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# Frontiers in seafloor mapping and visualization

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## Abstract

Over the past few years there have been remarkable and concomitant advances in sonar technology, positioning capabilities, and computer processing power that have revolutionized the mapping, imaging and exploration of the seafloor. Future developments must involve all aspects of the "seafloor mapping system," including, sonars, ancillary sensors (motion sensors, positioning systems, and sound speed sensors), platforms upon which they are mounted, and the products that are produced. Current trends in sonar development involve the use of innovative new transducer materials and the application of sophisticated processing techniques including focusing algorithms that dynamically compensate for the curvature of the wavefront in the nearfield and thus allow narrower beam widths (higher lateral resolution) at close ranges . Future developments will involve "hybrid", phase-comparison/beam-forming sonars, the development of broad-band "chirp" multibeam sonars, and perhaps synthetic aperture multibeam sonars. The inability to monitor the fine-scale spatial and temporal variability of the sound speed structure of the water column is often a limiting factor in the production of accurate maps of the seafloor; improvements in this area will involve continuous monitoring devices as well as improved ocean models and perhaps tomography. Remotely Operated Vehicles (ROV's) and particularly Autonomous Underwater Vehicles (AUV's) will become more important as platforms for seafloor mapping systems. There will also be great changes in the products produced from seafloor mapping and the processing necessary to create them. New processing algorithms are being developed that take advantage of the density of multibeam sonar data and use statistically robust techniques to "clean" massive data sets very rapidly. A range of approaches are being explored to use multibeam sonar bathymetry and imagery to extract quantitative information about seafloor properties, including those relevant to fisheries habitat. The density of these data also enable the use of interactive 3-D visualization and exploration tools specifically designed to facilitate the interpretation and analysis of very large, complex, multi-component spatial data sets. If properly georeferenced and treated, these complex data sets can be presented in a natural and intuitive manner that allows the simple integration and fusion of multiple components without compromise to the quantitative aspects of the data and opens up new worlds of interactive exploration to a multitude of users.

## Introduction

The 100th anniversary of the General Bathymetric Chart of the Oceans (GEBCO) was celebrated recently with a symposium in Monaco that reviewed the history of ocean mapping and the evolution of GEBCO. Ocean mapping techniques varied little over much of GEBCO's history until recently when concomitant advances in sonar technology, positioning capabilities, and computer processing power have revolutionized the mapping, imaging, and exploration of the sea floor. In the context of GEBCO's 100th anniversary it is appropriate to look at these revolutionary changes and speculate on how they might evolve in the near-term. In the spirit of GEBCO's focus on deep-sea bathymetry, this discussion will be limited to acoustic techniques used to provide depth information in deep water. Thus recent developments in coastal mapping provided by bathymetric Light Detection and Ranging (LIDAR; e.g., Irish and Lillycrop, 1999) and the use of satellite altimetry for predicting seafloor bathymetry (Smith and Sandwell, 1997), will not be discussed.

The future of ocean mapping cannot be discussed without first understanding its historical context. As soon as man mastered the ability to travel on the water, he was concerned with the depths of the water beneath him. A boat model found in the tomb of Meketre, buried in Thebes in about 2000 BC, shows an ancient Egyptian hydrographer poised on the bow, ready to heave a lead-line (perhaps a ‘‘stone line’’ would be more accurate) so as to prevent the vessel from running aground (Figure 1). This primitive technique for measuring depth, with slight variations, was, in essence, the only method of making bathymetric measurements in depths beyond the reach of a pole for nearly 4000 years. The lead line can be accurate in very shallow water but as water depths increase and currents interact with the cast, the accuracy of the measured depths decreases quickly. Lead line measurements are also very time-consuming, particularly in deep water. HMS Challenger, for example, during its four year (1872–1876) circumnavigation of the globe, made only 300 deep water depth soundings. Nonetheless, almost every depth measurement appearing on a hydrographic or bathymetric chart before 1940 was the product of a lead line measurement and many of the soundings that appear on today’s hydrographic charts are still derived from lead line soundings.

Thus, for at least 4000 years the technology used to measure depths in the deep sea remained basically the same. The lead line was improved through mechanization (the sounding engine) but the basic principle did not change until the early 1900s with the development of piezoelectric crystal- or ceramic-based transducers to generate and receive sound waves. The combination of these transducers with the ability to measure accurately the time for the sound wave to travel from the transducer to the seafloor and back, led to the development of single beam echo sounders which allowed depth measurements to be made in a matter of seconds, even in deep water. The single beam echo sounder became commonplace on vessels after the Second World War. In a compromise between the desire to overcome the attenuation of sound in the water column and at the same time obtain the highest resolution possible, frequencies around 12 kHz were typically used for full-ocean depth measurements. In the time it took to make one lead line measurement, thousands of echo-sounding measurements could be made, tremendously increasing the number of deep-sea soundings collected. Just as importantly, many of the ambiguities associated with the lead line in deep water (inaccuracies caused by current drift and uncertainty about when the lead line struck the bottom) were removed.

