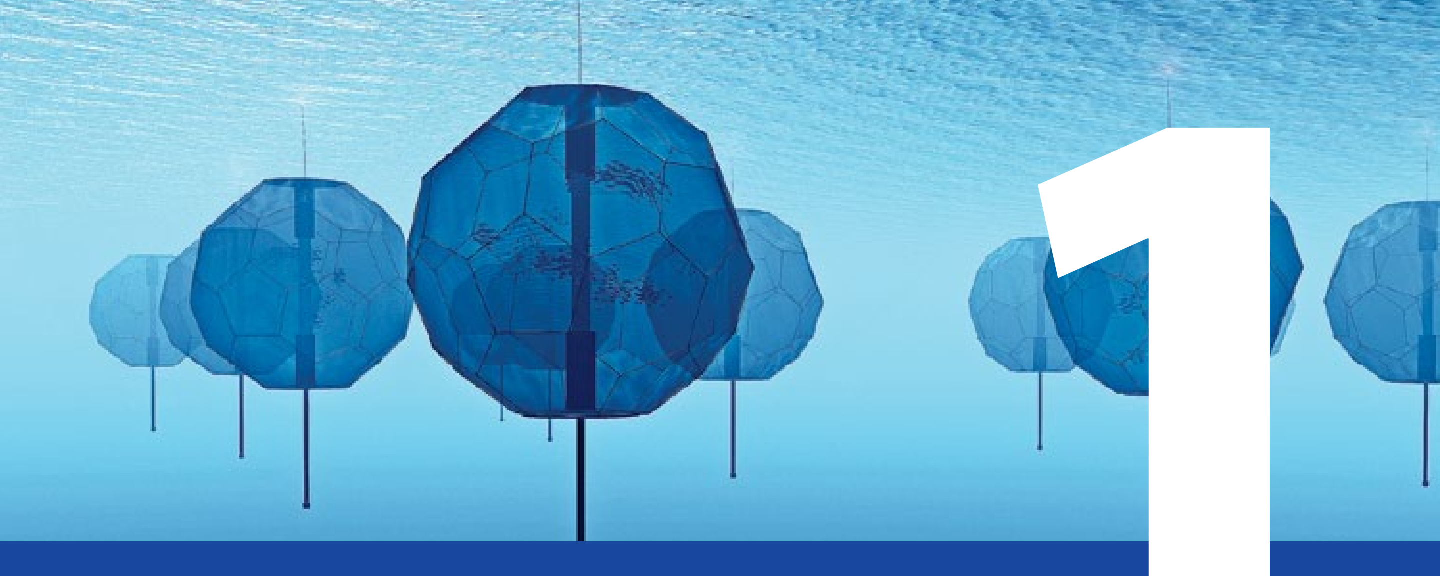

Bathymetry—the art and science of seafloor modeling for modern applications

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Introduction

Seafloor mapping is one of the oldest professions known to humankind. Mariners have been measuring the depths under their vessels for thousands of years, primarily for safe navigation. Striking the rocky ocean floor would imperil a ship, threaten loss of life, and jeopardize the livelihood of those aboard. As time passed, charts derived from seafloor mapping took on a decidedly military purpose for naval warfare and were kept as closely guarded national secrets. Today, national governments, militaries, telecommunication companies, petroleum corporations, and academic institutions map the seafloor for many applications. Knowledge about our benthic habitat and seafloor is imperative as we go forward to better understand the oceans and the Earth. The science of measuring and charting the depths to determine the topography of the seafloor and other bodies of water is known as bathymetry, and this chapter discusses how this type of information is collected, represented, and applied. Bathymetry is gathered from a variety of sources, including satellites, aircraft, surface ships,

1) ESRI
2) International Underwater Explorations

submersibles, and underwater platforms. Bathymetric data are used to generate navigational charts, 3D models, seafloor profiles, and other fusion images. Seafloor data are primarily collected by measuring the time that laser light, or an acoustic sonar pulse, takes to travel through the water column to the seafloor and back, based on the speed of sound in water, sensor characteristics, time, and other variables. Spatial resolution, coverage, temporal resolution, and data types vary among the different acquisition systems. Water clarity (turbidity), depth, surface roughness (rugosity), and benthic characteristics also can affect the quality of gathered information.

In this chapter we look closely at how models of the ocean floor are created, represented, and integrated for the digital map and globe of today. We describe the many ways to collect information about the seafloor, including satellite-based radar, aircraft-based lidar, and underwater single-beam and multibeam sonar. We also discuss what is being done with data after collection. These steps include postprocessing and integrating data into a GIS, ranging from GIS representations from the nautical chart to the representation of bathymetry as shaded relief or as a digital elevation model (DEM). We highlight some of the consumers and applications for bathymetric information: from the U.S. Navy to fisheries and from oil exploration to undersea cables. We look at the relationship of bathymetry to international law and the role of the seafloor in turning tides, waves, and currents into a form of renewable energy for the future called ocean power. Our perception of the ocean floor has expanded through the use of GIS tools and geospatial applications. The more we know about the underwater environment, so seldom visited by most people, the more our lives will benefit above ground.

Bathymetry from space

Synthetic aperture radar (SAR) is a technology that involves the transmission of phased microwave energy to measure subtle textural changes on the Earth's surface (figure 1). This

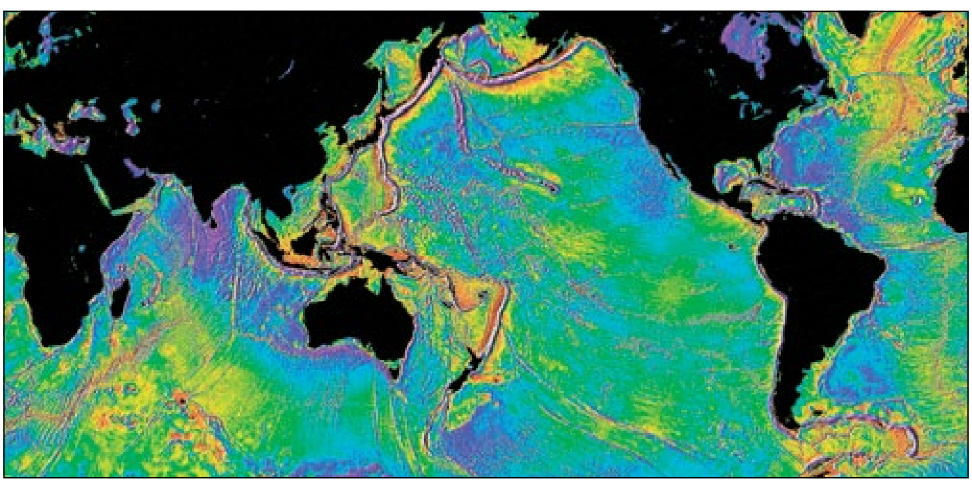

Figure 1. Satellite altimetry creates an image of the ocean floor. Courtesy of Walter Smith.

satellite-based earth-observation technology can be used with sophisticated modeling techniques to interpolate seafloor depths within a reasonable approximation for general bathymetric representation. When SAR data are modeled with sample measured depths from echo-sounding measurements or other source data, an interpolated model of bathymetry can be generated for the areas in between the source data. The technique has only been tested in relatively shallow waters, but the interpolated results thus far are consistent with traditional measurements, giving cautious credibility to this process. Although research is still being performed in this area, the possibility of creating bathymetric models from satellite-based imagery is promising, with the leading edge of technology currently being the low-resolution products generated from satellite altimetry.

The surface of the ocean bulges outward and sags inward, and these hills and valleys can be measured by a radar altimeter from a satellite. Altimeter data collected by the European Space Agency along with recently declassified data from the U.S. Navy provide detailed measurements of sea-surface height. While these measurements provide the first view of ocean floor structures in many remote areas of the Earth, the accuracy of these measurements has been debated, especially when compared to higher-resolution means of data collection. These derived seafloor datasets are comparable in value to the radar altimeter data collected by the Magellan spacecraft during its mapping of Venus from 1990 to 1992.

Bathymetry from the sky

Although it is still beyond reach to acquire precise and high-resolution seafloor depths from space, laser technology on fixed-wing and rotary aircraft can penetrate the water column to collect seafloor data. Lidar (light detection and ranging) uses a high-powered laser to transmit electromagnetic energy, specifically near-infrared and green, from the aircraft platform through the water column and make a time-difference measurement to calculate the seafloor depth (figure 2).

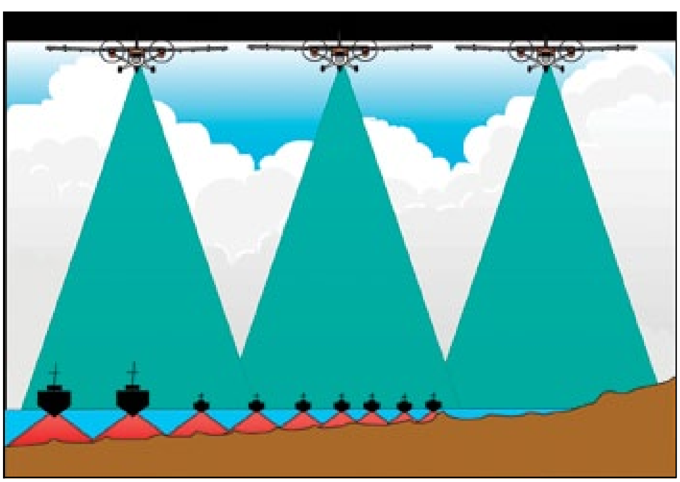

Figure 2. A typical lidar bathymeter can scan the surface and penetrate the water column. In shallow water, this form of data collection is faster than ships.
Courtesy of Optech Inc.

