on the current state of the art for this bathymetric workhorse.

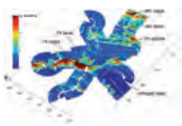
Sponsored article by Hypack

P. 16 **The HYPACK LiDAR Payload**

P. 21 **Bathymetry from UAV Imagery and Machine Learning**
This article presents a new framework for mapping the seabed in clear and calm shallow waters for small- and large-scale surveys using aerial imagery and machine learning to correct the geometric effects of refraction on the 3D point clouds and the imagery.



P. 27 **Measuring and 3D Mapping of Sea Ice in the Arctic**
Sea ice is one of the most important parameters when it comes to ice-albedo feedback; in other words, the fraction of incoming solar radiation that is reflected directly back into space. Because of the grave importance of the decrease in the amount of sea ice due to the climate crisis, gaining a full understanding of its complex structure is more important than ever.



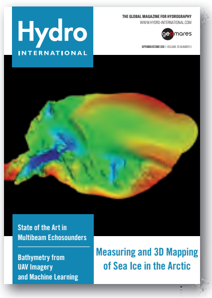
Sponsored article by Seafloor Systems

P. 30 **Unmanned Vessels to Assist in Saltwater Intrusion Research**

P. 04 Editorial
P. 07 Column IHO
P. 18 Surveying by Sailboat
P. 24 Headlines
P. 32 What is 'Hydrospatial'?
P. 34 Unmanned Subsea Asset Inspection
P. 37 Introducing MARIN's mAUV
P. 40 Automatic Calibration for MBES Offsets

Front Cover

The cover of this edition of *Hydro International* shows imagery acquired with the Kongsberg EM 2040P MKII, an advanced shallow water multibeam echosounder. In this issue, you will find an overview article that provides you with a major update on the current state of the art of the bathymetric workhorse known as the multibeam echosounder. Read more on page 12.



PRODUCTS FOR POSSIBILITIES

S-100 in CARIS HPD

The new S-100 Universal Hydrographic Data Model opens up a world of possibilities for data and services that can improve safety of navigation, open the door to economic opportunities and help conserve our marine environment.

CARIS HPD offers concurrent S-57 and S-101 ENC production from a single source database backed by fully customizable mappings. Stepping into the world of S-100 doesn't mean starting over.

Get ready to explore the possibilities with the partner you trust. Start the process today.

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Hydrospatial

▲ *Durk Haarsma.*

For the first time in months, I am sitting at my desk to put words to paper for this magazine. Due to the COVID-19 crisis, we were forced to cancel two planned issues of *Hydro International* – something that we never imagined would happen. However, with so many flights grounded and air cargo capacity severely reduced, it suddenly became extremely difficult to get a printed version of *Hydro International* to all of our readers. This crisis reminds us just how much we have taken smooth-running global logistics – among many other things – for granted in recent decades. It turns out that shipping a magazine all over the globe is not so easy after all. Needless to say, I am very happy that, in many parts of the world, things are gradually returning to normal (although, even as I write, I realize that the situation could take a turn for the worse in a matter of weeks or even days… let's hope not!).

The rapid standstill in global logistics due to the pandemic also had a few positive side-effects. The emission of greenhouse gases decreased dramatically almost overnight, and the slowdown in maritime traffic, fisheries, and so on had a positive effect on the health of the ocean. If anything else, it shows again that humankind needs to stop exploiting the globe immediately – oceans and landmasses alike – and reconcile all economic activities with preservation.

This edition of *Hydro International* sees the introduction of a new term: 'hydrospatial'. The term was coined at this year's Canadian Hydrographic Conference to express the three-dimensional interdisciplinary nature of new ocean-related datasets. Denis Hains, former Hydrographer General of Canada and Director General of the CHS, led the discussion on 'hydrospatial' at the Canadian Hydrographic Conference and sheds his light on the origin and meaning of the new term in an editorial piece in the Perspective section on page 32. Mathias Jonas, Secretary General of the International Hydrographic Organization, supports the introduction of hydrospatial in his IHO Column on page 7 and states that these ocean-related datasets are serving expanding groups of stakeholders and indeed could help to reconcile maritime use with maritime preservation.

If anything, let this global crisis teach us to do what is good for our oceans now, instead of going back to old habits of exploiting our resources for short-term economic growth. Hydrography, or should I say hydrospatial, has a natural role to play in the transition to the more sustainable use of the ocean. We need all the information that we can find about the deep and shallow areas of the ocean: this knowledge is crucial to know how to use the ocean in a responsible way, while taking care for it at the same time. It will bring prosperity and green growth to our business. So, let's accept the challenge now!

Durk Haarsma,
director strategy & business development
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Extraterrestrial Hydrography

▲ *Wim van Wegen.*

The oceans on our planet remain largely an unexplored world, far from divulging many of their secrets. Seabed 2030, which is a joint project between the Nippon Foundation of Japan and the General Bathymetric Chart of the Oceans (GEBCO), aims to collect all available bathymetric data in order to produce the definitive map of the world's ocean floor by 2030. As of today (and despite many years of effort), less than 20% of the seafloor of our planet has been mapped.

However, there are more oceans to be mapped; oceans that perhaps turn out to be even more mysterious than the oceans chartered by the Seabed 2030 mission, and oceans situated elsewhere in our solar system. Although we still have an awful lot of survey work to do on our own planet, there is no harm in taking a field trip across the moons of Jupiter and Saturn and even further – to Pluto!

Our solar system – as far as we know – comprises at least eight planets and an unknown number of dwarf planets, with Pluto as the most famous (although I am in favour of rehabilitating Pluto to its status of planet). Pluto is an extraordinary place with – we now know thanks to the exciting New Horizons mission that captured images of the dwarf planet in 2015 – the most remote ocean in our solar system, as most planetary scientists agree that Pluto has a global liquid ocean under its surface. These insights are based on recent analyses of images from NASA's New Horizons spacecraft. Perhaps I am letting my imagination run wild, but who says this ocean can't be habitable?

Anyway, to return to our industry: hydrography. Hydrography certainly is a profession that comes into play when mapping liquid environments other than those on our own planet. At NASA, there is a working group known as the Outer Planets Assessment Group (OPAG) Roadmaps to Ocean Worlds (ROW). The overarching goal of this group is to "identify ocean worlds, characterize their oceans, evaluate their habitability, search for life, and ultimately understand any life we find." Highly fascinating and sparking the imagination all that much more.

My thoughts wander off to faraway ocean worlds, such as the ice-encrusted moons Ganymede (a satellite of Jupiter) and Enceladus (Saturn). Geospatial and hydrographic technology will be useful tools to map the bathymetry of these remote oceans, and Lidar technology has the capability to help explore the secrets of these extraterrestrial marine environments. I can imagine spacecrafts carrying a vessel aboard equipped with a multibeam echosounder, and USVs capable of diving thousands of metres below the surface and conducting extraterrestrial ocean-mapping missions. There are two challenges: such oceans will generally be covered with a thick layer of ice, which might be a minor obstacle before the hydrographic instruments can do their job, and it should be noted that some of these oceans consist of other liquids than water…

Wim van Wegen, content manager
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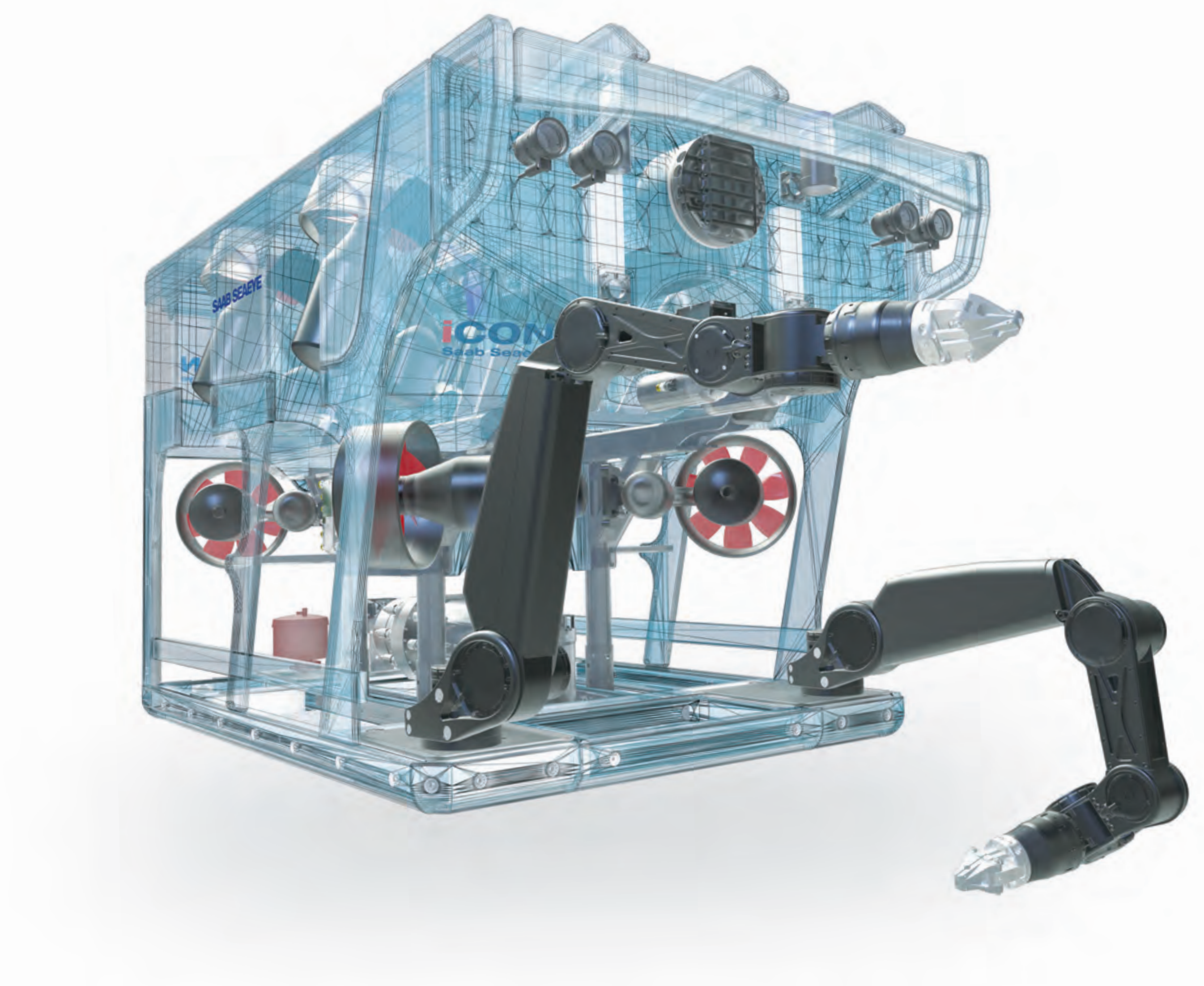
EMPOWERING

our new generation of electric work robots



more **powerful** more **intelligent** more **future-flexible**

world leader in electric underwater robotics

SAAB

SAAB SEAEYE

Ambitions

"In all beginnings dwells a magic force …". Hermann Hesse's famous verse seems to be particularly relevant to the coming decade when it comes to marine activities. Three ambitious global projects relating to the maritime domain will span the forthcoming 2020s. The broadest is without a doubt the Decade of Ocean Science for Sustainable Development (2021-2030), spearheaded by the United Nations "to support efforts to reverse the cycle of decline in ocean health". The second half of the proclamation "for Sustainable Development" seems to indicate two intentions: first, to link to the United Nations Sustainable Development Goals (2030), and second, to use ocean science to facilitate concrete measures for improvement.

Ocean science has various facets – many of which require baseline information about the ocean's seabed topography. Hydrographers know that, on a global scale, this data is fragmented and sparse. The global ocean map still presents many plain and empty blue fields. The joint Nippon Foundation – GEBCO Seabed 2030 project, with its ambition to fill the gaps within this decade, is therefore welcomed by the ocean science community. But where is the missing data to come from? Seabed 2030 is striving to be a 'concentrator' for all data that has been collected but not yet exploited. It also aims to induce effective new measurement technology. To begin with, there remains a lot of work to gather data from a variety of sources. There are technical questions to resolve as to how these datasets can be identified and brought together. However, a mental shift is also required. Many coastal states are still sceptical about supporting citizen science such as crowd-sourced bathymetry in their national waters. Commercial companies are not inclined to be 'digital philanthropists' and donate data which they had to pay for to obtain. And, with regards to scientists, perhaps the competitiveness of the field does not encourage data sharing.

To overcome these challenges, all that can be done is to repeat positive arguments and to be ambitious by trying to generate new data in poorly surveyed areas. Currently routine surveys are mostly concentrated along the coastal shelf and are dominated by expensive hydroacoustic methods. However, emerging technology may change this. Satellite-derived bathymetry is definitely on the rise and swarms of unmanned survey launches may soon follow to increase the daily survey area coverage. New calculations recently presented at the Atlantic Seabed Mapping International Working Group Meeting indicate that a full survey of the Northern Atlantic with decent resolution would cost approximately US$90 million. While this is high, perhaps we should compare it to other endeavours. Would we have accepted leaving huge areas of the continents unsurveyed because of the cost? Certainly not. And how much did it cost to make images of the dark side of the moon?

The third project of note for the upcoming decade concerns the digital data framework. The IHO Council, at its recent session in autumn 2019, agreed that the next ten years would be the S-100 implementation decade. Some seem to believe that data engineering helps but does not constitute a relevant contribution to ocean science in itself. I regard this as a misconception. Progression in geomatics is driven nowadays by the merger of previously isolated information. New methods such as artificial intelligence and deep learning depend on it. A new phrase, 'hydrospatial' was recently coined at the Canadian Hydrographic, Conference to express the three-dimensional interdisciplinary nature of new ocean-related datasets. These serve expanding groups of stakeholders and help reconcile maritime use and maritime preservation. The generic model of S-100 serves this holistic approach. If we want to be successful in our ambitions to save the oceans, all three of these campaigns are compelled to interact.

Dr Mathias Jonas, secretary general of the IHO.

sponsored article

How the S-100 Service Enables Safe and Optimized e-Navigation

Unlocking the Potential of Marine Geospatial Data

The Canadian Hydrographic Service (CHS), Teledyne CARIS (CARIS) and ECC/PRIMAR (PRIMAR) are partnering on a pilot project to implement an innovative data service to deliver S-100 products. The service will initially focus on S-102 bathymetric surface and S-111 surface current products and will grow to support additional S-100 products as the system enters operational service.

The S-100 service is subscription-based, taking a modern, web-services approach to product delivery. This service-oriented approach aligns with IMO's Maritime Service Portfolio (MSP) and e-navigation principles, while leveraging the existing IHO Regional ENC Coordinating Centre (RENC) distribution network. We spoke to Louis Maltais, director of Navigation Geospatial Services and Support; Karen Cove, senior product manager at Teledyne CARIS; and Hans Christoffer Lauritzen, director of PRIMAR, for their insights on exactly what value this project will offer the field.

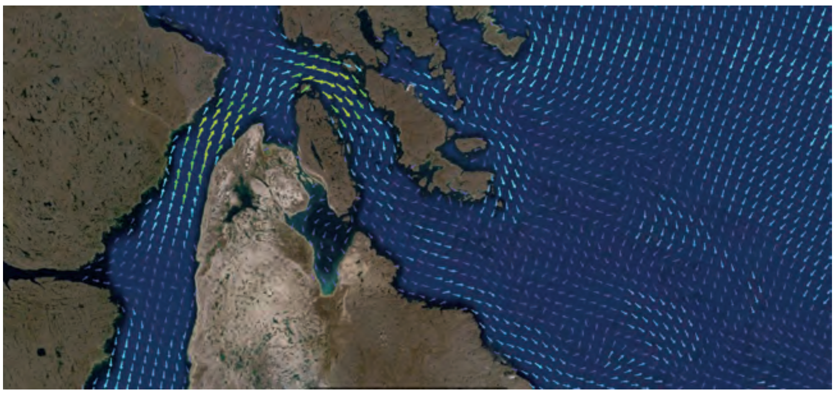
ROBUST PARTNERSHIP

This team has taken on an ambitious challenge, carving a path through the unknown and achieving a solution to bring to market, with CHS, CARIS and PRIMAR each contributing expertise. Maltais explains that the CHS represents Canada's hydrographic interests on the bodies that develop and oversee hydrographic and chart information standards and is a world leader in hydrography. For this project, CHS is the S-100 producer, and therefore in charge of several layers. For example, CHS publishes paper current atlases and has a mandate to lead and develop these layers within the digital context, as well as to receive and maintain data.

PRIMAR is a non-profit, international collaboration dedicated to providing a consistent and reliable electronic navigational chart (ENC) service, and playing a leading role in providing the best navigational solutions for the world's merchant fleet, navies, marine pilots and government agencies. On this project, PRIMAR collects S-100 data from several hydrographic offices, validates the data and makes the data available for distribution, functioning as a one-stop shop for S-100 data. It manages the business part and revenue stream on behalf of the hydrographic offices.

CARIS is the trusted technology provider for chart production and other hydrographic workflows, products and services at most hydrographic offices around the world. This put CARIS in a unique position as these hydrographic offices and the hydro community at large pivots to this new era of products and services underpinned by the S-100 standards framework, meeting the need to be prepared for e-navigation and autonomous shipping. Here, CARIS has

▲ *Potential use of innovative S-111 Portrayal for blue economy services, S-111 source data provided by NOAA.*



▲ *S-111 International Hydrographic Organization portrayal.*

taken the opportunity to leverage its research and development efforts to build cutting-edge cloud architecture that can support the marine community in this important transition. The S-100 CARIS Cloud provides the back-end infrastructure to move data from the CHS production environment into the distribution network. CARIS has purpose-built a technology stack to take advantage of cloud infrastructure in terms of scalability, security and access to provide optimal solutions for hydrospatial workflows and data distribution. Key to this are cloud services to facilitate access to software, the efficient management of data holdings within the service, providing cloud-native processing capability, and a robust security model.

