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Development of Digital Bathymetric Models from Hydroacoustic and Photogrammetric Data

Sentinel-2 Satellite-derived Bathymetry in Optically Complex Waters

Examining Developments in Constellations, Augmentation and Receivers

Incremental Improvements in GNSS

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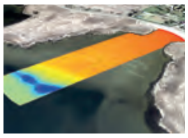
Coastal areas are highly dynamic environments that are subject to diverse pressures, both anthropogenic and natural. These pressures result in intensive and frequent seafloor alterations that demand efficient monitoring methodologies to produce repetitive updating of the seafloor morphology and bathymetry. Bathymetric information is essential in many coastal aspects, including environmental, management, research and economic.



Unmanned vehicles, both surface and airborne, are increasingly being used for hydrographic surveying. While the technology of data acquisition using these platforms is generally known, the fusion of this data is still the subject of much research, and the methods applied often depend on the sensors used and the properties of the survey area. This study presents a method for fusing data acquired using USV and UAV measurement platforms to develop a digital bathymetric model. The case analysed concerns shallow water and ultra-shallow water up to the boundary with the shoreline.

It is almost impossible these days to imagine geoinformation without GNSS, and even most geodetic services have switched to GNSS to maintain their geodetic reference network, rather than using traditional optical techniques. This article explores the state of the art in GNSS, from a constellation, augmentation and receiver perspective. Spoiler alert: it is more of an evolution than a revolution!

The monitoring of submerged deadwood and vegetation is gaining increased attention due to their socio-economic and ecological importance. Deadwood acts as an important underwater habitat but also poses a threat to bridges, hydroelectric power plants and riverside buildings. Underwater vegetation, in turn, is a proxy for climate change in general and global warming in particular. In this context, UAV-borne topobathymetric laser scanning constitutes a promising tool for accurately capturing and modelling these small-scale objects in high spatial resolution.

Cover Story

The front cover of this issue of *Hydro International* shows a WAM-V 8 autonomous surface vessel in action. The hydrography sector is increasingly turning to robotic, uncrewed and autonomous solutions to conduct systematic seafloor surveys for hydrographic applications. New sensors, system interfaces and algorithms are being developed for uncrewed systems at an impressive rate, which will have positive impacts on crewed operations as well. (IMAGE COURTESY: MARINE ADVANCED ROBOTICS)

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The Semantics of Positioning

What's In a Name?

Some time ago, I received an email containing questions from a reader of one of my publications. The questions were both easy and very hard to answer. The first was whether PPP should be considered an SBAS; the second whether QZSS and NavIC should be classified as a GNSS or an augmentation system. Those aware of my career may know that, for around ten years, I was responsible for a semantic standard for the exchange of water information. From that perspective, I should be jumping with joy at such questions. However, even while I was working on semantic standards, I usually gave more thought to the structure and content of data than to the semantics. To quote a famous author, a rose by any other name would smell as sweet. So, without mincing words, Shakespeare has my vote on semantics. A name is for stating what is meant but it is the item itself that is important, not its name. The name should be as unique as possible and have a clear definition, so that we do not get confused when talking about the item, but that is that as far as I am concerned.

Coming back to the two questions; from a semantic perspective, they were quite hard to answer. When terms like SBAS and GBAS were developed, GNSS life was simple. The S in SBAS referred to the mode of delivery, which was by radio signal from a satellite. In GBAS, the transmitter was on the ground. So, PPP from commercial suppliers in the offshore industry could still be classified as SBAS, as they usually convey their correction signals using satellites. However, what to do with the PPP computations we perform using similar data from the internet? Is the same system in that situation not a GBAS if we use landlines to obtain the corrections?

Moving on to NavIC (formerly known as IRNSS), this is a satellite navigation system and not an augmentation system, that much is clear. But notice that I do not say it is a global navigation satellite system and therefore a GNSS. NavIC is regional (over India) and therefore an RNSS. QZSS makes things even more difficult, as the system so far has been an augmentation to GPS over Japan. However, in the next few years the system will provide signals that should allow autonomous positioning, and then it will become an RNSS rather than an augmentation system.

A few days after I had replied to these questions, a newsletter from the European Space Agency (ESA) found its way into my mailbox. ESA is now developing a receiver for positioning a satellite orbiting the moon. Now, if GNSS is (Earth) global and RNSS is (Earth) regional, what do we call the same system if we start using it around the moon? The satellites will stay in the same place, it is just the receiver that will be in orbit around the moon. But to say it is a GNSS would be incorrect, I think. Maybe we should go for MNSS or, to prepare for the future, SSNSS (Solar System Navigation Satellite System)? After all, the signals from current GNSSs are already used for positioning other satellites and spacecraft. Or is a satellite orbiting the moon in the same league as the spacecraft circling the Earth, and therefore still part of the 'global' of the GNSS?

To come back to Shakespeare, should we really care about these discussions? To me, they are to a certain extent primarily academic. Many articles can be written about a topic like this and, in the end, we probably would have to agree to disagree as there might not be a unique set of classifications. After all, as a philosopher once asked me, are cough drops a medicine or sweets? Most supermarkets solved this issue a long time ago by placing them on both shelves to increase sales… In the end, the issue does not seem to be the definition, as we all agree on what GPS, QZSS or NavIC actually do or how PPP works and what sort of accuracy to expect from it. We can then label them so that we can distinguish them from other systems, ensuring that – on the system side – the definitions and terminology are clear enough. Things go wrong when we try to uniquely classify these systems and then find that there is always at least one system that does not properly adhere to our classification as it crosses an artificial (semantic) barrier or because the world has changed and a previously clear classification is now very confusing.

Back to the moon; it is not the question which type of navigation system this will create that is exciting, but the fact that we are now trying to build a system that will position a satellite to an accuracy of around 100m while orbiting the moon. This is quite a feat when you realize that most (yes, not all…) navigation satellites orbit Earth at a distance of around 20,000km, whereas the distance between Earth and the moon is around 363,000km at its closest point. That means that the signals will have to travel at least 17 times further, which in turn means that the signals will be very weak upon arrival, even considering that they only have to travel through space and not through the Earth's atmosphere. We also need to realize that the antennas of these satellites will be pointing towards the Earth and not necessarily towards the moon, making the signals even weaker. And then the orbiter disappears behind the moon for some part of its orbit…

Let us consider this step in navigation without discussing in which category it falls. And if you really want to classify the outcome, it falls in the category 'over the moon', which in a few decades will probably be classified by the majority of people as 'run of the mill'.

Huibert-Jan Lekkerkerk, technical editor
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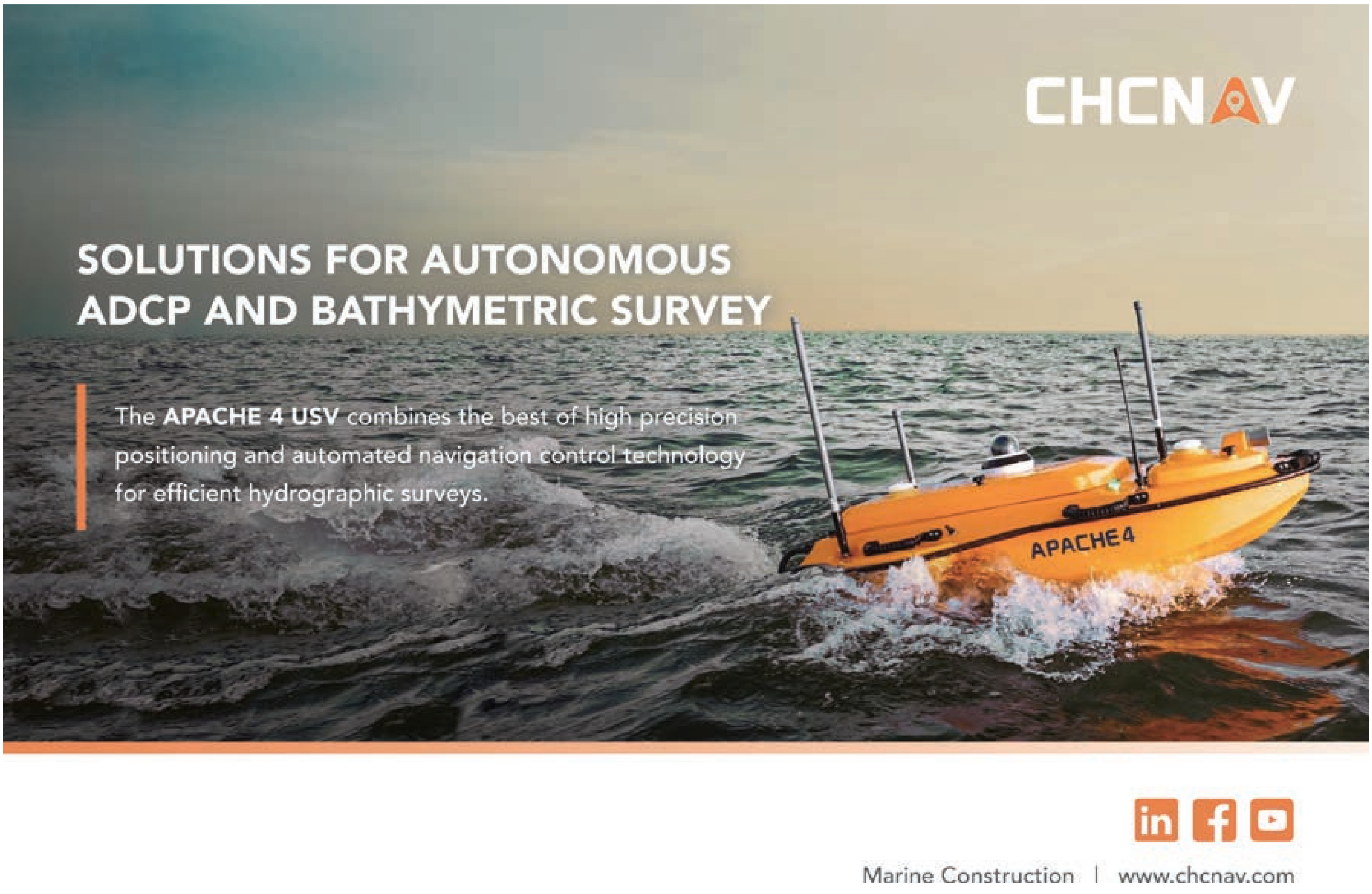
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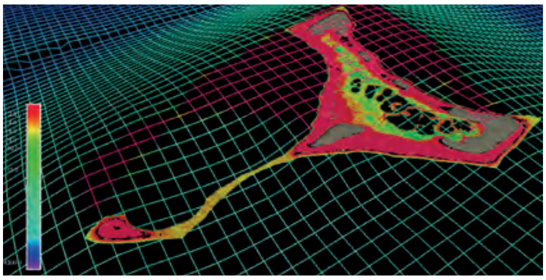
Tropical Seafloor Secrets Discovered as Seabed 2030 Gains Momentum



▲ Pukapuka Atoll satellite-derived bathymetry overlaying pre-existing data in the GEBCO Grid. (Courtesy: NIWA)

Satellite technology has been used to chart shallow areas of the Cook Islands' sea floor in never-before-seen detail by scientists at the National Institute of Water and Atmospheric Research (NIWA) and Toitū Te Whenua Land Information New Zealand (LINZ) working with the satellite data analytics company EOMAP.