Lidar bathymetry is an active remote-sensing system that involves the transmission of laser light using infrared and green wavelengths of the electromagnetic spectrum. A laser altimeter mounted on an aircraft pulses both of these wavelengths to the surface of the water and measures the time it takes for the energy to return. The infrared light is reflected back to the aircraft from the water surface while the green light travels through the water column. Energy from the green light reflects off the seafloor and is captured by a lidar sensor onboard the aircraft. The water depth is obtained from the time difference between the infrared and green laser reflections using a simple calculation that incorporates the properties of the water column along with system and environmental factors. Compared to the more commonly known radar, lidar comprises shorter wavelengths of the electromagnetic spectrum. It is only possible to image a feature or object that is about the same size as the wavelength, or larger. So lidar is very sensitive to things like cloud particles and has many applications in atmospheric research, meteorology, and seafloor mapping (figure 3).

Bathymetric lidar data are typically very dense, with millions of data points collected per hour of operation. Point spacing can vary from less than a meter to several meters, providing the ability to generate high-resolution DEMs or supplemental sounding data for hydrographic purposes. The spatial resolution of depth measurements collected by lidar systems varies by two predominant

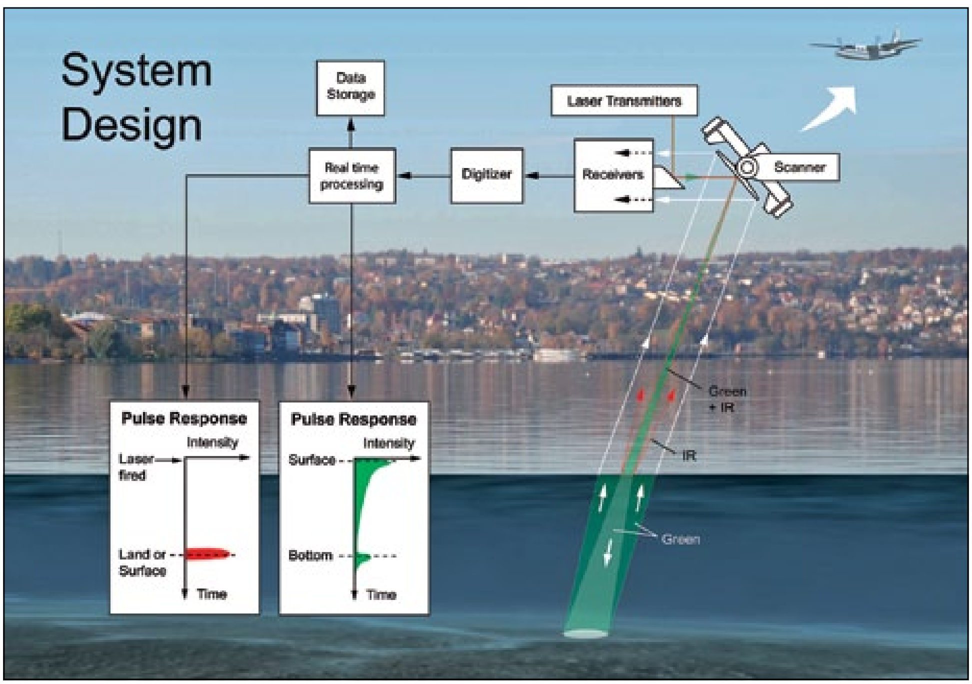

Figure 3. Laser light is transmitted from the aircraft to the water surface. Shorter wavelengths penetrate the water column to measure the seafloor depth while infrared energy is reflected from the surface. Courtesy Airborne Hydrography AB.

variables: 1) the physical characteristics of the scanning device, and 2) water depth. The aircraft altitude above the surface of the water plays a significant role in the spatial resolution of the footprint on the seafloor. An oscillating mirror scans back and forth across the surface of the water, pulsing laser light from a sensor head inside the aircraft. Altitude, scanning rates, and laser pulse rates all vary, affecting the spatial resolution of the measured data. Most modern units today use a frequency between 200 and 4,000 Hz, which can result in upward of 14 million measurements per hour and a horizontal spacing of approximately 0.5 to 6 meters on the seabed (figure 4).

Water depth also plays an integral role in the spatial resolution of collected data. Although laser light is highly collimated, it is still subject to refraction and beam spreading in the water column. Energy loss and scattering occurs primarily because of the presence of particulate matter and water molecules. The spatial footprint on the seafloor grows proportionally with increasing water depth to a maximum point where the energy of the signal is attenuated to a completely diminished return. Lidar data can extend to about 230 feet (70 meters) water depth, depending on the water clarity.

The temporality of airborne lidar is limited by the periodic nature with which the surveys are executed. Lidar bathymeters on aircraft can cover swaths of geography. Though typically expensive to operate, lidar from the sky can survey an area day and night as often as product and operational

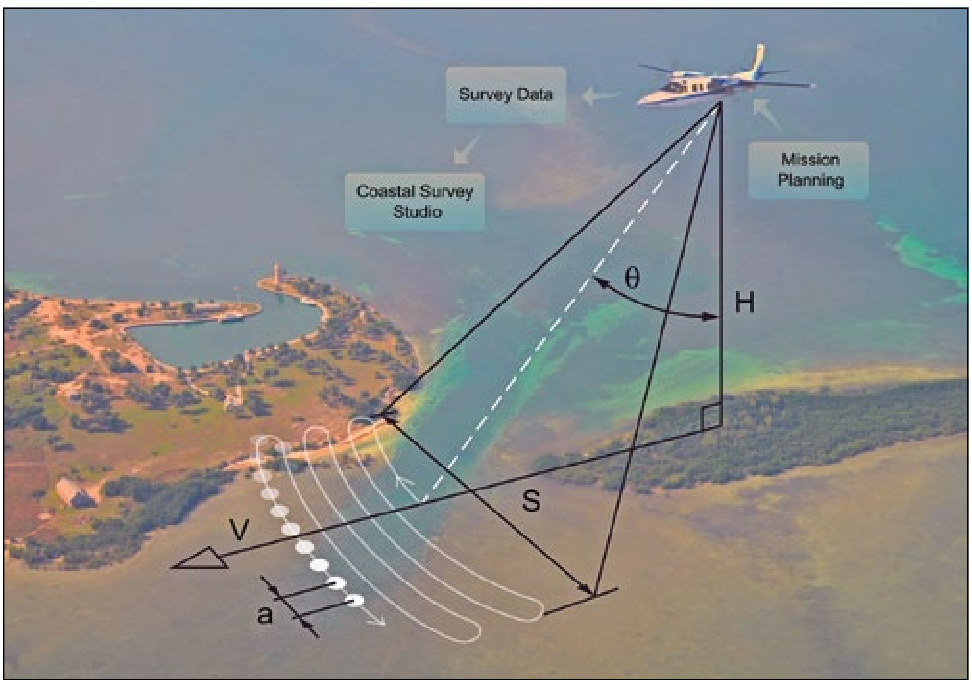

Figure 4. An oscillating mirror scans the surface of the water, transmitting laser light to the water below. A variety of factors, including the altitude of the aircraft and water depth, affect the quantity of data collected. Courtesy Airborne Hydrography AB.

needs dictate. The accuracies associated with lidar bathymetry are quite high and can comply with International Hydrographic Organization standards with the requisite measures employed to gather quality data. Inertial measurement units to measure attitude (roll, pitch, crab, heave), combined with high-precision positioning in four dimensions (x,y,z,t) can yield results with high horizontal and vertical accuracies of the measurements collected.

Bathymetric lidar systems receive both image-based and discrete vector data. Various types of data transformations are derived from the source data to create models rich with information and representation. The actual signal collected by the receiver is a waveform, and the characteristics of the waveform can vary from system to system. Software applications employ complex algorithms to extract the peaks of energy from the waveform and yield measurements that represent the water surface and seafloor reflectance. The actual water depth is simply a different analysis between the two peaks of the waveform depicting the two surfaces. Depths captured as point data can undergo further data processing to refine the seafloor model and account for any systematic errors introduced in the collection process. Lidar can also measure the surface difference between sea surface and seafloor based on the intensity of the signal from the seabed. This reflectance value is usually captured as a digital image value between 0 and 255 and is stored as a raster format associated with the depth measurement (figure 5).

Stronger energy returns indicate that the seabed absorbed less of the pulsed laser energy. Weaker returns suggest a higher rate of absorption. Scientists use this information to help them classify the surface geology of the seabed. They can enhance their analysis by integrating other sensor data such as photographic and other image-based systems.