SERVICE-ORIENTED APPROACH

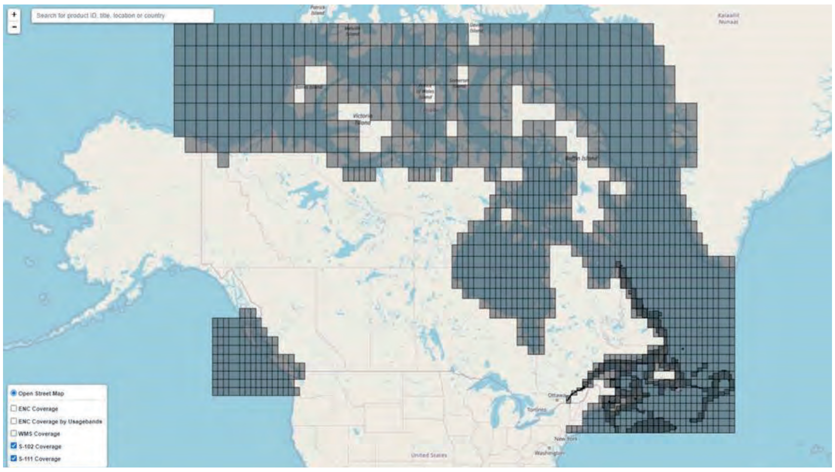
The service approach has been well established for many years concerning the distribution of ENCs, so it made sense to take a service-oriented approach using subscription-based pricing models when establishing the S-100 service. This services approach allows for data to move through the value chain to the consumer efficiently and with full assurance of data integrity and security. OGC Web Services offer the benefit of minimal data duplication and a streamlined workflow that facilitates the quick turnaround of data from survey-to-bridge, allowing for fully standardized access to data as required by the users of the S-100 service. Using a real-time service approach means that data is always up to date, and that users are able to access data much more rapidly.

The quality of the S-100 outcome is the result of strong communication, agile problem solving and a spirit of innovation, which all three experts agree has been a positive experience. CHS, CARIS and PRIMAR have worked constructively together throughout, contributing their strengths and valuing each other's competences and perspectives. As Lauritzen observes, this has led to optimization of the S-100 service.

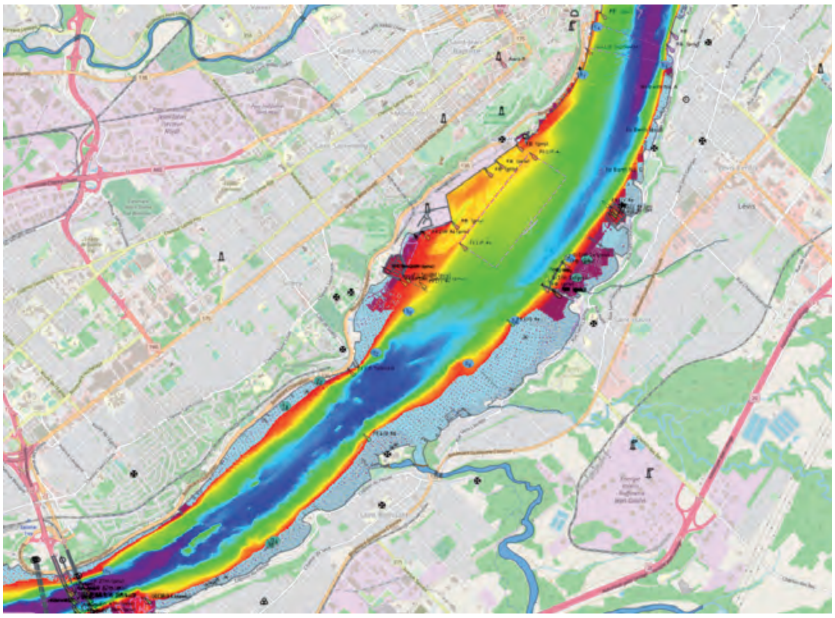
HYDROGRAPHIC OFFICES

S-100 opens up myriad opportunities for both the marine transportation industry and for hydrographic offices. Cove explains that the S-100 service revolutionizes the possibilities for data products and value-added services to be made available for navigation, making strides in terms of sensor-to-bridge turnaround time. The latest and best data, in some cases potentially near real time, will be collected on a continuous basis, and can then be pushed out to pilots and other end-users via a subscribed service. Both Lauritzen and Maltais note the improved safety of navigation and optimization without increasing risk. For example, the more exact calculation of under keel clearance and more economical navigation will be possible, since exact depth, current and tidal information gives the opportunity to optimize cargo load and enhance the timing of port entrance. With this quality of data, ships can leverage surface currents in the right direction or adjust their route, optimizing transit and reducing the carbon footprint.

For hydrographic offices, S-100 will function as an enabler to respond to that interest with relevant products and services that are based on an interoperable standards framework, allowing data to be used by many people in many ways. Lauritzen notes the potential opportunities to produce official datasets that have high value for end-users, leading to new possibilities for increased revenue. S-100 will indeed allow hydrographic offices to be agile and responsive to stakeholders as their needs evolve, and new kinds of stakeholders beyond the realm of navigation become more aware of



▲ *Current coverage of Canadian S-102 and S-111 in the PRIMAR Chart Catalogue.*



▲ *Picture from the PRIMAR web viewer showing Canadian S-102 data in combination with ENCs.*

hydrographic and marine data of all sorts, says Cove. Maltais adds that the S-100 framework could enable databases to be disseminated in a seamless way. This can provide a picture of what the end state could look like regarding metadata and data organization, assisting those operating within a national setting to determine what data items they may need to feed over the next few years, helping to identify and fine-tune key items for inclusion in their database design.

S-100 PRODUCT DEVELOPMENT

Feedback from end-users is absolutely a critical factor in the development of S-100 products and the success of the S-100 service, states Cove. The entire pipeline must be in place and working for the end-user to reap the benefits, plus the voice of the end-user needs to filter right up the value chain. She explains that the user trials organized by the CHS are an important check that what is being developed is effective and brings value to the intended end-user. The CHS is interested in obtaining early user feedback so that it, as technology partner, can move forward the development of tools informed by the end-users. In this case, CHS recognized that they needed to build interest and capacity along the entire chain. What we have found in this project is real engagement with pilots who see the benefits of having these products and services available to enhance how they do their jobs. Maltais adds that S-102 has improved their knowledge of their environment – an exciting development in terms of unlocking the potential and delivering it to clients. This has created a real feedback loop driving back through the chain to the hydrographic office, and even beyond into the IHO working groups, where the S-100 framework and product specifications are developed.

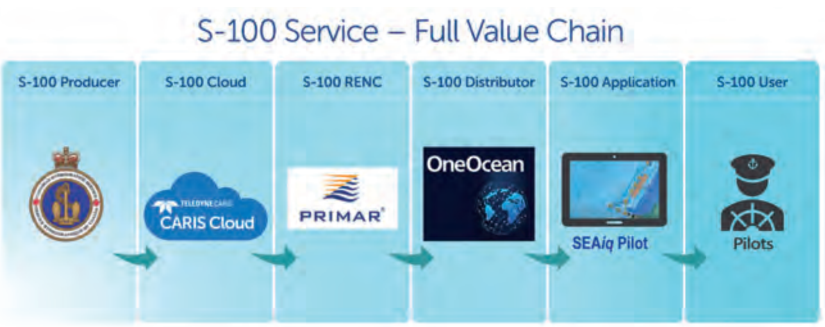
NEW ERA IN DIGITAL DATA

The impact on traditional static products and how they are produced is likely to be that they gradually diminish. The value that digital, data-centric software products offer to the field, in relation to automated compilation and validation, is continuing to transform the systems and workflows of the hydrographic office. Cove is excited to see how the world of navigation and marine GIS more broadly will continue to transform over the coming years. She thinks it is an opportunity to be at the bleeding edge, observing how emerging data products defined under the S-100 standards framework will be used in practice. In turn, we will be able to see what those end-users will then demand of hydrographic offices, other data providers and solution vendors in terms of even more new products and services.

Cove agrees that this is an exciting time for the hydrographic community, with new influences, new interest from the wider public, new technology available, and a new mindset about what it means to be a hydrographic data provider. She goes on to explain that the value of bathymetry and hydrographic data more generally is being recognized, demonstrated in part by the investment in Canada's Oceans Protection Plan, through the GEBCO Seabed 2030 initiative to map the world's seafloor and through the UN's designation of the next decade being focused on the oceans.

Lauritzen considers this project a perfect fit in the future digital ecosystem, since it allows for a more precise digital model of the real world.

All those with a stake in marine navigation should be watching this project, since the S-100 service has the potential to increase both the safety and efficiency of navigation, and in particular hydrographic offices should be engaging since they are responsible for producing the S-100 data, thinks Lauritzen. Cove adds that a sizeable segment of the ocean sector will be able to benefit from having high-quality, high-resolution and timely marine data readily available to use in a wide variety of applications. She believes the coming years will be driven by innovation all the way through the maritime value chain, from data collector to data provider through to end-user. The S-100 framework and the S-100 service are indeed well positioned to support and contribute to this dynamic future. ◂



▲ *Diagram outlining the S-100 value chain.*

Connect with our Experts

Hans Christoffer Lauritzen

Hans Christoffer Lauritzen graduated from the Royal Norwegian Naval Academy in 1990. He served on board various Norwegian submarines, including as CO of Kobben and Ula class submarines. He left the Navy in 2006 to start work in a shipowners company. After completing a Master's degree from the Norwegian Business School, he joined the Norwegian Hydrographic Service as director of PRIMAR in 2012.

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Karen Cove

Karen Cove is senior product manager at Teledyne CARIS. Since receiving her MSc Eng in Geodesy and Geomatics (UNB), Karen has enjoyed a career in marine geospatial. Before joining CARIS, Karen worked with Fisheries and Oceans Canada and has a keen interest in mapping to support the safe and sustainable use of the ocean and coastal environments.

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Louis Maltais

Louis Maltais is director of Navigation Geospatial Services at Canadian Hydrographic Service. He was highly involved in drafting S-102, S-111 and S-104 IHO product specifications and now leads the delivery of S-100 Hydrographic Dynamic Services contributing to e-navigation in Canada. Louis is the chair of Canada's S-100 interdepartmental committee.

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The Evolution of a Bathymetric Workhorse

State of the Art in Multibeam Echosounders

Although the single beam echosounder is still in use, it has over the last 25 years gradually been replaced with new and less expensive multibeam echosounder (MBES) systems. And, although some side-scan sonar (SSS) systems also offer bathymetry, the MBES is the go-to system when it comes to bathymetry today. MBES technology has gone through an evolution rather than a revolution in recent years. In this article, we focus on the current state of the art for this bathymetric workhorse.

THE MULTIBEAM ECHOSOUNDER

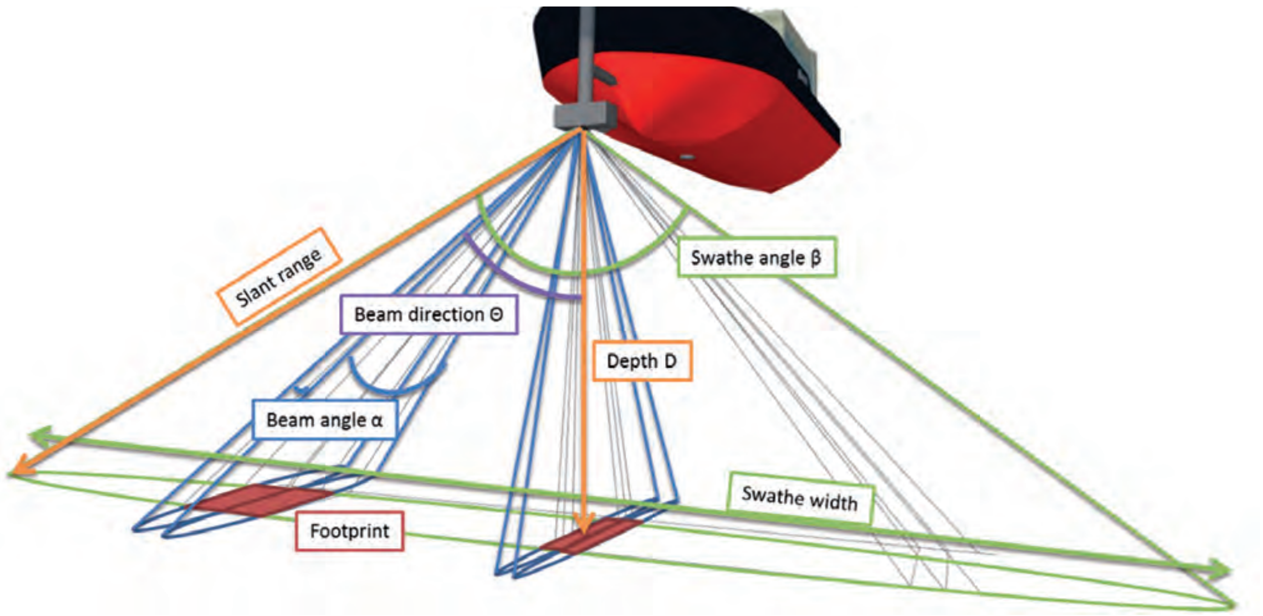
The main function of an MBES is to detect a number of depths along a swath of bottom. To obtain these depths, the transducer sends out a pulse of sound that is reflected off the bottom and received by an array of transducers in a certain angular sector or swathe. The system has a single transmit beam and a number (often 256) of receive beams. The receive beams are formed on reception (and not, as some think, on transmission). The swathe angle varies per system but is generally somewhere between 120° and 170°, giving swathe widths on the bottom in the order of 3.5 to 25 times the water depth.

Most MBESs are 'shallow-water' MBESs, with ranges between a few tens of metres and a few hundreds of metres. A modern shallow-water MBES has a weight of a few kilograms up to tens of kilograms and can be installed on a surface vessel, ASV, AUV or ROV. Although large and heavy special deepwater versions with ranges up to full ocean depth are also available, the 'basic' MBES is described below.

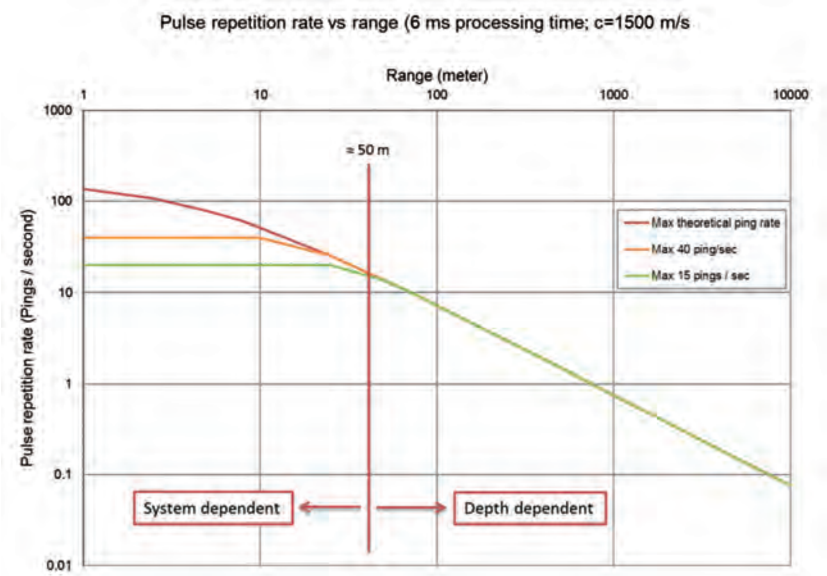
DATA DENSITY

An MBES is not only about measuring depth; it is about measuring as many depths as possible with a high accuracy and resolution. The resolution is defined by the across- and along-track beam angles. That beam angle in turn defines the 'footprint' from which the depth for that beam is returned. Modern MBESs have beam angles between 0.3° and 4°.

The beam angle (and swathe sector) define the basic number of depths that can be measured. Depending on the set-up, these depths are



▲ *Parameters of a Multibeam Echosounder.*



▲ *Depth-dependent update rate.*

measured in 'equi-angular' or 'equi-distant' mode. Equi-angular means that all the beams have the same angle and that the footprint varies. In equi-distant mode, the footprint is kept constant but the beam angle is reduced.

Most modern MBES systems offer more than the 'base' number of points per swathe. Often, this is done by creating overlapping beams (of the base beam angle) and measuring depths for the intermediate beams. The number of depths is thus increased; depending on the bottom and implementation in the MBES, more detail can be shown with up to 1,024 depths per swathe.

The final data density is defined by the number of beams (depths) and the ping rate, or the number of swathes that the MBES can measure per second. The ping rate depends on the water depth, but can be as high as 60 pings per second in shallow water.

ACCURACY

For nautical charting, the Special Publication 44 of the IHO sets the standard for sounding accuracy to which an MBES should adhere (together with the other sensors). Some countries, and especially the offshore and dredging industry, do not find the S44 standards strict enough and impose their own accuracy standards on the work to be performed.

For the MBES to meet these standards, it not only needs to give full bottom coverage (sounding density) but also to measure each depth point with a minimum accuracy. That accuracy depends both on the local situation and, more specifically, the sound velocity and the pulse length of the system.

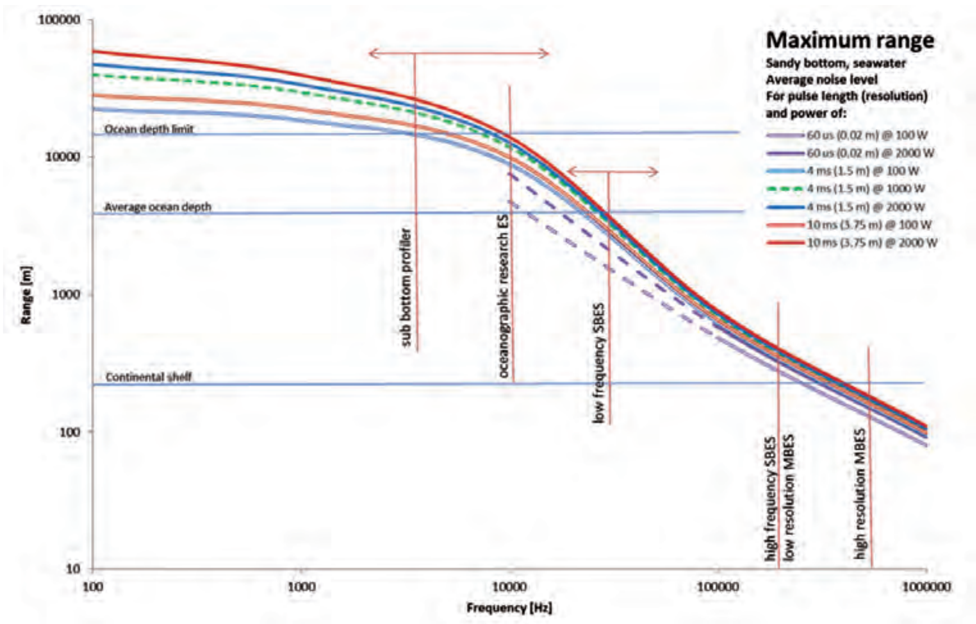
Where in the past the transmitted signal was a 'continuous wave' (CW), a modern MBES can often also transmit what is called an FM or CHIRP (Compressed High Intensity Radar Pulse) signal. The main advantage of the CHIRP is a longer range with better range resolution.

For a CW type MBES, the range resolution is defined by the pulse length of the signal, whereas for a CHIRP type MBES the range resolution is defined by the bandwidth of the signal, allowing longer pulses and therefore more power to be transmitted. For a high frequency, shallow-water FM MBES, the range resolution is sub-centimetre for short ranges, allowing high accuracy for the sounded depths.