While the echo sounder was a vast improvement over the lead line, it was still far from ideal. The single beam echo sounder returns only one depth value per ping. Early echo sounders typically had broad beams (30–60 degrees) ensonifying a very large area on the seafloor (an area with a

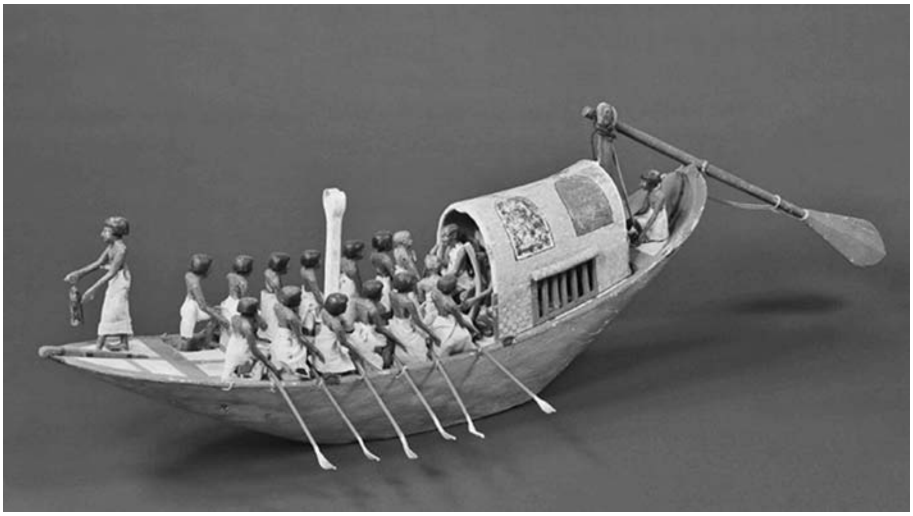

*Figure 1.* Model of riverboat found in the tomb of Meketre buried at Thebes from the q12 Dynasty ca. 1985 B.C. From the collection of the Metropolitan Museum of Art – http://www.metmuseum.org/explore/newegypt/htm/wk_river.htm. Also discussed in Bass (1972).

diameter 0.5–1 times the water depth). Given this broad beam, the first seafloor echo (the depth recorded) could return from anywhere within the ensonified area. In the absence of angular discrimination within the beam, this shoal depth could only be assumed to be directly below the vessel. The result was a "defocused" and somewhat inaccurate picture of seafloor topography. Narrow beam echo-sounders were developed but these covered a very small area resulting in very sparse sampling of the seafloor. In all cases, (broad or narrow beam), single beam echo sounders collected soundings that were dense only in the along-track direction; widely spaced ship tracks resulted in an overall sparse sampling of the seafloor.

In the late 1970s, multibeam sonar became generally available for sea floor mapping. Multibeam sonars typically use two orthogonal arrays of transducers mounted on the hull of the survey vessel. The array that is in the along-ship direction generates a transmitted pulse that is wide in the across-ship direction and very narrow in the along-ship direction. An array that is long in the across-ship direction is used to form many receive beams that are narrow in the across-ship direction and wider in the along-ship direction (Renard and Allenou, 1979). These early systems formed only 16 beams with a swath width of 45 degrees (0.75 times the water depth). Today's systems generate much wider swaths (typically 120–150 degrees) and form many more beams (typically 100–240) than the early systems. The intersection of the transmit pulse and the receive beams results in many (100–240) simultaneous depth measurements across a wide swath (as much as 7.5 times the water depth), with each measurement having excellent horizontal (typically a small percent of the water depth) and vertical (typically less than 1% of the water depth) resolution. There are now a wide range of multibeam sonar systems available, operating at frequencies from 12 kHz (for deep-water mapping) to 455 kHz (for working in water depths less than 100 m). With the sonar firing rapidly as the vessel steams along track (firing rate is typically constrained by the two-way travel-time of the widest beam), multibeam sonars have provided, for the first time, the opportunity for complete bathymetric coverage of the seafloor (Figure 2a and b). With this full coverage has come an unprecedented new perspective of seafloor morphology and seafloor processes that has been as revolutionary to those studying the seafloor as the first aerial photographs and satellite images must have been to those studying terrestrial earth processes.

## The Ocean Mapping System

Advancements in sonar technology alone were not enough, however, to provide this revolutionary new perspective of the seafloor, as the modern ocean mapping system is not just a sonar, but rather a complex and integrated collection of positioning, motion sensing, processing, and display subsystems. Fortunately, in parallel with developments in sonar technology, there have been concomitant developments in positioning, motion sensing and processing as well as in computer capabilities.

As the spatial resolution of a multibeam sonar (determined by the acoustic footprint on the seafloor) improves, so does the demand to know precisely where on the seafloor the depth or backscatter value is measured. The first step in the positioning of a sounding on the seafloor is to know the position of the transducer with respect to the coordinate framework being used. This is done through the very careful measurements of offsets between the transducer and the locus of the positioning system on the ship (e.g., the GPS antenna). Over the past 40 years there have been remarkable advances in our ability to determine the position of a vessel at sea – from navigation by sextant in the 1960s with accuracy of approximately 1 nm, to the transit satellites of the 1970s with accuracies of approximately 100 m provided intermittently, to the Global Positioning System (GPS) of the early 1990s with 100 m accuracy provided continuously (Wells et al., 1986), to the differential GPS (DGPS) systems of the late 1990s with accuracies of 10 m provided continuously (Bisnath et al., 2003), to the Real Time Kinematic (RTK) GPS systems of today which can provide continuous positions with accuracies of about 5 cm in $x$, $y$, and $z$ (Zhang and Lachappelle, 2001; see El-Rabbany, 2002 for and overview of GPS developments).