The work was carried out as part of The Nippon Foundation-GEBCO Seabed 2030 Project – a collaborative project aiming to bring together all available bathymetric data to produce the definitive map of the world ocean floor.

The chart of Suwarrow and Pukapuka in the Cook Islands builds on decades-old surveys, with more accurate positioning and wider coverage, including information on harder to reach areas such as shallow lagoons.

Kevin Mackay, a marine geology researcher at NIWA, also heads Seabed 2030's South and West Pacific Ocean Data Centre – one of the project's four regional centres, each responsible for data gathering and mapping in their territory. Commenting on the use of satellites as a tool for measuring the shallow parts of the ocean floor, he said: "To measure the depth of the ocean, you would traditionally have to send out a boat with an echosounder, which costs a lot of money and can be dangerous in rough and shallow seas. With satellites, we can access extremely remote locations, with a smaller carbon footprint, and without having to endanger people."

UKHO Provides S-100 Navigation Data for Mayflower Autonomous Ship

▲ The Mayflower Autonomous Ship. (Courtesy: IBM/ProMare)

The UK Hydrographic Office (UKHO) has announced that it is the provider of S-100 navigation data for the Mayflower Autonomous Ship (MAS) project. This marks the first time that S-100 data will be tested aboard an unmanned or autonomous marine vessel. The vessel is currently in Plymouth Sound in the UK, undergoing a sea trial that started on 28 March 2022 and testing the ability of the ship to read, integrate and use S-100 data.

The UKHO is funding the integration and testing of S-100 Universal Hydrographic Model data into the artificial intelligence (AI) and machine learning (ML) software stack for the MAS project. The S-100 data provided by the UKHO is designed to be machine readable and have a higher resolution than S-57 electronic chart data, which MAS previously relied on to inform the onboard mission manager – and will be the future standard supporting digital navigation products globally.

Sonardyne Technology Helps Locate Shackleton's Historic *Endurance* Vessel

▲ One of the Endurance22's two Saab Seaeye Sabertooths, showing the blue cap of Sonardyne's AvTrak instrument near the front of the vehicle. (Photo: Esther Horvath / Falklands Maritime Heritage Trust)

After more than 100 years lost more than 3,000m beneath sea ice in the Antarctic's Weddell Sea, the almost fully intact wreck of Ernest Shackleton's *Endurance* has been found, supported with underwater navigation and positioning technology from Sonardyne.

The pioneering search, launched in February this year, saw the Endurance22 team deploy Saab Seaeye Sabertooth hybrid autonomous underwater vehicles (AUVs) from the icebreaking polar supply and research ship S.A. *Agulhas II*.

During their hunt of the seabed, close to where the 1914–1917 expedition came to its end, these underwater robots used Sonardyne's SPRINT-Nav hybrid acoustic-inertial navigation system (INS) technology to navigate their search routes. They also used Sonardyne's AvTrak 6 tracking and telemetry transceiver, to send commands and position updates from a Ranger 2 Ultra-Short BaseLine (USBL) system, also from Sonardyne, onboard the S.A. *Agulhas II*.

Tonga Eruption Seabed Mapping Project to Study Effects of Tonga Eruption

The SEA-KIT USV Maxlimer preparing for despatch to Tonga. (Courtesy: SEA-KIT International)

NIWA and The Nippon Foundation are undertaking a mission to discover the undersea impacts of the recent Tongan volcanic eruption. In a rare opportunity to improve our understanding of the nature and impact of a major volcanic eruption, NIWA scientists are sailing to Tonga to survey the ocean around the Hunga Tonga-Hunga Ha'apai (HT-HH) volcano and surrounding regions.

The scientists will survey thousands of square kilometres of the sea floor and collect video images of the eruption's impact from NIWA's research vessel, RV *Tangaroa*, and use SEA-KIT International's Uncrewed Surface Vessel (USV) Maxlimer to conduct further mapping.

Project leader and NIWA chief scientist oceans Mike Williams predicts that there will be extensive changes to the underwater landscape around Tonga: "Before the eruption, much of the volcano was above water, but now none of it is and the neighbouring islands of Hunga Tonga and Hunga Ha'apai were reduced in size. We expect similarly dramatic changes to have occurred in the underwater topography. Submarine cable breakages show impacts up to 50 kilometres from the volcano caldera, implying changes to the seabed over an area of at least 8,000 square kilometres. This survey will investigate the impacts of the eruption in the water column and on the seabed around HT-HH."

NOAA's Ocean Exploration Cooperative Institute Takes Delivery of DriX USV

iXblue DriX USV and Exploration Vehicle Nautilus.

The University of New Hampshire's Center for Coastal and Ocean Mapping (UNH CCOM), a member of the Ocean Exploration Cooperative Institute (OECI) and funded by NOAA Ocean Exploration, has taken delivery of an iXblue DriX Uncrewed Surface Vehicle (USV) and its Universal Deployment System. The autonomous solution will help expand the footprint and efficiency of the OECI's ocean exploration operations.

Delivered to UNH CCOM in July, DriX and its novel Universal Deployment System successfully completed sea acceptance trials and extensive personnel training during the summer of 2021 as well as integration and a first shakedown cruise onboard Ocean Exploration Trust's E/V *Nautilus* in March 2022.

"We are delighted to embark on this exciting endeavour, working collaboratively with our partners to develop and enhance autonomous technologies that will expand the limits of our capabilities and bring new efficiencies to our efforts to explore and characterize the vast unknown areas of our oceans," said UNH CCOM director Larry Mayer.

Braveheart Marine Adds 70-metre-long Offshore Survey Vessel to Fleet

Braveheart Marine has added the *Braveheart Spirit*, a 70-metre-long modern offshore survey vessel, to its fleet. The company describes the latest addition as its largest and most advanced vessel, making it possible to work further from the coast and offer more hydrographic survey services.

The number of requests for projects offshore has increased in the last few years. Jelle Hakvoort, CEO at Braveheart Marine: "In these requests, we saw the opportunity to expand our services. Our new vessel brings those opportunities to life. It is an upgrade in all aspects. It's not just about the size of the vessel, but also the survey equipment, functionality and crew."

This Dutch-flagged DP2 vessel is over 70 metres long, has a large aft deck, crew accommodation for 52 persons, and will be outfitted with the latest survey technology. The size of the vessel, the powerful diesel-electric engines and the high-end survey equipment make it a very suitable vessel for the subsea service industry, with a special focus on the expansion of the offshore oil & gas and offshore wind markets. Services that can be offered with the *Braveheart Spirit* comprise, amongst others, geotechnical, geophysical and environmental surveys, IRM (ROV and diving-supported), UXO survey, boulder clearance and cable repair support activities.

The Braveheart Spirit has been refitted into a high-end hydrographic survey ship.

GEOxyz Presents New Hybrid Survey Vessel

▲ *The Geo Ocean VI offshore survey vessel.*

The acquisition of the offshore survey vessel *Geo Ocean VI* marks the next step in the expansion of the offshore survey capacities of GEOxyz, the Belgium-based geodata specialist.

With a focus on delivering next-generation geodata acquisition solutions, the GEOxyz Group is strategically investing in its offshore survey fleet. With the acquisition of the hybrid propulsion vessel *Geo Ocean VI*, GEOxyz is further specializing in providing greener, more sustainable and smarter solutions for hydrographic, geophysical and geotechnical surveys.

Equipped with a fully integrated launch and recovery system, the vessel is also ready to act as mother vessel for hydrographic survey ASVs. This creates a flexible all-round platform that is cost and operationally efficient and meets today's and tomorrow's offshore survey requirements. The *Geo Ocean VI* is a green and versatile multidisciplinary offshore survey vessel, fitted for geophysical as well as geotechnical survey work. She will be permanently equipped with specifically selected survey equipment and ready to serve the offshore industry.

TerraSond to Support Vineyard Wind 1 Project

TerraSond, a product and service line brand in Acteon's geoservices segment, plans to invest in a new base in Massachusetts as part of its commitment to support the Vineyard Wind 1 project and wider U.S. offshore wind developments.

The company, which already has facilities in Alaska and Texas, has been confirmed as a preferred supplier for the subsea balance of plant inspection and survey services for the Vineyard Wind 1 wind farm, a joint venture between Avangrid Renewables and Copenhagen Infrastructure Partners. The wind farm will be situated 15 miles south of Martha's Vineyard and Nantucket, and 35 miles from mainland Massachusetts. It will be the first major commercial-scale offshore wind farm in U.S. waters. The new TerraSond facility is likely to be located in the Bristol County area of Massachusetts and will create local employment opportunities.

TerraSond is already committed to the U.S. East Coast offshore wind industry through its site investigation surveys and operating and maintenance inspections. The Vineyard Wind 1 balance of plant work, which will add to the company's solid experience and track record, covers turbine foundation remotely operated vehicle inspections and export and array cable seabed surveys, alongside a range of other subsea integrity and operational services from across the Acteon group.

▲ *TerraSond's new facility and the wider services offered by Acteon are set to deliver a world-class offshore wind farm for Massachusetts.*

Dublin Bay Case Study

Sentinel-2 Satellite-derived Bathymetry in Optically Complex Waters

BACKGROUND

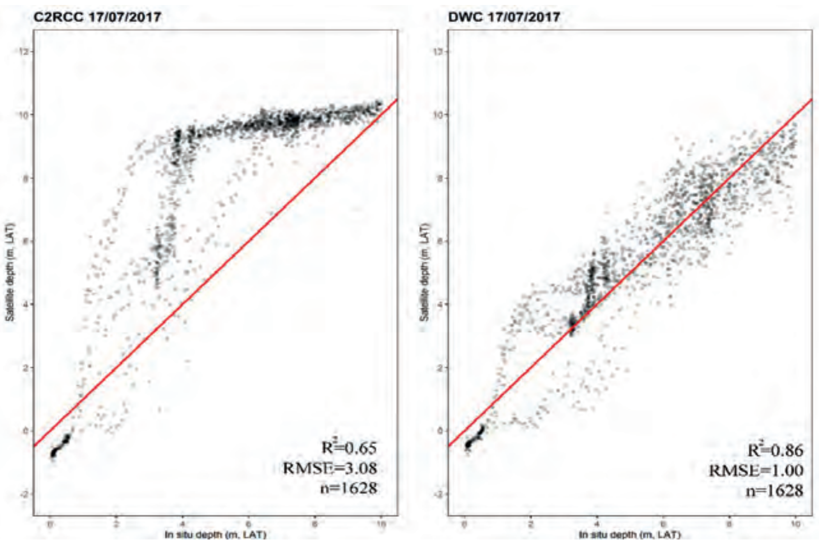
Coastal areas are highly dynamic environments that are subject to diverse pressures, both anthropogenic (e.g. urban development, fishing, habitat modification) and natural (e.g. storms, erosion, floods). These pressures result in intensive and frequent seafloor alterations that demand efficient monitoring methodologies to produce repetitive updating of the seafloor morphology and bathymetry. Bathymetric information is essential in many coastal aspects, including environmental, management, research and economic.