FREQUENCY

The capabilities and dimensions of any acoustic system are mainly defined by physics. Underwater acoustics tell us that a high frequency will have a smaller range than a low frequency system. However, a high frequency system can, at a given size, produce a smaller beam angle than a low frequency system. Also, frequency dictates whether the system can penetrate the top layer of the sea bottom or will be reflected by it. Finally, the frequency defines the smallest possible pulse length or bandwidth.

As can be seen, beam angle, size and range are all a function of frequency and counteract each other. As such, there is no ideal frequency. For highly detailed, close range bathymetry, a high frequency system will give the best results in a relatively small form factor. For full ocean depth bathymetry, a low frequency needs to be chosen; if a small beam angle is then required the transducer will become large (and heavy). In



▲ *Maximum range depending on frequency, power and pulse length.*

general, shallow-water MBESs operate at a frequency between 100 and 700kHz, which reflects off the top of the sea bottom but generally does not penetrate it.

To counteract frequency limitations, most manufacturers now offer shallow-water MBESs that are frequency-selectable. That is, the MBES can be tuned to a specific frequency in the range of 100–700kHz. Of course, the above remains true and the specifications of the MBES therefore change with a different frequency.

MULTI-FREQUENCY AND MULTI-PING

Some manufacturers allow the user to not just select a single frequency but to use multiple frequencies simultaneously. Although all the previous limitations still hold, using multiple frequencies can reduce the amount of noise encountered. So, rather than not having some (high frequency) depths, these data points can be filled in using lower frequency data (although with a larger footprint and thus showing less detail).

Another option for especially deepwater MBES is the use of multi-ping. In this situation, two to four pings are transmitted at slightly different angles simultaneously. This counteracts the long travel times of the signal in deep water and allows for greater coverage without gaps at higher survey speeds.

WATER COLUMN DATA

A traditional MBES measures a single depth per beam per ping. In general, the ‘first depth strong enough to be detected’ will result in the depth displayed. Less strong depths that may be closer to the multibeam are not detected. Also, a strong reflector close to the transducer may give a depth rather than the weaker bottom below it.

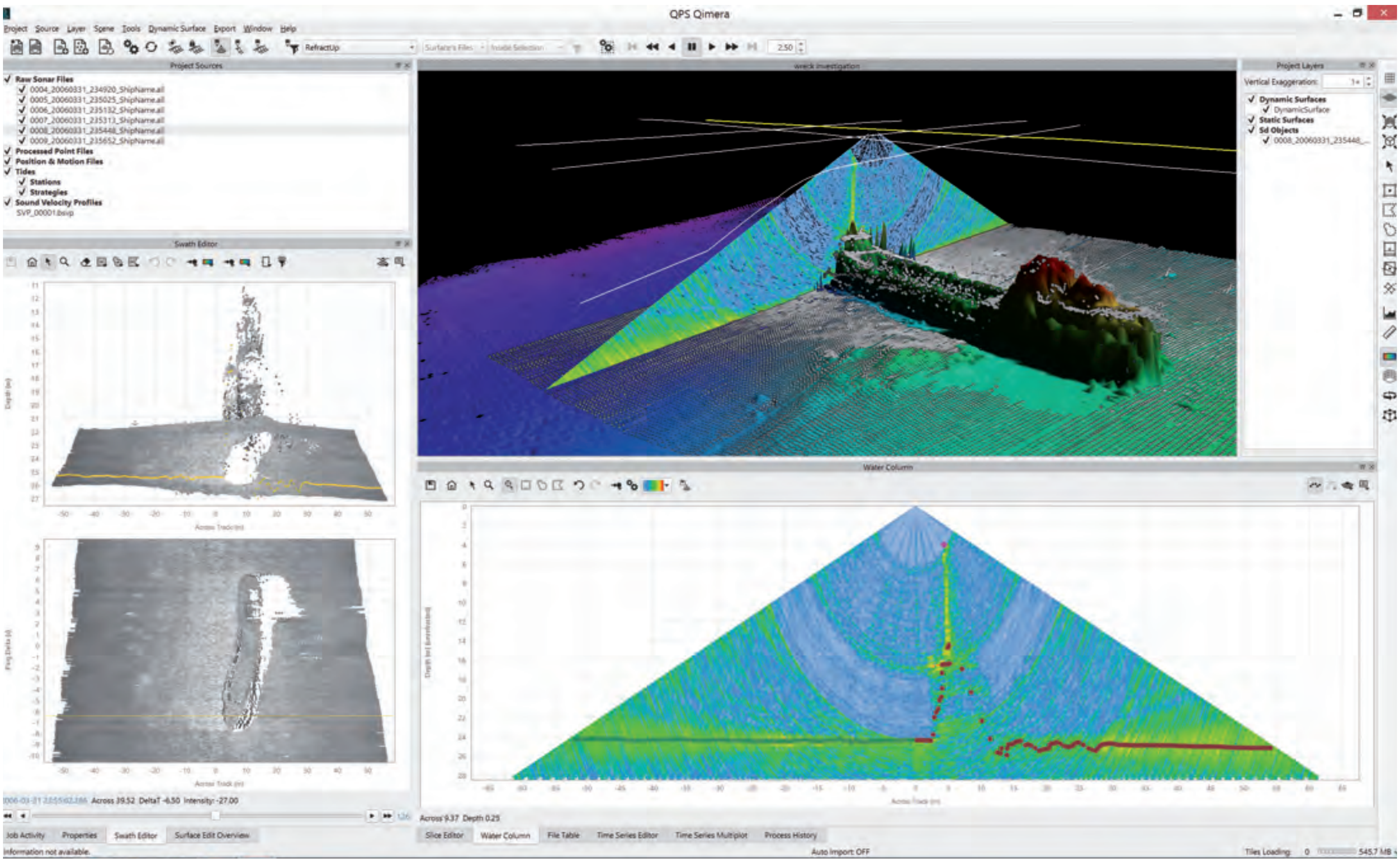
Many modern MBES systems circumvent this limitation by offering water column data as an option. With this technique, the water column of each beam is divided into a number of ‘bins’. The MBES now looks for a return within each bin for each beam for each ping. This allows the MBES to measure multiple reflections and thus create 3D images of objects in the water column (or to see the bottom through, for example, vegetation). Some manufacturers even support multi-frequency in combination with water column data, allowing even more objects to be positively detected.

As can be deduced, especially with many beams, multi-frequency and a high ping rate make the amount of data gathered enormous. To compensate, the water column data is often compressed to make it manageable. Despite this, the data volumes (and thus the time spent processing) are still large.

BACKSCATTER DATA

Backscatter is the amount of signal returning from the bottom. Depending on the type of material, more or less signal will be received thus allowing object and bottom classification. Most modern MBES systems have the option to receive backscatter data together with the depth information and show an SSS-like image.

Some manufacturers combine the backscatter data with both water column and multi-frequency capabilities, allowing even more information to be collected. The advantage of combining backscatter with water column data is that objects in the water column can be better identified. The combination of backscatter with



▲ *Water column data. (Image Courtesy: QPS.nl)*

	MBES Backscatter	SSS
Footprint	Discrete beams across track.	Constant signal across track; high across track resolution
Angle of incidence	Large due to surface mounting	Low due to sensor towed close to the seabed
Positioning	Accurate when vessel mounted	Variable (can be improved with USBL)
Impact of roll / pitch	Large; changing angles	Stable platform
Effect of ray bending	Large due to surface mounting	Can be towed under the layer

▲ *Multibeam vs. SSS backscatter.*

multi-frequency is especially useful for bottom classification. As materials can react differently to different frequencies, measuring the backscatter at different frequencies but at the same moment in time can give classification algorithms better information to work with.

SSS VS MULTIBEAM ECHOSOUNDERS

With the backscatter option on the MBES, a common question is whether an SSS is still required. As described in an earlier article on SSS technology, the brief answer is that it is. The difference between MBES backscatter and a true SSS is that the MBES will provide one backscatter value per beam, whereas the SSS will provide an almost continuous signal, thus giving a higher resolution. So, an MBES provides at most around 1,024 backscatter points per swathe, whereas an SSS has a continuous signal. However, the MBES data may be more than enough for a general classification. If, however, more detail is required, it is advisable to use an SSS.

OTHER OPTIONS

Besides the options described above, manufacturers offer additional options in their systems. An example is a dual head set-up. With this option, a much larger swathe can be created with swathe angles up to 240°, allowing surface to surface measurements for inspection work. The dual head option is often used in pipeline inspections. Some manufacturers also offer a pipeline mode, where a small sector beneath the transducer gives highly detailed information (at a high frequency).

Another option often offered is the integration of an Inertial Motion Unit (IMU) with the MBES. This is often advertised as not needing any calibration, although most manufacturers mean that there is no additional calibration required between the MBES and the IMU. Performing an MBES calibration will also give the IMU calibration parameters. Sometimes ignored is the fact that the IMU also plays a role in the positioning system. This means that, even though the values can be obtained from the MBES calibration, they still need to be entered into the survey software to compensate for any positioning offsets. ◀

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Complete Lidar Surveying Solution for Aerial and Marine Topographic Surveys!

The HYPACK LiDAR Payload *Versatile, Portable, Affordable*

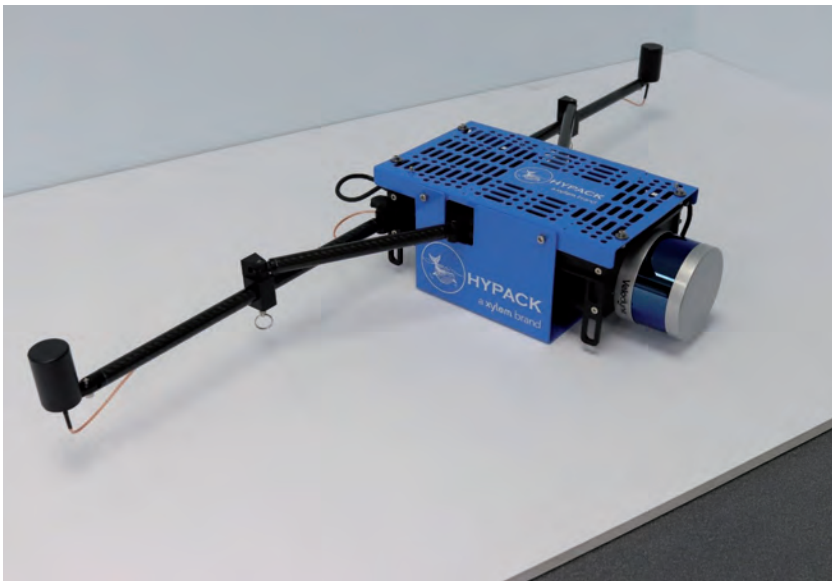
The HYPACK LiDAR Payload is an end-to-end solution suited for use on boats, drones or terrestrial vehicles. Land or water, this solution is designed to meet your topo Lidar surveying needs quickly and easily.

The surveying and mapping sector perpetually pushes for innovation. In today's professional climate, resources are thin. Companies or agencies must accomplish surveys with minimal staff while maintaining safe public health practices. Tools that increase workplace efficiency and reduce operating costs are more vital than ever. HYPACK has risen to the occasion with the HYPACK LiDAR Payload. The payload is a stand-alone, cost-effective Lidar surveying solution that features a VLP 16 Puck Lite Lidar sensor, an SBG Ellipse 2D INS/GNSS, HYPACK Max/HYSWEEP, and a Pico 500 mini PC. The sensors are enclosed within an IP67 rated unit suited to withstand inclement weather for marine surveying or field work in rugged environments. The unit is self-powered through a battery insert and boasts a three-hour run time. The power autonomy of the payload is an advantage for UAV users because it provides increased run time and mission efficiency.

The payload is delivered in a ruggedized Pelican case for ease of transport. Inside the case, there is a charging system for the unit, standardized documentation, and two mounting systems. The first mounting system features UAV mounting clamps that attach to the DJI Matrice line. The mounting clips are drone agnostic, meaning they are designed to attach to industry-standard attachment rods so that they can pair with the UAV of your choice. The second mounting system is a U-shaped bracket that attaches to the outer enclosure of the unit. The bottom portion of the U-shaped bracket is flat and can easily attach to a moving vehicle.

Good Lidar data depends on accurate and reliable GNSS data. The HYPACK LiDAR Payload addresses this in a few different ways. First, the system's antennas extend to a set distance of one metre, effectively reducing the need for repeat heading calibrations. The antenna arms are held in place by specialized links that prevent movement while the unit is in motion. For easy transport in a Pelican case, the arms then retract into place and rest against the unit enclosure.

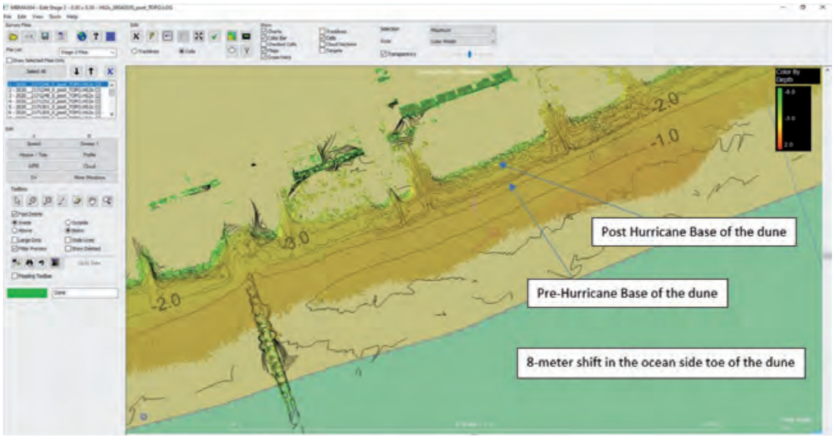
The payload can support RTK corrections and collection of GNSS data to produce a PPK solution. To broadcast RTK data into the unit, you can leverage the USB port on the back of the payload to establish a Wi-Fi connection. One simple way in which HYPACK has created a Wi-Fi connection with the unit is by 'tethering' a mobile phone to the payload. First, HYPACK uses the Ethernet port to create a remote desktop connection with our testing laptop to initialize the appropriate software programmes. Then, a mobile phone is plugged into the available USB port to allow the connection on the phone. Once a Wi-Fi connection is established, an NTRIP subscription and broadcasting software are required. Many state and local governments operate are required free RTK/NTRIP networks. HYPACK uses NTRIP software called Lefebure. When Lefebure has established a connection to the server, it broadcasts RTK data to HYPACK SURVEY



▲ *Figure 1: The HYPACK LiDAR Payload with extended antenna arms.*

and HYSWEEP during data acquisition. Data acquisition software runs on the payload for raw GNSS data; SBETS can be post-processed in the SBG Qinertia software. This solution is capable of producing data with PPK accuracy within three centimetres.

While the payload was designed with UAVs in mind, the autonomous nature of the tool supports multi-environment use. After Hurricane Isaias brushed the shores of South Carolina in early August of 2020, a Coastal Carolina University (CCU) research group led by Director Paul Gayes used the HYPACK LiDAR Payload to survey the extent of the environmental damage caused by the storm. Gayes and his research group at CCU used the HYPACK LiDAR Payload as a tool to educate their community about the environmental effects of major storm cycles and improve the resilience of the coastal community. Gayes has studied the dunes of Myrtle Beach for about three decades. His group uses Lidar to quantitatively analyse beach erosion rates, volumes and movement patterns. These beach erosion surveys ultimately help to inform local officials on the erosion patterns of the dunes, guiding their planning decisions in the face of natural disasters and for beach renourishment projects. Gayes and his research team attached the payload to a stable beam attached to a four-wheeler to analyse dune erosion caused by the storm (Figure 2). The team used a local RTK network and processed pre- and post-storm data in a HYPACK multibeam editor. After a preliminary analysis, the data showed an eight-metre landward shift of the dunes (Figure 3).



▲ *Figure 3: Contour data derived from Lidar XYZ data; the contours show an eight-metre landward shift, or net loss, of the dunes.*

▲ *Figure 2: HYPACK LiDAR Payload attached to four-wheeler for beach renourishment surveys.*

The HYPACK LiDAR Payload is an effective tool for beach erosion surveys, with numerous other applications, including shoreline/obstruction charting for navigation, pipeline mapping, infrastructure assessments, vegetation surveys, bare earth analysis, corridor mapping, defense and military applications, and more. HYPACK is working on several exciting partnerships to bolster its Lidar processing tools and to expand your surveying capabilities. The HYPACK Payload is a cost-effective, versatile solution that will meet and exceed your project needs. Please contact HYPACK, a Xylem Brand, for questions or additional information about this system. ◂

Webinar

HYPACK LiDAR Payload Webinar:
www.youtube.com/watch?v=_uVltfwPa-8&feature=emb_logo

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SURVEYING BY SAILBOAT: BATHYMETRIC MAPPING OF THE CANADIAN HIGH ARCTIC

There is a big need to develop new cost-effective mapping programmes in the Canadian High Arctic to improve data coverage, particularly in the shallow uncharted near-shore areas that larger vessels with deep draft are unable to access. This photo displays the *Vagabond* sailboat with the pole mount installed on the side, with Arctic landscapes around. The *Vagabond* is an expedition yacht designed for sailing in ice. The insert shows a photo taken by captain Eric Brossier last year in which we can see the sonar in the water.

The bathymetric survey was deployed in the summer of 2019 to acquire nearly 300nm of multibeam echosounder data and 500nm of single beam echosounder data from the 47ft. (14m) polar sailboat *Vagabond*. The datasets were collected between the eastern coast of Ellesmere Island and northern coast of Baffin Island, and surveys targeted uncharted near-shore regions of the continental shelf, glacial fjords, and gaps in existing coverage.