Precise knowledge of the position of the transducer is not enough however. We must also know where the sonar beam leaving the

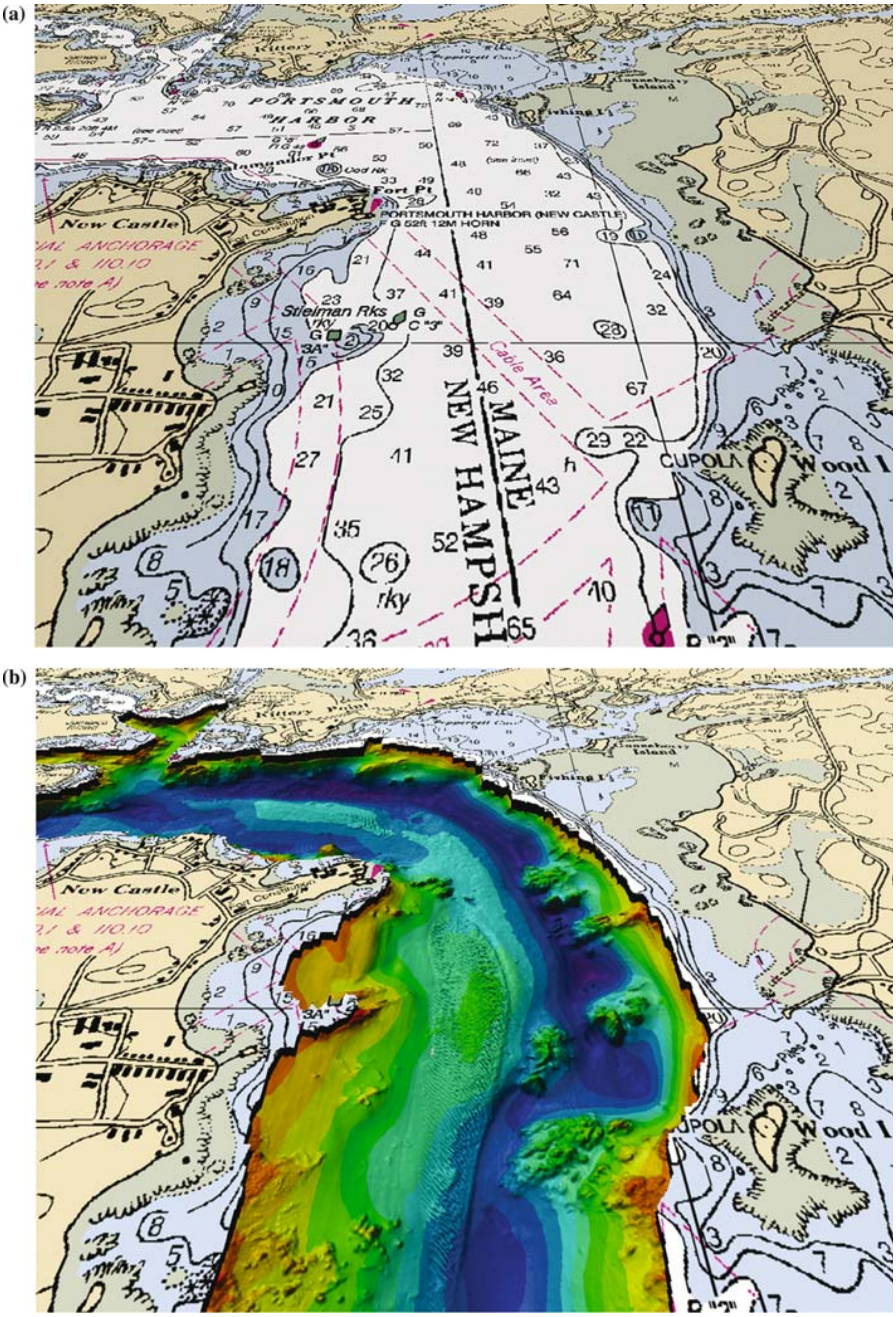

*Figure 2.* (a) Single beam sonar data allow us to construct traditional hydrographic charts, which consist of selected soundings and contours interpolated from sparse sounding (b) Multibeam sonar data offers complete bathymetric coverage of the seafloor providing an unprecedented perspective of seafloor morphology and processes.

transducer strikes the seafloor and where on the seafloor the return comes from. With the large moment angles associated with wide-swath systems, small amounts of vessel motion (heave, pitch, roll or yaw) can radically change the transmit and receive geometry of the sounding. Without the ability to precisely monitor and correct for vessel motion, soundings collected by a multibeam sonar would be improperly distributed all over the seafloor. Fortunately there have also been tremendous advances in the ability to measure vessel motion. The early motion sensors of the 1970s were very large devices based on damped pendulum technology. In the 1990s these were replaced with a series of inertial motion sensors that first used a vertical gyro algorithm, then were loosely integrated with GPS systems, and today are tightly coupled with GPS systems to provide attitude measurements with an accuracy of approximately 0.01 degrees; heading measurements with an accuracy of 0.02 degrees; ship speed measurements with an accuracy of approximately 0.01 m/sec, and; positional information with the accuracy of RTK GPS (0.02–0.10 m) – all at rates of 200 times per second (Woolven and Scherzinger, 1996).

Combined with the ability to precisely measure vessel motion, the proper prediction of the position of a sounding on the seafloor also depends on the ability to measure the changes in the path of non-vertically incident acoustic beams as they pass through a water column that has varying properties (causing refraction). The sound speed structure of the water column is determined from the measurement of temperature, salinity and depth (with a Conductivity, Temperature and Depth sensor – CTD) or from the direct measurement of sound speed with a Sound Velocity Profiler (SVP). In some environments, the spatial and temporal variability of the sound speed structure of the water column is so great that it is virtually impossible to efficiently make enough measurements to capture this variability properly. The ability to measure, and thus correct for, the spatial and temporal variability of the sound speed structure of the water column remains one of the largest sources of error in multibeam depth measurements.