Optical satellite data provides an efficient alternative to bathymetric derivation in shallow coastal waters (<30m), overcoming financial, temporal and logistical constraints. In 2015, the European Commission, in partnership with the European Space Agency (ESA), launched the first satellite of the Sentinel-2 mission within the Copernicus Programme. This mission currently has two satellites, Sentinel-2A and Sentinel-2B, which register data with a spatial resolution of 10m in some spectral bands. The combination of both satellites provides a revisit time of five days, depending on the latitude. These characteristics offer new potential for coastal applications in general, and satellite-derived bathymetry in particular.

SATELLITE-DERIVED BATHYMETRY APPROACHES

When using remote sensing data to extract bathymetry, three main techniques can be differentiated: empirical approaches, empirically tuned physics-based approaches, and optimization-tuned physics inversion approaches. Empirical approaches such as machine learning are the newest methods and are not commonly used. The empirically tuned physics-based approaches have the most extended history and are still the most frequently used. In these methods, water column contributions and light attenuation properties are empirically derived from the satellite images by regression with in situ depth data (e.g. nautical charts, echosounder data or Lidar). However, water turbidity and the seafloor's influence can limit the performance of these algorithms, which may also be location- or data-limited.

The optimization-tuned physics inversion approaches are more complex, but their use has been consolidated for satellite-derived bathymetry. The application of inversion models does not require in situ depth data, but rather the specification of a range of water optical properties and the seafloor substrates reflectances. These approaches can provide per-pixel uncertainties.



▲ *Figure 1: Results showed that the DWC approach produced more accurate and less biased satellite-derived bathymetry maps.*

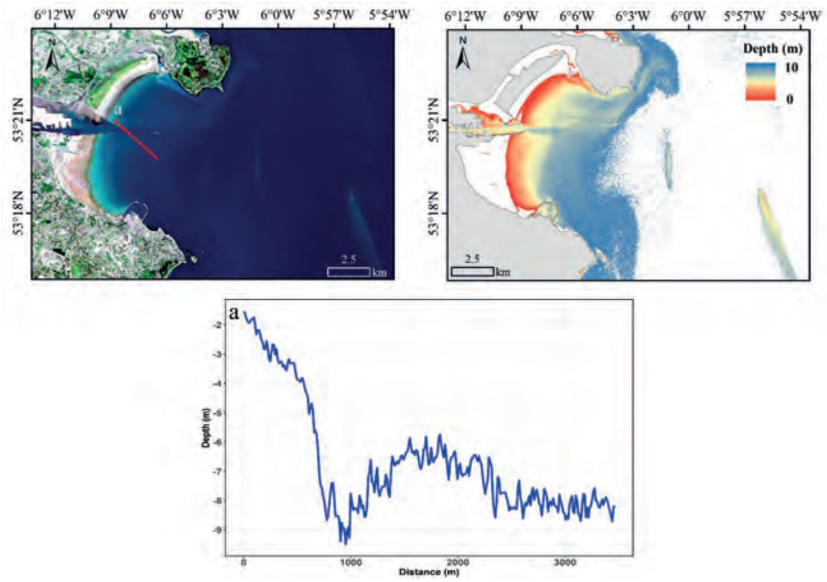
ATMOSPHERIC CORRECTION

The correction of atmospheric effects is considered a critical step for obtaining accurate satellite-derived bathymetry data. At satellite altitude, up to 90% of the sensor-measured signal can be due to atmospheric and surface reflectance. In this project, several atmospheric correction processors were evaluated to test their influence on satellite-derived bathymetry maps. These processors were OLI 'lite' (ACOLITE), the Sentinel-2 data correction (Sen2Cor version 2.4), the image correction for atmospheric effects (iCOR), the Case 2 Regional CoastColour processor (C2RCC), and the Depth Water Correction (DWC). All of these use an image-based approach, which means that all input data is derived from the image itself or provided through pre-calculated lookup tables. Sen2Cor, C2RCC and iCOR are available through the ESA's Sentinel toolbox in the Sentinel Application Platform (SNAP), and DWC is implemented in the Image Data Analysis (IDA) software developed by Numerical Optics Ltd.

Results showed that the DWC approach produced more accurate and less biased satellite-derived bathymetry maps. This result was not surprising, since the DWC method is specifically designed to correct imagery for applying the bathymetric model.

EMPIRICAL TUNING MODELS VS MODEL INVERSION METHODS

The availability of two Sentinel-2 satellites that can provide a revisit time of three days in Ireland is of enormous importance. This temporal resolution increases the chance of



▲ *Figure 2: Under suitable conditions with the best images, depth could be detected in Dublin Bay up to 10m and possibly more.*

obtaining good images in areas with significant limitations due to weather and water surface conditions. However, even when the Sentinel-2 images were registered in 'optimal' conditions, some areas presented certain challenges for satellite-derived bathymetry.
The analysis of the scatterplots (with associated diagnostics) between satellite-derived depth and in situ depth revealed high variability in the results and a clear dependence on the 'quality' of the image used. Local and variable turbidity events had an impact on satellite-derived bathymetry, causing an underestimation of depth values. Dark bottom types such as rock and macroalgae also had an effect on satellite-derived bathymetry, potentially causing an overestimation of depth values.
The comparison of empirical tuning models and optimization-tuned physics inversion models showed similar results in Dublin Bay. Model inversion approaches produced an average RMSE and R^2 of 1.60 and 0.74 respectively between 0 and 10m depth. The lowest RMSE value was obtained in Dublin Bay on 17/07/2017 (RMSE = 1.00), and was coincident with the image where the highest R^2 value (R^2 = 0.86) was found. These numbers were quite similar to the ones obtained in previous studies using empirically tuned methods in the same study area. These studies reported values of R^2 > 0.80 and average RMSE values of 1.05.

Empirically tuned methods worked well in Dublin Bay because the bay presents a homogenous bottom type and the Sentinel-2 images were selected close to optimal conditions (e.g. low turbidity). However, even if they are more straightforward and easier to use, empirically tuned methods require in situ training data, which is a significant limitation. If such data is lacking, they cannot be used. Empirically tuned methods are also hard to verify since in situ validation data is frequently not really independent of the training data and effectively just repeats the calibration regression fit. The demonstrated accuracy of inversion approaches on the Irish coast could offer a potential solution to cover a different variety of study areas, not only the ones with homogenous bottom types and good water quality conditions. Moreover, inversion approaches can provide information about uncertainty and have the potential to estimate water-inherent optical properties and bottom cover. Nevertheless, under suitable conditions with the best images, depth could be detected in Dublin Bay up to 10m and possibly more, but with decreasing precision.

CONCLUSIONS

Sentinel-2 data quality and availability for worldwide coastal regions have increased the attention of coastal managers regarding satellite-derived bathymetry applied research. These results obtained with the optimization-tuned physics inversion approach were comparable to those achieved by empirical tuning methods, despite not relying on any in situ depth data. This conclusion is of particular relevance as optimization-tuned physics inversion approaches might allow future modifications in crucial parts of the processing chain, leading to improved results.
Understanding the specific characteristics of each particular site is essential for satellite-derived bathymetry as water turbidity and the influence of the seafloor can limit the performance of satellite-derived bathymetry algorithms.

ACKNOWLEDGEMENTS

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Further Reading

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Dr Gema Casal holds a degree in marine biology and a PhD on coastal remote sensing and GIS. She is interested in the application of remote sensing technologies, especially optical sensors, to the study of marine and coastal ecosystems. In recent years, she has been involved in several projects for the integration of remote sensing data to evaluate the effects of climate change on coastal biodiversity and ecosystem services.
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Marinestar Global Satellite Positioning

Fugro Marinestar measures GNSS satellite orbit and clock corrections for GPS, GLONASS, Galileo and BeiDou. These corrections are sent over six geostationary L-band satellites and over internet and can be used to calculate highly accurate positions in real time. MarinestarG4+ position accuracy has continuously improved over the years, and here we present the performance of the Marinestar service in 2022.

Marinestar can be used by the following (and more) GNSS receivers: Fugro 9205, Septentrio AsteRx-Marine, AsteRx4 OEM, AsteRx-m3 Marine, AsteRx-U3 Marine, Trimble SPS, MPS and BD/BX series, Applanix POS MV, SBG, Norbit and Kongsberg DPS 110/112, 3610, 3710.

GLOBAL STATIC POSITIONS

The position performance is measured daily at around 130 places in the world. The global 95% height position performance is shown on the world map below for January 2022.

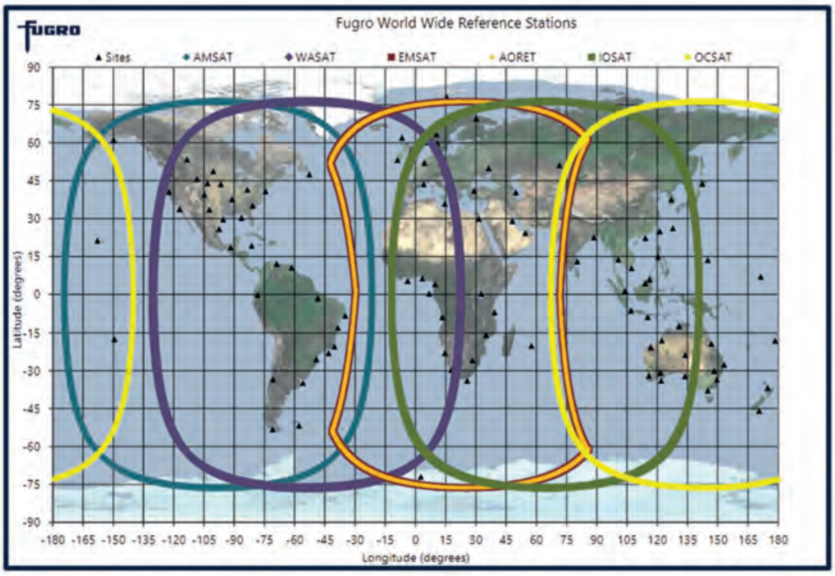


Figure 1: MarineStar transmits corrections over six geostationary L-band beams and internet.

Figure 2: 95% height Marinestar accuracy in January 2022 for G2+.

As can be seen, the 95% height accuracy is around 5cm in Europe, northern Asia, Chile, Argentina and southern Australia. In the equatorial zone, tropical rain reduces the results to 6–7cm, and accuracy is slightly more than 10cm over the Pacific Ocean. Dynamic accuracy is at the same level as the above static results.

STATIC POSITION OVER TIME

Figure 3 shows the static G4+ position results in the Netherlands using a Septentrio M3 receiver.

The standard deviation of the height is 1.9cm, and 95% of the height measurements are within 4.3cm. The horizontal offset is within 1.9cm for 95% of the positions. On average, 32 GNSS satellites were used.

THE VALUE OF "+"

Plus is used if at least one GNSS satellite has its integer number of wavelengths fixed, which improves the position accuracy to the centimetre level. Using one year of global "+" data improved the 95% height accuracy by 1cm. The "+" corrections also remove small residual orbit and clock errors.

IMPROVEMENTS USING FOUR CONSTELLATIONS

Using four GNSS constellations (GPS, Galileo, BeiDou and Glonass) has several advantages over using single or dual satellite constellations for the Marinestar service.

GPS

GPS typically has 31 useable satellites around the globe. In January 2020, G11, G22 and G28 were unavailable, reducing the minimum number of available satellites temporarily to 28. For users in the field, the minimum number of available GPS satellites in this period was six. This is close to the minimum number of four satellites for GPS-only Marinestar positioning.

