Draft for Discussion

White Paper

Understanding the characteristics of the seafloor and sub-surface of the North Atlantic – Technology Considerations

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Atlantic Seabed Mapping International Committee

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Technology is the application of knowledge to the practical benefit of humanity; the bridge between 'knowing' and 'doing'. Ocean technology enables mankind to utilize the ocean environment and resources efficiently, safely, sustainably and profitably.

Developments in technology are always motivated by human need and rely on careful design and skillful synthesis of inputs from many disciplines such as, in the case of ocean mapping: computer science, physics, chemistry, acoustics, nautical science, engineering, surveying, materials science, etc., etc., to tackle the problems at hand – in this case, characterizing the predominantly deep areas of the North Atlantic outside national jurisdictions as set out under UNCLOS. It is given under the terms of the Galway statement that international collaboration on understanding the seafloor and sub-surface characteristics of this vast and largely uncharted area will have broad applicability to ocean enterprise, ocean science, ocean engineering and good ocean governance.

Any initiative to characterize the seafloor and sub-bottom of the deep North Atlantic Ocean should be technology-enabled, not technology-driven. In a general sense, the broad objective will be to gather the necessary data as efficiently and safely as possible, at the greatest spatial resolution possible, and with consistency of data from survey to survey. The specific objectives, to be determined and confirmed collectively by those with hydrographic, oceanographic, policy, business and science objectives, will include metrics such as - How efficiently? In what detail? How often? etc. Questions such as these, and others will need to be asked and answered well before work begins.

'What is included in 'characterization of the seafloor and sub-surface''?

There can be a tendency to refer to our objective as 'mapping the North Atlantic'. Whereas 'mapping' infers the collection of data with a specific output (map) in mind, this is rather an exercise in the acquisition of data to support a broad range of applications. It is, in this regard, more like a space-based remote sensing mission than a hydrographic survey.

'Characterization of the seafloor and sub-surface' almost certainly includes the acquisition of high resolution elevation data that is made possible by modern multibeam echosounder systems. This is a 'foundation' dataset for all others. Acoustic backscatter, another parameter commonly recorded by multibeam echosounders, gives a surrogate measure of the physical properties of the seafloor (mud, silt, sand, gravel, etc.). Sub-bottom profiling systems help to reveal the 'structure' of the first few meters below the seabed. Beyond these three (depth, backscatter and sub-bottom profiles), there is a need to consider what else might be needed. For example, benthic fauna (which could be addressed by deep sea cameras/video); the grain size, mineralogy and microfossil content of seafloor sediments (which could be addressed by grab samples); the structure and geotechnical properties of sub-bottom sediment (which could be addressed by piston or gravity cores); and so on.

A clear Requirements Specification for an international, multiyear mission to characterize the seafloor and sub-surface of the North Atlantic Ocean should be established through consultation with stakeholders.

One approach that could be considered as a starting point for discussion would be to adopt the LINZ MBES Order 2 survey specifications (http://www.linz.govt.nz/docs/hydro/stds-and-specs/hyspec-v1-2-aug2010.pdf). These specifications recognize the need for seabed information beyond the immediate hydrographic concerns of safety of surface navigation, such as environmental, scientific and engineering challenges in deeper water.

The LINZ MBES Order 2 specification requires complete (overlapping) multibeam swath coverage for all areas of the seafloor. Furthermore, within this coverage a number of critical points must be met:

- All depths to be within +/- 1.5% of water depth
- Data density no sparser than 5% of water depth in both along and across track direction
- Proven ability to resolve all geomorphic features with horizontal dimensions greater than 10% of the local water depth.
- Collection of bottom backscatter strength data.

In practice this requires careful field calibration of the sonar and thorough water column monitoring procedures. In addition, the sonar will need to be able to maintain a sufficient sounding density. This will be achieved through three main factors:

- Ability to maintain a high enough ping rate.
- Ability to maintain a dense and even across track data density
- Ability to have full active compensation for roll, pitch and yaw.

Most swath sonar systems provide a form of bottom backscatter intensity estimate. However, not all are able reduce this data to quantitative measures of bottom backscatter strength. This requires compensation for variables including:

- Source level
- Pulse length
- Beam pattern
- Spherical spreading
- Path length attenuation
- Ensonified area
- Bottom slope and aspect

Beyond the collection of multibeam echosounder data, other data sets that may reasonably be taken to satisfy the objective of 'characterization of the seafloor and sub-surface' are:

<u>Single beam sounder:</u>

The single beam echosounder serves as a check on the multibeam echosounder, and should at a minimum have the following characteristics: hydrographic quality sounder; dual frequency (typically 200 and 38 KHz); 30 degree minimum beam width; digital and analogue recording; motion reference unit sensor interface (heave, pitch and roll data to be supplied by the MRU).