The final technology needed to bring seafloor mapping to its present state is associated with advancements in computing power. The price payed for the revolution in seafloor mapping capability is data density. While an experienced hydrographer could make perhaps 10 lead line measurements per hour in 100 m of water, a single beam echo sounder can make ca. 20000 measurements and a modern multibeam echosounder several million soundings per hour. With the addition of the backscatter data that is also collected by most modern multibeam sounders, data rates are often between 10s and 100s of megabytes per hour. In very shallow water these rates can be on the order of 1 gigabyte of data per hour.

Again, the evolution of technology, in this case, computing technology, has allowed us to keep up with these rates of data generation. Over the past 30 years the speed of computer processors has doubled on the average every 50 months, with the costs of computers cut in half every 32 months and the cost of memory cut in half every 18 months At the same time data transmission speeds have increased vastly over the last few years going from 75 hours to transmit a gigabyte of data over a 28.8 kbaud modem to 8 seconds to transmit the same gigabyte of data over a T-1000 line (see http://www.cs.washington.edu/homes/lazowska/faculty.lecture/chips ).

It has been this combination of advances in sonar technology, positioning systems, motion sensors, and computer power that has brought about a new era in seafloor mapping. As we look at the future of ocean mapping, we must therefore consider all the components of the ocean mapping system.

## Sonars

Several trends are clearly on the horizon for improved sonar capability. Most multibeam sonars use orthogonally-mounted transmitter and receiver arrays to achieve narrow footprints across a wide swath along the seafloor (known as a Mills Cross or Mills T). Backscatter (sidescan sonar-like imagery) is mapped by recording the average backscatter over a beam footprint or the full time-series of the return across each beam footprint. A second type of swath mapping system uses multiple, parallel, sidescan sonar-like arrays of transducers mounted on either side of the vessel. A comparison of the phase of the return between pairs of these arrays is used to determine the depth of the seafloor (called Phase Comparison or Interferometric Sonars). These sonars usually produce higher quality backscatter imagery than traditional Mills Cross multibeams, but slightly inferior bathymetry (see Lurton, 2002 for an overview of current mapping sonar technology). The coming years will see the development of "hybrid" sonars that use complex array design to combine both of these techniques and produce multiple phase comparison depth solutions within a number of angularly resolved beams. There will also be efforts to create synthetic aperture multibeam sonars where a “virtual” array that is longer than the physical array is created by signal processing that takes advantage of improved navigational accuracy and newly developed positioning algorithms to produce greatly enhanced along-track resolution.

One of the more exciting recent developments in sonar technology has been the introduction of dynamically focused multibeams sonars. All sonars have fundamental constraints and trade-offs with respect to frequency of operation, resolution (lateral and vertical) and range of transmission. Increased temporal (vertical) resolution is typically achieved by increasing the frequency of operation (usually providing broader bandwidth), but at the price of greater attenuation and thus shorter propagation ranges. Lateral resolution is determined by the beam width, which will be a function of the operating frequency of the sonar as well as the length of the transducer array (the longer the transducer the narrower the beam). Thus the key to achieving high lateral resolution at a given frequency is increased array length. Increased array length also increases the range at which the contributions of the different emitting points on the transducer face are out of phase with each other (the near-field). Interference of the emitted waves in the near-field makes it difficult to work in this region and thus most sonars limit their working range to beyond the near-field where the wavefront approaches a plane and interactions are linear (the far-field). The requirement to work in the far-field limits the lateral resolution achievable by a multibeam sonar. New signal processing capabilities, however, have recently enabled manufacturers to dynamically focus beams in the near-field. This dynamic focusing compensates for the curvature of wavefront in the near-field and allows the sonar to achieve the beam-width predicted by the array length. This has allowed the construction of sonars that have relatively long arrays (and thus narrow beams) but can operate in the near-field. The combination of narrow beams and high-frequency operation has resulted in unprecedented resolution of complex structures (Figures 3 and 4) and sets the scene for a new generation of high-resolution sonars.

Another new development looming on the horizon for multibeam sonars is the move to broad-band or swept frequency (chirp) sonars. Bandwidth (the frequency range around the center frequency) is the key to information content but limitations in transducer and processing capabilities have kept multibeam sonars rather narrow band (typically about 10% of their center frequency). New developments in transducer materials (see below), as well as greatly advanced signal processing capabilities, have now opened the