BeiDou3
BeiDou3 has 42 healthy satellites using the B1 and B3 frequencies. BeiDou inclined and geostationary satellites at 36,000km are accurate to the metre level and provide support when going under bridges or during short periods of radio interference. There are around 27 useable BeiDou satellites over China and between 7 and 12 over the Americas.

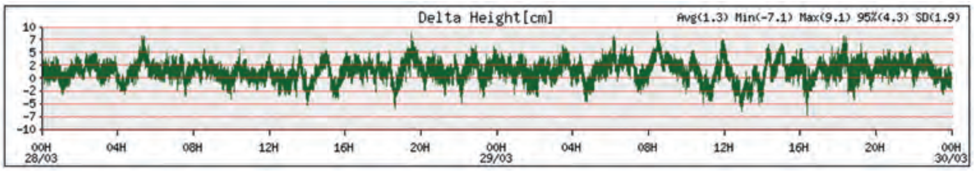
Galileo
Galileo typically has four to nine satellites available during the day worldwide. When E19 became unhealthy, this was reduced to a minimum of just three useable Galileo satellites in parts of the world. The December-launched E10 and E34 will soon become healthy, improving Galileo satellite availability. The accuracy level of orbit and clocks offsets is in the same order as for GPS.

Glonass
Glonass currently has 24 satellites, but R6, R10 and R23 (no L2) and R11 and R16 (unhealthy) are currently unavailable, reducing the number of useable Glonass satellites to just two during short periods of the day. Glonass orbit and clock offsets are in the order of three times less accurate than for GPS and Galileo.

It is clear that all four constellations (G4) increase availability. In general, there are between 25 and 40 GNSS satellites available for Fugro Marinestar positioning. Using four constellations also helps in the following cases:

- **Blockage of the sky**
  If a survey vessel needs to map the sea bottom of a harbour near quays where large ships are moored, a large part of the sky can be blocked. More GNSS satellites increases the ability to continue precise positioning.

- **Radio interference**
  Radio interference can be due to local electronic devices accidentally transmitting at higher harmonics in the GNSS bands. Also, GPS L1 Jammers are quite common. In large parts of the world, amateur radios can use the 1,240–1,300MHz band, interfering with Glonass L2, BeiDou B3 and Galileo E6. Iridium and Globalstar at 1,602MHz can interfere with Glonass L1 and GPS L1 if the GNSS antenna has no bandwidth protection.

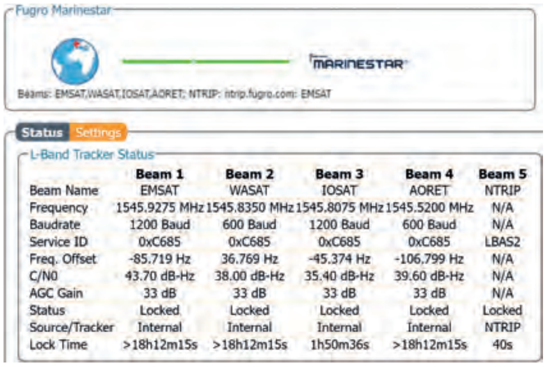


▲ *Figure 3: Two-day height offset for 28–30 March 2022.*

- **Scintillation**
  During ionospheric storms, the ions in parts of the upper atmosphere can move so fast that tracking of GNSS signals gets difficult. This is called scintillation. Scintillation around the equator – in particular near Brazil – and in the Arctic regions reduces the number of useable satellites in parts of the sky. Having more GNSS satellites helps to overcome resets and reduce position noise, especially as solar activity increases to a solar maximum in around 2025.

AUTOMATIC L-BAND BEAM SELECTION
The AsteRx-Marine M3 with the Marinestar service tracks four correction beams over L-band and two internet NTRIP (Networked Transport of RTCM via Internet Protocol) correction streams. In many places in the world, there are two (Americas, India, Asia, Australia) to four (Europe, Africa, Middle East) L-band satellites visible. The receiver automatically selects the best available correction beam.

BRIDGING GAPS
A test was carried out by driving slowly 14 times backwards and forwards underneath a bridge to establish the time required to recover to original accuracy. If MarinestarG4+ loses lock on all GNSS satellites, for example when passing under a bridge or with heavy GNSS L1 radio interference, the receiver can acquire the original position accuracy within 8–10 seconds after passing the bridge. The maximum period without GNSS measurements after which the position can be restored is more than one minute.



	Beam 1	Beam 2	Beam 3	Beam 4	Beam 5
Beam Name	EMSAT	WASAT	IOSAT	AORET	NTRIP
Frequency	1545.9275 MHz	1545.8350 MHz	1545.8075 MHz	1545.5200 MHz	N/A
Baudrate	1200 Baud	600 Baud	1200 Baud	600 Baud	N/A
Service ID	0xC685	0xC685	0xC685	0xC685	LBAS2
Freq. Offset	-85.719 Hz	36.769 Hz	-45.374 Hz	-106.799 Hz	N/A
C/N0	43.70 dB-Hz	38.00 dB-Hz	35.40 dB-Hz	39.60 dB-Hz	N/A
AGC Gain	33 dB	33 dB	33 dB	33 dB	N/A
Status	Locked	Locked	Locked	Locked	Locked
Source/Tracker	Internal	Internal	Internal	Internal	NTRIP
Lock Time	>18h12m15s	>18h12m15s	1h50m36s	>18h12m15s	40s

▲ *Figure 4: AsteRx-M3 Marine tracking four L-band beams and NTRIP in parallel.*

CONCLUSIONS
- Vertical and horizontal accuracies for the Marinestar service are better than 5cm (95%).
- During bridging periods without GNSS measurements, Marinestar is capable of acquiring the original position accuracy within 8–10 seconds.
- Multiple L-band/NTRIP input increases the robustness and availability of corrections, while using more GNSS satellites improves the accuracy and robustness of the position solution. ◀

▲ *Figure 5: Test passing a bridge 14 times. Purple is Marinestar, blue is standard GNSS.*

Geoinformatic Techniques to Combine Bathymetric Data for Shallow and Ultra-shallow Waters

Development of Digital Bathymetric Models from Hydroacoustic and Photogrammetric Data

Unmanned vehicles, both surface and airborne, are increasingly being used for hydrographic surveying. While the technology of data acquisition using these platforms is generally known, the fusion of this data is still the subject of much research, and the methods applied often depend on the sensors used and the properties of the survey area. This study presents a method for fusing data acquired using unmanned surface vehicle (USV) and unmanned aerial vehicle (UAV) measurement platforms to develop a digital bathymetric model. The case analysed concerns shallow water and ultra-shallow water up to the boundary with the shoreline.

APPROACHES FOR COMBINING BATHYMETRIC DATA

Various methods are currently used to acquire bathymetric data, including hydrographic methods using hydroacoustic sensors at the water level or below, and remote sensing methods from an aerial platform or satellite. Traditional hydrographic methods include a wide range of survey techniques, ranging from survey poles through single beam echosounders (SBES) to advanced hydroacoustic techniques such as multibeam echosounders (MBES). Remote sensing methods involve the processing of multispectral aerial and satellite images and bathymetric Lidar (Light Detection and Ranging) measurements. It is worth noting that USVs are increasingly being used for many surveying techniques, with the key advantage that they reduce the workload for operators and make it possible to carry out measurements in shallow and restricted waters. UAVs, on the other hand, can be used both as a photogrammetric as well as a Lidar platform. There are also hybrid solutions that enable the acquisition of bathymetry using an echosounder towed by a low-flying UAV or an integrated ground penetrating radar (GPR). Many solutions for hydrographic surveys using USV-based platforms are also increasingly used.

▲ *Figure 1: USV used in the research.*

Each of these methods has its limitations and works best in different conditions and types of water bodies. In the case of hydroacoustic surveys, the main constraint is the depth of the water, to allow safe passage of the hydrographic unit, while in the case of remote sensing the parameters of the water and the water body are the main concern, such as water transparency, water depth or bottom type. For this reason, data from different sources is often combined in a fusion process to produce an integrated bathymetric model covering the entire survey area.

Two special areas when it comes to the use of photogrammetry and remote sensing are shallow and ultra-shallow waters, which are usually inaccessible to hydrographic survey units. For effective measurement in these waters, hydrographic and photogrammetric methods must be combined. Unfortunately, different datasets acquired with different sensors have different ranges and structures, related to the density of the points, their quantity or spatial distribution and the measurement errors. The proper integration of data therefore requires the development of dedicated techniques.

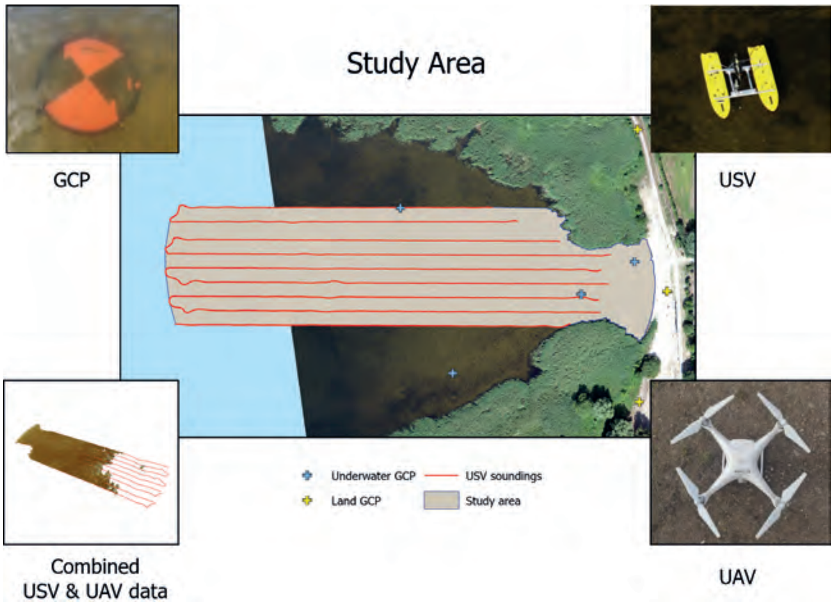


Figure 2: Map of the study area and USV soundings shown against the background of the generated UAV orthomosaic and pictures of survey platforms used; in the upper left corner a photo of an underwater GCP used in the photogrammetric data elaboration.

DATA ACQUISITION IN SHALLOW WATER

This case concerns data acquired by UAVs and USVs. The study area is part of Lake Dabie, in Poland, and includes a small bay with a beach. The area of the investigated region is 2.71ha and the bottom of the water area is mostly flat, with more depression at the entrance to the bay. The average depth of the studied area is about 1m and the maximum depth is 3.95m.

Photogrammetric data was acquired with a DJI Phantom Pro surveying platform, using a classical approach with ground control points (GCPs) established on the lake bottom. During image processing, datasets with a density of up to 300 points per square metre with a scattered distribution were obtained. The advantage of this method was the possibility to acquire bathymetric data from the shoreline, through the ultra-shallow to the shallow water. The ultra-shallow water zone is particularly important because, when creating a digital bathymetric model of this area, the lack of bathymetric data cannot always be compensated for using interpolation methods. Previous studies have indicated that doing this results in a much higher compilation error.