<u>Sub-bottom profiling:</u>

The sub-bottom profiling system (high resolution seismic; boomer or sparker) will be the primary instrument for gathering sub-surface data. Due to the water depths anticipated over much of the target area, a deep tow system will most likely be the most effective technology, but positioning and heave/pitch/roll of the tow fish will be factors to be considered.

<u>Potential Field Data:</u>

Potential field data, in particular gravity and magnetics, are widely used for regional-scale geological mapping. The three primary controls on the density and magnetic susceptibility of a volume of rock are lithology, structure and metamorphic mineral assemblages. As a first-order approximation, lithology controls the density and magnetic properties via the mineralogy, and sharp variations in rock properties typically coincide with lithological contacts (i.e. unconformities or intrusive contacts). The structural evolution of an area will change the position and orientation of these contacts, and may introduce new ones (e.g. faults). The role of metamorphism is to alter the mineralogy either locally (e.g. within shear zones) or regionally (e.g. the gradual densification associated with burial). The combination of these factors leads to geophysical properties that vary spatially in relation to the sub-surface geology.

Magnetics:

The magnetic anomalies due to basement structure will typically be on the order of tens of nanotesla's (nT) (for basement at 1 km depth), lithology changes will typically have amplitudes of hundreds of nT. For the slope and abyssal regions, where the survey will have a line spacing of on the order of 2km to 5 km, a resolution of 0.5 - 2.0 nT is required.

The cycling rate of the magnetometer should allow for sampling at the desired interval based on ship speed. Overhauser proton-precession magnetometers are capable of sampling at 1 - 4 Hz, whereas conventional proton magnetometers cannot sample during polarizing intervals, hence sample rates are less than 1 Hz. Operationally, proton magnetometers are omni-directional and are not subject to temperature drift, heading errors, or sensor orientation dead zones as are optically pumped sensors (such as cesium vapor).

The diurnal variations of the magnetic field can be recorded using base station(s), established as close as possible to the survey area. In some cases, particularly when surveying mid-Atlantic, ocean bottom magnetometer(s) may be required. Magnetic forecasts from the nearest observatory should be consulted prior to surveying (CCMC, 1999).

Gravity:

The track spacing for gravity data will be dictated by the multibeam survey requirements. The along track sample interval will be a function of the gravimeter response and half-width of the shortest anticipated signal anomaly wavelength. Forward modeling of anticipated source types/shapes/depths of gravity anomalies will be necessary to determine the ideal acquisition parameters.

For anomalies with wavelengths of 500m - 2 km in shallow water to slope regions, an accuracy of 0.3 to 0.7 mGal is typically required. This is comparable to (or less than) the expected noise levels during marine gravity surveys. For longer wavelengths, in deeper water, an accuracy of 1 mGal is required. Note that in deeper water, the multibeam surveys can obtain full coverage, using a track spacing that is wider than would be optimum for gravity data acquisition. Therefore, there is a need to consider the scale of anticipated gravity anomalies when planning the surveys (CCMC, 1999).

Bottom sampling, photos/video

Bottom samples (grabs or cores) and still photos/video will be used to 'ground truth' the acoustic data. Sampling density will need to be a consideration, as will how the data and samples will be archived.

Ancillary data

In addition to data collected to characterize the seafloor and sub-surface, certain ephemeris and other ancillary data will be critical to correction and processing of the acoustic and potential field data.

Position and Orientation:

For each remotes sensing platform, ship or AUV, the minimum parameters to be provided by the positioning system are:

- 3D position: Latitude, longitude, ellipsoidal height; minimum horizontal accuracy of 2 m at 95 % confidence;
- Velocity - accurate to 0.03 m/s;
- Roll and Pitch - accuracies to 0.02 degrees RMS;
- Heave - accuracy to 5% of heave amplitude for periods 10 seconds or less;
- Heading - accuracy to 0.05 degrees RMS

Differential GPS will be necessary to meet these specifications, with differential corrections to be supplied by a network of shore based stations or from satellite based systems in the offshore areas. Even better precision will be needed if the full capabilities of synthetic aperture processing are to be realized.

Water Level:

Accurate water level data are required during data acquisition (accurate to 10 - 20 cm). One option will be to establish a tidal or water level model for the entire survey area. This approach, using the best water level data available should be used for consistency throughout the survey to minimize differences between adjacent data sets. The model output of water levels based on time and position for use during the data acquisition can be revised/improved during subsequent data processing and map production. It is important to correct for time variant water levels, otherwise these systematic errors (low frequency noise) will be evident in the seabed bathymetry as artifacts and may be mis-interpreted as geomorphic features.