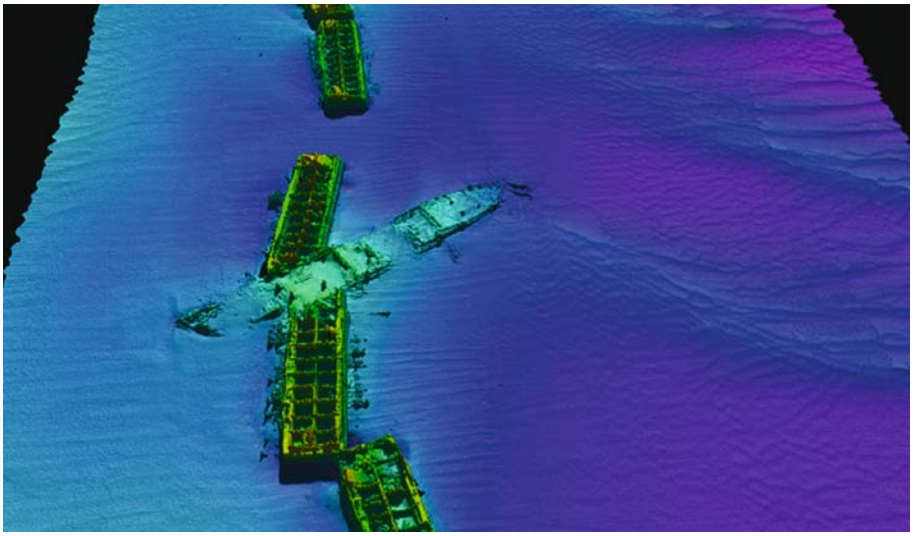

*Figure 3*. Color-coded bathymetry over wreck and caissons of submerged Mulberry harbor off Omaha Beach, Normandy, as imaged by 8125 dynamically focused sonar (from Mayer et al., 2003).

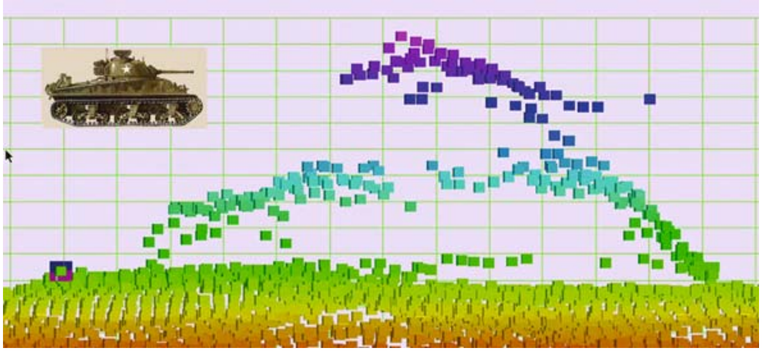

*Figure 4.* Resolution achievable with dynamically focused sonar. Here a Sherman tank lost off Normandy beach is profiled with an 8125 (see Mayer et al., 2003) for details.

door to the development of broad-band multibeam sonars (approaching 50% of their center frequency). Increased bandwidth has several immediate benefits. First increased bandwidth will result in increased temporal resolution as resolution is directly related to the reciprocal of the bandwidth. Secondly, increased bandwidth will provide the opportunity for manufacturers to increase the spatial density of soundings along track by putting multiple pings into the water column at one time. At the present, multibeam sonars must wait until they receive the return from the outermost beam until they fire again (so as not to confuse the processor). With a broad-band multibeam, pings can be coded so that they can be separated out by the processor, allowing multiple pings in the water column and thus increased ping rates. Finally, and perhaps most importantly, a broad-band multibeam will provide the opportunity for a multispectral look at the seafloor, which opens the door for powerful remote seafloor classification techniques. The tremendous bandwidth of satellite remote sensors offer the opportunity to do spectral analyses of satellite imagery that divide the returned signal into various bands to provide ‘‘thematic’’ images of the earth’s surface and allow the discrimination of vegetation and soil types (Figure 5). Similar types of analyses cannot be done on today’s multibeam sonars because there is just not enough frequency content (bandwidth) in the returned signal. The next generation of multibeam sonars, however, may very well have the bandwidth needed for ‘‘thematic mapping’’ of the seafloor.

Achieving the bandwidth necessary for full bandwidth multibeam sonars will also require new developments in transducer materials. Fortunately there is much research underway on the use of 1–3 piezocomposites (transducers that combine the properties of a piezoelectric material and a polymer to produce a composite with exceptionally good acoustic characteristics; Benjamin et al., 1998) and cymbals (minature flextensional transducers that can be tuned and formed into efficient arrays; Zhang et al., 2001).

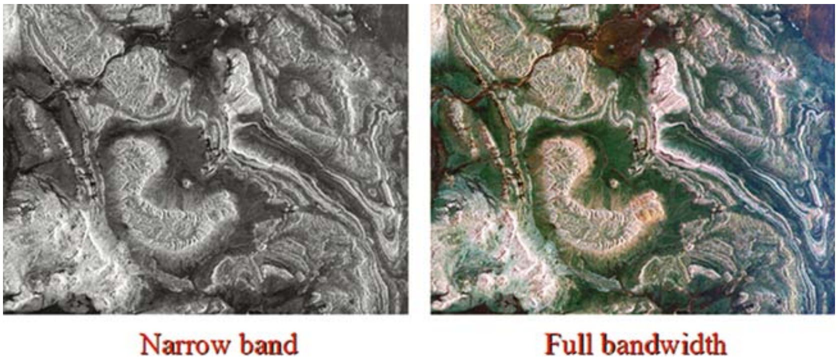

*Figure 5.* Full bandwidth Radarsat image (right) showing ability to discriminate vegetation and soil types. Image on left is same image displayed with bandwidth equivalent to typical multibeam sonar system (as percentage of central frequency). Image courtesy of Luciano Fonseca.

## Ancillary Sensors

As discussed above, motion sensor technology has progressed tremendously over the past few years. With the present generation of inertial motion sensors tightly coupled to RTK GPS, the motion of vessels can be measured better than our ability to measure other parameters that effect our final map product. These capabilities are continuing to improve, but even at their present level, they are not constraining future developments in seafloor mapping. While the motion sensors themselves have sufficient capability, problems often arise with how the motion sensor is integrated with the multibeam sonar and navigation system. Small errors in sensor alignment or offset measurements can create serious problems in data quality and new approaches must be developed to ensure the proper orientation and integration of these sensors.