Unfortunately, due to poor water transparency, it was effectively possible to only acquire data to a depth of 1.3m using photogrammetric methods. It should be noted here that, for inland waters, depth measurements are in many cases only possible to a depth of 1.6–2m, even using Lidar bathymetric sensors. A natural complement to bathymetric data for greater depths is data acquired by hydroacoustic methods. For this purpose, a USV with an SBES sensor was used (see Figure 1).

The survey was performed on planned profiles at intervals of 10m. In the profile, data was acquired approximately 0.3–0.4m apart. The acquired data was processed to improve the quality by analysing individual echograms and selected depths. The advantage of this type of survey is that it is possible to obtain accurate correction data in a single profile and measurements at greater depths. On the other hand, the disadvantage is the inability to survey ultra-shallow depths or areas with navigational hazards (submerged vegetation, branches of submerged trees, fishing nets, etc.). The survey area together with the measurement platforms is illustrated in Figure 2.

GEOPROCESSING METHOD

The data fusion approach uses geoinformatic data processing methods and was developed based on the research methodology described in the article listed in the reference. The main element of this process is the concept of a bathymetric reference surface on the basis of which a selection is made of post-processed depth data acquired from UAVs. An uncertainty of 25cm was taken as the threshold for acceptable deviations from the bathymetric reference surface. This means that all points within this deviation tolerance were retained. The final processing of the data was preceded by tests to select the appropriate data filter mask, point cloud type and interpolation method. A generalized diagram of the geoprocessing with examples of data is shown in Figure 3.

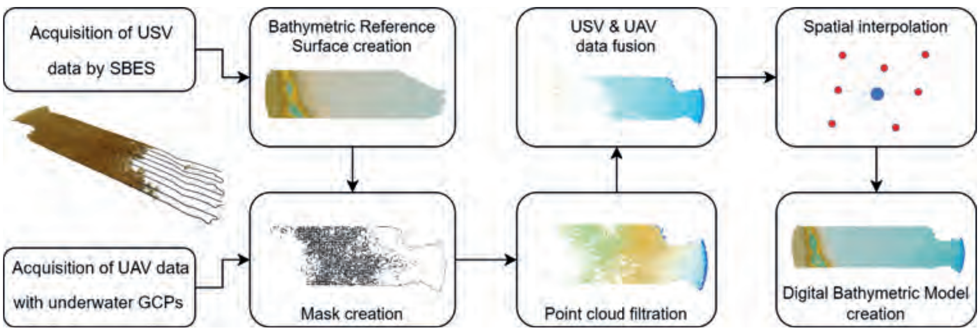


Figure 3: Generalized geoprocessing scheme.

Surveying in all waters

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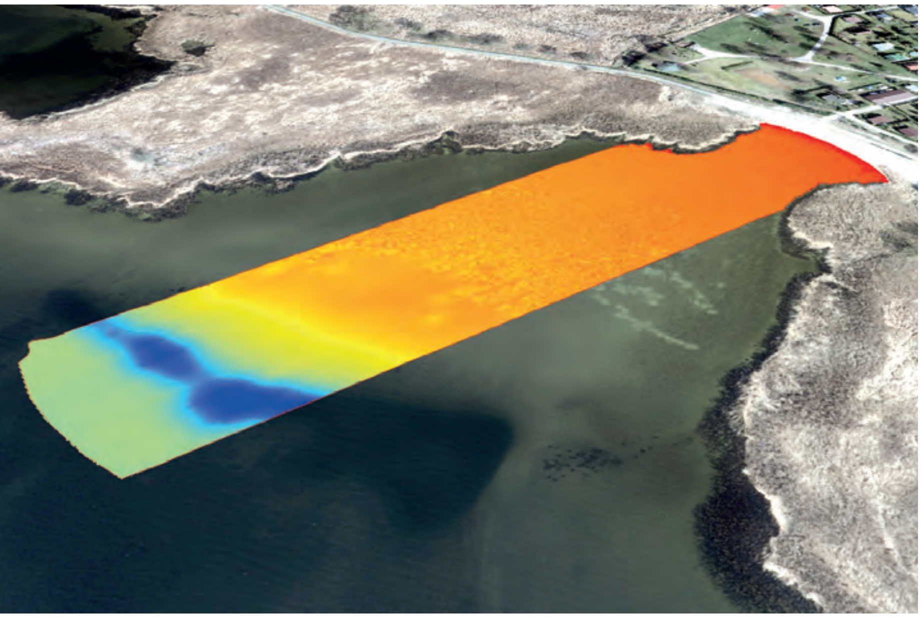

▲ *Figure 4: The developed hybrid bathymetric model from USV and UAV data.*

As the acquisition and processing of the SBES sensor data took place in accordance with the hydrographic methodology used, more attention was paid to the UAV data. During the experiment, photogrammetric data was processed using the traditional method, but with a GCP network established underwater. This approach does not take into account refraction of the electromagnetic wave in water, unlike most of the methods that use passive remote sensing. Additionally, two types of UAV point cloud were analysed. The first was a full cloud, including all point classes, while the second was a ground class cloud. The universal mask for filtering the points was developed on the basis of deviations from the bathymetric reference surface with respect to maximum and minimum values. In the final step, a qualitative and quantitative analysis of the different interpolation methods by which a digital bathymetric model can be developed was carried out. The analysis indicates that the best results for developing the final product were obtained using a UAV point cloud developed from a ground class cloud. Unfortunately, not all interpolation methods performed well on the data structure consisting of USV profiles and a UAV cloud, such as the Radial Basis Function (RBF) method. The adopted digital bathymetric model (DBM) data processing can be developed using methods such as triangulation, nearest neighbour, kriging or inverse distance to a power, which gives comparable results in terms of accuracy of the reconstructed surface. The developed hybrid bathymetric model is illustrated in Figure 4.

CONCLUSIONS

The experiment shows that it is possible to develop a data fusion method and a final bathymetric model based on the proposed geoinformatics data processing for shallow and ultra-shallow water areas. This includes UAV point cloud generation, point filtering using masks and the use of spatial interpolation methods. The essential elements of the proposed method include the acquisition of bathymetric data using a classical photogrammetric approach; in other words, the use of an underwater GCP network, the application of a ground class UAV point cloud and the use of selected interpolation methods. An additional important element of the method is the processing of UAV data based on a bathymetric reference surface. The proposed method certainly simplifies the development of bathymetric data by not taking refraction into account, but its limitations must also be considered. These include an applicability to small areas and the necessity of establishing an underwater photogrammetric network. As photogrammetric methods are formally one of the sources of bathymetric data acquisition, any research that assesses the practical applicability of this type of data and its processing methods is valuable. ◀

It is possible to develop a data fusion method and a final bathymetric model based on the proposed geoinformatics data processing for shallow and ultra-shallow water areas

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Grzegorz Zaniewicz, hydrographic surveyor, received an MSc in Navigation from the Maritime University of Szczecin (MUS), Poland in 2009. He has been employed as a research assistant at MUS since 2011, where he has taken part in many R&D projects related to geoinformatics and hydrography. His main scientific interests include hydrography, underwater data acquisition and processing.

Seagate's Lyve Mobile Mass Storage and Data Transfer Solution Gives the Geosciences Industry a New Option to "Bring Data Home Safe"

Geoscience survey companies face a constant challenge in securing and moving data. Operating in far-flung, barely connected parts of the world, with temperatures and weather hard to predict, they deploy scanning and sensor technologies that can generate gigabytes of data in a single shift, and terabytes every few days. Storing such massive amounts of data in the field (or on an ocean vessel) and moving large datasets quickly and reliably to a cloud or on-premises processing centre present tough dilemmas.

Understanding that data expansion will continue in the foreseeable future, Seagate has introduced **Lyve Mobile Edge Storage and Data Transfer Service.**

With its fleet of Lyve Mobile™ data shuttles and arrays, Lyve Mobile enables geoscience businesses to move mass data quickly, securely and simply. Scalable, modular and vendor agnostic, this storage solution eliminates network dependencies so that companies can transfer mass datasets in a fast, secure and efficient manner, making sure no time is wasted waiting for data to upload.

A conversation with Nir Elron, Seagate's director of global commercial activities for Lyve Mobile, and Darren Biggs, geoscience services manager at ET Works.

Seagate is rolling out Lyve Mobile first to industries that generate a lot of data. That certainly applies to hydrography and oceanography.

N.E.: Today, everything needs to be digitized and done quickly. Everybody's running in the same race, trying to map their terrains or the ocean floor quicker than the competition. Seagate is the single largest storage vendor in the world in terms of sheer media capacity. We make and deploy more than 600 million terabytes of storage solutions every year. Almost half the data in the world is stored on our devices. Over the last few years, we've added another leg to the business. Instead of just 'make and sell', we now also 'make and deploy as a service'. That is Lyve Mobile (pronounced as in 'alive'). It is a subscription-based service, so customers can scale up or scale down according to their present needs.

Managing high data volumes at sea

Terradepth, based in Austin, Texas, was an early adopter of Lyve Mobile. The company needed a data transfer solution that could withstand environmental extremes, and easily connect to their autonomous surface and subsurface vessels (AxVs). At the end of a mission, the accumulated data is retrieved from the AxVs via a cable connection and saved to 96-terabyte Lyve Mobile arrays. The edge-collected data is then transferred in bulk to an on-premises cloud access point. (Image courtesy: Terradepth)

HOW DOES LYVE MOBILE WORK?

N.E.: Lyve Mobile resolves technical issues around data acquisition and movement for customers. It doesn't matter if it's an oil rig or ship, or a vehicle on land that is performing seismic surveys. The data is recorded in the field on mobile arrays. These are Seagate's highest grade, enterprise self-encrypted drives (SED), meaning that every bit copied onto the array is encrypted. The encryption keys are manged by our clients, providing access to the data stored on the arrays only to their trusted targets.

The mobile arrays are totally host agnostic and cloud agnostic, with a capacity of up to 100 terabytes per unit. It's about a shoebox in terms of size. You can connect these devices in the field to any kind of host, any kind of streamer, any kind of sensor you want to record. At the end of the session – every day, every week, every month, every six months, depending on the cycles of moving the data from the endpoint to the cloud – the mobile arrays are put in a Peli case. It is then the customer who decides what to do next. One option is to leverage our logistics services, meaning that we deliver the data wherever it needs to go via our extremely well-established logistics networks. Seagate manufactures and ships around a half a million devices every day.

▲ *The mobile arrays fit into the Rackmount Receiver. Once devices are active, the included client software allows you to customize your settings and create copy workflows. (Image courtesy: Terradepth)*

NEXT-DAY DELIVERY

D.B.: It's effectively like leasing data storage and mobility solutions. For every project, you have the latest version. In the Lyve Management Portal, users can set up their project scope and data storage requirements. In most cases, their caddies arrive the following day, ready to be plugged into the vessel. If you need more, you add more. If you need less, you take less. You get the exact components you need. You use them for the life of the project, then they go back to Seagate and get refreshed and updated. So you're always going to have the latest generation.

N.E.: You might have a burst where you suddenly need to move 5 terabytes or 50 terabytes every day, or you might have a 500-terabyte event that you need to move and ingest. Within 24 hours, we get you what you need to move it. That's the kind of flexibility we're offering.