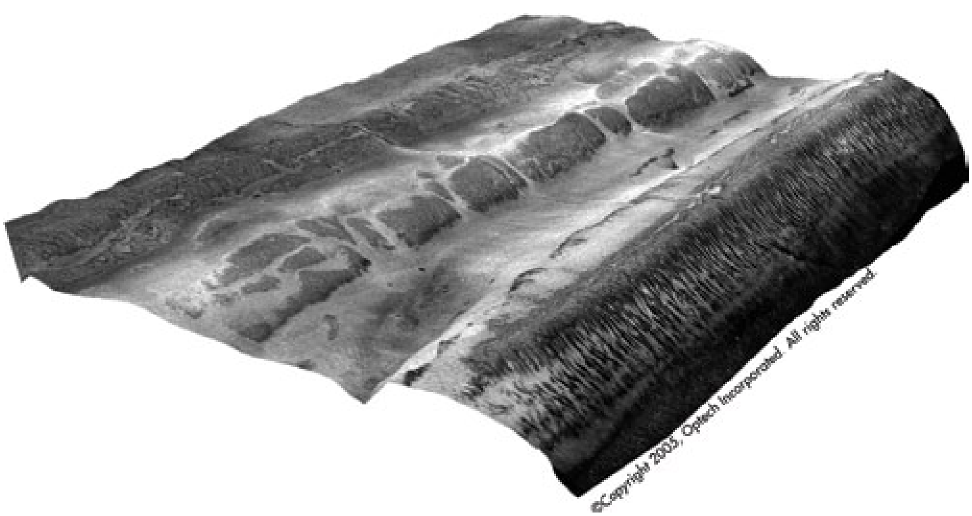

Figure 5. High-resolution 3D models of the seafloor with reflectance values draped over the surface provide a realistic representation of what the seafloor actually looks like. Courtesy of Grady Tuell, Optech International Inc. (Tuell, Park, Aitken et. al. 2005)(Kopilevich, Feygels, Tuell et. al. 2005).

This relatively new technology is becoming more widely used in hydrographic offices, naval commands, engineering groups, and coastal-zone management. Lidar bathymetry works well in delineating coastlines and measuring elevations because it is designed specifically for nearshore environments, and some systems collect both topographic and bathymetric datasets simultaneously.

Lidar is also used to measure the coral reef, a primary feature in shallow tropical ocean waters near the equator. Maps of coastal zones can represent reef as linework (polygons/polylines) or as imagery, among other ways. Some maps show the results of remote sensing and the analysis of hyperspectral imagery, while others illustrate reef boundaries determined from lidar and interpolation. Representing the unique ecosystem is one of the more challenging feats of underwater mapping since the perimeter of the reef is often hard to delineate and georeference back to the coastline. The coral reef is not a plant as many people assume but actually an animal composed of small polyps that cover a skeletal structure, continuously opening and closing, filtering water, and producing sand.

Nature demonstrates the dynamic quality of the ocean floor through sedimentation, or the accrual of sand in one place, and the transport of sand across the ocean floor. Surface currents can change direction with the wind, wave activity can fluctuate with a storm, and even the moon's phase influences the tidal cycle; all of these variants can be expressed as change on the ocean floor. Sometimes subtle and other times drastic, the sediment regime and sand movement can be difficult to capture on the seafloor map. Circulation and outflows of water are also often governed by processes of sediment suspension, transport, and deposition. Since the variation and change to sediment composition and the depth of the sand layer can be minute, lidar can be one of the ways to detect change to the ocean floor.

Single-beam and multibeam echo sounders

Single-beam echo sounder technology is generally accepted as the most traditional, low-risk, and common form of seafloor data collection in wide use by naval commands, hydrographic offices, academia, and the private sector. Invented as a listening device in the early 1900s, sonar (sound navigation and ranging) wasn't developed for bathymetry measurements until the 1930s. It is a proven and versatile technology that can be used in shallow to extremely deep water.

Figure 6. In this example of a single-beam echo sounder transducer, the device is mounted on the hull of the vessel underneath the water line, usually adjacent to the keel of the vessel. Courtesy of Kongsberg Maritime AS.

A single-beam echo sounder (figure 6) uses a transducer to transmit an acoustic pulse through the water column and then receive and measure the returned signal. It is almost always mounted on the hull of a vessel, and accuracy and quality varies depending on the complementary technologies used, such as positioning and measuring vessel attitude.

Single-beam echo sounders are particularly well suited for generating seafloor profiles and are most commonly used for measuring the depth immediately below the vessel to assist in real-time navigation. Single-beam echo sounders are not designed for full, bottom coverage of the seafloor. Unlike bathymetric lidar and multibeam echo sounders (discussed later), single-beam systems are designed to collect samples of depth of the seafloor in either a regular or irregular pattern.

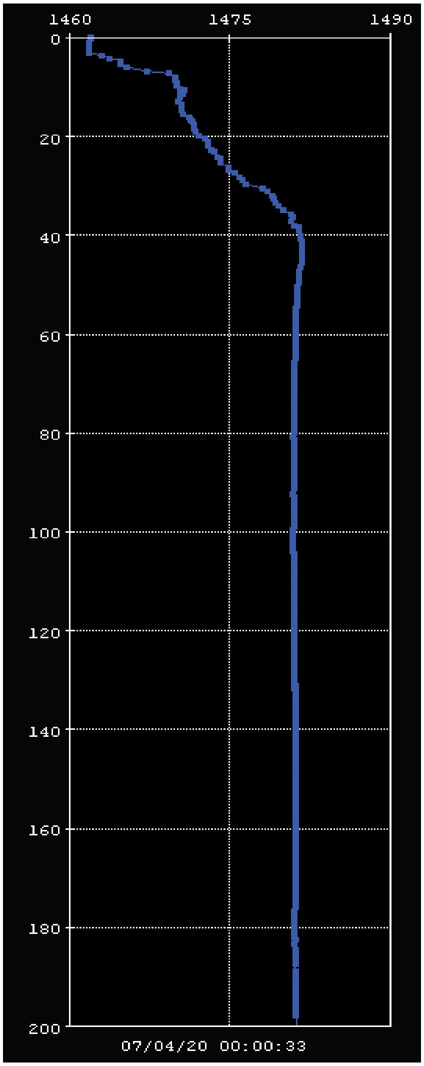

Figure 7. A typical sound-velocity profile shows thermoclines in the water column that affect the speed of sound in water. In this example, depths of 5, 10, and 40 meters indicate shifts in sound-velocity measurement. Courtesy of Kongsberg Maritime AS.

Single-beam technology collects and compiles bathymetric information for navigational products and for models depicting the seafloor. Sound energy, usually ranging between 12 and 710 kHz, transmits an acoustic pulse through the water column. The amount of time it takes for the sound, or ping, inaudible to humans, to travel to the seafloor and back to the receiver is precisely measured to help derive the depth. Additional processing takes into account vessel attitude, sound speed in the water column, tides, and other systematic offsets. The speed of sound in water varies and is primarily affected by salinity, temperature, and pressure (depth). These variables affect the conductivity of electricity through water, which in turn can either speed up or slow down the rate at which sound energy travels through the water column. Tide is another major factor that can affect the recorded measurement. Historically, tide is measured by land- or water-based observation recorders (either digital or analog), which are used to "postprocess" data. For the postprocessing of nearshore soundings, atmospheric pressure can be used as a variable to correct for daily differences in sea-surface height, though the variation found is minute. The solution for each measurement is considered a depth and is ready for modeling or inclusion into navigational and other products (figure 7).

The spatial resolution of bathymetry data collected from single-beam systems is largely governed by three predominant factors: the characteristics of the sensor, water depth, and the survey route design. The echo sounder transducer can vary across the many available platforms, including the frequency of the esonified energy, sampling rate of the transducer, and beam width of the pulse. Sound energy traveling away from the energy source is subject to spherical spreading, meaning that the energy content grows weaker and the coverage area broadens as the sound travels. For example, an approximate beam width of a transducer may be six degrees. While this may sound narrow, the footprint of the sonar ping on the seafloor increases as the depth increases. The footprint generally measures one tenth the water depth, so one could expect a footprint of 10 meters at a depth of 100 meters, although this could vary depending on the beam width, frequency, and algorithm (figure 8).

The survey route design also plays an important role in the sample spacing of depth measurements. Surveys are usually carried out for a particular need. For example, to create a nautical chart or plan the route of a transoceanic cable might require a profile transect. Since the depth of water affects the spatial resolution of the sounding footprint, the distance between transect lines is carefully planned to account for this. Systems such as lidar and multibeam echo sounders usually employ an overlap factor to ensure complete and continuous coverage of the seafloor. Though a sampling system such as a single-beam echo sounder measures only a representative sample, the line spacing is still important. The spacing may be reduced to just a few hundred meters between survey lines in shallower waters and extended to several kilometers in deeper waters (figure 9).

The temporality of single-beam echo sounders is governed only by how often a survey or transect is carried out. However, the nature of single-beam systems makes it virtually impossible to precisely measure the exact same position on the seafloor at separate intervals. Approximations usually suffice, and this is a key difference between full-bottom coverage and a sampling system such as the single-beam echo sounder. The horizontal and vertical

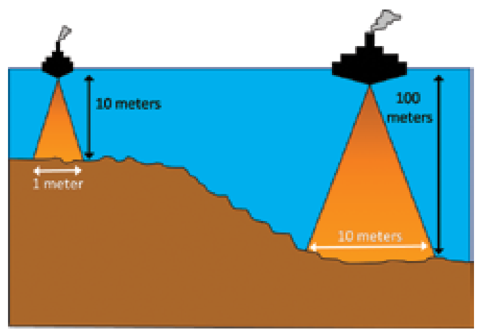

Figure 8. The relationship between water depth and the size of the illuminated "footprint" on the seafloor is illustrated here. Courtesy of Timothy Kearns.