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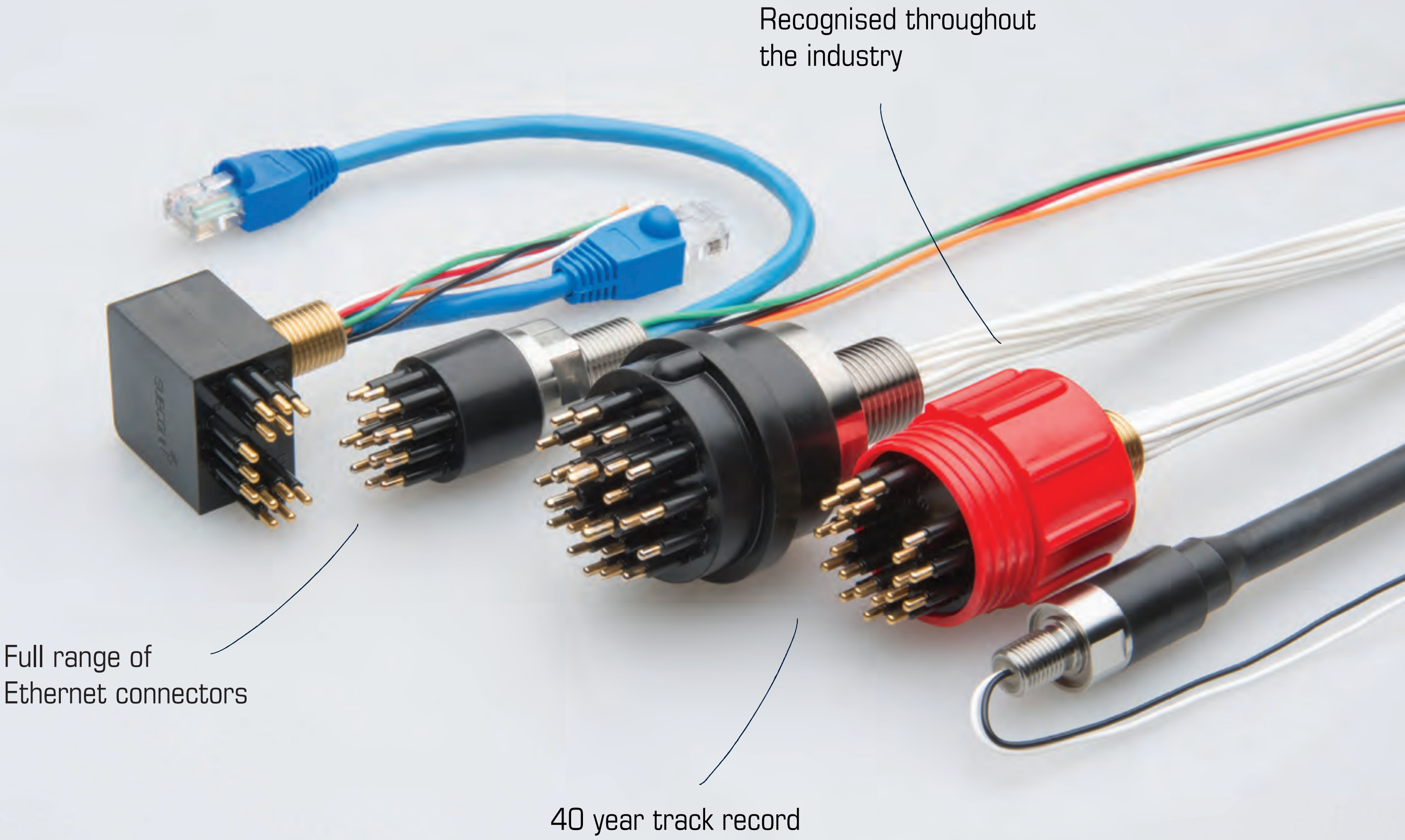

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Improving Results with Refraction Corrections

Bathymetry from UAV Imagery and Machine Learning

Accurate bathymetric mapping of shallow areas is essential for a plethora of offshore activities. Using Structure from Motion (SfM) and Multiview Stereo (MVS) techniques, images can provide a low-cost alternative compared to Lidar and sonar systems while also offering important visual information. This article presents a new framework for mapping the seabed in clear and calm shallow waters for small- and large-scale surveys using aerial imagery and machine learning to correct the geometric effects of refraction on the 3D point clouds and the imagery.

▲ *UAV images are used to derive the bathymetry in shallow clear, calm waters and seabeds with texture.*

STRUCTURE FROM MOTION AND MULTIVIEW STEREO TECHNIQUES

SfM is a photogrammetric technique for estimating 3D structures from 2D image sequences. It involves acquiring images from several positions relative to the object of interest. To establish the spatial relationships between the camera positions, features appearing in multiple images are identified automatically. Then, a self-calibrating bundle adjustment is used to calibrate the cameras and derive a sparse 3D point cloud to represent the object. External geometric constraints can also be applied to transform the 3D data to a desired coordinate system. MVS techniques are used to generate a very high-resolution 3D point cloud. MVS algorithms can construct highly detailed depth maps and consequently 3D point clouds that exploit the stereo correspondence of more than two images. Most commercial photogrammetric software currently delivers 3D point clouds by combining these two techniques.

IMAGE-BASED BATHYMETRIC MAPPING AND REFRACTION EFFECT

Compared to onshore aerial mapping, bathymetry mapping from aerial platforms in shallow waters is considered a much more time-consuming process. This is mainly due to the necessary compensation of refraction effects, which affect the geometry and radiometry of the primary data and consequently of the results by delivering apparent depths, as aerial imagery depicting the bottom of water bodies is heavily affected by the refraction of the optical rays. Refraction acts on these images similarly to the radial distortion, differing practically at each pixel of every image, leading to unstable solutions and erroneous depths. More specifically: according to Snell's law, the refraction of a light beam is affected by water depth and the angle of incidence of the beam in the air/water interface. The problem becomes even more complex when multiview geometry is applied, as the 3D position is derived from multiple images and thus from multiple refraction sources.

In shallower, clear water areas, and when refraction effects are successfully treated, bathymetry mapping from aerial platforms is a more efficient operation than ship-borne echo-sounding or underwater photogrammetric methods. A very important additional feature of image-based seabed mapping is that a permanent record of other features is obtained in the coastal region, such as approximate tidal levels from the waterline markings showing in the images, coastal dunes, benthic communities, marine litter, rock platforms, and beach erosion when results are compared with archival data. These benefits are especially evident in the coastal zones of up to 15–20m depth, in which most economic activities are concentrated.

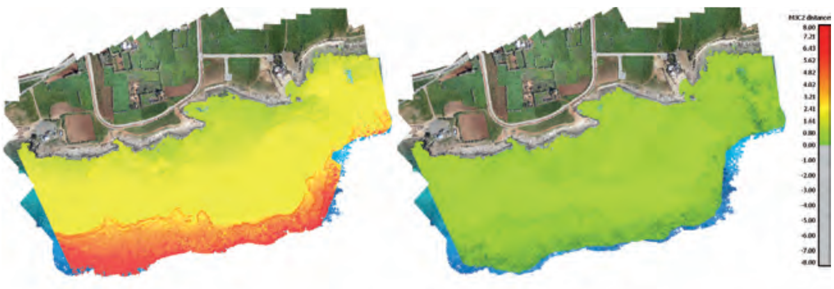
The presented framework developed by our team at the National Technical University of Athens and the Cyprus University of Technology corrects the refraction effect on the 3D point clouds and the aerial images of the bottom in two complementary modules. The first module corrects the apparent depths of the 3D points generated by the SfM-MVS methods and can also be used stand-alone. In that case, only a 3D point cloud, a 3D mesh, or their derivates such as depth contours, result. The second module transfers this correction to the image space, correcting the effects of refraction on the aerial imagery. The restriction on the framework is that there should be a calm water surface, non-turbid waters, and a textured seabed. More details for each module of the framework are given below.

CORRECTING THE APPARENT DEPTHS OF 3D POINT CLOUDS

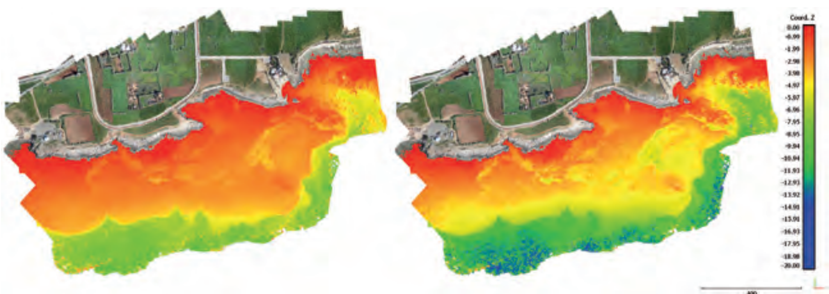
To correct the apparent depths of 3D point clouds of the bottom of water bodies which are derived by SfM-MVS processing of low-altitude aerial imagery, a linear support vector regression model was trained. In machine learning, support vector machines are supervised learning models that analyse data used for classification and regression analysis. This model was trained on synthetic and real-world data to learn to predict the correct depths, knowing only the apparent (erroneous) depths derived from the photogrammetric process. The model can generalize over different UAV systems, cameras and flying heights, regardless of the area to be mapped. This module delivers 3D point clouds of the seabed with the corrected depths.

CORRECTING THE REFRACTION EFFECTS ON THE AERIAL IMAGERY

To correct the geometric effects of refraction on the low-altitude aerial imagery, a state-of-the-art image correction method has been developed which builds on and exceeds earlier methods developed by our team. This module follows the first one and corrects the refraction effect on the original imaging dataset. This correction can be briefly described as a sophisticated reduction of the radial distance of each pixel, according to the depth and the incidence angle of the beam in the air/water interface. This module delivers refraction-free images that can be used directly with photogrammetric SfM and MVS processing pipelines, resulting in highly accurate bathymetric maps and image-based products.



▲ *Difference between bathymetric Lidar point cloud and the uncorrected imagery (left) and the difference using corrected imagery from the presented framework (right).*



▲ *Seabed point cloud depths (Coord. Z) before (left) and after (right) the applied machine learning correction on the 3D point clouds. Points on dry land remain untouched.*

RESULTS IN REAL-WORLD APPLICATIONS

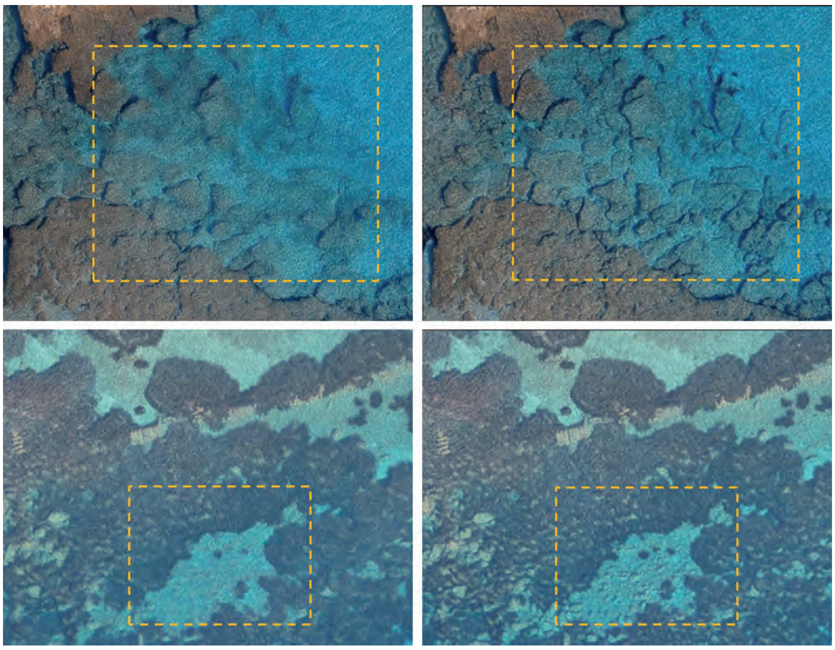
The method was tested through experimental results and validation over three synthetic and five different real-world cases in Greece and Cyprus with flying altitudes ranging from 35–210m. To evaluate the results of the framework, the initial (uncorrected) 3D point clouds of the SfM-MVS procedure and the point clouds resulting from the presented framework were compared with bathymetric Lidar point clouds and total station measurements available for the areas. An example is given where the depth differences between the Lidar data and the uncorrected image-based point clouds are presented. This comparison makes clear that the refraction effect cannot be ignored in such applications. In the presented case, the Gaussian mean of all the differences is significant, reaching 2.23m (RMSE 2.28m) in the test site. Since these values might be considered negligible in some applications, it is important to stress that more than 30% of the compared uncorrected image-based depths represent a difference of 3.00–6.07m from the Lidar points, or 20–41.1% of the real depth.

By applying the presented framework and correcting the refraction effects, a more than 97.3% reduction in the remaining vertical RMSE of the depths of all the sites was achieved. In some cases, the initial vertical RMSE of 3.34m, mean of 2.96m and standard deviation of 1.54m of the uncorrected data were reduced to 0.09m, 0.02m and 0.09m respectively after the refraction correction, while in other cases the initial vertical RMSE of 2.28m, mean of 1.71m and standard deviation of 1.18m were reduced to 0.13m, 0.04m and 0.12m respectively. In the same cases, the most popular state-of-the-art solution achieved a reduction of the vertical RMSE to 0.52m and 0.45m respectively, indicating that the new framework presented here outperforms current methods. By examining specific points instead of all the test sites, it was observed that, in some cases, the initial vertical difference from the Lidar data of 5.10m was reduced to 0.05m at the depth of 14.20m.

It is also important to note that the second module achieves a reduction in the noise of the sparse point clouds, which resulted from the SfM process and improved the accuracy and the quality of the resulting orthoimages and textures. This module also increased the resulting accuracy of the state-of-the-art method fivefold, extending the operating depths from 7.50m to 15–20m.

CONCLUSION

The framework developed and presented proves that through-water photogrammetry can deliver accurate bathymetric information in clear and calm waters with textured seabeds. What is required is that refraction is addressed thoroughly. Contrary to the current state-of-the-art methods, the presented framework is designed to achieve high generalization, expanding the applicability of and boosting SfM-MVS techniques for aerial bottom mapping. It delivers highly accurate and detailed bathymetric maps and image products, satisfying the International Hydrographic Organization's S44 Special Order TVU of 0.29m at 20m depth at the 95% confidence level. The implementation of the framework on UAV images facilitates the detailed and accurate monitoring and mapping of the sensitive coastal area. Moreover, it supports low-cost mapping strategies and enables a wide usage of UAV imagery in shallow clear and calm waters instead of more expensive Lidar and sonar systems, increasing the amount of information. ◀



▲ *3D models' textures generated with the original (left) and corrected (right) for refraction imagery.*

Further Reading

- Correcting Image Refraction: Towards Accurate Aerial Image-Based Bathymetry Mapping in Shallow Waters: www.mdpi.com/2072-4292/12/2/322

- DepthLearn: Learning to Correct the Refraction on Point Clouds Derived from Aerial Imagery for Accurate Dense Shallow Water Bathymetry Based on SVMs - Fusion with LiDAR Point Clouds. www.mdpi.com/2072-4292/11/19/2225

- Shallow Water Bathymetry Mapping from UAV Imagery Based on Machine Learning. https://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XLII-2-W10/9/2019/

- A Novel Iterative Water Refraction Correction Algorithm for Use in Structure from Motion Photogrammetric Pipeline: www.mdpi.com/2077-1312/6/3/77

Panagiotis Agrafiotis holds a doctorate in Engineering from the National Technical University of Athens as well as an MSc in Geoinformatics and an MEng diploma in Surveying Engineering. His current research focuses on image-based bathymetry mapping for shallow and deep waters using photogrammetry and machine learning techniques. His expertise includes 3D computer vision, remote sensing and machine learning. During the past 8 years, he has worked on more than 16 research projects as a member of the Lab of Photogrammetry of NTUA, the Photogrammetric Vision Lab of CUT and the Institute of Communication and Computer Systems of NTUA. He also serves as the secretary of the ISPRS WG II/9: Underwater Data Acquisition and Processing.

✉ pagraf@central.ntua.gr

Finnish Diving Team Discovers Rare Wreck of 17th-century Dutch Merchant Ship

While undertaking documentation dives on some supposedly World War I or II wrecks at the mouth of the Gulf of Finland, Badewanne divers descended on one of the biggest surprises during their long careers of diving the wrecks of this eastern extension of the Baltic Sea. The Baltic Sea has been an important trade route since the Middle Ages, as the navies of Holland and England needed endless supplies of wood, tar and hemp, all of which were available around the Baltic. From the 13th century onwards, the Hanseatic League controlled the trade, but during the 17th century the very efficient merchant navy of the Dutch Republic gained control. The trade route received a significant boost in importance and profitability after Tsar Peter the Great founded his new capital St. Petersburg at the estuary of the Neva River, in the easternmost part of the Gulf of Finland.

▸ *https://bit.ly/2GL8DNO*

▲ *Port side hull view of the stern of the fluyt shipwreck. Decorated stern cabin portholes are visible. (Image Courtesy: Badewanne)*

Russian Survey Vessel Explores 14,000km Cable Route across Arctic Seabed

▲ *Professor Logachev survey ship. (Image Courtesy: Polar Marine Geosurvey Expedition, pmge.ru)*

On 6 August 2020, the *Professor Logachev* survey ship set out from Kirkenes, Norway on course for Russian Arctic waters. Over the next three months, the ship and its crew will sail 6,500km along the north Russian coast. The Norwegian border town could become a hub for an almost 14,000km-long telecom cable between Asia and Europe. Researchers are this summer exploring the best route across the Arctic seabed. Their mission is to look into the deep to examine the sea bottom. Their findings will be crucial for the future of Arctic Connect, the project developed by the Finnish company Cinia together with Russia's MegaFon. The cable connection between Kirkenes and Japan will bridge northern Europe with Russia, Japan and North America, and also meet growing needs in the Arctic region itself, project developers argue. It will have a transmission capacity of 200Tb/s, says MegaFon.

▸ *https://bit.ly/3leXjIU*

Unmanned Technology Narrows Data Gap of the World's Most Sediment-laden River

With a total length of 5,464km, the Yellow River is the second-longest river in China. Its middle section runs through the Loess Plateau, where it picks up sand and dust, making it the most sediment-laden river in the world. Yellow River runs through nine Chinese cities and affects the daily lives of tens of thousands of people who live alongside the river. To better protect the ecology of the watershed, monitoring changes in the underwater terrain and studying the pattern of river evolution can provide important data to support river management and flood control. However, technical limitations and harsh environmental conditions mean that the Yellow River watershed has not yet been mapped accurately. The water system is complex, with rapid currents and many shallow areas, making it difficult to install survey equipment using traditional measurement methods and to find a suitable workboat. Operations on the water also pose high risks to personnel.

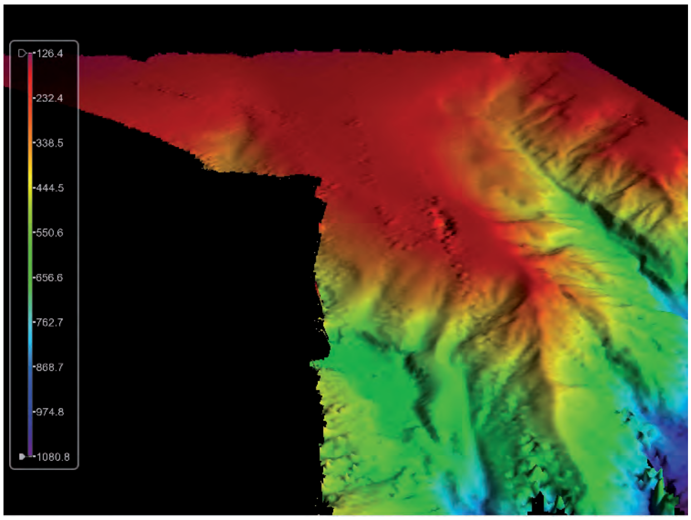
▸ ***https://bit.ly/3nnKJck***

▲ *ME120 USV navigates autonomously to perform mapping task.*

Teledyne CARIS AI Software Contributes to Successful UTAS USV Mission

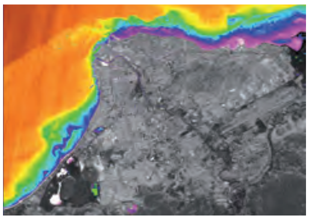
Teledyne CARIS, a Teledyne Technologies company, was an integral part of the illustrious team involved in the ground-breaking uncrewed offshore survey mission in the Atlantic Ocean. Teledyne CARIS' Mira AI and CARIS Onboard software were present on the vessel to enable autonomous survey and real-time processing operations. The mission's Uncrewed Surface Vehicle (USV) built by SEA-KIT mapped over 1,000 sq. kms of the ocean floor in 22 days, while being continuously monitored via satellite communications at its Remote Operations Centre in Essex, United Kingdom. A specialized team comprised of the GEBCO-Nippon Foundation Alumni Team operated the survey equipment and provided quality control of the data from various 'work-from-home locations' around the world.