D.B.: With Lyve Mobile we can scale up to the petabyte level, which is necessary for a lot of oceanographic data. But equally, Seagate has ingestion points at key locations globally. These are on 100 gigabyte lines, which then talk to the Seagate Lyve cloud environment. An ecosystem is the best way of describing it.

BYPASSING PUBLIC NETWORKS' VULNERABILITIES

N.E.: There's a mentality today that every dataset can go over 4G or 5G networks, or over fixed landlines. But when we're talking about terabytes of data, there's no way to move tens of terabytes daily using networks. You need to physically perform some sort of forklifting, moving data from point A to another point, then ingest it to a trusted target, whatever that may be. Security is also an issue. Data is very vulnerable if you try moving it using public networks. With Lyve Mobile, all data copied onto an array is 'encrypted at rest'. That is by definition more secure and less costly compared to 'encryption in transit'. With our encryption and built-in security elements, the mobile arrays become like a data vault.

GEOSCIENCE USE CASES

N.E.: We see upstream use cases around exploration and drilling, activities like site mapping, offshore modelling, geophysical surveys, seismic surveys, environmental and drilling monitoring and acoustic sensing. These generate tens and in some cases hundreds of terabytes every day. Midstream, too, in production and transport, there is a need to acquire a lot of data and move data quickly. Offshore pipe performance monitoring, for example. It all uses high-fidelity, high-resolution sensors. Those sensors are storage hungry, and their resolution keeps growing.

D.B.: ET Works serves clients in oil and gas, but also in offshore wind and renewables, all of which use offshore data. For our acquisition and processing clients also, storage is a big concern. Seagate came to us with the Lyve portfolio for edge data storage, high-speed, ruggedized, large datasets where you can't transfer the data over the wire or over cloud or over satellite. We said yes, this looks very exciting.

N.E.: Everything with the 'Lyve' label is made by Seagate and offered to customers as a service. It is part of a general evolution within the company, and globally. It lets customers shift costs for data storage and movement from capital expenditures to operating expenses. That dramatically reduces any capital expense barriers for customers.

D.B.: Because of the cyclical nature of the oil and gas industry, it helps if you can expand and contract your project portfolio as needed. Many companies have moved away from owning even the vessels. Seagate's Lyve Mobile is well aligned to that because it's next-day delivery. ◀

▲ *For more use cases and to learn what Lyve Mobile can do for you, please visit www.seagate.com/products/data-transport*

Innovations and Partnerships in Ocean Mapping: What More Could We Achieve?

Most people working in hydrography know very well that better ocean data can be used to inform a variety of decisions, from storm preparedness to helping develop the blue economy. But could we do more in terms of fostering innovations or partnerships within our network? Could we do more with our existing partners?

These questions are prompted by a review of some of the work being done within the IHO. We initiated this year for example a trial project with CSIRO in Australia, funded by the Australian Hydrographic Office, to see whether accurate and reliable depth data can be extracted from Argo recordings. Argo is an international programme that collects information on the ocean using a fleet of robotic instruments that drift with the ocean currents and move up and down the water column. During deployment, Argo floats often touch the sea floor and record when this happens. Of the 2.7 million data profiles collected, initial analysis shows that up to 8% of these could be groundings, which could potentially reveal 216,000 new depth measurements from around the world. The trial has already provided new data in the Norwegian Sea and in New Zealand, with an excellent median accuracy of 7 or 8m. Considering there are currently 3,959 Argo floats operating across the globe, this could open the door to valuable new data.

Another innovation recently released by a consortium made up of The Nippon Foundation-GEBCO Seabed 2030 Project and Seatrec could also have an impact: this is a thermally recharging float equipped with an echosounder. This float, which is the first of its kind specifically designed for bathymetry, will be tested to map the area in the ocean near Point Nemo, the point furthest from land. This remote oceanic location is located about 2,688 kilometres from the nearest land – Ducie Island, in the Pitcairn Islands to the north, Motu Nui, one of the Easter Islands, to the north-east and Maher Island, in Antarctica, to the south.

The initial results of our cooperation with Argo look promising, and I sometimes ask myself, why didn't we think of this sooner?

Argo floats provide information on parameters such as temperature and salinity throughout the water column. This sheds light on the 'real' temperature profile of the ocean at different depths, as opposed to just the surface. This information is important for many disciplines, including storm predictions, as storms and hurricanes are powered by heat stored in the ocean. The more heat, the more powerful the storm. This data can enable communities to be better prepared for such events. It would be interesting to see in the coming months if this work could be adapted to the latest generation of Argo floats, known as Deep Argo, which can go to depths of up to 6,000m and are equipped with multiple sensors to track the ocean's chemistry and plankton ecology.

But what else could we do with this data? How could hydrographic offices participate more actively in such discussions? How could we get more data?

▲ *Mathias Jonas, Secretary-General, IHO.*

As we all know, we currently only have high-quality maps for about 20% of the ocean. If we want to increase this number, we need to start thinking out of the box and looking at the big picture. In which areas on the seabed mapping data value chain are there gaps? How can we work collectively to address challenges? What innovations in other disciplines could be used by hydrographic offices?

We are going to be looking into the value chain in more detail at the IHO in the coming months, and hope to pinpoint some of the gaps and highlight some opportunities. More to come on this topic…

Incremental Improvements in GNSS

Examining Developments in Constellations, Augmentation and Receivers

It is almost impossible these days to imagine geoinformation without GNSS, and even most geodetic services have switched to GNSS to maintain their geodetic reference network, rather than using traditional optical techniques. This article explores the state of the art in GNSS, from a constellation, augmentation and receiver perspective. Spoiler alert: it is more of an evolution than a revolution!

Global navigation satellite systems (GNSS) are everywhere. Try to imagine hydrography without GNSS, and you will probably fail. Some might say, “But what about underwater acoustic positioning?”, but these systems too rely on external positioning sources that are almost invariably GNSS-based. So, what is the current state of play when it comes to GNSS?

GNSS CONSTELLATIONS

The number of GNSS constellations has remained constant in the past few years. Listed in the order in which they first became fully operational in their current configuration, they are: the USA’s GPS, Russia’s Glonass, China’s BeiDou and Europe’s Galileo. In fact, Galileo should not be included in this list of fully operational systems, since – at the time of writing – only 22 of the planned 27 plus three satellites were fully usable, with another two in the commissioning phase. However, Galileo will hopefully reach full operational status at some point in 2022.

Besides these four global navigation satellite systems, there are two regional systems. The Japanese QZSS is probably the best-known of these, with both geostationary and quasizenithal geosynchronous satellites, providing coverage of Japan. Another three satellites are planned for QZSS in 2023 that will provide positioning over Japan (and Australia), bringing the constellation to seven satellites. The second regional system is NavIC (or IRNSS, as it was known until 2016), which orbits over India. Again, this system has both geostationary and geosynchronous satellites and covers India and the Indian Ocean. As both QZSS and NavIC are purely regional, they cannot be used outside their particular regions. This is in stark contrast to ‘true’ GNSS, although BeiDou is actually both regional and global as the system employs geostationary and geosynchronous satellites over China and satellites that orbit the world in a medium Earth orbit like the other three GNSS. The advantage of this is greatly improved coverage over China (and Australia). As a result, the Australians probably have the best GNSS coverage in the world, with a total of five available systems. India can also use five systems for navigation, although it is close to the edge of BeiDou’s coverage.

In terms of development within the various systems, the signal structure has remained the same for most systems and improvements have mainly been made in the control and positioning of the satellites themselves. Although these are relatively small improvements, they do have a sizable impact because a more accurately positioned satellite translates into better on-the-ground accuracy. The only system to have undergone intrinsic improvements is Glonass. Starting in 2018, a series of satellites were launched with the new L3OC signal. This

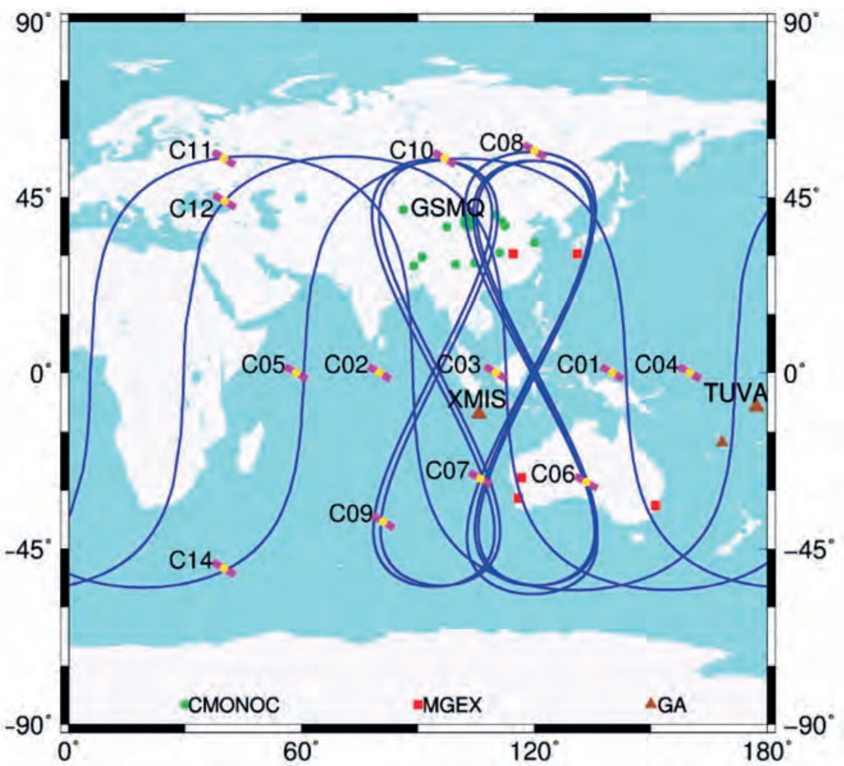
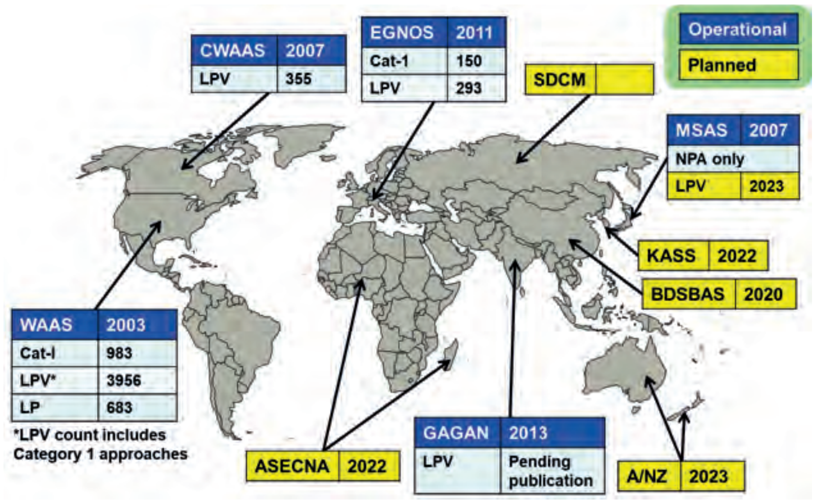


Figure 1: Beidou ground tracks. (Image courtesy: mdpi.com)



▲ *Figure 2: Various SBAS systems. (Image courtesy: africanews.space)*

CDMA signal is easier to implement than 'standard' FDMA signals because the CDMA signal uses similar techniques to those in the other GNSS. However, it has now been well over a year since the last launch (in 2020) and – especially considering the current conflict situation – the current plans for Glonass are unclear.