The ability to monitor the spatial and temporal changes in the sound speed structure of the water column is also a severe limitation to the accuracy achievable in seafloor measurements and thus an area where new developments are critical. A recent advancement in our ability to measure the spatial and temporal changes in sound speed structure is the development of "moving vessel profilers" (Figure 6). These devices can be deployed while the vessel is underway and produce repeated profiles of sound speed or temperature and salinity. While a great improvement over sparse measurements, they still may not capture the true range of variability, and thus, other approaches need to be investigated including the potential for acoustic tomography to capture the 3-D water column structure in a given area, and the potential of using ocean models to capture the spatial and temporal variability of the sound speed field (Calder et al., 2004). Perhaps the most exciting development along these lines comes from the Naval Sea Systems Command (NAVSEA), where a towed fiber-optic cable that is capable of measuring the temperature profile of the water column nearly continuously at high speed is being developed.

## Platforms

The spherical spreading of an acoustic wavefront away from its source, combined with the need to use lower frequencies to overcome attenuation in the water column, limits the resolution achievable from a surface-ship-deployed sonar in deep water. To obtain high resolution bathymetry in deep water we must move the sensors closer to the seafloor. Thus Remotely Operated Vehicles (ROV's) and particularly Autonomous Undersea Vehicles (AUV's) are becoming increasingly important tools for deep sea mapping. For example, a surface-ship deployed multibeam with a one degree beam width in 2000 m of water will achieve a spatial resolution on the order of 35 m while an ROV or AUV, 50 m off the bottom, will achieve a spatial resolution of less than 1 m. AUV's, while in

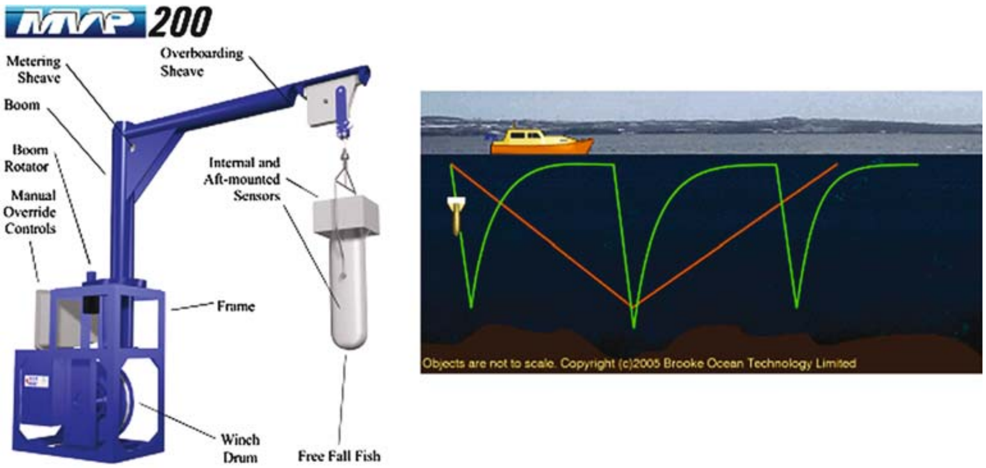

*Figure 6*. The Moving Vessel Profiler from Brooke Ocean Technology. The profiler allows many vertical profiles of water column properties to be collected while the vessel is underway.

the infancy of development, have already been demonstrated to be far more efficient and cost effective than tethered ROV's, which must be towed very slowly and are very difficult to turn (Bingham et al., 2002). One of the real challenges in collecting high-resolution acoustic data from AUV's is data telemetry, but progress is being made in the development of clever compression algorithms that allow data to be transmitted effeciently through acoustic modems (e.g., Pelekanakis et al., 2000). Though presently limited by endurance and available power, rapid developments in AUV technology, driven by both industry and research needs, may make it feasible in the near future to map the entire deep sea floor at very high resolution by fleets of AUVs.

## Data Processing

Historically, bathymetric data collected by single beam and early multibeam sonars has been cleaned, edited and processed in a fashion that involves a tremendous amount of human interaction and subjective decision making. As data rates increase, however, it will be impossible to manually edit and clean the massive data sets produced by modern multibeam sonars. Recently, a sophisticated new statistical technique has been developed that can automatically and very rapidly edit and clean multibeam sonar data sets, identifying specific problem areas that need operator intervention (Calder and Mayer, 2003; Calder, 2003). Initial verification trials of this approach have shown a decrease in processing time of 30–70 times as compared to standard hydrographic practice (Calder and Smith, 2004). Not only does this approach greatly increase the speed with which multibeam sonar data sets can be processed, it also produces a quantitative measure of the uncertainty associated the depth estimates. Unlike traditional hydrographic and bathymetric data processing which focuses on individual soundings, this new approach (know as CUBE – Combined Uncertainty and Bathymetry Estimator) directly estimates depths at grid nodes; its output is a bathymetric grid (model) rather than discrete soundings. The direct production of a gridded bathymetric product is a radical departure from both standard hydrographic charting practice (which bases charts on shoal-biased "selected soundings") and from the GEBCO approach of contouring soundings (the GEBCO digital grids are interpolations of their contours). This new approach of directly generating uncertainty attributed bathymetric models of the seafloor holds much promise for the production of a wide range of new bathymetric products, as well as for the production of more accurate charts that properly reflect our knowledge of the quality and density of the data used to generate them.