▸ ***https://bit.ly/33wBGxN***



▲ *The image displays initial results following a fully automated processing workflow. Final deliverable of the survey will be processed using CARIS HIPS and SIPS.*

Venezuela Performs Bathymetric Surveys with Own Satellite

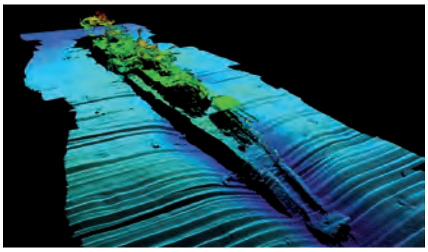


▲ *Calculation of depths by applying the Stumpf algorithm, using the green, blue, red and infrared bands of the satellite images.*

Ever since the launch of the VRSS-2 Antonio José de Sucre satellite in 2017, researchers have been looking into how best to use and apply the information that it provides for the benefit of environmental development and sustainability. For example, the bathymetry derived from satellite images is very beneficial for hydrographic services, since it allows information to be obtained that has not been explored with traditional acoustic methods. The Venezuela Hydrographic Office has started to use this method, also to improve its hydrographic coverage. The Antonio José de Sucre satellite is Venezuela's third artificial satellite. It was launched from the Jiuquan Launch Center in Gansu Province, China and captures images for cartographic survey work, with a new high-definition camera and an infrared camera for soil, water resources diagnosis and seismological prevention data.

▸ *https://bit.ly/3jDLuvj*

iSURVEY Helps Identify North Sea Shipwreck



▲ *Multibeam imagery of the wreck of the long-lost German warship Karlsruhe.*

During a recent offshore power cable cut and seal project on the *Olympic Taurus*, iSURVEY were part of the team tasked with identifying a shipwreck found three years previously during a routine inspection of the Skagerrak power cable. The wreck lies 13 nautical miles from Kristiansand in southern Norway, and was investigated using an ROV-mounted multibeam echosounder. Following the survey, it was determined that the wreck was that of the long-lost German warship *Karlsruhe*, famous for leading the assault on Kristiansand during the invasion of Norway in 1940. Until this discovery, Karlsruhe had remained the last World War II German warship whose whereabouts were unknown.

▸ *https://bit.ly/3jDC3Mz*

Underneath the Top of the Iceberg

Measuring and 3D Mapping of Sea Ice in the Arctic

Sea ice is one of the most important parameters when it comes to ice-albedo feedback; in other words, the fraction of incoming solar radiation that is reflected directly back into space. Because of the grave importance of the decrease in the amount of sea ice due to the climate crisis, gaining a full understanding of its complex structure is more important than ever.

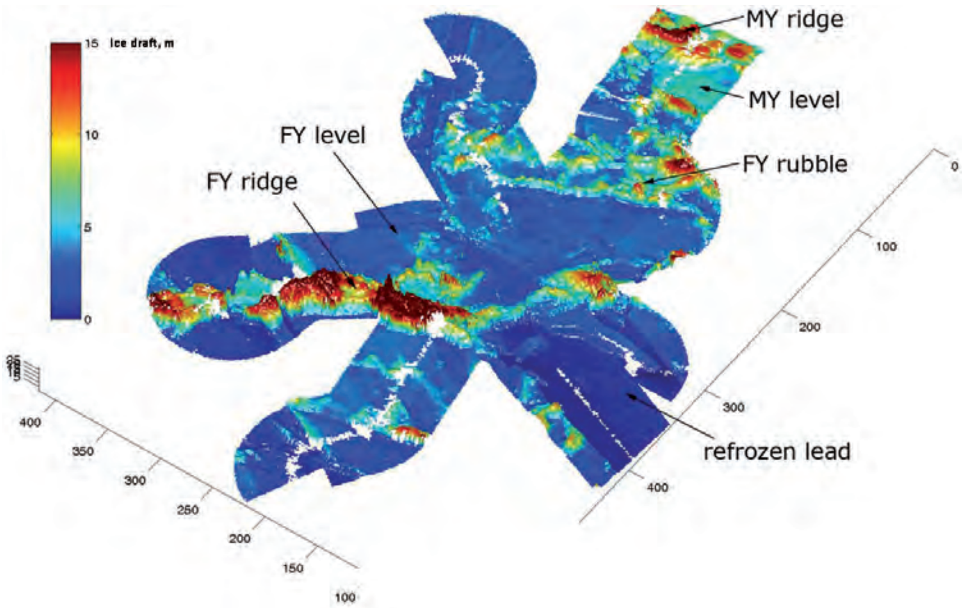
Both large and small Autonomous Underwater Vehicles (AUVs) have been used successfully to map the 3D structure of the underside of sea ice, but always in an experimental context. The challenge is to determine the best way forward to improve the quantity and quality of data gathering, and to turn the under-ice AUV into a reliable vehicle for routine use. This, as well as a wish to understand the full scope of sea-ice variability and not just the 'top of the iceberg', is what is driving us, Bo Krogh and Peter Wadhams, forward in our research and through trial and error. Our goal for this article is to share our experiences, difficulties and suggestions for future solutions.

HISTORIC OVERVIEW

Mapping sea ice has been done by drilling samples since Fridjof Nansen's 'Fram' expedition in 1893-1896. However, such drilled samples give a very limited view of the variability of sea ice. They are statistically weak and exclude the option to consider the shape of the underside of the sea ice, the distribution of pressure ridge depths, or the difference between the roughness levels of ridged and level ice, or between first-year and multi-year ice. All of these aspects are important to understand the multifaceted concept of sea ice and its effect on the surrounding climate.

Before the invention of the AUV, the ice mapping field was driven by military submarines and the upward sonar with which they were equipped, and this set the basis for our understanding of sea-ice thickness distributions. First came single-beam upward sonar, yielding a linear profile. Then came the side-scan sonar, with a fan-shaped beam in which the backscattered signal strength from each pulse is plotted against time, being interpreted as slant range. This constructs a map as the vessel proceeds along its track, with strong reflectors showing echoes and shadow zones. The ultimate solution, however, is the multibeam sonar, which gives a proper 3D picture of a swath of ice underside. The first use of upward-looking multibeam sonar from a submarine was by Wadhams in 2007 from HMS *Tireless* (Wadhams, 2008) using a Kongsberg EM2000 system.

A new development within this field is the stand-alone Ultra-Short BaseLine (USBL) positioning buoy, a method of underwater acoustic positioning which enables the more rapid and secure insertion, tracking and retrieval of AUVs, as well as in-mission low bandwidth communication. It consists of a USBL transducer with an integrated Attitude and Heading Reference System (AHRS) – a compact unit that provides 3D positioning of the AUV with high accuracy. Above-water, it has a Global Navigation Satellite System receiver (GNSS), which also includes a compass and a long-range Wi-Fi data



▲ *Gavia AUV study in Beaufort Sea (2007): sonar data gathered around the deployment hole, showing a refrozen lead, a young pressure ridge (eight days old), FY level ice, a rubble field, and an MY pressure ridge at the top of the image. The contrasting roughness and shapes of FY and MY ridging are clearly shown. Running depth of the vehicle was 20m. (Image Courtesy: Wadhams, 2012).*

radio to ensure contact with the mother vessel. This is mounted on a spar buoy together with batteries and interfacing equipment. The concept was first tested during a cruise with USCGS *Healy* in 2014 in the Beaufort Sea, north of Alaska, and further developed with stand-alone functionality for a cruise with M/V *Polarsyssel* in the Barents Sea in April 2017.

THE 3D SEA-ICE MAPPING CONCEPT (OF THE FUTURE)

Based on experience from sea-ice mapping operations since 2002, the following list of requirements and recommendations has been created, in order to enhance the operational capabilities of an AUV system in ice-infested waters. The reason for suggesting these changes in the conduct of AUV operations under ice is to improve both the amount of data gathered and the quality of such data.

RISK ANALYSIS AND MISSION PLANNING

In order to provide an easy overview of all operational units; that is, the vessel, the USBL positioning buoys, the AUVs and the UAVs, their online position should be plotted on one screen, where the operations scenario can be transmitted to several stations aboard the vessel. In this way, the AUV supervisor is not doing the operational planning alone, as was the case in 2014 and 2017 from a laptop PC in a small boat. It now becomes a joint decision, where all operational conditions such as ice, icebergs, current, tides and weather are considered together, prior to the start of an AUV mission. The lack of this type of communication was a major contributor to the lack of reliable results in 2014 and 2017.

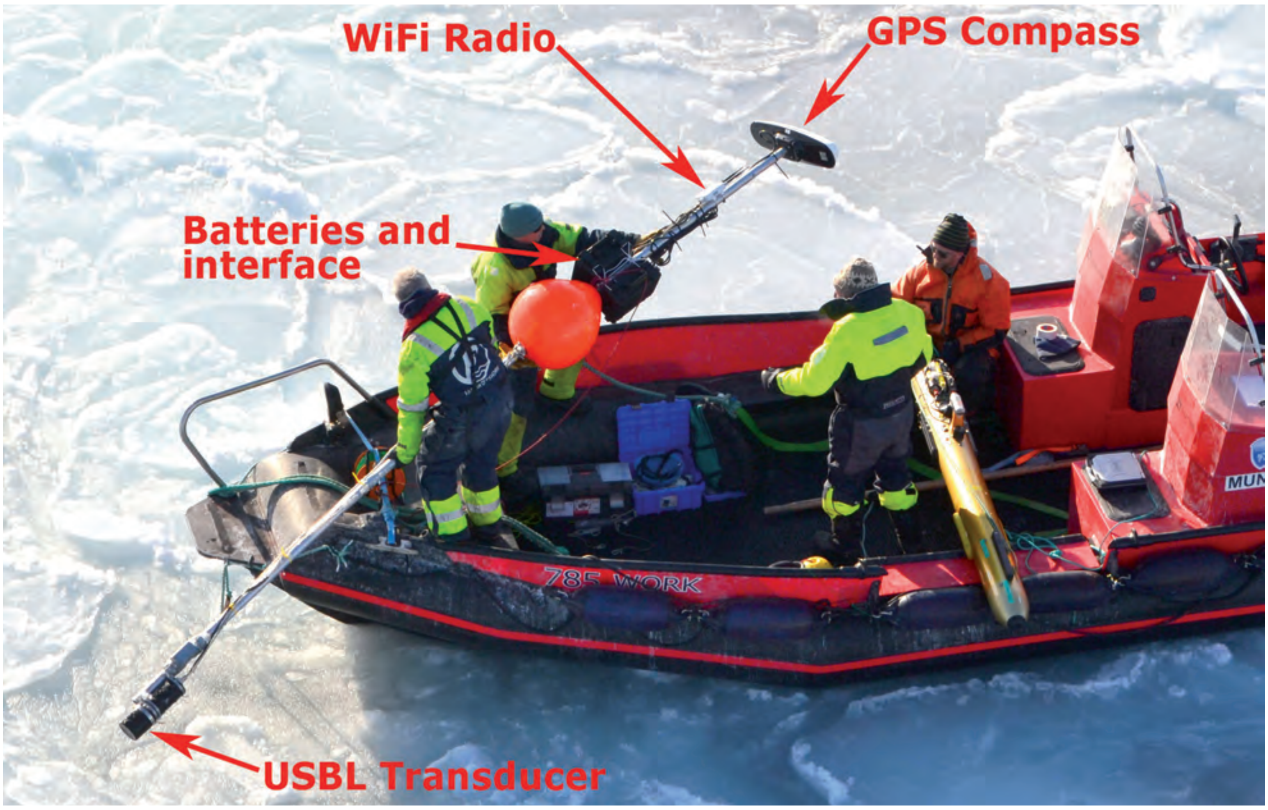
In the 2007 and 2008 expeditions, the AUV was deployed through a hole cut in the ice and was operated with a tether attached to the vehicle. This was needed both for insurance purposes and to ensure control in the event that the vehicle ignored its programmed instructions. In 2014 and 2017, the AUV was operated from a ship's man overboard boat, again with a tether. The experience gained from these operations is that the tether reduces the operational capabilities of the AUV so much that it cannot even carry out a track consisting of a lawnmower pattern. During all the operations mentioned above, only smaller areas than desired and planned were covered, which again reduced the amount of reliable data.

These experiences created a foundation on which the idea for the USBL buoy was built, where the purpose is to remove the requirement for the tether. When it is no longer necessary to operate the AUV with a tether, it can be launched and recovered from the mother vessel, which eliminates the use of small boats, something which has a high-risk exposure in ice-infested Arctic waters. In general, it can be said that the tether is an insurance-required safety feature that extremely limits the scope and quality of the data gathering which is, after all, the main point of the AUV mission. The addition of the stand-alone USBL positioning buoy to the mission means that the positioning and communication of and with the AUV will be more reliable, the process of collecting data will in turn become smoother and the safety of the crew will be higher.

Deploying one or maybe even two of this type of buoy means that the position of the AUV under the ice is always tracked. This also reduces the risk of losing the AUV underneath the ice, as was the case during our expedition in 2012.

"GO THERE AND LOITER"

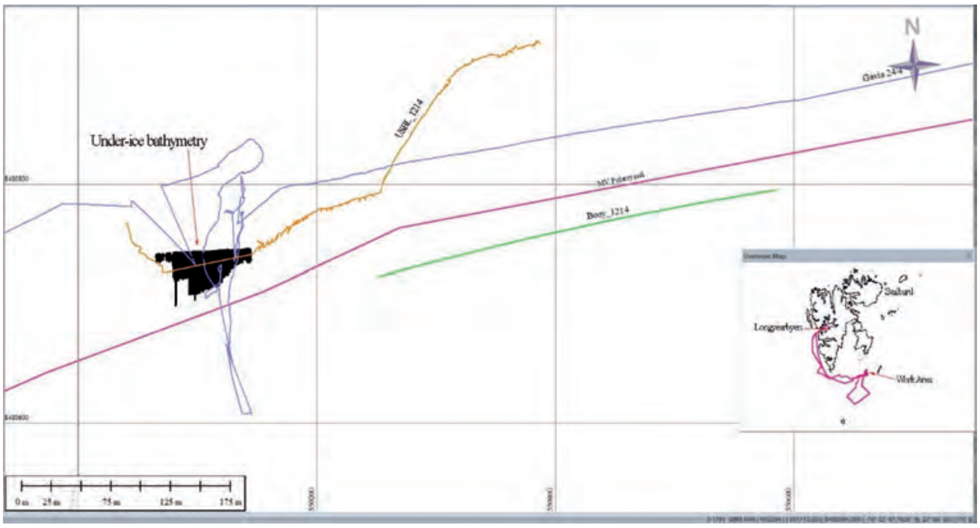
After the USBL positioning buoy has been deployed and the AUV has been launched from the mother vessel, the obvious survey plan is to programme the vehicle's navigation to carry out a systematic survey of the ice area or ice features that are of interest. However, the question arises



▲ *The stand-alone USBL positioning buoy and Gavia AUV in small boat from M/V Polarsyssel, April 2017. (Image Courtesy: Bo Krogh, 2017).*

of how best to terminate the survey and recover the vehicle. When ending or aborting a mission, it seems obvious that the vehicle should be brought to the surface for recovery. But supposing the surface is ice-covered, or the survey lines leave the vehicle at a considerable distance from the ship – what then?

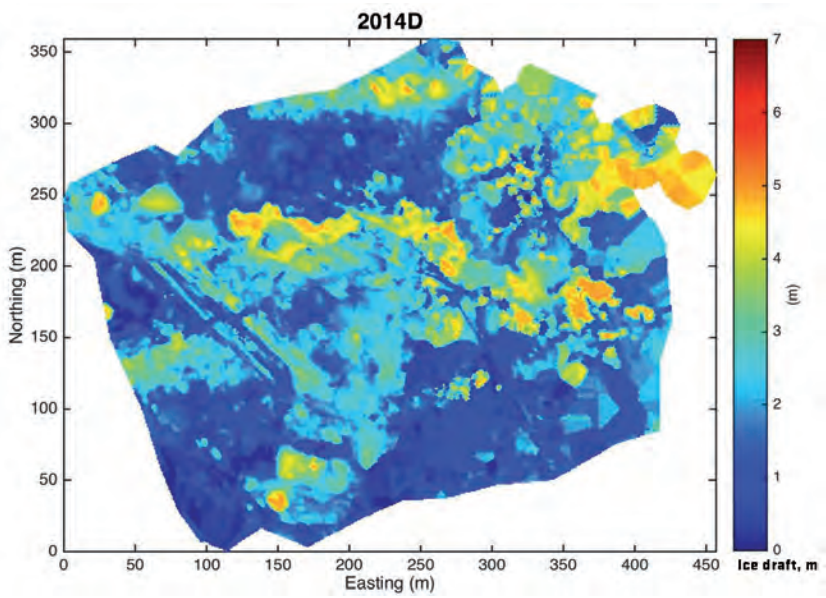
To deal with this problem, Krogh suggested the concept of "Go there and loiter", in which a position is specified to which the vehicle goes and then circles around at a pre-determined depth until the operator decides upon surfacing or some new navigational instruction. This can also be the default option for an aborted mission. If this step is not considered, the recovery of the AUV can prove difficult due to the sea ice. Consider the situation where the AUV develops an error and the mission is aborted. In that situation, the AUV is normally ballasted slightly light, meaning that it will stop the engine and drift to the surface. If there were no sea ice, the vehicle would arrive at the surface and would be found by the mother vessel by its Wi-Fi link, the strobe light, or even a communication satellite such as an Iridium modem. However, these safety features cannot work under water and if the AUV drifts up under an ice floe it is almost impossible to reach. This is the worst place to find an AUV again if it is 'dead' under drifting sea ice.