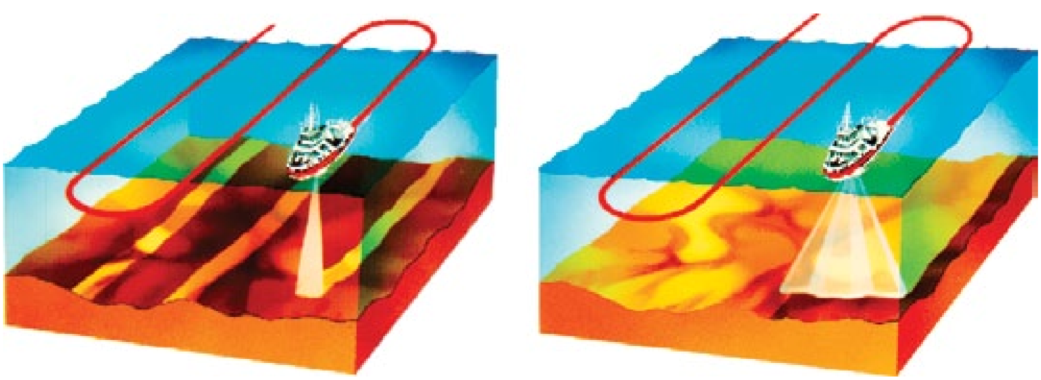

Figure 9. A single-beam echo sounder illuminates only a narrow portion of the seafloor, while multibeam echo sounders can provide continuous coverage. Courtesy of Kongsberg Maritime AS.

position of a vessel, the 3D position of the transducer, and the measurement of sound speed in the water column all contribute to the accuracy associated with these systems (figure 10).

Before the use of GPS to position vessels, the horizontal accuracy of soundings was subject to a higher degree of error. Traditional positioning included using a sextant, celestial navigation, and later, Loran-C, a radio-based system transmitting frequencies from shore-based stations to help determine a latitudinal and longitudinal coordinates. As GPS evolved, so did the accuracies associated with positioning vessels using echo sounding systems. Differential global positioning systems (DGPS) introduced in the mid-1990s improved horizontal positioning a great deal through the use of a ground-based receiving station in conjunction with the satellite constellation. The ground-base station measures local errors that can be translated into a positional variance on the data the vessel collects. Accuracies of at least 3 meters are normal for DGPS. However, this method still must account for the vertical measurement of the water level at the time of the survey. This can be achieved three ways: tidal prediction models, measurements from onshore tidal observation posts, and measurements from devices towed by a vessel, anchored on the seafloor, suspended in the water column, or floating on the surface (figure 11).

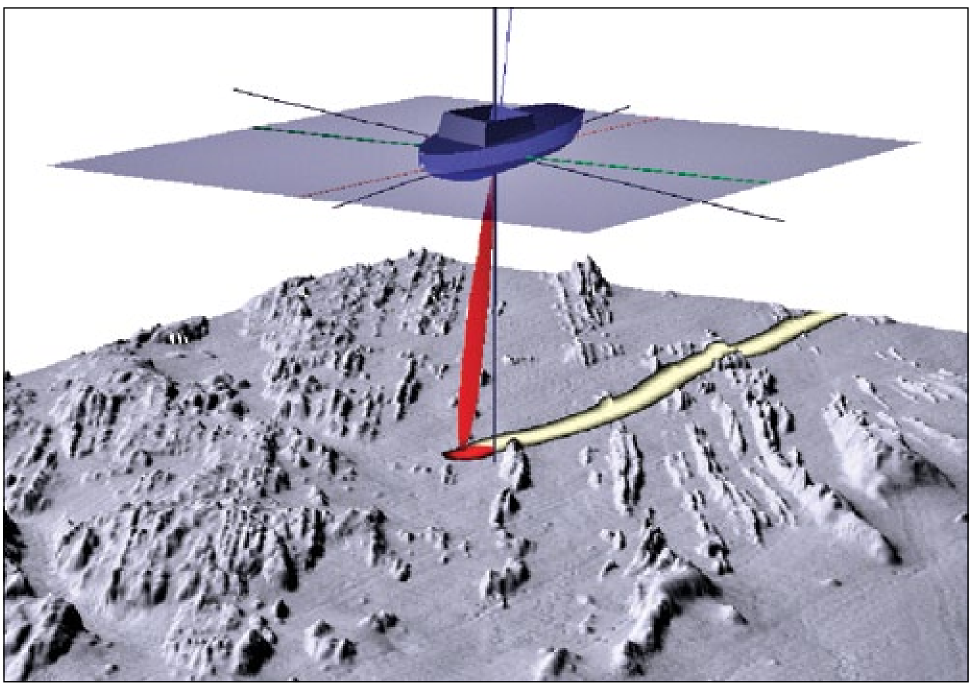

Figure 10. The "attitude" of a vessel is measured by roll, heave, pitch, and yaw. For single-beam data, all of these physical motions must be accounted for in the position of the measurement. Courtesy of J.E. Hughes Clarke, Ocean Mapping Group, University of New Brunswick.

Kinematic GPS (KGPS) was introduced in the late 1990s and is now widely used among collection systems. KGPS references the World Geodetic System of 1984, which negates the need to collect a local mean water level measurement. This removes the tidal variation to the source data and improves the overall vertical accuracy, because the vertical measurement is taken at the location of the horizontal coordinate and is not a predicted or modeled value.

Data collected by single-beam echo sounders are discrete point data, measured as depths. One of the primary applications of this type of system is to measure the amount of clearance, under keel, that a vessel has at the present moment. This type of collection is for instantaneous purposes and is typically not stored as long-term measurements. For applications where the data are intended for modeling or analysis, postprocessing of the collected data usually involves correcting for tidal, sound-velocity, and vessel attitude adjustments. Historically, the soundings were plotted by hand. In recent years, hydrographers have used large format printers to create a series of map sheets of all the collected depths. Modern systems store the discrete points on disk, along with the geographic coordinates and relevant attributes associated with the measurements such as date, time, ship identification, model of the transducer, and track identification. Depending on the application, the data could be supplemented by other data to help answer questions about the seafloor. If used strictly for measuring depths, derivative products usually include measurements plotted on nautical charts, contour lines, and special soundings indicating rocks, wrecks, or other hazards to navigation. Single-beam data are too sparse for high-density seafloor modeling and are more useful for identifying general seafloor depths over very large areas.

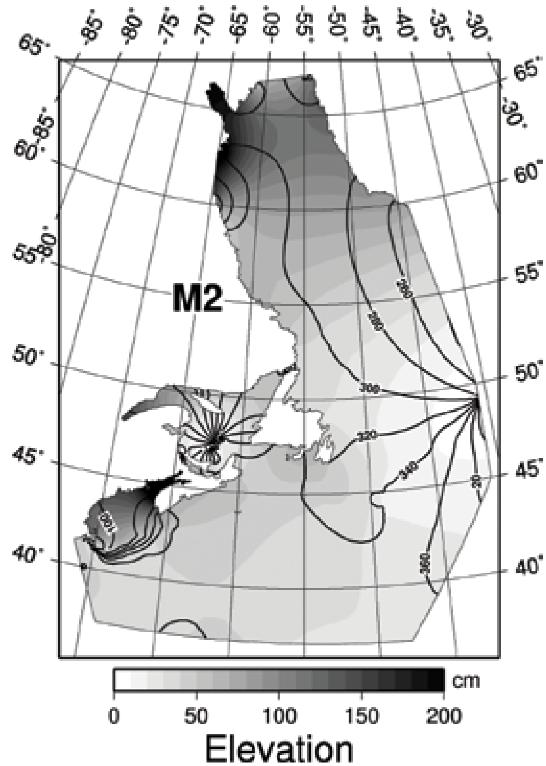

Figure 11. Using a series of observed and predicted measurements, complex algorithms can be used to create tidal models to accurately portray sea surface heights. Courtesy of Department of Fisheries and Oceans, Government of Canada.

Multibeam echo sounders are the most revolutionary advancement in seafloor mapping since the advent of the lead line several thousand years ago. Although multibeam technology was developed in the 1950s, it wasn't until the late 1970s that civilians and commercial interests began using these systems, primarily for hydrographic surveying. Because echo sounders were the first devices used to collect continuous sea-bottom coverage, this gave scientists a view of the ocean floor they had never before seen (figures 12 and 13).

This technology effectively blankets the seafloor with pulses of sound energy that provide an array of measured depths. GIS is used to process these soundings to reveal information about the topography and geology of the seafloor. The same principles of single-beam echo sounders are applied, but there are some fundamental differences in the systems, which result in vast differences in the way collected information can be interpreted and represented. Both systems use sonar energy to transmit a signal to the seafloor and measure the time difference of the returned pulse. However, multibeam echo sounders use a transducer, with varying designs among different companies, to transmit a fan-shaped array of pulsed energy divided into a series of beams. Each beam has a unique identification, and because the returned signal is associated with an individual beam, each beam derives a separate sounding and measurement of the seafloor (figure 14).

Early multibeam systems had around sixty beams, but some systems today have as many as 800. Additional configurations and variations among systems can lead to "double pings," resulting in two times the number of soundings per beam. The volume of data collected by these types of bathymetric systems is unprecedented in the hydrographic community, and organizations are constantly adjusting operational and business processes to accommodate these datasets. As an example specific to GIS, to load the millions of points that typically comprise a collection of multibeam soundings may require special point loaders and the use of an enterprise database together with a spatial database engine like ArcSDE (figure 15).