There may be a need to establish additional coastal water level gauges, as well as offshore submersible gauges. Water levels can also be determined from DGPS data, but this is typically limited to the near shore (up to about 20 km from a shore base station) (CCMC, 1999).

Sound Speed Compensation:

Given the depths of water under consideration, sound speed variations in the water column represent potentially significant sources of error in the acoustic data. Accurate sound speed data will be required at the transducer face, and as water column profiles. These data will be used by the multibeam sonar system and will also be logged separately for use during data processing and for oceanographic use.

It is recommended to use a moving vessel profiling system to collect continuous sound speed profiles while underway. This will save considerable ship time, thereby increasing productivity. As well, continuous profiles will minimize refraction effects in the multibeam data. A CTD may be used also. In addition, the tow fish on the moving vessel profiling system can be instrumented to collect other ancillary data such as plankton or turbidity at the same time.

To compensate for sound speed variations at the transducer face, a temperature sensor (allows calculation of sound speed from measured temperature and modeled density and salinity) can be used, or direct measurements of sound speed can be made. For the most flexible and redundant set-up the ability to do both would be optimal (CCMC, 1999).

‘**What are the existing best-of-breed technologies currently available for the task at hand, and what are their limitations?**’

This question can only fully be answered once clear requirements for the above have been specified.

However, by way of illustration we can consider the capabilities and limitations of current multibeam echosounder systems.

The multibeam echosounder is one of the most advanced technologies for mapping our oceans. This technology is doing for the oceans what satellite remote sensing technology has been doing for terrestrial areas since the late 1970’s – providing high resolution images of those bits of our planet which, through an accident of history, are covered by seawater.

The modern multibeam echosounder is complex technology that draws on science and technology from several disciplines. The multibeam sonar itself is the heart of the system and exists based on knowledge of materials science for the transducer, physics (acoustics) and computer science. Peripheral equipment includes a very sophisticated device to measure the heave, pitch and roll of the vessel, so that such can be factored into the data processing, a conductivity/temperature/depth probe to calculate the speed of sound in water (varies with temperature and salinity), a high precision global positioning system based on a constellation of 24 satellites, very high end computational power to record and crunch the data and, of course, the vessel itself.

Advancements in conventional multibeam echosounders are focused on tuning the frequency and beam angle to achieve better spatial resolution. These are analogous to developments in optical imaging sensors onboard satellites which have seen improvements in spatial resolution from many meters in the 1970's to a few centimeters today. Other, related devices, such as interferometric and synthetic aperture sonars are currently under development, with the promise of being able to image the seabed in ever increasing detail.

While multibeam echosounder technology has been revolutionary in terms of our ability to image the seafloor, it is not without its limitations. For example, unlike vertical-incidence single beam sounders, most data in a multibeam survey is acquired at oblique angles. While the near nadir data of a multibeam survey is invariably of much higher vertical accuracy than a single beam dataset (because of the smaller beam angles), those data collected in the outer part of the swath do not have the same absolute accuracy levels. This uncertainty is further compounded by errors introduced by vessel roll and increasing refraction errors with range. Thus, in order to specify the accuracy requirements for a multibeam sonar survey, there is a need to provide a realistic accuracy level that can be achieved by the worst case (normally outer swath) beams. While the tendency may be to demand the highest achievable feature resolution, this must be tempered by the fact that, to do so, would impose strong financial constraints on the survey (principally by demanding tighter line spacing). Thus a trade-off may need to be established between feature definition and cost. For a given line spacing, however, sonars with narrower beam widths (especially transmit); tighter beam spacing; and active motion compensation (for all three axes) will provide the best definition (CCMC, 1999).

A 'standard' set of minimum performance criteria should be established for all components of the remote sensing system (vehicle, sensors, etc.) and used as a benchmark for evaluation of existing technologies against the requirements specification recommended above.

'**What advancements in marine technologies are anticipated over the next 5 – 10 years that would significantly improve our ability to meet our objectives?'**

With regard to technology in general, a few considerations should be kept in mind:

- The pace of scientific and technological advancement is steadily accelerating, with new discoveries and technologies emerging at increasing rates. This means that organizations will need to react quickly to adopting new technologies that best fit their needs and the needs of their stakeholders.
- Technologies tend to have interdependencies and overlap with one another. This implies the need to keep a 'weather eye' on advancements in other areas, and to be ready and willing to

integrate developments of concepts in related and parallel fields in a more timely and efficient manner.