▲ *Track chart from 24 April 2017, showing the tracks of the vessel, the USBL positioning buoy, the AUV as tracked by the buoy and the track from the AUVs internal positioning system. Also shown is where the under-ice bathymetry was located. (Image Courtesy: Bo Krogh, 2017)*

CONCLUSION

This is an exciting time for the development of ice sensing using autonomous vehicles. The invention of smaller, more efficient and reliable designs of AUVs makes it easier and cheaper to deploy vehicles under ice, conduct surveys and obtain systematic results on ice mapping. At the same time, the very rapid development of UAV technology gives a low-cost tool which can supply equivalent data on the upper surface topography of the same ice. All that remains is the perfection of the technology that will allow these two systems to be joined together and used in the field to provide full 3D mapping of ice floes. This technology could also be used to research and understand other ice phenomena such as icebergs and pressure ridge distributions. The most important role of such surveys will be to help us understand and map the rapid decline in the ice extent and especially thickness, which result from the Arctic amplification of global warming. ◀



▲ *An example from a recent operation from USCGS Healy in an icefield in the southern Beaufort Sea that was in an advanced state of melt (August 2014).*
Here, all ridged ice has been worn down or melted to the point where the maximum draft does not exceed 5m, the deepest ice being the remains of a ridge which ran W-E across the centre of the image. A few days later, this entire icefield disintegrated. Rotten as it is, the area of icefield shown would have weighed approximately 300,000 tons. (Image Courtesy: Wadhams, 2014)

Bo Krogh, senior surveyor, has more than 35 years' experience in hydrographic, engineering, environmental and archaeological survey projects, including offshore construction surveys, seabed mapping surveys, marine archaeology surveys with AUVs, AUV surveys under Arctic ice, pipeline route surveys, pipeline and cable laying, rock dumping, trenching and dredging, installation of subsea templates, and 3D seismic surveys. He has held positions such as AUV supervisor, company site representative, senior survey engineer, project engineer – survey & rock dumping, and offshore vessel manager, and has therefore gained vast experience as a project manager.

Professor Peter Wadhams, head of Cambridge Polar Consultants Ltd., Cambridge, and Emeritus Professor of Ocean Physics at the Department of Applied Mathematics and Theoretical Physics, Cambridge University. He was formerly director of the Scott Polar Research Institute. He is a highly experienced sea-ice field researcher, with more than 55 missions to the Arctic and Antarctic, including six submarine voyages to the North Pole to map the changing ice thickness as well as work from icebreakers, aircraft and ice camps.

Utilizing New Methods to Research Impacts on a Precious Waterway

Unmanned Vessels to Assist in Saltwater Intrusion Research

Seafloor Systems, Inc. was recently contracted by the U.S. Geological Survey (USGS) to develop two custom HydroCat-180 unmanned surface vessels (USVs) that will be used to monitor the impacts of saltwater intrusion from the Pacific Ocean into the Sacramento-San Joaquin Delta in California. The subsequent research using the new autonomous vessels will provide new insights into maintaining balance within the complex ecosystem.

TURNING TIDES

The Sacramento-San Joaquin Delta, commonly referred to as the California Delta, is the hub of the state's water supply system and a teeming wetland bionetwork (Figure 1). About 500 plant and animal species call the area home, making it one of the largest estuaries in western North America. Two-thirds of California's salmon pass through the delta on their way upstream to spawn, as well as half of the state's migrating waterfowl.

As settlers began to inhabit the area in the mid-nineteenth century, they saw enormous agricultural potential in the natural peat soils, which are rich in nitrates from partly decomposed organic matter. Reclaiming the land for farming meant building dirt levees to prevent periodic flooding of brackish semi-salty waters that could ruin crops. In the process, it disrupted natural habitats.

Many species, including the delta smelt, have experienced habitat loss and detrimental change since farmers began to convert their territory into agricultural lands. In addition to agricultural activity, the man-made California Aqueduct system that transports fresh water to southern California redirects the flow of water from north to south as opposed to the natural west to east direction. Coupled with increasingly common droughts, the flow of fresh water from the Sierra Nevada Mountains to the delta has been reduced, causing significant salinity intrusion.

▲ *Figure 1: The California Delta is formed at the western edge of the Central Valley by the confluence of the Sacramento and San Joaquin rivers and lies just east of where the rivers enter Suisun Bay. (Image Courtesy: USGS)*

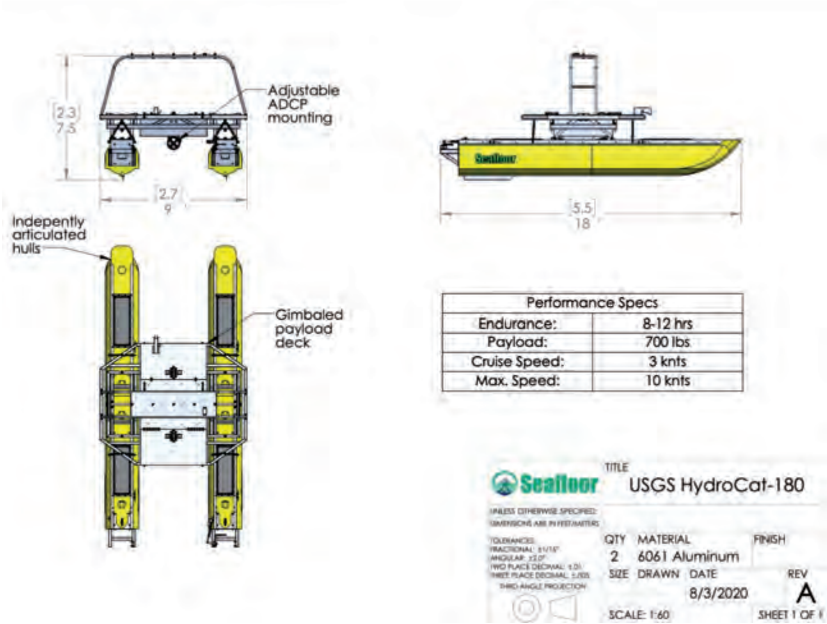
The growing delta water quality issue provides the impetus for agencies like the USGS to observe and mitigate the effects of saltwater intrusion. On the one hand, California relies on the water arteries for farm irrigation and drinking water. On the other, the fragile habitats of native species are being altered at an alarming rate.

SURVEYING A DYNAMIC ENVIRONMENT

The delta is an extremely diverse environment, meaning that traditional hydrographic survey methods struggle to account for the constant change that takes place from one minute to the next. The delta is heavily influenced by the Pacific Ocean, taking its cues from the motion of high and low tides. Consequently, the flow rate and water levels can change rapidly in a given day. Pile on the potential for rainfall upstream in the neighbouring Sierra Nevada Mountains and Central Valley, and survey readings can become skewed. From a safety standpoint, sediment and debris can wash downriver, creating potentially hazardous conditions for the use of manned vessels in the delta during the winter and spring months.

Previous survey efforts by the USGS relied on a manned vessel to hold a strict transect across the water, which can often take more than 30 minutes to complete. During this time, the water level can change by more than 10 feet (3 metres), resulting in inconsistent data acquisition. With their new HydroCat-180 USVs (Figure 2), the USGS hopes to cut the data collection time in half, improve the track line by 95%, and significantly increase the accuracy of the resulting water flow and depth model. Personnel will reduce their exposure to risks caused by rainfall and flooding events.

Flow rate and depth data will be collected using an RD Instruments Acoustic Doppler Current Profiler (ADCP), mounted under the payload deck of the USVs. The two USVs will simultaneously conduct surveys along pre-programmed routes, transferring the task of maintaining a precise track line to Seafloor's AutoNav system (Figure 3). Known in the hydrographic survey industry as 'mowing the lawn', the action of the two vessels traversing the water while emitting high-frequency pulses of sound ensures an adequate amount of data collection. The USGS cannot disclose many of their practices with the new vessels, but the corresponding data will shed light on the intrusion of saltwater into freshwater zones of the delta.



▲ *Figure 2: Design blueprints show key features of the HydroCat-180, Seafloor's largest unmanned vessel built to date.*

▲ *Figure 3: Two HydroCat-180 unmanned surface vessels will work in tandem to survey the California Delta.*

PRESERVING THE DELTA FOR THE FUTURE

The landmark contract with the USGS was awarded to Seafloor Systems with a six-month deadline and, despite some supply chain issues caused by the COVID-19 pandemic, the vessels were completed and delivered ahead of schedule. Seafloor, which up until now has focused its efforts on smaller, calm water vessels, hopes that this application of the two 18ft (6m) HydroCat-180s will expand its reach into the nearshore maritime sector. Located a mere hour's drive from the delta region, Seafloor has a vested interest in protecting the precious natural resources in the region. There is no easy answer to how the state will handle this growing issue, but frequent scientific observation is a key component in taking the next steps. The HydroCat-180 USVs will strengthen efforts to form a symbiotic relationship between a modern society and the natural environment. ◂

What is 'Hydrospatial'?

In the last decades, we have progressed from 'graphic' to 'digital' and now to 'spatial'. During the opening plenary session of the Canadian Hydrographic Conference (CHC) 2020, the author made a presentation on 'What is Hydrospatial?', before inviting a panel of four senior figures and the audience to discuss the topic.

THE ISSUE

The objective is not to oppose the words Hydrography and Hydrospatial; but to present that Hydrospatial is an expansion of Hydrography. What we do and its impact is obviously more important than a word can convey. However, words are how we express ourselves and, in particular, how we transmit our ideas and concepts to others. The marine geospatial revolution is so dramatic that it is recommended to adopt a new word to describe it; a word that conveys the image of the modern, hi-tech, multi-role, digital data environment in which we now operate. This word is 'hydrospatial'.

WHY, WHEN, WHO, WHERE, HOW & WHAT!

The type of data and the way in which hydrographers collect it is expanding, and the scope now goes well beyond nautical charting for safe and efficient navigation. This variety of data is now used and fused with data from land, coastlines, inland waters and offshore. This is the 'why' and the 'when' of hydrospatial!

Both defence and commercial shipping users of traditional hydrographic products, data and information now seek additional information and capabilities from hydrographic data. An ever-increasing community of additional users that seeks a green future through a sustainable blue economy is joining them. These are the users 'who' need hydrospatial data.

The managers of coastal zones must consider sea-level rise, coastal erosion, crustal subsidence and much more. Nearshore, offshore and remote areas everywhere

▲ *Denis Hains (speaker), seated left to right: Dr Mathias Jonas, Secretary General of IHO; Rear Admiral Sheppard Smith, Director of the Office of Coastal Surveys with the United States National Oceanic and Oceanographic Administration (NOAA); Dr Geneviève Béchard, Hydrographer General of Canada and Director General of the Canadian Hydrographic Service (CHS); Dr Ian Church, Chair of COMREN and Assistant Professor at the Ocean Mapping Group (OMG) of the University of New Brunswick (UNB), Canada.*

(including polar regions) are becoming more accessible and attractive both for natural resources and for adventurers. All of this drives the need for 'where' hydrospatial is needed.

Faster adoption of all remote sensing technologies and various autonomous crafts for marine data acquisition (satellite, airborne, surface, underwater, etc.) is needed. These are 'how' high-tech capabilities evolve and they deserve to be recognized with a name like 'hydrospatial', which inspires inclusion beyond the traditional.

THE SUGGESTED DRAFT DEFINITION

It is suggested that the definition of 'what' hydrospatial is be based on a modified version of the existing February 2020 International Hydrographic Organization (IHO) definition of hydrography, as follows:

25/02/2020: Hydrospatial is the branch of applied sciences which deals with the analysis, understanding and access to static and dynamic marine geospatial digital and analogue data and information, digital signals, measurement and description of the physical, biological and chemical features of oceans, seas, coastal areas, lakes and rivers from all possible available data sources in near-real time and real time, including their history and the prediction of their change over time. This for the purpose of: timely access to a standard, high-quality and the most up-to-date marine spatial data infrastructure; safety and efficiency of navigation; and in support of aquatic and marine activities, including sustainable blue environment and economic development, security and defence, and scientific research.

QUOTES FROM THE PANELLISTS

Based on the opening presentation, the four panellists aired their views, including the following quotes:

The IHO Secretary General commented: ... "to adopt a new word and official definition in the IHO Hydrographic Dictionary S-32 would require a formal proposal put forward to the affected experts of IHO's Hydrographic Dictionary Working Group. Hydrography is clearly going through major important changes that will require an expanded role serving an increasing group interested in the blue economy proponent... If this requires a new word to express the expanded scope and to address the third and fourth dimension of our undertakings, 'hydrospatial' will find its way into our spoken and written language."

▲ *Dr Mathias Jonas providing his perspective.*

The Hydrographer General of Canada remarked: …"showing how a new word can fill a gap by using it in sentences is more important than having it officially adopted. Just use it!"

The Director, US Office of Coastal Surveys, provided the comment: …"The field of hydrography is changing rapidly – we have access to both a wider variety and a bigger volume of relevant data than ever, and the demand for our data and expertise is growing beyond charting. This conversation about the language of identity is just the beginning. We need to also take a hard look at our education and qualifications in light of these changes."

The Chair of the Canadian Ocean Mapping Research & Education Network (COMREN), representing Academia, said: … "accredited academic programmes have already added material, courses and learning objectives that go beyond international requirements to adapt and keep up with the rapid technological changes in hydrography that could be qualified as hydrospatial... "

ENGAGING THE PARTICIPANTS

During this session, a live voting application to engage the audience was used. Detailed questions and results can be found in the Note published in the IHR. The vast majority considered that hydrography is going through a very important period of change, that education and training is adapting well, that hydrography is impacted by Artificial Intelligence (AI), that more time will be invested in data quality from multi-sources than from field work, and that more data will be acquired through crowd-sourced bathymetry, satellite-derived bathymetry and autonomous platforms. The majority agreed to adopt the word 'hydrospatial'.

CONCLUSION

Traditional hydrography as we know it, both in the past, now and for the future, is essential. Hydrospatial does not replace nor diminish hydrography, it expands it. As we enter the United Nations Decade of Ocean Science (2021-2030) and start the Nippon Foundation Seabed 2030 Project, moving toward the greater use of the word 'hydrospatial' highlights the traditional benefits and role of hydrography, while also emphasizing the new roles for our hydrographic geospatial data and the expertise in an exciting, modern and inspirational way. ◂

This article is a summary of a detailed published note in the International Hydrographic Review (IHR), May 2020 Edition on page 84-93 at: https://iho.int/uploads/user/pubs/ihreview_P1/IHR_May2020.pdf.

Denis Hains hold a Bachelor Degree in Geodetic Sciences from Laval University and is a Québec Land Surveyor. He worked for 35 years in the Public Service of Canada in Fisheries and Oceans Canada – including the Canadian Hydrographic Service (CHS), the Canadian Coast Guard and Natural Resources Canada's Canadian Geodetic Survey. He retired as Director General of CHS and Hydrographer General of Canada in 2018. He is the founder and CEO of H2i. He is also a Member of the Editorial Board of the International Hydrographic Review and the Strategic Advisory Group of The Nippon Foundation-GEBCO Seabed 2030. He is an Affiliate Research Scientist at the University of New Hampshire and a member of the Québec Land Surveyors Modernization Committee.

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Reducing Requirements for Manual Intervention

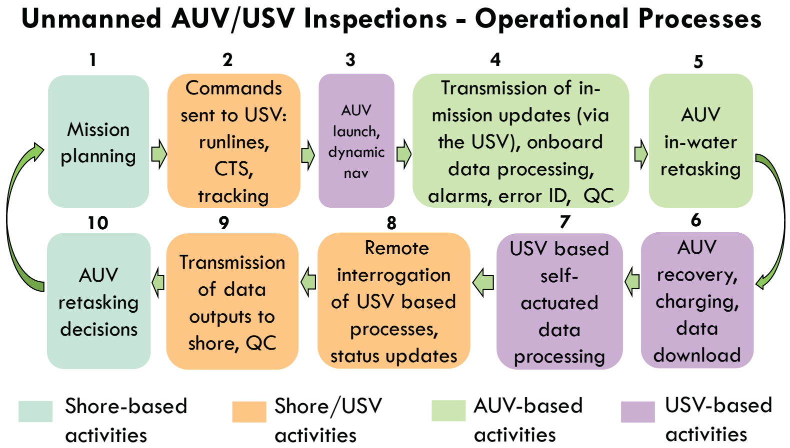
The Road to Autonomy: Unmanned Subsea Asset Inspection

In 2019, Swire Seabed successfully used a novel AUV/USV solution to complete a commercial pipeline inspection campaign, surveying 175km of pipe. This involved the use of a HUGIN AUV paired with the Sea-Kit Maxlimer USV. The 2019 survey campaign formed the final part of a developmental project involving Swire Seabed, EIVA, Kongsberg and Sea-Kit in which inspection work scopes were completed for Equinor. In this, emphasis was placed on the automation of survey processes, allowing remote command and control of operations. This work typifies the direction in which the industry is heading, with many survey companies now seeking to reduce requirements for manual intervention.

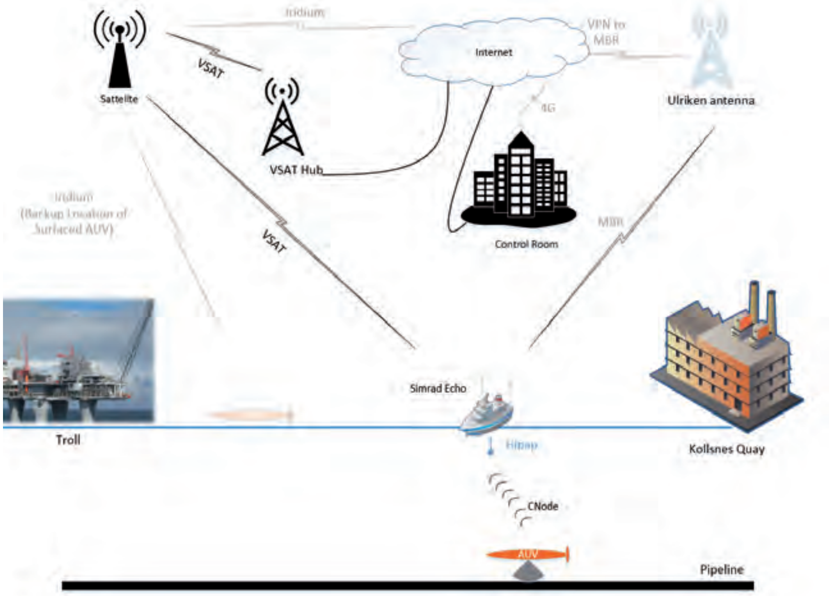
We are currently witnessing a rapid shift in the field of subsea survey and inspection, towards remote operations completed by unmanned vehicles. Automation is at the heart of this shift, and to reduce reliance on manual intervention and control, increasing levels of automation are required. Between 2018 and 2020, a commercial developmental project was undertaken by Swire Seabed, with Equinor as a client. The project aimed to implement automated processes in remote survey operations, to enable unmanned subsea pipeline inspections to be completed. The project successfully demonstrated how inspection campaigns can be undertaken with no personnel at sea, using an Autonomous Underwater Vehicle (AUV) operated from an Unmanned Surface Vehicle (USV), with missions controlled from a remote operations centre on land. Survey software running onboard the AUV facilitated in-mission data processing and the generation of vital alarms and quality control (QC) messages. These were relayed to shore, allowing mission alterations and retasking decisions to be made. The project resulted in the successful completion of the first commercial combined AUV/USV pipeline inspection campaign with over-the-horizon operations, and with pipline extents surveyed up to 100km from shore. This unmanned system was effectively used to create a standard set of pipeline inspection deliverables, as defined by Equinor.