The geometric distance between the centers of the footprint in each beam approximates the spatial resolution of bathymetric data collected from multibeam echo sounders. The size of the beam footprint is governed by two primary factors. The first is beam

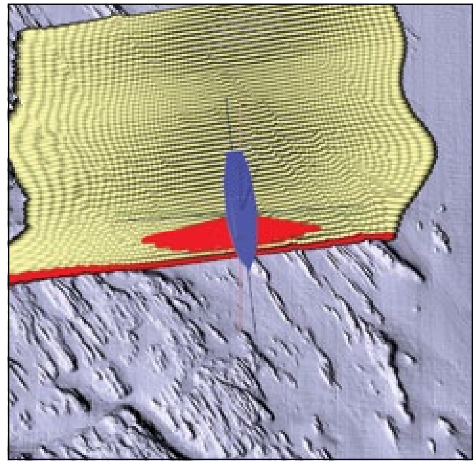

Figure 12. Multibeam echo sounders can blanket the seafloor with acoustic energy, providing 100 percent coverage. Courtesy of J.E. Hughes Clarke, Ocean Mapping Group, University of New Brunswick.

Figure 13. A dual-head multibeam echo sounder can be mounted on a retractable pole on the bow of a vessel, as shown here. Echo sounders are often mounted underneath the water line on the hull of the vessel adjacent to the keel. This Kongsberg EM3002D echo sounder can collect measurements from 0.5 meters to 150 meters. Courtesy of Kongsberg Maritime AS.

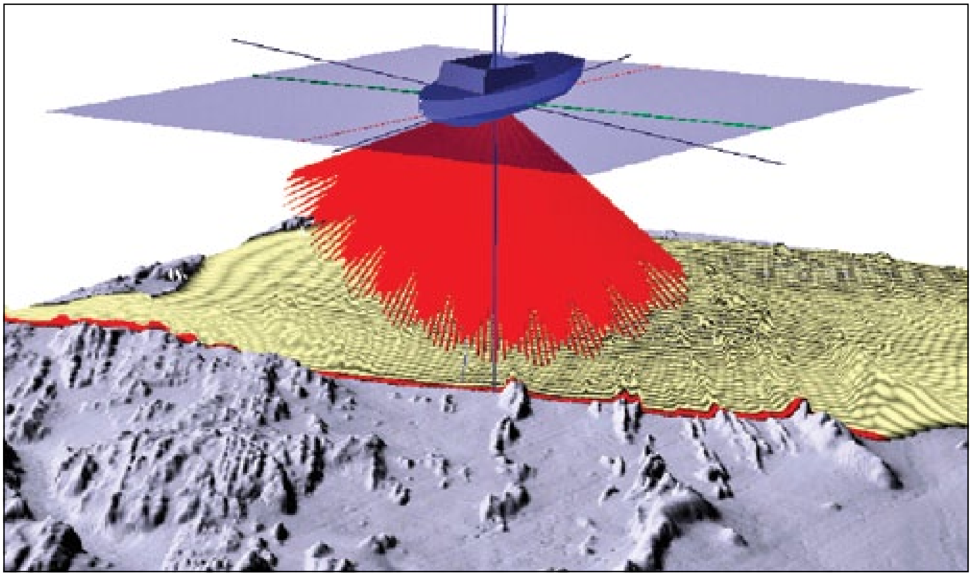

Figure 14. Hundreds of individually formed beams are transmitted and received by the transducer of this multibeam system. Courtesy of J.E. Hughes Clarke, Ocean Mapping Group, University of New Brunswick.

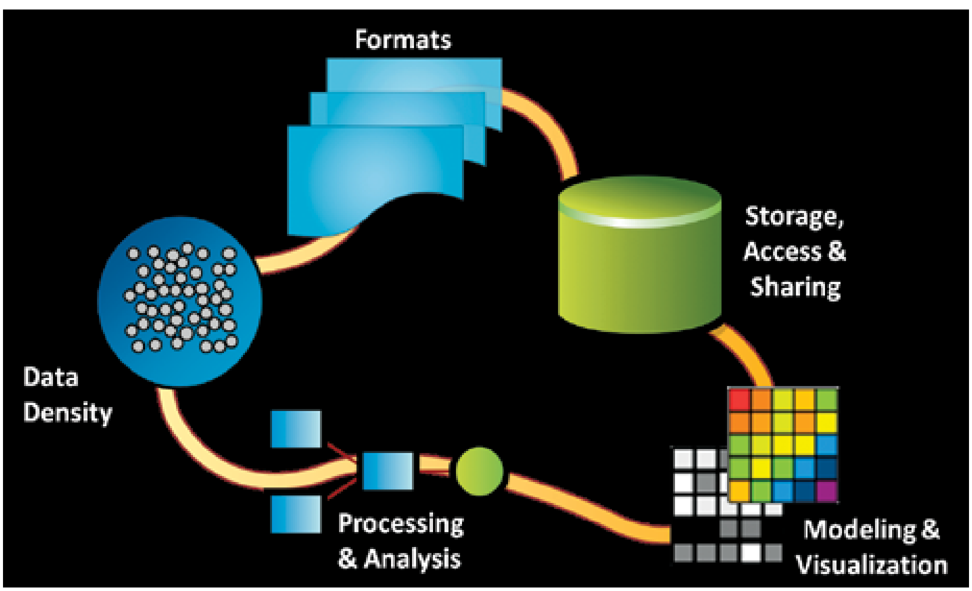

Figure 15. The millions of points produced by multibeam systems pose challenges for users, including format interoperability, visualization and modeling, storage and retrieval from database systems, and geospatial analysis. Courtesy of Timothy Kearns.

width. A narrower beam width results in a small sonar footprint on the seafloor; when combined with hundreds of other beams, this can result in a finer spatial resolution. Most multibeam echo-sounders use a beam width that can vary from 0.5 degrees to 2.0 degrees. The second primary factor is water depth. As the sonar pulse travels away from the transducer array, it is subject to spherical spreading, meaning that the area affected by the ping gets broader with increasing distance. Shallower water returns the signal much faster, and the resulting data are associated with significantly higher spatial resolution. Although spatial resolution can vary from system to system—again, because of the band width, frequency, and algorithm—it is generally about 10 percent of water depth, taking into account an appropriate vessel speed. Like the single-beam system, a multibeam echo sounder operating under normal conditions for the purposes of hydrographic surveying generally would produce bathymetry data with a resolution of 10 meters in 100 meters of water, a key difference being the high-resolution "swath" or belt of data produced by the multibeam. For this reason, gathering data from multibeam systems is often called "swath hydrographic surveying." The width of the swath is governed by the water depth and the design of the multibeam echo sounder system itself. More than two dozen multibeam systems are available on the market today, and most have a swath-width range that varies with the water depth.

Hydrographic surveyors must plan their surveys according to the water depth, system type, vessel speed, and survey application. The beams in the center of the fan-shaped array are called nadir beams. Pulses of energy are sent perpendicular from the sensor head of the transducer to the seafloor. Overlap of at least 20 percent is usually planned to account for any degradation in the data collected from the outer beams. This ensures good quality data from the center 60 percent of the beams and 100 percent coverage of the seafloor with no data gaps (figure 16).

Significant advances in multibeam echo sounder systems today have greatly improved data quality and accuracy. Horizontal and vertical positioning is precisely measured through the use of GPS and inertial measurement units (IMU). Measuring the movement and position of the vessel is imperative to preserve the accuracy of the data because the position of the sounding will change as the vessel moves in the water due to roll, heave, pitch and yaw. IMUs measure the angular offsets of the transducer resulting from vessel movement. These devices are usually mounted very close to the transducer to minimize any variation in the offset between them. The results of the IMU are combined with the measurement either at the time of collection or in a postprocessing workflow to refine the accuracy of the sounding position. Some systems today can account for vessel attitude at the time of the ping, increasing the data quality.

The accuracy of sounding data also depends on the measurement of sound traveling through

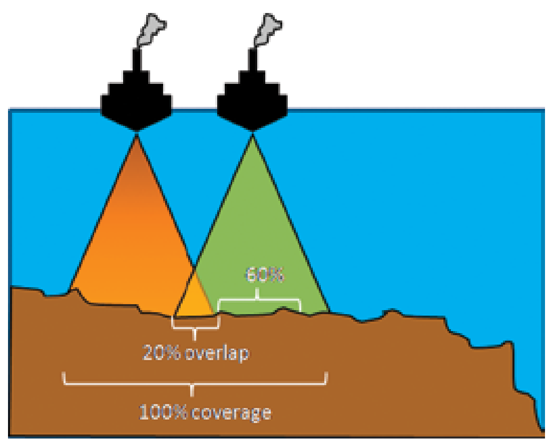

Figure 16. Hydrographic multibeam surveys usually employ a 20 percent overlap to ensure 100 percent coverage of the seafloor. Courtesy of Timothy Kearns.

water at the time of acquisition. The speed of sound in water increases with rising temperature, salinity, and pressure (depth), causing it to vary slightly from less than 1,500 meters per second to more than 1,600 meters per second at depths greater than 2,500 meters. Sound velocity is measured using a probe deployed by a cable or chain during the survey. The sound-velocity profile normally is taken at predefined intervals at least once a day. The profile involves stopping the survey, deploying and retrieving the probe, and verifying the accuracy of the collected data. Some newer systems can deploy a probe while the vessel is under way, allowing survey operators to collect many samples of water column profiles in a day. The sound velocity is applied to the data as part of the postprocessing routine (figure 17).

Figure 17. Sound-velocity measurements can be collected while the vessel is under way. Shown here is a deployed sound-velocity measuring device (a Brooke-Ocean Technology MVP–200) on the *Anne S. Pierce* over Georges Bank in the Atlantic Ocean. Courtesy of Timothy Kearns.