## Visualization and Data Products

While the tremendous increase in data density and volume brought about by modern multibeam sonars creates a number of data processing, manipulation, and storage challenges, the rapid developments in computer processing power allow this increase in data density to be turned into a benefit. In particular, the great density of multbeam data provides, for the first time, redundancy of bathymetric data (over some spatial scale) and thus the ability to quantify the quality and uncertainty associated in our final chart products. In addition, the great density of modern multibeam data allows the display and exploration of seafloor data using modern scientific visualization tools in ways never justifiable with sparse sounding data. The combination of quantitative, high-density geospatial data with state-of-the-art visualization tools offers an array of new ways to display and explore seafloor data and, in doing so, will help redefine the nature of seafloor charts. No longer does seafloor bathymetry need to be displayed as a series of contours interpreted from sparse soundings, but rather the full coverage and high-density of multibeam data can be used to generate intuitive looking displays of measured bathymetry. The ability to interactively and quantitatively explore complex data sets in an intuitive 3-D environment offers the opportunity to gain new scientific and engineering insights into the nature of ocean and seafloor processes, as well as provide increased safety for navigation (Figure 7). Multiple data layers and multiple levels of resolution can be displayed in a georeferenced framework with primary data (e.g., bathymetry or sidescan sonar data) and derived products (e.g., seafloor characterization or habitat data) blended as needed depending on the mission requirements. The

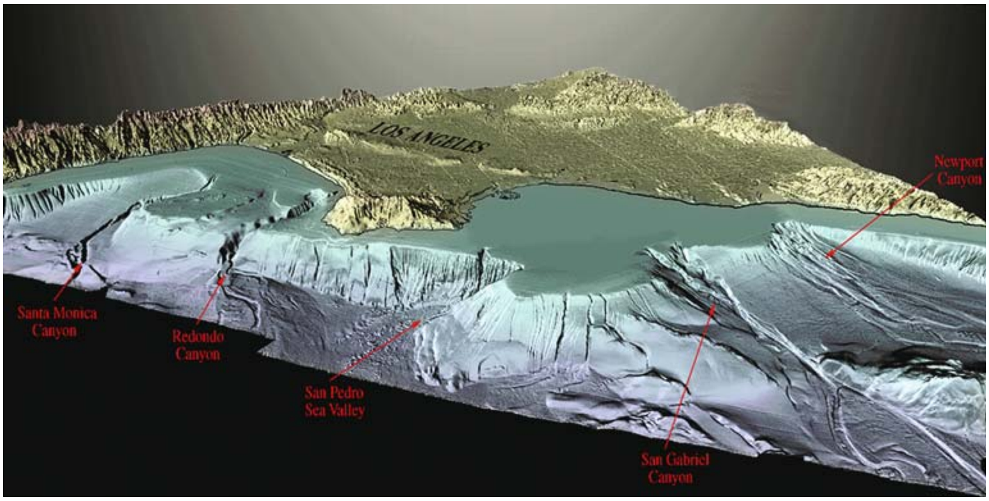

*Figure 7*. Multibeam sonar data from the southern California margin, rendered in 3-D and fused with land topography and satellite imagery. Courtesy of USGS (Jim Gardner and Peter Dartnell).

quantitative extraction of information about the nature of the seafloor (seafloor characterization) is an area that is the focus of much research today.

Bathymetric data is, for the most part, time-invarient (although there are certainly many areas of the seafloor where dynamic processes create changes in seafloor bathymetry). Other parameters, however, like currents, tides, temperature or salinity, are much more dynamic. Visualization techniques will be developed that allow the simultaneous interactive exploration of parameters changing in both space and time. Using these techniques, mariners will be provided with interactive charts that are "tide-aware" (the bathymetry will vary with the state of the tide) and show the state of currents at various levels below the surface. Researchers will be able to fuse multiple data sets that vary in both space and time and explore the relationships amongst these data sets in an intuitive fashion (Figure 8).

## Conclusions

Over the past few years, there have been remarkable changes in the ability to map and visualize the seafloor. These changes have come about through a convergence of many technologies all of which will

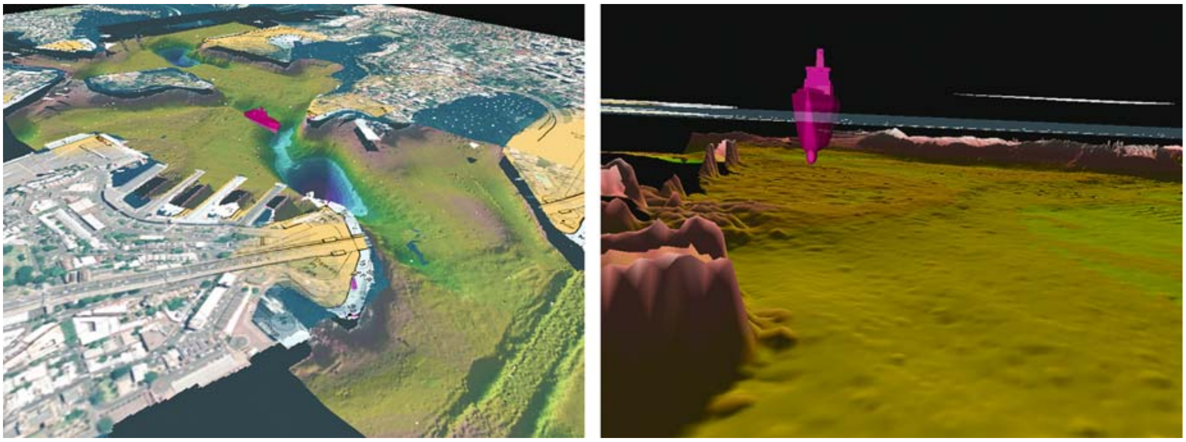

*Figure 8*. The chart of the future will provide, interactive, multiple-linked windows with 3-D perspectives of underkeel clearance with respect to high-resolution bathymetry as well as the ability to overlay other information layers such as seafloor habitat, obstructions, navigation aids, etc.