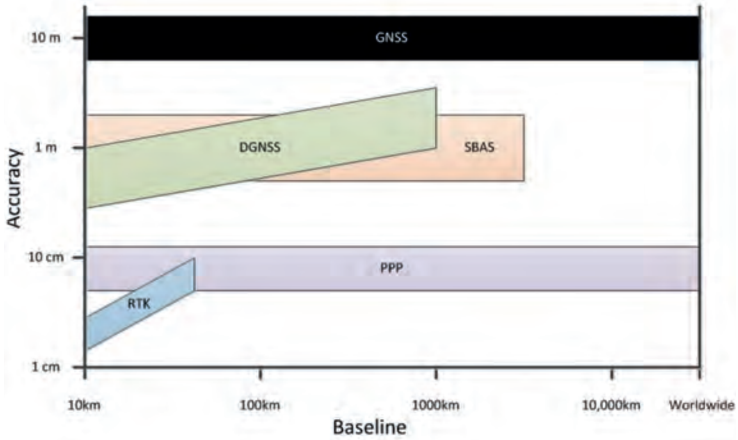
GNSS AUGMENTATION

Whether for hydrographic surveying and other professional geoinformation work or for smartphones and vehicles, and whether in the USA, Europe or Asia, the 'raw' GNSS signal is rarely used. Rather, an improved, augmented signal is used thanks to a number of 'free' (i.e. government-sponsored) space-based augmentation systems (SBAS): WAAS in the USA, MSAS in Japan, Egnos in Europe and Gagan in India. Other systems are at varying stages of development or certification, including SDCM (Russia), KASS (Korea), BDSBAS (China), SouthPAN (Australia), SACCSA (South/Central America and the Caribbean) and A-SBAS (Equatorial Africa). Each of these systems essentially functions as follows. Control ('base') stations on the ground receive the satellite positioning signals and compare the signals actually received to those expected. Based on a number of these measurements, corrections for the augmentation area are developed and transmitted to a geostationary satellite, from where they are sent back to the receivers in the GNSS frequency bands. These satellites are often recognizable in the sky plot by the 'high' satellite numbers they display. Due to the rather large areas covered by SBAS, the resulting accuracy is reasonable but not extremely high.

When a high horizontal and vertical accuracy is required and when close to the coastline, real-time kinematic (RTK) augmentation systems are used. Depending on the set-up, surveyors can use their own base station with UHF corrections, for example, or make use of an existing network. If an existing network is used, they can use corrections from a single base, but surveyors often use a virtual reference station whereby the network 'computes' a set of corrections as if the base station were located at or near the survey area. Sub-centimetre accuracies can be achieved using a local base station and post-processing the results (rather than using them in real time). However, the disadvantage of RTK is that the range is limited to around 15km from a (virtual) base station. As a result, RTK is unusable for 'true' offshore work, unless a base station can be installed locally. This could be the case in for example a wind farm, where a base station is installed on a transformer platform. In other conditions, RTK is only usable for inshore and near-shore survey work.

Precise point positioning (PPP) lies somewhere between these two technologies. Although it is not as accurate as RTK, the advantage of PPP is that it works over large areas without having to install a base station and is therefore usable in the offshore environment. In PPP, data from ground-based stations is used to model the local errors in the GNSS observations (rather than transmitting corrections). Using an iterative process of predicting the model errors and comparing them to the real results, the receiver iterates stand-alone positions to a high accuracy. A data link is still required to receive the model data, but this method is not limited by a range of just a few kilometres or the need to have local reference points. The latest commercial services using all available GNSS coverage are now achieving sub-decimetre results in terms of both horizontal and vertical precision. The Galileo High Accuracy Service, which is expected to become initially operational somewhere in 2022 and fully operational from 2024 onwards, is based on the same principle but with a horizontal accuracy of around 20cm and a vertical accuracy of around 40cm. For single points, results similar to the commercial PPP systems can often be obtained (but without guarantees) by various freely available post-processing services such as Auspos CSRS-PPP and Trimble CenterPoint RTX post-processing. These services can therefore aid in the establishment of platform (and base station) locations without having to resort to a commercial PPP solution. Depending on the service, it may even be possible to post-process kinematic data (PPK) rather than just static data, therefore allowing vessel tracks to be post-processed at a later stage using highly accurate positions.

▲ *Figure 3: Trimble R12i with tilt sensor.*



▲ *Figure 4: Various augmentation techniques: range and accuracy.*

GNSS RECEIVERS

As with all hardware, the GNSS receiver is continuously being developed. However, based on recent specifications, it is apparent that the development is more of an evolution than a revolution. For hydrographic survey work, perhaps the greatest change has been that units are becoming smaller and smaller and have become truly black box systems. Besides some LED lights indicating the main status, everything is operated using a web interface. Also, more and more units support heading computations rather than just position computations. And of course, almost every unit now has PPS output, as networked sensors require an accurate time stamp to operate correctly.
For those in coastal construction, perhaps the greatest change to the GNSS receiver has been the addition of an IMU, allowing the user to hold the pole 'at an angle' while measuring. This allows surveys to be completed much faster since the user no longer needs to wait for the bubble to centre before taking a measurement. Depending on the brand and model of the receiver, the achievable angles are anywhere between 15° and 60° of tilt.
The second major development in coastal construction is of course that the units are becoming ever-smaller for use on unmanned vehicles (both small ASVs and UAVs or 'drones'). Whereas PPK on a drone would have been regarded as a benefit a few years ago, multi-frequency RTK systems are now becoming the standard for high-end systems. This trend is enabling surveyors to obtain much better models of construction projects without requiring as many ground control points to tie the photographs or Lidar data into the geodetic network.

CONCLUSION

As outlined above, incremental changes have taken place in GNSS positioning over the last few years. With ever-growing GNSS constellations, further developments in augmentation systems and upgrades to receivers, the improvements seem set to continue in the near future. ◀

About the author

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The Benefits of Progress in UAV and Lidar Sensor Technology

Underwater Deadwood and Vegetation from UAV-borne Topobathymetric Lidar

The monitoring of submerged deadwood and vegetation is gaining increased attention due to their socio-economic and ecological importance. Deadwood acts as an important underwater habitat but also poses a threat to bridges, hydroelectric power plants and riverside buildings. Underwater vegetation, in turn, is a proxy for climate change in general and global warming in particular. In this context, UAV-borne topobathymetric laser scanning constitutes a promising tool for accurately capturing and modelling these small-scale objects in high spatial resolution.

Alluvial forests surrounding natural rivers constitute an ecologically important and sensitive habitat. Seasonal flood waves carry deadwood into the active river channels, where it floats downstream until either natural or artificial barriers (river bends, bridge piers, hydropower stations, etc.) stop its movement. Such stranded driftwood plays an important role in aquatic ecosystems, for example as a shelter for juvenile fish stages, but log jams can also damage infrastructure and residential areas. In addition to deadwood, the monitoring of littoral vegetation (i.e. submerged vegetation down to a depth where sunlight can penetrate to support photosynthesis) is gaining ever more interest, as such vegetation acts as a proxy for climate change. Submerged macrophytal vegetation reacts in a very sensitive way to increased water temperature and other parameters induced by global warming. Therefore, the monitoring of the volume and distribution of driftwood in rivers and lake outlets and of littoral vegetation is an important topic from both an ecologic and socio-economic point of view.

▲ *Figure 1: RIEGL VQ-840-G topobathymetric laser scanning system mounted on Skyability Octopcopter UAV in front of Pielach River study area.*

GAME CHANGER

Topobathymetric Lidar is an established tool for mapping the littoral zone of coastal and inland water areas. Bathymetric Lidar uses short laser pulses in the green domain of the electromagnetic spectrum to measure objects above and below the water table. Compared to topographic sensors that use infrared laser radiation, bathymetric sensors employ a large beam divergence, which results in typical footprint diameters in the range of about 50cm for data acquisition from manned platforms. This, however, hampers the detectability of submerged logs and branches, especially for stem diameters of less than 30cm. The advent of UAV-borne topobathymetric Lidar sensors has changed this situation fundamentally, as these systems provide small laser footprint diameters of around 10cm and a high laser pulse density of > 200 points/m^2.

In this article, we present the early results of detecting and modelling submerged driftwood and vegetation based on 3D point clouds acquired with a survey-grade UAV-borne topobathymetric laser scanner. We demonstrate that stems, branches and littoral vegetation are recognizable in the point cloud. The achievable point density and measurement precision furthermore allow the derivation of relevant parameters such as the length and diameter of driftwood logs and the vegetation height of macrophyte patches. This enables the quantitative analysis of submerged biomass at a high spatial resolution.

SENSOR

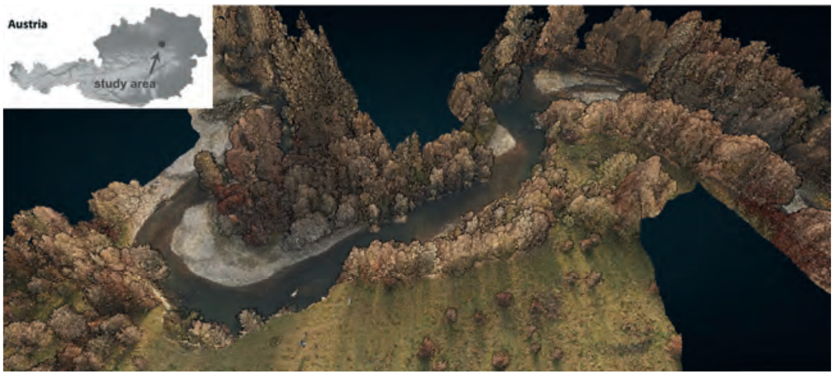
The RIEGL VQ-840-G is an integrated topobathymetric laser scanning system including a factory-calibrated IMU/GNSS system and a camera, thereby implementing a full airborne laser scanning system (see Figure 1). The lightweight, compact VQ-840-G Lidar can be installed on various platforms, including UAVs. The laser scanner comprises a frequency-doubled IR laser, emitting pulses of about 1.5ns pulse duration at a wavelength of

532mrad and a pulse repetition rate of 50–200kHz. At the receiver side, the incoming optical signals are converted into a digitized electrical signal. The laser beam divergence can be selected between 1–6mrad to allow a constant energy density on the ground for different flying altitudes and therefore balancing eye-safe operation with spatial resolution. The receiver's iFOV (instantaneous field of view) can be chosen between 3 and 18mrad. This allows the balancing of spatial resolution and maximum depth penetration.