Most multibeam echo sounders of today can estimate the overall accuracy of individual soundings based on a variety of characteristics and known measurements. This calculation, total propagated error (TPE), when combined with sophisticated algorithms, can produce an error model for seafloor data that assists in automated data cleaning and postprocessing of the raw data. For navigational products, this type of information is extremely useful in helping create datasets from a variety of source data, providing the best available resolution and accuracy for a given area.

Multibeam systems produce discrete point data similar to single-beam systems, albeit at exponentially increased volumes. These points are stored in an onboard system for further processing. All point measurements are tagged with attributes that at the very least include beam identification, track identification, date, time, ship identification, system model, and depth. Most systems can apply vessel attitude corrections and GPS positions at the time of acquisition, reducing postprocessing time and improving the workflow. A substantial amount of interactive postprocessing, data cleaning, sound-velocity profile application, tidal adjustments and other systematic corrections are required to process these data. The preparation of the data for additional modeling will become increasingly efficient as technologies for data capture and automated algorithm processing evolve.

Multibeam echo sounders also collect backscatter information, which can provide information about the geology of the seafloor. Backscatter is characterized by the intensity, or strength, of the returned signal. As sound energy propagates through the water column, some energy is lost through attenuation and absorption. More energy is lost in the sediment; softer sediments such as mud and sand typically absorb more energy than rocky surfaces. A sensor will record a stronger intensity from a rocky surface than from sand because more energy returns from harder surfaces. Backscatter data are recorded in image format, with darker pixels representing weaker returns from softer sediments and lighter pixels represent stronger returns from harder sediments (figures 18, 19, 20).

GIS data representations

The systems described above collect bathymetric data in two types of data: discrete points and backscatter images. All geospatial data are organized into either vector or raster format. Points are a form of vector data, as are lines and polygons, the three basic geospatial data types. Raster data are also referred to as image data, with a matrix of rectangular cells aligned in rows and columns (figure 21).

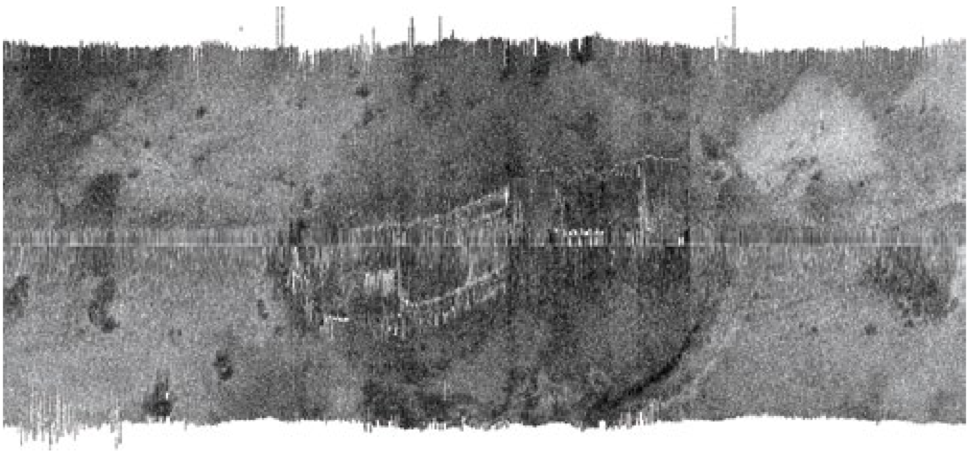

Figure 18. Backscatter imagery of a wreck recently discovered off the coast of Peru can help scientists identify seafloor targets. This example is from Kongsberg EM 3002 multibeam data. Courtesy of Dirección de Hidrografía y Navegación—Marina de Guerra del Perú.

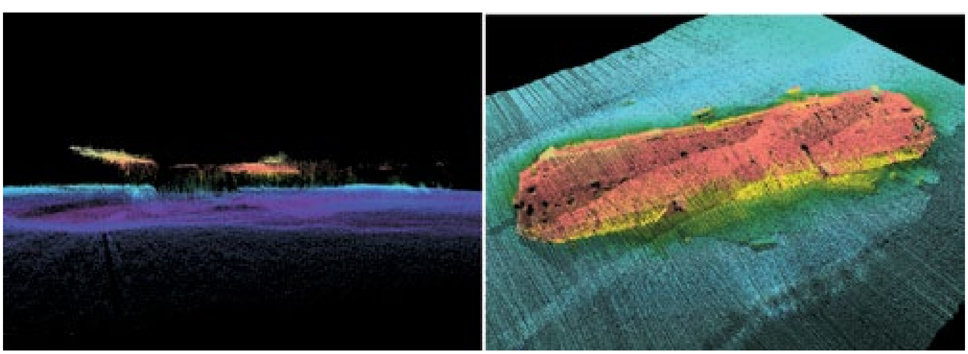

Figure 19. The wreck identified in figure 18 is shown again in point form. Two different views show the height of the top of the wreck, based on Kongsberg EM 3002 multibeam data. Courtesy of Dirección de Hidrografía y Navegación—Marina de Guerra del Perú.

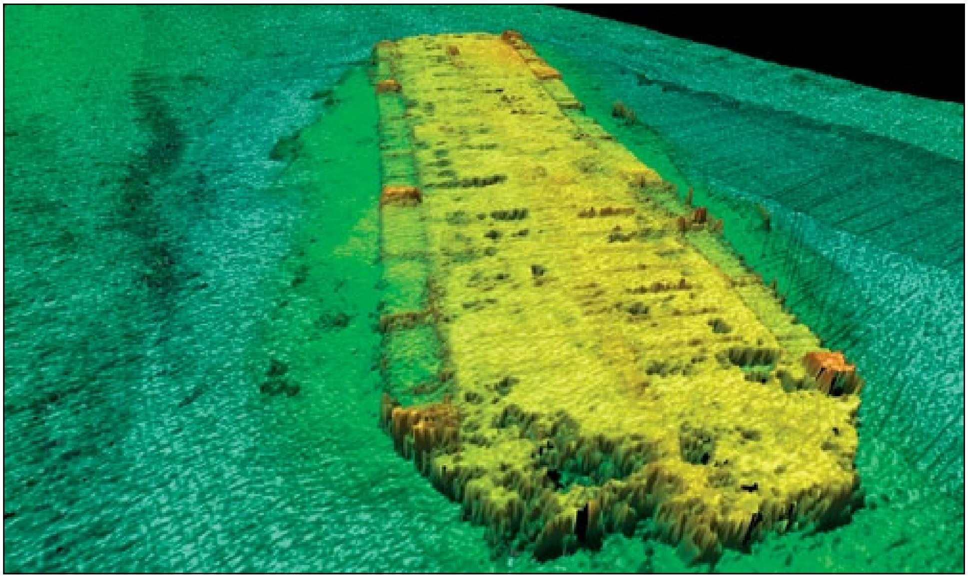

Figure 20. The same wreck is visualized as a 3D surface using specialized software (Fledermaus by IVS-3D). Creating models like this allows scientists to do advanced geospatial analysis such as surface-height measurements, slope measurements, volumetric calculations, and navigational route modeling. This example is based on Kongsberg EM 3002 multibeam data. Courtesy of Dirección de Hidrografía y Navegación—Marina de Guerra del Perú.

Postprocessing dense data points from bathymetric lidar and multibeam echo sounders results in a "cleaned" dataset that can be used for further analysis and modeling and for creating derivative products. Depending on the application of the data, different methods are used to create seafloor models and other secondary data. A seafloor model can be generated to show a certain bias of measured depths. Taking into account that millions of soundings are collected with significant overlap among the data points, not all values for a position on the seafloor will be the same. For an end user concerned about safe navigation, modeling can account for shallower measurements to represent the minimum depths. Other applications may be interested in the deepest values and will generate respective surfaces with this focus. Postprocessed point data go through a data transformation to generate new derivative products and data. The following table summarizes some of the common types of data transformations that bathymetry data follow.

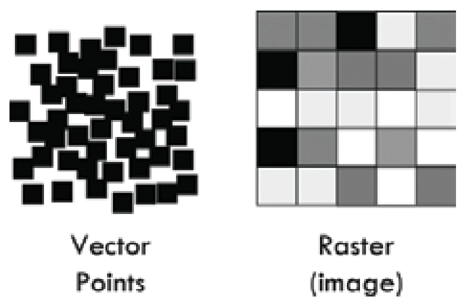

Figure 21. The two basic forms of geospatial data are raster and vector structures. Courtesy of Timothy Kearns.

ORIGINAL DATA TYPE	To points	To lines	To areas
From points	Interpolated and representative points through binning	Contour isobaths	Buffered points, triangular irregular networks, depth area polygons
From lines	Line intersections	Smoothed contour isobaths at smaller scales	Depth-area polygons, buffer zones.
From areas	Sampling at points	Medial axis (called skeletonizing)	Spatial analysis through overlay techniques

Table 1. Bathymetric points can be transformed into other points, contoured into lines, and modeled into areas. Lines and areas can be transformed into other data structures too.

High-density bathymetric data are seldom used in the full resolution but is transformed into new points, contour lines, triangulated irregular networks (TINs), raster products, polygons such as depth areas, or a combination of these. Dozens of different modeling algorithms can perform these spatial processes, and new research continually yields innovative and more efficient ways to accomplish these transformations (figure 22).