SURVEY WORKFLOW

In 2018, Swire Seabed (who have now ceased operation), formed an agreement with Equinor to undertake a series of pipeline inspection work scopes using unmanned survey methods. The project required the combination and integration of existing technologies and methods in a novel manner. This also required new processes and procedures to be formulated, in addition to the automation of some of the standard, routine tasks usually completed as part of a survey workflow. Therefore, to meet obligations to Equinor, operational capacity had to be developed to allow unmanned subsea pipeline inspections to be completed using an AUV, launched and recovered from a USV. The Kongsberg Maritime (KM) HUGIN AUV was selected for the project and two additional onboard computers, supplied by EIVA, were installed on the HUGIN, one of which ran automated survey workflows (via Workflow Manager (WFM) software), and the other Deep Learning (DL) processes. A simple set of objectives was linked to the software implemented on these boards, including the implementation of functionality for real-time pipeline tracking and eventing, the creation of self-actuating data processing workflows, active QC, alarm generation, the automation of data analytics, and navigation aiding. Together, these functions form some of the fundamental actions required within the data ETL (Extract, Transform, Load) pipeline for autonomous subsea inspection operations. Furthermore, if successfully implemented onboard unmanned maritime systems (UMS), these processes could pave the way to removing existing client requirements for the use of large survey vessels,



▲ *Figure 1: AUV/USV unmanned inspection process diagram (CTS – course to steer).*



▲ *Figure 2: Pilot 1 operations – communication set-up.*

▲ *Figure 3: Sea-Kit Maxlimer transiting to commence inspection operations with the HUGIN AUV onboard.*

manned by extensive crews, for the completion of subsea pipeline inspection tasks.

The main activities completed during the project comprised of ongoing R&D works undertaken by development teams at Swire Seabed and EIVA, sea trials completed at KM's base in Horton using the HUGIN, and two pilot projects in which inspection campaigns were completed for Equinor. These pilot projects, which ran in 2018 and 2019, involved the inspection of seven of Equinor's pipelines located close to Bergen, Norway, with a combined length of over 350km. The project was drawn to a premature close early in 2020 due to the unexpected closure of Swire Seabed. Prior to this, however, the next phase of the project had commenced. This involved the design and build of a large USV, with facilities for launch, recovery and charging of an AUV, capacity for data download, and an onboard data management centre. Construction and subsequent use of such a craft was recognized as necessary to allow completion of extended missions, involving multiple AUV dives. The concept of UMS subsea pipeline inspection was effectively proven during the pilot projects; however, for this to be realized as a realistic commercial alternative to existing survey solutions, the operational limitations, which imposed constraints on the number of AUV dives per USV voyage, would need to be removed.

A flow diagram of the typical processes to be completed in a combined AUV/USV inspection campaign is detailed in Figure 1. During this project, it was not possible to implement all the processes listed in this diagram as only a single AUV dive was completed within each mission offshore. The operational capacity implemented during the pilot projects did allow processes one through to five to be completed. It was envisaged that utilization of the larger, planned USV would facilitate completion of the remaining processes.

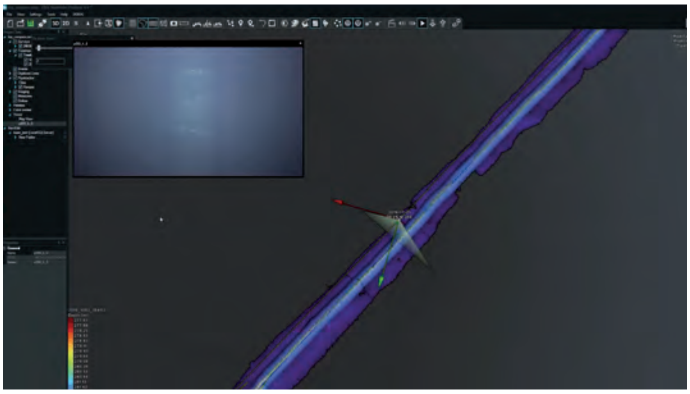
PILOT PROJECTS

The first pilot project was completed for Equinor in 2018. This tested the operational procedures that Swire had developed for running a full survey campaign remotely from a shore-based control centre. Overall, Pilot 1 was successful and the pipeline assets linking Equinor's Troll field to their Kollsnes processing plant on the island of Sotra, close to Bergen, were inspected. The communication infrastructure at the heart of these remote operations was, and is, the enabling factor allowing such unmanned processes to occur. Figure 2 provides a rough indication of the communication lines utilized in the project, with satellite communications and Maritime Broadband Radio (MBR) forming the main communication links.

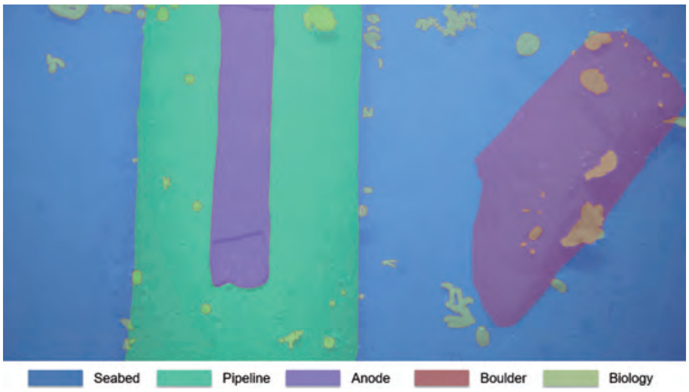
The Sea-Kit Maxlimer USV was planned for the project in Pilot 1, but due to a clash in timings it was not available. As a result, the project resorted to using a manned vessel (the *Simrad Echo*), which simulated the role of a USV. Operations were still completed in the same manner, with command and control situated onshore, but manual AUV launch and recovery was required. This was not the case in Pilot 2, where it was possible to pair the HUGIN with the Sea-Kit USV (Figure 3). During Pilot 2 missions, successful unmanned AUV launch and recovery was completed offshore. Data acquisition was controlled and monitored from the shore-based control centre, and four pipelines with a combined length of 175km were surveyed. Operations undertaken as part of Pilot 2 included a world-first for an over-the-horizon commercial pipeline inspection using UMS. No external assistance was provided to the operation of the USV and AUV; however, due to regulatory requirements in place in 2019, a guard vessel remained in the vicinity of the USV during missions.

SOFTWARE AUTOMATION

EIVA developed software functionality during the project, which was installed on the two boards integrated into the HUGIN AUV. In pilot project operations, EIVA's DL board was used primarily for pipe tracking using image data, while their WFM board enabled data processing to begin onboard the AUV, for alarms to be generated and transmitted to shore, and for data QC and analysis to be undertaken. Figure 4 shows a post-mission visualization generated, illustrating the Top of Pipe (TOP) position created in real time, using functionality installed on the DL board; image data corresponding to the on-screen tracking point is shown in the left of the figure. Additional pipe tracking methods based on Multibeam Echosounder (MBES) and laser data were developed during the project and tested in simulator dives following Pilot 2; however, it was not possible to implement these methods on the HUGIN prior to the project's cessation.



▲ *Figure 4: Image showing a pipeline track as detected in real time from image data during Pilot 2. The tracking point on-screen accompanied by red and green arrows indicates the camera focal point that the image in the top left of the screen relates to.*



▲ *Figure 5: An example of DL-based automatic pipeline eventing using image data (Image Courtesy: EIVA).*

The DL pipeline eventing methods developed by EIVA were implemented offline during the course of the project and tested using data obtained from both pilot projects. However, the longer-term goal was to migrate these processes to the DL board onboard the HUGIN, so that eventing could be carried out in near real time. The DL eventing methods that were developed did prove effective in identifying field joints and anodes (Figure 5), and in addition to providing event listings, functionality was developed to use detected features for navigation aiding. Post Pilot 2, EIVA refined a navigation aiding method based on anode identification, which involved comparison of the known and observed positions of detected anodes. The long-term aim of this, and other similar navigation aiding methods under development, is to generate outputs that can feed back into the HUGIN's control system to form dynamic navigation aiding inputs.

It was possible to implement a range of software functions during the pilot projects, most of which involved processes developed for the WFM board. Self-actuating data processing workflows were tested during Pilot 2, and these allowed data processing, cleaning and QC tasks to commence onboard the AUV and then to continue onshore post-mission. In addition to this, the WFM board also ran processes that triggered alarms when specific conditions were present, such as poor visibility, inadequate data coverage, missing sensor inputs, and the pipeline not being detected. It was possible to transmit these alarms to the USV via a low-bandwidth acoustic link. The alarms were then transmitted back to shore, alerting operators of critical conditions so that a manual decision could be taken for the in-mission retasking of the AUV. During the pilot project, alarms were only used to inform operators; however, the longer-term plan is for the outputs of these alarms and QC processes to form inputs to automated AUV retasking routines.

A range of pipeline inspection-specific analytical processes were also developed during the project and run offline. However, EIVA's aim is to slowly migrate these processes to the onboard computer running WFM. Despite these processes not being tested operationally onboard an AUV, simulator tests revealed that significant time and efficiency gains were possible by running the automated analytical processes developed, such as pipeline digitization, tagging, data classification and QC. For example, functionality was developed for the automated cleaning of MBES data points based on pipe diameter, once TOP was determined from pipe tracker data. The automation of data processing, cleaning, QC and analysis was recognized as essential to furthering the levels of automation possible in UMS inspection missions. Many of these tasks would normally be completed manually offline, yet they form vital inputs to AUV retasking decision-making processes. Automation of such functions, and the ability for these to be completed onboard an AUV prior to its recovery, could radically reduce the overall duration of inspection campaigns, especially if it were possible for the outputs of these tasks to form inputs to automated retasking routines.

THE END OF THE BEGINNING

Despite this project having ended, in the words of a great man: "Now this is not the end, it is not even the beginning of the end, but it is, perhaps, the end of the beginning" (Winston Churchill, 1942). Work in this field is progressing rapidly, and the benefits of further progressing unmanned pipeline inspection solutions are obvious: efficiency gains, reduction in costs (vessel time and man hours), and minimization of environmental impacts. However, a significant distance is yet to be covered along this road to automation. While we are now able to complete unmanned operations with humans in the loop as remote decision makers, in the near future we aim for the automatic in-mission retasking of UMS, allowing larger work scopes to be completed. The ultimate goal is for the role of humans in this loop to diminish to a level where we are only required to oversee operations. Lessons learnt during this project have highlighted the importance of focusing on a number of key areas to achieve this goal, including hardware and software development, optimization of maritime communications, automation of data processing and analysis, navigation aiding, and automated AUV retasking. ◀

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Research Platform with Unique Six Degrees of Freedom Control Capabilities

Introducing MARIN's mAUV

Autonomous underwater vehicles are becoming more and more common in the maritime industry, and technology is rapidly developing for different applications, such as inspection, maintenance and surveillance. Meanwhile, more advanced autonomous capabilities are required, to be able to perform complex tasks and challenging missions. The Maritime Research Institute Netherlands (MARIN) has designed and built a modular Autonomous Underwater Vehicle (mAUV) for research projects in its model basins. The objective of this research effort is to expand the knowledge of vehicle control and to gain a better understanding of autonomous underwater operations.

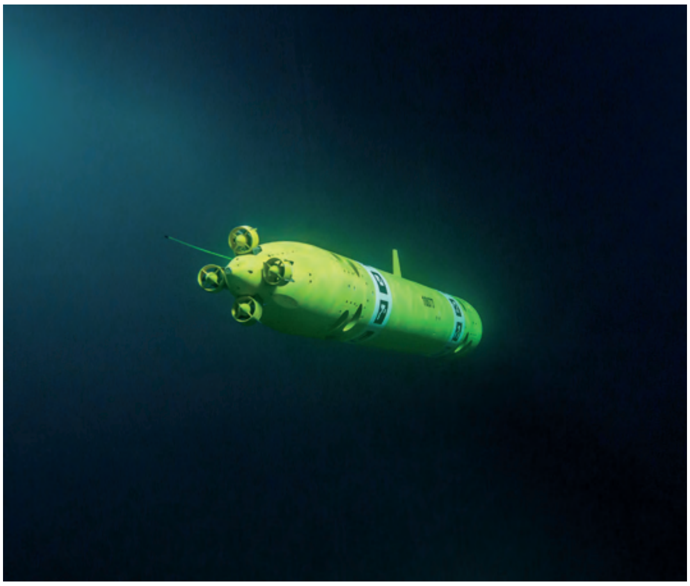
MARIN has a lot of previous experience with dynamic positioning (DP) systems for ships and offshore structures and with autopilots for sailing ships. It has also built free sailing models of submarines, which include autopilots and control with rudders and sail planes. Experience in these areas played an important role in the development of the mAUV. The challenge was to develop an underwater vehicle with full six degrees of freedom (DoF) control, without any limitations. Furthermore, the aim was a vehicle capable of efficient travel at high forward speed while also able to hover in a fixed position and orientation. This is a unique combination of capabilities.

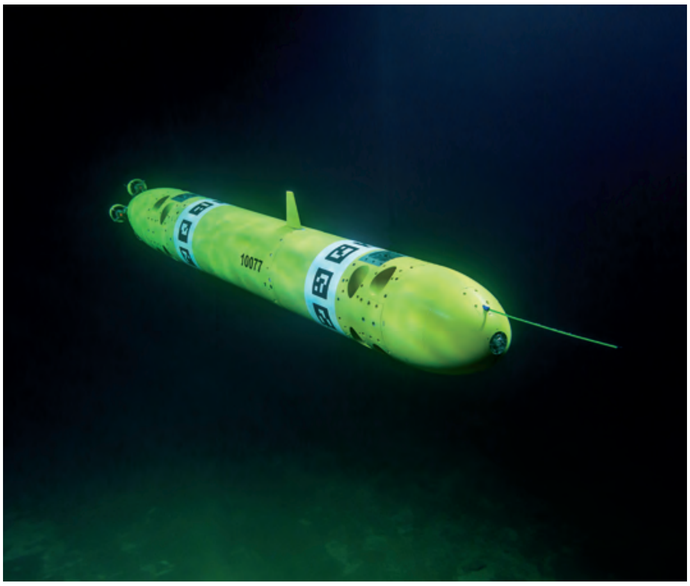
The mAUV is now operational, with vehicle control and path-following available and tested. The next steps are autonomous capabilities, including advanced navigation, collision avoidance and additional actuators.

VEHICLE CONCEPT

The vehicle concept development started with the definition of a number of (self-imposed) design requirements, including the ability to control in all six DoF, combining hovering with travelling at high forward speeds, and a modular construction, allowing for future modifications. The set-up of the control software is also modular, to allow easy reconfiguration.

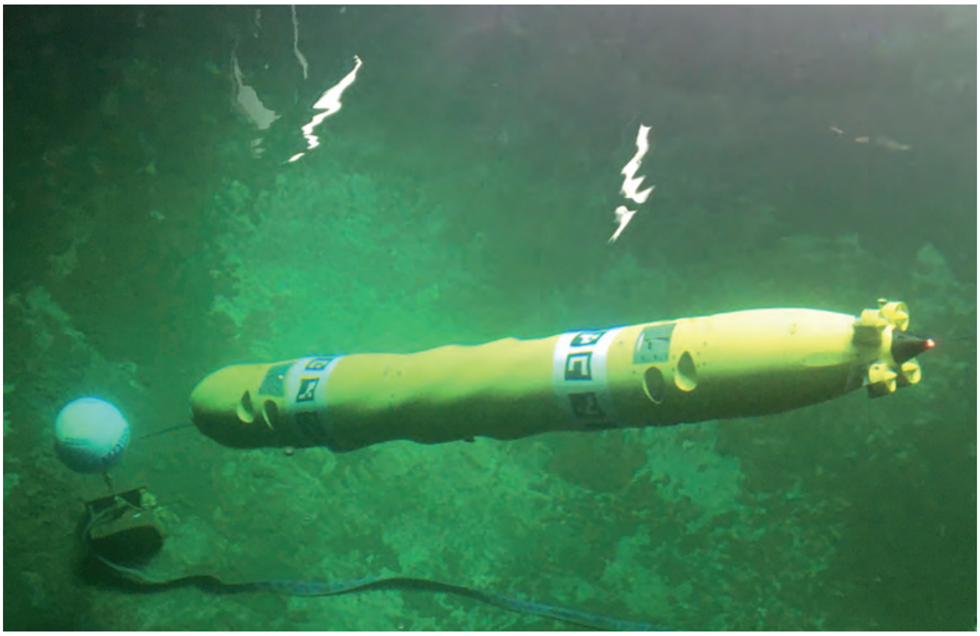
Subsequently, the general vehicle layout, thruster configuration and main particulars were selected. The cylindrical hull shape was selected for its streamline, easy manufacturing, and the possibility to include additional segments for future modifications and additions. The bow section has a cylindrical shape and the stern section a parabolic shape, both of which have also been used in concept designs of submarines. This resulted in a geometry with good streamline properties. The length and diameter were based on the internal space necessary to place all actuators, sensors and electronic systems.





HARDWARE, SENSORS AND ACTUATORS

MARIN has a lot of experience with developing and building free running ship models for basin experiments, as well as submarines. This means that most of the necessary technology to design, develop and build the mAUV is available in-house. The vehicle design was centred around a 3D CAD model, which was continuously updated, as all sub-systems (electronics, motors, sensors, computer hardware, electrical systems, communication systems and software) were developed and finalized by the various technical specialists.