- The linkages between technology and humans will become increasingly more complex to deliver an improved performance at the system level. The management of the complexity will require better understanding at the design, manufacturing and operational phases of product and system development.
- Increasing complexity of the technologies will mean a steady demand for enhanced skills and competencies of the people designing, manufacturing and operating systems and equipment.

It is safe to say that improvements in sensor technologies and survey platforms will present new opportunities for mapping the deep ocean more efficiently and in greater detail. Benefits can be anticipated, for example, from deploying sensors using fleets of autonomous vehicles. Swarms of very small, self-ballasting underwater vehicles have already been used to measure ocean currents in three dimensions. New scanning lidar imaging systems have been developed for autonomous vehicle deployment, and could be combined with active sonar to survey anything from zooplankton to whales. Mini-floats equipped with sensitive hydrophones have been envisioned to characterize sonic landscapes. Perhaps when combined with CTD sensors, these mini-floats will provide data about the water column (temperature and salinity variations) that will be critical to calibration and correction of acoustic data.

Some trends to watch:

Sensors: The key trends here will be – miniaturization; low-power; low-cost; closer integration of sensors and processing (intelligent sensors); and increasing modularity and interoperability. As noted above, improvements in multibeam sonars in terms of increased spatial resolution and ability to quantitatively and consistently measure acoustic backscatter will be watched with interest, as will developments in synthetic aperture and multi/hyper-spectral sonars. A key challenge for medium to long term deployment of sensors, including sonars, in the marine environment is biofouling. This is where advanced materials (see below) will come to the fore. In particular, development of ceramic, polymeric and/or composite materials to achieve improved resistance to biofouling by design at the nano-scale. With regard to interoperability and standardization, building open-architecture sensor systems that leverage commercial off-the-shelf (COTS) technology will allow for increased economy and adaptability. By nature, marine mapping and monitoring systems are composed of a huge diversity of sensors and platforms. Managing the massive data flow from sensor to user will require standard protocols— to facilitate integration of new sensors into existing platforms and to improve discovery and visualization of data. In other words, moving from 'plug and pray' to 'plug and play'. The Smart Ocean Sensor Consortium was established in 2009 with a mandate to work towards accepted international standards for ocean sensors. The SOSC advocates a number of Open Geospatial Consortium (OGC) standards—including OGC PUCK, SensorML, and the Sensor Observation Service.

Autonomous systems: these include autonomous surface vehicles (ASV's), autonomous underwater vehicles (AUV's); unmanned aerial vehicles (UAV's) (or drones) and drifters/buoys. Stand-alone systems, will increasingly be replaced by interconnected intelligent systems to the point that fleets of autonomous platforms will not only be possible but accepted. Together with development of bio-fouling resistant sensors, these autonomous vehicles will enable long-endurance sensing, including repetitive mapping of the deep oceans. Developments in the area of satellite technology will hold clues to improving the spatial resolution of deep ocean mapping systems. In particular, precise control and measurement of vehicle ephemeris data will become increasingly important to support, for example, synthetic aperture processing of sonar signals.

Technology is available to build cheaper, long-endurance marine-robotic platforms that can be equipped with powerful sensing, communications and navigation systems. Improving their reliability and robustness will lead to the ability to deploy marine autonomous systems in mass joint operations between AUVs, ASVs and UAVs. The use of autonomous systems will increasingly enable cost-effective data gathering in remote regions of ocean space. The cost of such systems is expected to fall by 90% over the next 30 years, meaning that large-scale operations will become economically viable (Lloyds Register, Qinetiq and University of Southampton, 2015).

One of the key challenges in the area of autonomous systems is energy management. The need for efficient production, storage, delivery and use of energy onboard autonomous vehicles at sea and the technologies associated with the whole energy management system are particularly important in autonomous vehicles where the demand is for long term deployment with minimum intervention. In energy production, the attraction is likely to be to flexible hybrid-power solutions involving electricity generated from renewable sources such as solar and vehicle motion (kinetic). Over time, economically viable small-scale, lightweight, high energy density fuel cells which convert hydrogen (produced via variety of methods) into usable electrical energy, will continue. The management of energy is equally important, and the combination of improved system architectures and the application of more advanced materials for electrical transmission will reduce energy losses and consequently reduce heat onboard. Increasingly flexible and adaptable power system architectures will enable improved power availability to allow the rapid allocation of power according to the dynamically changing operational roles and mission dependencies of autonomous vehicles.