Processed soundings are primarily used as the inputs to the transformation process. Thinned soundings are decimated copies of the original sounding set, though usually at a data density that is appropriate for a fixed scale, such as a nautical chart. Themed soundings are designated as special, because those individual soundings represent either a particular shallow point which must be displayed on all chart products (also called "golden" soundings) or are other subsea features, such as wrecks, rocks, or other hazards to navigation. Regularly spaced points are derived from the original

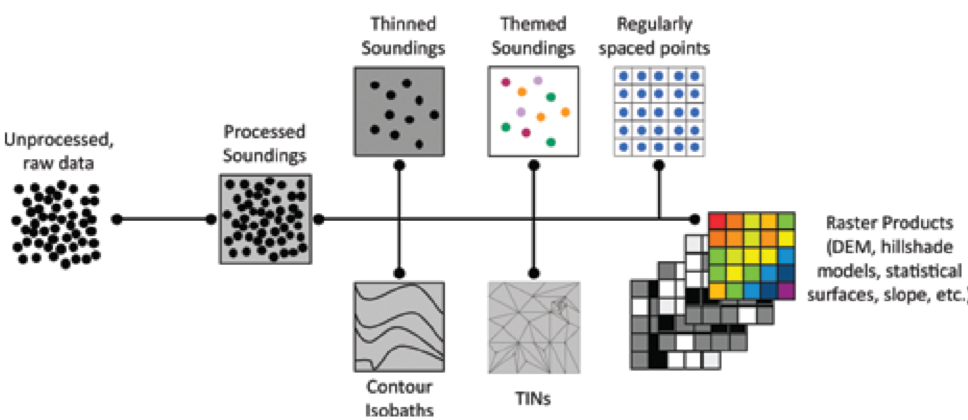

Figure 22. Bathymetric datasets go through a transformation from raw soundings to a variety of derivative products including thinned soundings, contour isobaths, TINs, and raster surfaces. Courtesy of Timothy Kearns.

sounding set through a process called "binning." The most common of many ways to accomplish this is to take a representative sample of soundings within a rectangular grid cell and assign one unique value to that cell based on averaging, shoal (shallow) bias, deep bias, or through more complicated means (figure 23).

This procedure can generate datasets with regularly spaced points or surface models that are raster data. DEMs, also commonly referred to as surface models or digital terrain models, are composed of a series of pixels arranged in rows and columns where each cell represents a depth value. DEMs are particularly well-suited for visualization in software applications and integrating with other raster data. By adding an artificial sun illumination and some vertical exaggeration, a more realistic picture of the seafloor emerges with a shaded relief model. Until multibeam echo sounder data were available and used in conjunction with sophisticated software, this type of imagery had never been available before. Shaded relief models enable hydrographers to visualize their data to look for systematic errors or artifacts. These models also allow visualization of the seafloor with high resolution and fidelity (figure 24).

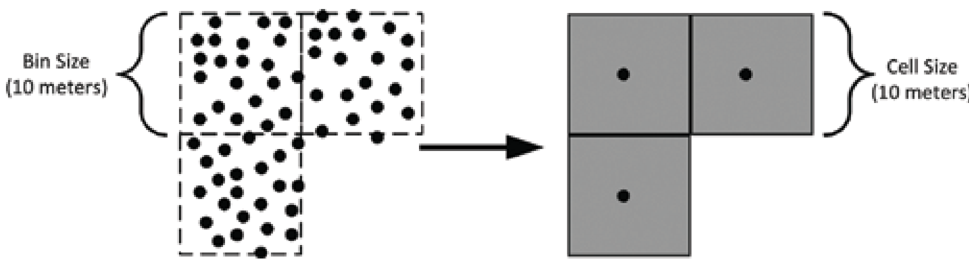

Figure 23. Binning is a common method of interpolating points from a dense collection into a regular spaced rectangular array of cells with single values representing the depth for that area. This representative depth can be shoal (shallow), deep, or median biased, but it can also be a depth calculated from advanced algorithms such as combined uncertainty bathymetric estimation (CUBE). Courtesy of Timothy Kearns.

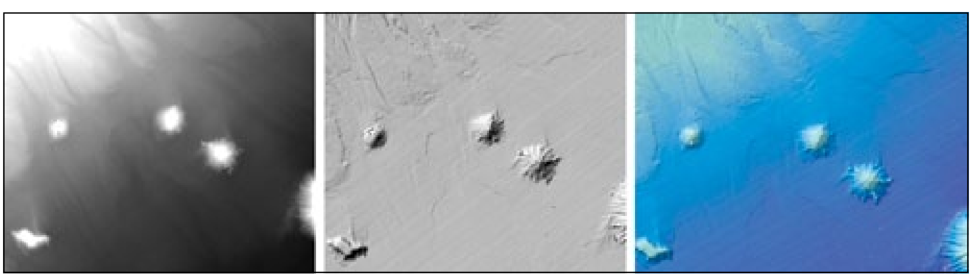

Figure 24. The first example shows a DEM. The second shows a model with artificial illumination and shadow applied. In the third model, color has been added for effect. Courtesy of NOAA.

Contour isobaths also can represent bathymetric data. Contour isobaths are vector data represented as lines connecting depths of equal value. The interval between lines is dependent on scale, application, and other factors, but contours that are closer together represent a highly variable or steep terrain, whereas contours that are farther apart indicate a smoother and more flat seafloor. Contour isobaths are often used to represent bathymetry when vector data are the most appropriate choice for engineering purposes. Contour isobaths are also used as safety boundaries for ships navigating in shallow waters. When navigating into shallow waters beyond a designated depth contour, an alarm can sound to warn the boatswain or operator of the vessel. Contour isobaths are also used on navigational products such as charts (figure 25).

Profiles allow investigators to see a slice of the seafloor from a cross-sectional perspective. They can be created from the data collection systems mentioned above but are most versatile with high-density data. These are particularly useful for cable and pipeline route analysis and infrastructure installation and serve as an excellent complementary representation of other bathymetric products (figure 26).

Most bathymetry maps that historically represent continuous global seafloor coverage are artist renditions. It wasn't until recently that concerted efforts have been made to compile single-beam and multibeam bathymetric data in the public and classified domains to produce higher-resolution global bathymetric models. As a result, models are now available to the public that allow everyone to visualize the seafloor as a generalized representation. Because continuous global high-resolution data do not yet exist, the most common representations of bathymetry for large-scale visualization result in three types of products: nautical charts, and 2D and 3D seafloor models (figures 27, 28, 29).

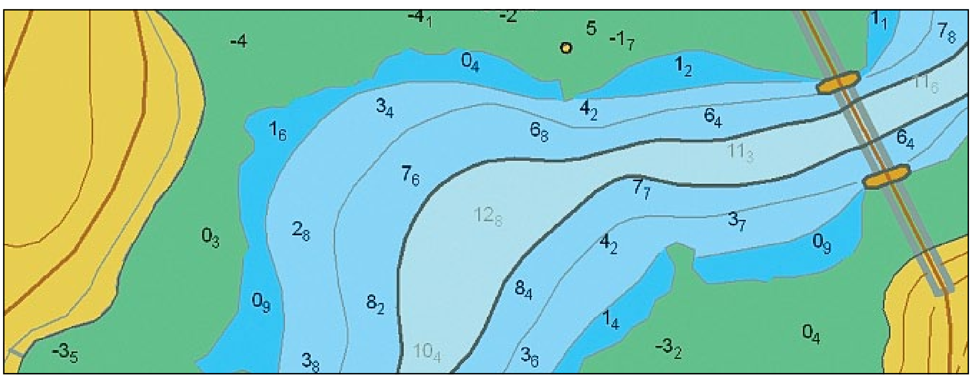

Figure 25. Bathymetric data are often represented as both numeric soundings and contour isobaths on navigational charts. Courtesy of Timothy Kearns.

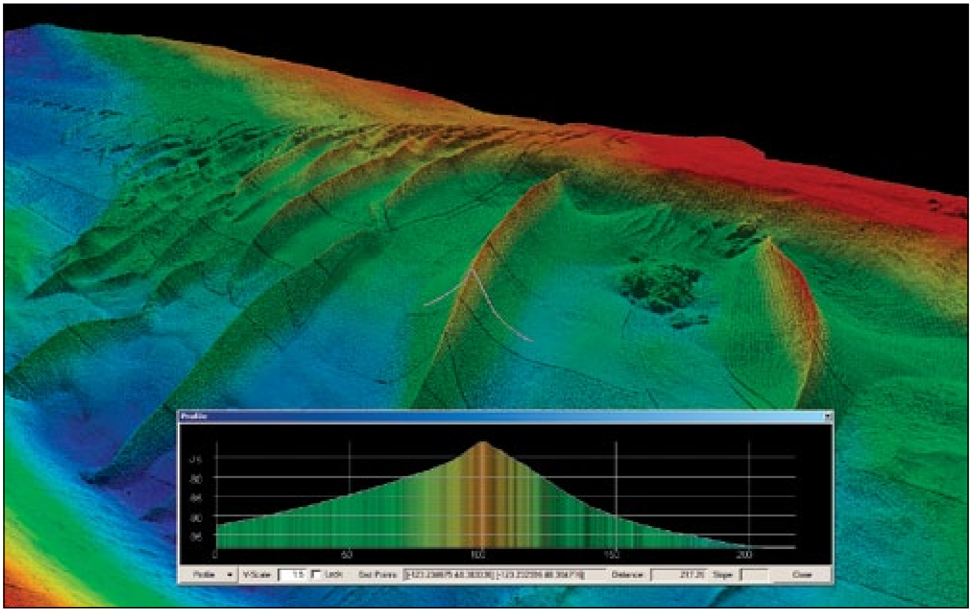

Figure 26. Creating profiles along transects of the seafloor assists in analysis and visualization. These sand waves are more than 20 meters high in almost 100 meters of water off Canada's west coast. This example is based on data from a Kongsberg EM 710 multibeam system. Products that have traditionally seen bathymetric representation are printed nautical charts that depict bathymetry as soundings and contour isobaths. Readers will find a more detailed overview of historical bathymetry in the appendix, "The history of seafloor mapping." Courtesy of Canadian Hydrographic Service.