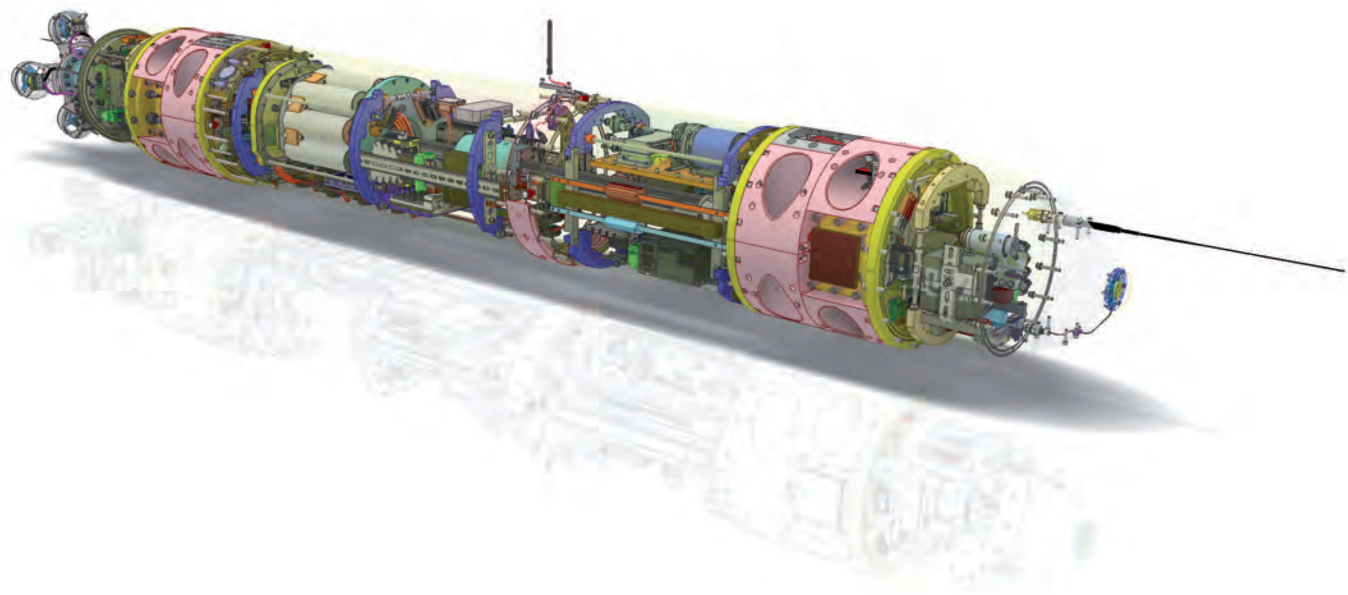


Several actuators can be used to control the position and orientation of the mAUV. These include multiple thrusters: four stern thrusters (main propulsion), four horizontal tunnel thrusters (transverse motions and heading change) and four vertical tunnel thrusters (vertical motions and pitch control). To reduce development time, readily available T200 thrusters from Blue Robotics were selected. Two internal trim tanks were also added at the bow and stern to adjust the vehicle's weight. The capacity is limited, but sufficient to change from the floating condition to neutrally buoyant at the start of each mission.

The vehicle has several internal sensors for navigation and control. For example, it has an Inertial Navigation System (iXblue Phins C3 INS) to measure the vehicle's attitude, acceleration and rotational speed. Aiding signals (position) are used to estimate vessel position and linear velocities. Finally, an Attitude Heading Reference System (Xsens Mti-300 AHRS) was added to measure vessel attitude and acceleration.

VEHICLE CONTROL STRATEGY

The mAUV can be controlled in all six DoF. This means that the vehicle can follow any track imaginable, offering maximum flexibility to perform its missions. PID control is currently used for the vehicle position and orientation. A non-linear mapping is applied to the quaternion attitude measurement that transferred the non-linear model into a linear one. A state feedback controller is designed based on this transferred model, controlling position and attitude. Robust stability was explicitly tested for uncertainty in the hydrodynamic coefficients and for a range of surge velocities. Alternative control approaches, such as model-based control, will be investigated in the future."
During operation, the vehicle changes between different operational states, such as 'idle', 'trim' and 'waypoint tracking'. Each operational state has its own behaviour. Switching between states



is handled by the state machine, a part of the vehicle control system that defines the behaviour of the mAUV. If necessary, the state machine also performs safety procedures, using the operational states 'brake' and 'surface'. This avoids possible damage to the vehicle in the case of technical problems, such as a thruster or sensor failure.

SIMULATION MODEL

The control system of the mAUV was developed and tested in parallel with the design and construction of the vehicle itself. This was made possible using a digital twin of the mAUV. The digital twin is a time-domain simulation model of the mAUV, which describes the rigid body dynamics, hydrodynamic reaction forces, all 12 individual thrusters, ballast tanks and the internal moving mass. The model was made using MARIN's in-house XMF modelling software. The simulated vehicle can be controlled manually by joystick, or linked to the vehicle control software. The digital twin is a complete representation of the vehicle dynamics and can therefore be used to design and test the vehicle control system. This allowed for the vehicle hardware and software to be developed in parallel. Furthermore, development and testing with a digital twin instead of a physical vehicle is much less time consuming, allowing the analysis and optimization of many different conditions.

BASIN EXPERIMENTS

After completion of the mAUV, the performance of the vehicle was assessed in a series of model basin tests. The advantage of testing in a basin rather than an outside location is that the environmental conditions can be controlled and access to the vehicle between tests is very easy.

After connecting the control system, all vehicle hardware components were carefully checked and all communication connections were tested. Then, a series of experiments were carried out in MARIN's Seakeeping and Manoeuvring Basin (SMB). The first was a set of parameter identification tests, the objective of which was to determine the vehicle added mass and damping, as well as the maximum thrust values. These parameters were derived from the measured vehicle motions and the results were used to improve the accuracy of the vehicle's digital twin. The second series of tests were operational limits tests to find the current performance limits of the vehicle. Maximum forward and transverse speeds were determined, as well as maximum rotational speeds. Furthermore, tests were carried out with the mAUV travelling at different drift angles. The last series of tests aimed to demonstrate possible applications of the mAUV. The demonstrations included manoeuvres that represented a mine inspection mission, a lawn mower pattern for a survey mission, a fast spiral, vertical positioning with the nose above water and a quay wall inspection.

A demonstration day was organized at the end of the test campaign, attended by representatives from various companies in the Dutch maritime sector. The many interesting discussions resulted in new ideas for potential applications of the vehicle and further research.

FUTURE DEVELOPMENTS

The mAUV is currently capable of following a predefined track, defined in six DoF. For real autonomous operation, however, additional capabilities need to be developed. Several topics are on MARIN's research agenda, including relative navigation for precise navigation near fixed objects (e.g. docking stations, underwater structures) or other vehicles (e.g. moonpool for launch and recovery). These research efforts will involve hardware development, position estimation algorithms and vehicle control strategies. MARIN will also look at additional actuators for more efficient vehicle control at a higher forward speed. This will involve actuator design, vehicle control strategies and allocation algorithms. Lastly, sensor fusion and situational awareness algorithms will be used to investigate the performance of lower cost motion sensors. For certain applications, this may be an alternative to a navigation grade INS.

CONCLUSION

MARIN has designed and built a modular Autonomous Underwater Vehicle (mAUV) for research projects in its model basins. The vehicle has unique control capabilities that may be applicable for different autonomous tasks in the maritime domain. The vehicle, its control system and its capabilities for autonomous operation will be further developed through ongoing coordinated research projects. MARIN actively seeks partners to continue developing the mAUV technology. Finally, it aims to assist industry parties in their vehicle developments, using simulation studies and basin tests that focus on vehicle design and optimization. ◀

Videos

https://vimeo.com/403010822 (MARIN mAUV project)

https://vimeo.com/383072983 (mine inspection mission)

https://vimeo.com/383961461 (lawn mower pattern)

References

- "Design of an Underwater Vehicle for use in Basin Experiments - Development of MARIN's Modular AUV", Hans Cozijn, Haite van der Schaaf, Bas de Kruif, Egbert Ypma (MARIN), IFAC-CAMS Conference, Daejeon, Korea, 2019.

- "Control Design for a Multi-regime 6-DOF Underwater Vehicle - Development of MARIN's Modular AUV", Bas J. de Kruif, Hans Cozijn, Haite van der Schaaf, Egbert Ypma (MARIN), IFAC-CAMS Conference, Daejeon, Korea, 2019.

Hans Cozijn
Hans studied Naval Architecture and Marine Engineering at Delft University of Technology. After 20 years of experience in hydrodynamic scale model testing and computer simulations of offshore structures, Hans moved to MARIN's new Autonomy & Decision Support team to work on the development of autonomous vehicles.

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Bas de Kruif received his MSc and PhD in control engineering at the University of Twente, the Netherlands. He has been working between industry and academia ever since, and enjoys bringing cutting edge solutions to practical problems. For the last few years, he has been working on maritime applications within MARIN's Autonomy & Decision Support team.

Haite van der Schaaf
Haite studied Electrical Engineering at the University of Twente. After his graduation, Haite started developing instrumentation, software and systems with a strong focus on Mechatronics and Measurement & Control technologies. For 20 years, Haite has held various positions at MARIN in the field of instrumentation development and project management.

Egbert Ypma
Egbert studied Naval Architecture & Marine Engineering at Delft University. After his military service in the Dutch Navy he worked for Heerema (working on simulations, DP systems), Imtech (Integrated Bridge & DP) and Global Maritime (DP, FMEA). He joined MARIN in 2005, where he worked in various departments. Since 2019, he has been team leader of the new MARIN Autonomy & Decision Support team and responsible for the similarly named research programme.

A New Way to Monitor Your Data

Automatic Calibration for MBES Offsets

Currently, calibration of MBES for hydrographic surveys is based on the traditional 'patch test' method. This subjective method, although rigorous, has major drawbacks, such as being time-consuming (both data acquisition and processing) and supposing that potential angle misalignments can be considered as uncoupled. A new algorithmic solution, providing an objective and repeatable first step to the automation of the calibration process, is offered through the MSPAC solution.

Hydrography is essential in many marine activities:

- Ensuring navigational safety for nautical charts and dredging.
- Acquiring accurate knowledge of environmental background for offshore installations and dredging.
- Modelling the seabed for marine energy prospection.

Multibeam echo-sounder technology has evolved rapidly in recent years (multi-frequency, multi-swath, real time compensation, etc.), which has led to major improvements in spatial resolution and bottom coverage. To maximize benefits from these improvements, a careful calibration of the survey system has to be undertaken, but after the work carried out in the 1980s and 1990s that lead to the well-known patch test method, the subject has received limited attention. It is therefore time to move forward.

CLASSICAL PATCH TEST

The patch test decouples the three boresight angles by surveying characteristic areas following a specific pattern. For the roll angle, a flat bottom is surveyed in opposite directions. For the pitch angle, a slope or a particular seabed feature is surveyed in opposite directions. The effect of yaw is classically determined by identifying a target over a flat bottom, and surveying it from two parallel and overlapping survey tracks heading in the same direction. As an example, Figure 1 sketches the configuration needed to determine the roll boresight angles.

While this method is particularly efficient, it has a series of drawbacks, such as:

- Prior knowledge of the area is required.
- Very accurate horizontal positioning is assumed.
- Boresight angle estimation is operator-dependent (manual data processing and morphology fitting).
- No estimation is made of the precision of the resolved angles.
- Only angles are resolved; lever arms are assumed to be correct.
- Latency between the IMU and multibeam is not resolved.

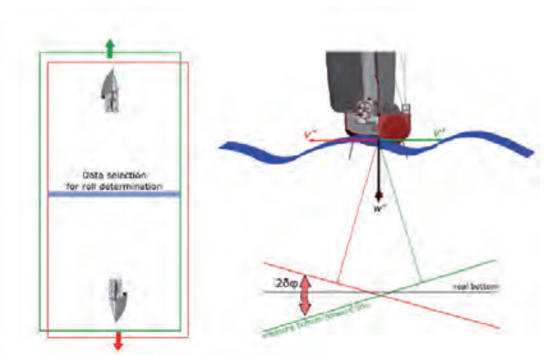


Figure 1: Top view of the two reciprocal lines on the left and effect of roll boresight on two opposite lines on a flat seafloor on the right, from [1].

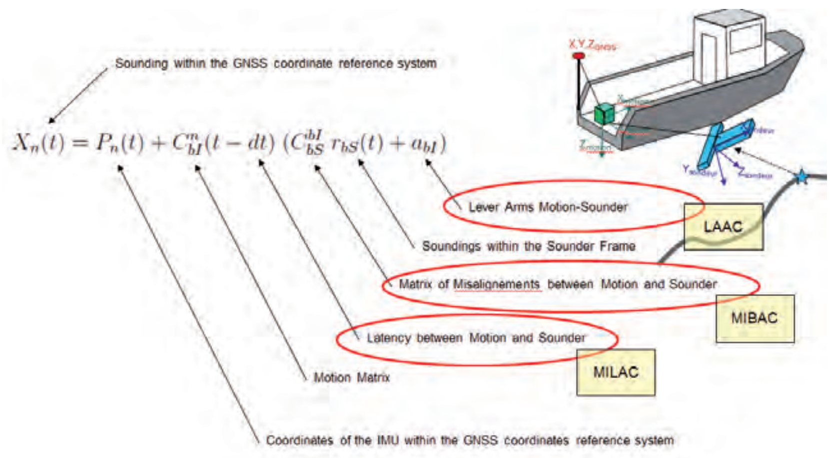


Figure 2: Geo-referencing equation for bathymetric data and the MSPAC software suite Shom.

MSPAC SOLUTION

To address some of these shortcomings, a new calibration procedure has recently been developed by CIDCO, Shom and ENSTA Bretagne. The ambition is a new robust and objective methodology that provides a solution for the boresight angles and the latency and lever arms estimation, based on a specific data selection procedure for a plane-robust least squares adjustment model. This solution also saves time during acquisition and processing. Figure 2 details the classical geo-referencing equation of bathymetric data as well as the quantities that MSPAC (Multibeam System Parameters Automatic Calibration) aims to resolve using three sub-modules: MIBAC (Multibeam IMU Boresight Automatic Calibration), LAAC (Lever Arms Automatic Calibration) and MILAC (Multibeam IMU Latency Automatic Calibration).

RESULTS AND DISTRIBUTION

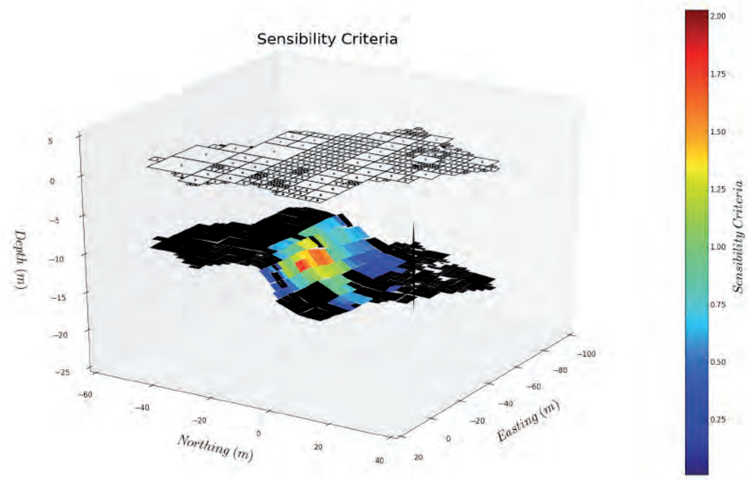
The results of these algorithms are presented in detail in articles [2] and [3]. An example of the data selection made by MIBAC is shown in Figure 3. In this figure, the seabed is modelled as a grid of surface elements. For each element, a sensitivity criterion is calculated to indicate areas where boresight angles cause the most distortion of the seabed.

Figure 4 shows the results of the comparison between a traditional patch test and MIBAC. These results have been freely distributed, so that everyone can experiment with and test these algorithms. The study reports (under 'licence ouverte'/, a French open license) and the source codes (under CeCILL license, GPL compatible license) can be found at gitlab.com/GitShom/mspac/shom-mibac. The Shom disclaims any responsibility for the operational transfer as well as the maintenance of this software. Stakeholders are of course invited to use, improve and industrialize these source codes.

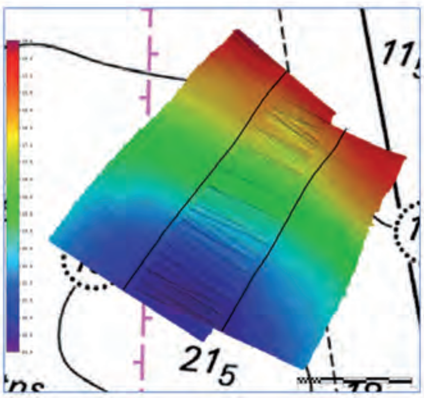
INDUSTRIALIZATION

The software is being continuously improved by the open source community to allow customizations of various aspects such as:

- Total propagation of uncertainty.
- Planar surface element detection.
- Least squares estimation.



▲ *Figure 3: MIBAC data selection on a real dataset, from [1].*



	Roll	Pitch	Heading
Patch Test	+0.83°	+0.70°	+1.30°
MIBAC	+0.8519° (±0.0005°)	+0.7457° (±0.0044°)	+1.3946° (±0.0044°)
Difference (Patch Test-MIBAC)	-0.0219°	-0.0457°	-0.0946°

▲ *Figure 4: Above, EM2040c Brest harbour survey strips in order to compare the methods (the DTM highlights the angular misalignments over the overlap area). Below, the difference between patch test and MIBAC offset values on these survey strips.*

This will allow, for example, the incorporation of different methods for identifying planar surface elements, such as [4]. Several internal parameters are currently inaccessible to the user, such as:

- Iterative thresholds.
- Statistical test parameters.
- Planar surface elements modelling.

As with all open source endeavours, the code can be parameterized to suit customer-specific needs either by CIDCO or third-party developers.

The current state of MSPAC is only available from a command line interface and a graphical user interface would greatly improve the user experience. We welcome this initiative to publish MSPAC codes under open source licences and we look forward to working with stakeholders and members of the open source community on further developments of the MSPAC calibration suite.

CONCLUSION

The automation of the calibration workflow is an essential step in the droning of acquisitions at sea. Even if the results seem very interesting, it is also necessary to have a good quality positioning source (RTK or PPP) and a bottom morphology corresponding to a gentle slope to obtain the best results. In addition, the proposed solution makes it possible to provide a statistical uncertainty on the measurement as well as an objectivity that is difficult to achieve with the classical patch test. It also makes the automation of calibration procedures possible, especially for drones. The contact person for the MSPAC solution industrialization is jordan.mcmanus@cidco.ca. ◂

Acknowledgements
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Further Reading

- [1] Le Deunf, J., 2015. Data selection for a boresight estimation algorithm. Master thesis report.

- [2] Keyetieu, R., Seube, N., Multibeam Echo Sounders-IMU Automatic Boresight Calibration on Natural Surfaces. Marine Geodesy, Volume 40, 2017, pp 172-186.

- [3] Keyetieu, R., Seube, N., Djine, V., Roue, G., Clement, B., Bosser, P., 2018. Multi-Beam Echo Sounders–INS Automatic Latency Calibration. Marine Geodesy, Volume 41, 2018, pp 477-493.

- [4] V. Dupont, S. Daniel and C. Larouche, "A region growing algorithm adapted to bathymetric point clouds," OCEANS 2019 MTS/IEEE SEATTLE, Seattle, WA, USA, 2019, pp. 1-6. DOI: 10.23919/OCEANS40490.2019.8962821

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