Maritime regulation may inhibit the roll-out of autonomous systems for ocean exploration. An appropriate legal structure for the mass deployment of marine autonomous systems is required to deal with issues associated with underwater navigation in international waters, such as collision avoidance and traffic obstruction.

<u>Advanced materials</u>: Increasing use will be made of new materials, such as carbon nano-tubes and graphene, which have attractive mechanical properties and are capable of withstanding the extremely harsh environments in deep oceans. These materials will result in structures and artefacts in the oceans being light-weight yet very strong and durable. These materials will afford the opportunities to embed sensors (e.g. optical fibre Bragg gratings) which will enable remote sensing and passive 'smart' operations. These advanced materials will also afford opportunities to embed piezoelectric and ceramic actuators, enabling the adjustment of material behaviour depending on a changing environment or structural state. A major advance will be building into the materials and structure systems the ability to self-repair if any damage occurs in service. This self-healing ability will be automatically actuated when embedded sensors detect any defects or failures arising during the service life. The performance of the healed material and structure will mimic the original state (Lloyds Register, Qinetiq and University of Southampton, 2015).

<u>Sub-sea navigation:</u> Precise sub-sea navigation will be a critical challenge to the widespread use of AUV's for deep ocean mapping. In April, 2015 the U.S. Defense Advanced Research Projects Agency (DARPA) released a broad agency announcement (DARPA-BAA-15-30) for the Positioning System for Deep Ocean

Navigation (POSYDON) project. POSYDON seeks to develop an undersea system that provides accurate, reliable, robust and affordable positioning, navigation and timing independent of GPS and inertial navigation. DARPA experts say they envision a small number of acoustic sources, analogous to GPS satellites, scattered across an ocean basin. By measuring the absolute range to several source signals an undersea platform can obtain continuous, accurate positioning without surfacing for a GPS fix. POSYDON also seeks to eliminate the need for expensive IMU and velocity sensors (http://www.militaryaerospace.com/articles/2015/04/darpa-underwater-navigation.html).

Big data: Gathering data to characterize the seafloor and sub-bottom of the deep oceans will logically lead to challenges in the management and analysis of large volumes of data. The four 'V's of 'big data' - volume, velocity, veracity and variety - will increasingly demand cost effective and innovative approaches to data management and processing to enable enhanced insight and decision making. Conventional hydrographic approaches to collection and management of data will be need to be reviewed and perhaps revised. Approaches that have been developed by the space-borne remote sensing sector, particularly space-borne synthetic aperture radar, should be carefully considered. 'Ancillary' data including met/ocean conditions, and salinity/temperature profiles will be as important as depth and physical characteristics of the seabed. Maximizing the use of ocean data collected outside national jurisdictions will likely require a restructuring of regulatory and business practices. Mechanisms for trading data and information will need to be developed, at an increasing pace. These new paradigms will transcend traditional business sectors and practices, leading to new opportunities. National governmental, as well as international entities, are also likely to play a role in enabling or deterring data sharing by means of regulation.

Common sense and the experience of others tell us that collection and, as importantly, sharing of ocean data is vital to safety at sea, sustainability of the marine environment and resources, efficiency of maritime operations and profitability of maritime commerce. Sharing data enhances its value many times, enables the development of new value-added data products not otherwise anticipated, and does not in any way jeopardize the security or competitiveness of the entity that collected it. Sharing data requires a simple shift in the way we, as a community of interest, united by a desire to safely and sustainably exploit ocean resources for socio-economic benefit, think about data. Instead of 'collect and protect', those who collect ocean data should adopt the principles of: collect data once; maintain it closest to source, and; use it many times."

New business models related to 'data as a service', will need to be further developed. The concept here is that the product, data, is provided on demand to the user regardless of their geographic or organizational affiliation. In the 'classical' world of ICT, this means that the data and software can be unbundled. In the world of ocean mapping, it may mean that service provider can sell data (and/or derived information products), rather than the system(s) used to collect it.

Communications: Remote operation will increasingly be the norm in the marine industry (e.g. AUV's and floats). Communication technologies will therefore increasingly be critical for situational awareness and exchanging information between, for example autonomous vehicles and shore based data centres. In some cases, particularly when considering the monitoring and control of vehicle/sensor operations, real time communications will be key. The capability to connect, communicate and interact with systems at sea is much more difficult than on land, and it comes at a higher cost. Increasing adoption of satellite communication systems onboard ships is likely to help to drive cost down and bandwidth up, thereby helping to enable the development and deployment of autonomous ocean mapping systems that rely on good communications. It is anticipated that the number of maritime in-service satellite communications units onboard ships will double over the next 15 years (Lloyds Register, Qinetiq and University of Southampton, 2015).

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