continue to advance in the future. New developments in sonar and transducer technology will lead to the development of broad-band, dynamically focused sonars with greatly improved spatial and temporal resolution, but also with the ability to provide thematic information about the nature of the seafloor. There will be great improvements in our ability to monitor changes in water column structure that will also increase the accuracy of our measurements. Improvements in remotely, and particularly, autonomously operated vehicles will lead to fleets of AUV's equipped with multibeam sonar systems mapping the entire deep sea floor at very high-resolution. Most importantly, the nature of the seafloor chart will fundamentally change. Paper products will be of very limited use. Instead charts will evolve to be dynamic digital entities, tied to large data bases that can be continuously and automatically updated. Data sets will be interactively viewed in 3-dimensions with users bringing in layers and changing views, resolution and content in order to meet the needs of a specific mission. These map products will be tied to postitioning systems serving as both survey planning and real-time navigation tools. The challenge for organizations like GEBCO is to ensure that they can provide data that is relevant and timely enough for this new mode of seafloor chart.

## Acknowledgements

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## References

Bass, G.F., 1972, *A history of seafaring based on underwater archaeology*. New York: Walker and Company, pp. 320.

Benjamin, K.C., van Buren, A.L. and Petrie, S., 1998, The development of affordable constant beam width transducers using injection molding 1-3 composite, *J. Acoust. Soc. Am.* **103**(5), 2942.

Bingham, D., Drake, T., Hill, A. and Lott, R., 2002, The application of autonomous underwater vehicle (AUV) technology in the oil industry: Vision and experiences, *Proceedings of the FIG XXII International Congress* Washington, D.C. USA, April 19-26 2002.

Bisnath, S., Dodd, D. and Wells, D., 2003, Evaluation of recent developments in high precision GPS correction services, *Proceedings of the Hydro Conference 2003*, Biloxi MS.

Calder, B R., 2003, Automatic statistical processing of multibeam echosounder data, *Int. Hydro. Review* **4**(1), 36–52.

Calder, B.R., Kraft, B.J., de Moustier, C., Lewis, J. and Stein, P., 2004, Model-based refraction correction in intermediate depth multibeam echosounder survey, *European Conference on Underwater Acoustics*, Delft, The Netherlands.

Calder, B.R. and Mayer, L.A., 2003, Automatic processing of high-rate, high-density multibeam echosounder data, *Geochem, Geophys. Geosyst.* (G3), **4**(6) doi:10.1029/2002GC000486.

Calder, B.R. and Smith, S.M., 2004, A time comparison of computer-assisted and manual bathymetric processing, *Int. Hydro. Review* **5**(1), 10–23.

El-Rabbany, A., 2002, *Introduction to GPS: The global positioning system*. Norwood, MA: Artech House Inc, pp. 176.

Irish, J.L. and Lillycrop, W.J., 1999, Scanning laser mapping of the coastal zone: the SHOALS system, ISPRS, *J. Photogr. Remote Sensing* **54,** 123–129.

Lurton, X., 2002, *An introduction to underwater acoustics: Principles and applications*. Chichester, UK: Springer Praxis Publishers, pp. 347.

Mayer, L.A., Calder, B.R., Schmidt, J.S. and Malzone, C., 2003, Exploring the third dimension: High-resolution multibeam sonar as a tool for a Investigations–An Example from the D-Day beaches of Normandy, in Akal, T., Ballard, R.D. and Bass, G.F. (eds.), The Application of Recent Advances in Underwater Detection and Survey Techniques to Underwater Archeology, Uluburun Publishing, Bodrum, Turkey, pp. 71–79.

Pelekanakis, C., Stojanovic, M. and Freitag, L., 2000, High rate acoustic link for underwater video transmission. *IEEE J. Oceanic Eng.*, **25**, 4–27.

Renard, V. and Allenou, P., 1979, SEA BEAM multi-beam echo sounding in "Jean-Charcot" Description, evaluation and first results, *Int. Hydro. Review* **56,** 3567.

Smith, W.H.F. and Sandwell, D.T., 1997, Global sea floor topography from satellite altimetry and ship depth soundings, *Science* **277**(5334), 1956–1962.

Wells, D.E. *et al.*, 1986, *Guide to GPS Positioning*. Canada: GPS Associates, Fredericton, New Brunswick, pp. 291.

Woolven S. and Scherzinger B., 1996, The benefits of tightly coupled inertial/GPS, Hydrography and Marine Navigation: Defining the Future Direction, *Canadian Hydrographic Conference*, Halifax, Nova Scotia, 74–79.

Zhang, J., Hladky-Hennion, A.C., Hughes, W.J. and Newnham, R.E., 2001, Modeling and underwater characterization of cymbal transducers and arrays, *IEEE. Trans. Ultrason. Ferroelectr. Freq. Control* **48**(2), 560–568.

Zhang, J. and Lachapelle, G., 2001, Precise estimation of residual tropospheric delays using a regional GPS network for RTK applications, *J. Geodesy* **75,** 255–266 Springer Verlag.