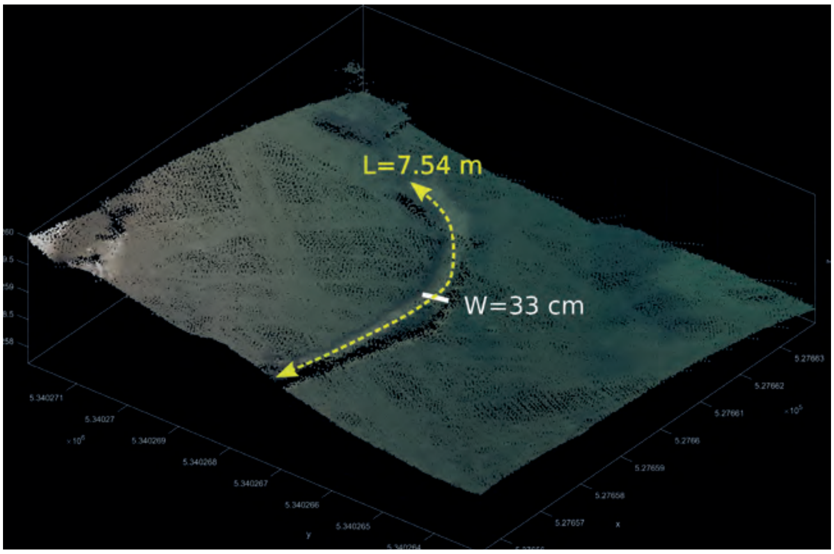
The VQ-840-G employs a Palmer scanner that generates a nearly elliptical scan pattern on the ground. The scan range is 20° x 14° along the flight direction, which means that the variation of the incidence angles hitting the water surface is low. Onboard time-of-flight measurement is based on online waveform processing of the digitized echo signal. In addition, the digitized waveforms can be stored on disc for offline waveform analysis. For every laser shot, echo waveform blocks with a length of up to 75m are stored unconditionally (i.e. without employing prior target detection). This opens up possibilities such as waveform stacking, variation of detection parameters or waveform analysis algorithms. The depth performance of the instrument has been demonstrated to be in the range of more than two Secchi depths for single measurements.

STUDY AREA AND DATASETS

The study area is located at the tailwater of the pre-Alpine Pielach River, a tributary of the Danube River in Lower Austria. The study site is located in a Natura 2000 natural conservation area and the gravel bed river features a meandering course with frequent geomorphic changes in response to flood peaks. The mean width of the river is around 20m with a mean annual discharge of 7m^3/s and a maximum depth of around 3m, allowing full coverage of the entire river bottom with topobathymetric Lidar. Alluvial vegetation (trees, bushes, shrubs) often reaches from the shore into the wetted perimeter, leading to the frequent input of wooden debris into the river. In addition, larger flood peaks transport driftwood logs from upstream into the study area, where the logs often remain for a longer period before drifting further downstream with the next flood peak. The subsurface of the adjacent flood plain is dominated by river gravel, which was quarried in the past, leaving around a dozen groundwater-supplied ponds with a maximum depth of 5.6m and featuring patches of underwater vegetation. The occurrence of



▲ *Figure 2: Pielach River study area; 3D topobathymetric Lidar point cloud coloured with simultaneously acquired aerial RGB images.*



▲ *Figure 3: 3D point cloud of submerged driftwood stem coloured by RGB.*

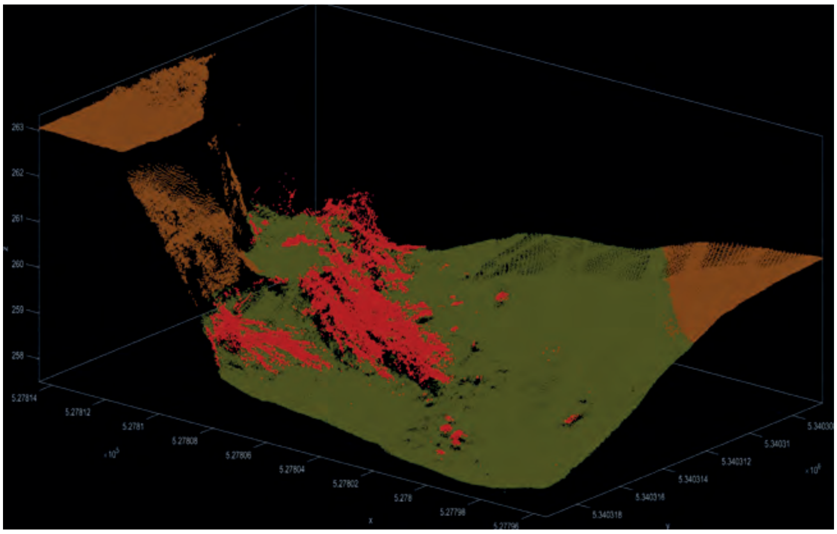
complex bathymetry as well as the presence of submerged driftwood and littoral vegetation makes the site an ideal study area for UAV-borne topobathymetric Lidar.

The area has been surveyed twice with the RIEGL VQ-840-G in the recent past. In November 2021, the scanner was mounted on an octocopter UAV operated from 50–60m above ground level with a beam divergence of 1–2mrad, providing footprint diameters of around 1dm, and with a pulse rate of 50kHz and 200kHz. A simultaneous UAV-based photogrammetry flight mission served as a basis for colouring the Lidar point cloud (see Figure 2). In February 2022, the same instrument was mounted on a helicopter platform. While the aim of the UAV-borne acquisition was maximum spatial resolution to detect submerged logs and branches, the focus of the helicopter integration was to maximize the penetration depth. For this reason, a larger beam divergence of 5mrad was used together with a receiver FoV of 9mrad, delivering full bottom coverage of the surveyed ponds alongside additional vegetation heights.

METHODS AND RESULTS

The processing pipeline mainly followed the standard bathymetric Lidar workflow. After strip alignment and georeferencing, we modelled a continuous water surface model from all air-water interface Lidar reflections and performed run-time and refraction corrections of the raw measurements. The corrected points served as the basis for deriving the DTM (bare ground + submerged bottom). In addition, the volumetric point density of all remaining water column points enabled automatic classification of the underwater vegetation. Visual analysis revealed two categories of submerged vegetation: (i) single broad tree stems and (ii) bunches of smaller branches and vegetation patches.

Figure 3 shows a 3D point cloud of a large



▲ *Figure 4: 3D point cloud of submerged bunch of willow tree branches coloured by class ID (red).*

individual stem coloured by RGB and Figure 4 features many thin branches of an entire willow tree coloured by classification. Both examples prove the feasibility of (i) detecting and (ii) automatically classifying underwater vegetation from UAV-borne topobathymetric point clouds. The length and width of the stem in Figure 3 are 7.54m and 33cm respectively. In contrast to deadwood in dry forests, submerged driftwood is often sparser and the absence of understorey facilitates detection. On the other hand, forward scattering of the laser signal underwater leads to blurring of the point clouds, which complicates the automatic detection of dense small structures (branches) and the precise estimation of vegetation patches due to progressive broadening of submerged driftwood point clouds with increasing water depth. Patches of submerged macrophyte vegetation are shown in Figure 5.

CONCLUSIONS AND OUTLOOK

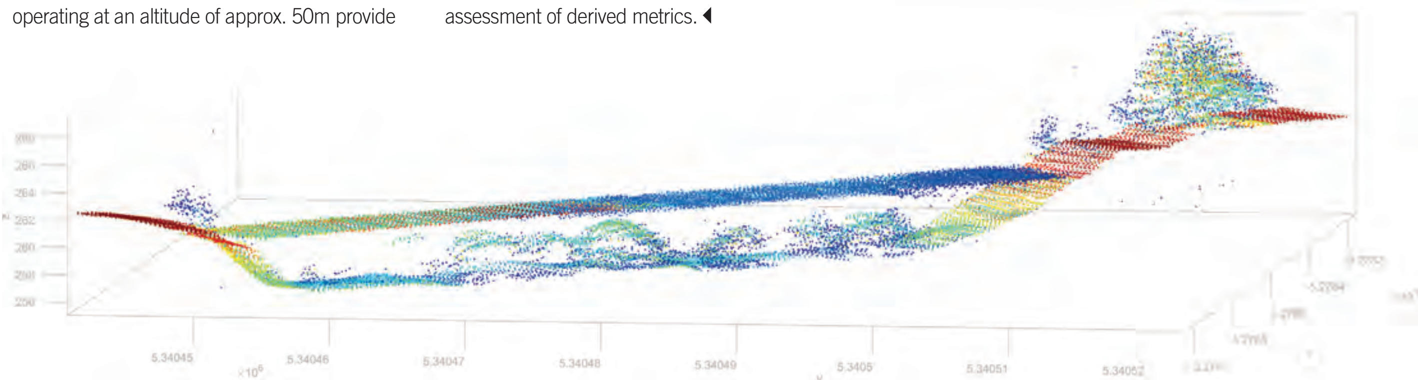
Progress in UAV and Lidar sensor technology is enabling the capture of submerged topography and the detection of complex features such as deadwood and submerged vegetation in high detail. UAV-borne topobathymetric sensors featuring laser beam divergences of ~1mrad operating at an altitude of approx. 50m provide sub-decimetre laser footprint diameters. Together with high pulse repetition rates of 200kHz and slow flying velocities of 5–6m/s, this results in point densities of more than 200 points/m^2, and thus very high spatial resolution. Furthermore, sensors featuring user-definable beam divergence, receiver's field of view and scan rate make it possible to balance depth performance and spatial resolution.
Based on the automatic classification of 3D points, it is now possible to quantify parameters of submerged deadwood (stem length and width) and littoral vegetation (vegetation height and volume). Further improvements to the processing pipelines are subject to future research. The focus is on gaining a better understanding of the interaction of green laser radiation with water and multiple small-scale objects within the laser's line-of-sight to improve established full-waveform processing techniques to handle these complex target situations. Other topics of interest include improving the automatic classification of submerged driftwood, vegetation and the water bottom, the segmentation of individual deadwood logs, the characterization of littoral vegetation, and the independent accuracy assessment of derived metrics. ◀

About the authors

Gottfried Mandlburger studied geodesy at TU Wien, where he also obtained his PhD in 2006. After completing a three-year research position at the University of Stuttgart (2017–2019), he returned to TU Wien in 2020, where he is currently working as senior researcher and lecturer in the Photogrammetry research division within the Department of Geodesy and Geoinformation. In November 2021, he obtained his venia docendi (post-doctoral qualification) in Photogrammetry for his thesis on Bathymetry from Active and Passive Photogrammetry. His main research areas are airborne topographic and bathymetric Lidar from both manned and unmanned platforms, multimedia photogrammetry, bathymetry from multispectral images, DTM modelling, topographic data management and scientific software development.

Martin Pfennigbauer holds a PhD in electrical engineering from Vienna University of Technology. He has been employed by RIEGL Laser Measurement Systems since 2005, presently as chief research officer. His special interest is the design and development of Lidar instruments for surveying applications, with a focus on rangefinder design, waveform processing and point cloud analysis.

David Monetti holds a DI from TU Wien. He is currently CEO at Skyability GmbH, a drone service provider based in Austria. He manages daily business and research projects funded by Austrian national funds. His product development activities focus on Lidar systems; using Lidar on platforms such as ULS, MLS or TLS has turned it into a tool used daily that now creates the best obtainable digital twin of a target of interest. For more than a year, David has also been responsible for implementing Lidar bathymetry at Skyability. His research activities and more than five years of hands-on work experience have made him a true expert in the field.



▲ *Figure 5: 3D topobathymetric Lidar point cloud coloured by reflectivity (blue: -30dB, red: -10dB) showing patches of macrophyte vegetation.*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