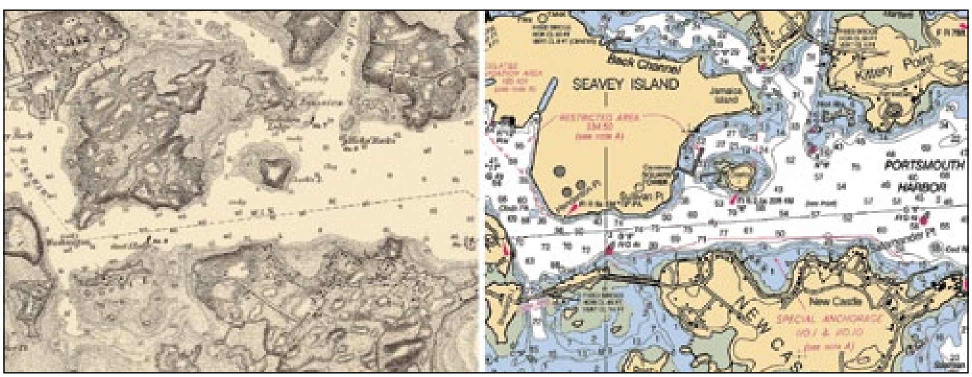

Figure 27. A historical chart of Portsmouth Harbor, New Hampshire (1866, 1:20,000), adjacent to a modern publication of the same chart (1980, 1:20,000). Soundings from the historical chart (in fathoms) closely match the measurements on the modern chart (in feet). Courtesy of NOAA.

Figure 28. This artist's rendition of the Atlantic Ocean seafloor is from a map published in 1968. Digital data and imaging techniques were not yet available for the creation of models in common use today.

Courtesy of National Geographic Maps, www.natgeomaps.com.

Figure 29. With the advent of analog-to-digital conversion and modern data collection techniques, this image of the Atlantic Ocean published in 2009 demonstrates advances in technical capability. Courtesy of National Geographic Maps, www.natgeomaps.com.

Nautical charts

A nautical chart provides information about depths, coastlines, navigational aids, selected topographic information, and other navigational data. Nautical charts identify navigational hazards with the primary purpose to help mariners reach their destinations safely. A nautical chart is actually a planar surface that represents a portion of Earth, which is a spheroid, not a flat surface. For centuries, mariners have plotted their courses, bearings, dead reckonings, and fixes from paper nautical charts.

As technology has evolved, the use of electronic navigational charts has become more commonplace and prevalent. An electronic navigational chart (ENC) uses digital data and an approved display system to provide visualization in electronic form. An electronic chart display system (ECDIS) is now common on all large sea-going vessels. This system displays the same features found on a traditional paper chart, but in vector format, allowing mariners to overlay other types of navigational information such as radar and special features not normally displayed on paper charts. Both paper and electronic charts display soundings in selected locations to show depths and chart scale, among other reasons.

These charts depict an appropriate amount of soundings for the mariner at a certain scale. Even if higher-resolution data exist, the chart-producing agency will “reduce” the soundings from their full-density dataset to a decimated sample. When compiling bathymetric data for navigational products, a representative sample of the data is gathered at a fixed scale, such as 1:20,000 or 1:40,000. These products are often called “field sheets” or “smooth sheets” and form the basis for further sounding reduction and contour isobaths selection. Hydrographers and cartographers select the appropriate soundings for display on the chart products, each with incrementally less density on smaller-scale charts. Nautical charts are still the most predominant method of understanding the bathymetric environment for mariners today (figures 30 and 31).

As described earlier, the advent of computers and electronic display systems onboard large and small vessels has changed the way mariners visualize their environment, and in particular, the surface below the keel of their ship or boat by using an ECDIS. This system also allows mariners to see bathymetry in a new and different way. Soundings and contour isobaths are complemented by depth areas and automated signals that issue warnings when vessels reach or cross certain depths (figure 32).

Further advances in computing have extended the use of bathymetry far beyond navigation. Probably the most dramatic impact on the representation of bathymetry is the ability to view high-resolution images of the seafloor in 3D. During the 1990s significant advancements were made in the area of 3D computer visualization. They soon evolved to take advantage of rendering the high rate of data volumes being collected with the new multibeam echo sounding systems (figure 33).

Using specialized software, hydrographers, scientists, engineers, geologists, and academics can visualize high-resolution surfaces of the seafloor. Today, dozens of applications take advantage of high-resolution bathymetric data, as the next section explains in more detail.

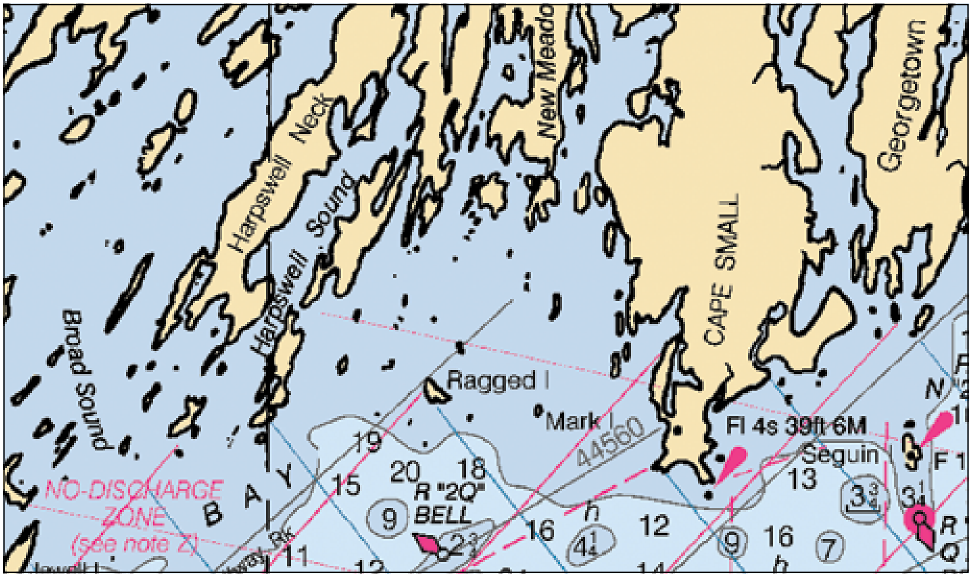

Figure 30. This small-scale chart depicts features along the New England coast of the United States. Courtesy of NOAA.

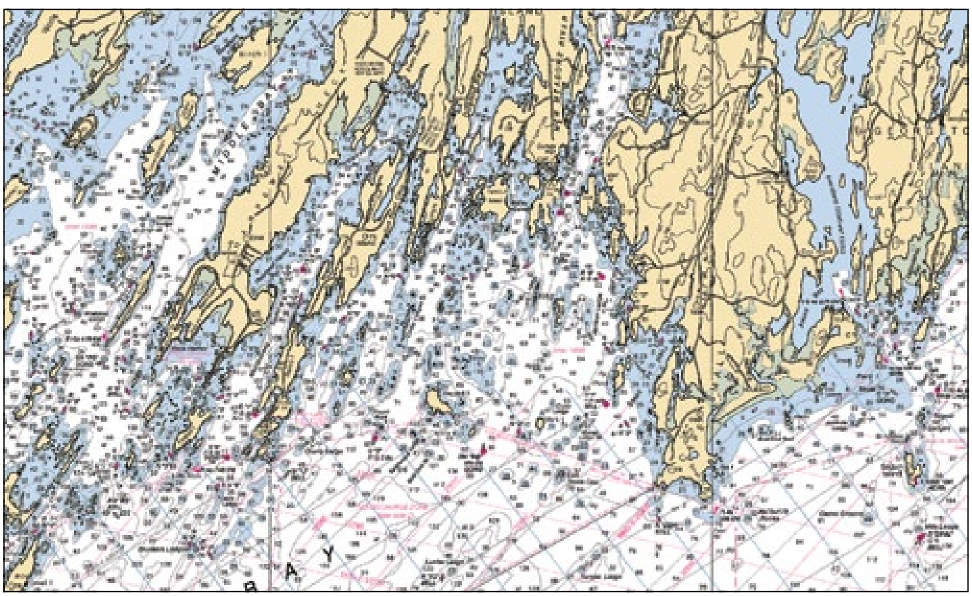

Figure 31. This large-scale chart depicts features along the same New England coast in the United States. One can easily see the differences in feature representation between the two charts. Courtesy of NOAA.

Applications of bathymetric data

The uses of seafloor mapping have grown almost exponentially from the time when it served mainly as a guide for safe navigation. A comprehensive review of the many bathymetric applications is beyond the scope of this chapter. However, the next sections will provide a brief overview of some of the important, varied, and increasing uses of bathymetry and the often-unnoticed role it plays in our daily lives.

Submarine utilities

In our busy world, most people give little thought to the role of Internet-based technology as they talk on the phone, pass data back and forth, and communicate with friends and relatives across the sea. These communications are carried between continents and countries via satellites, but they are also dependant on submarine communication cables that stretch across the ocean floor. Nearly

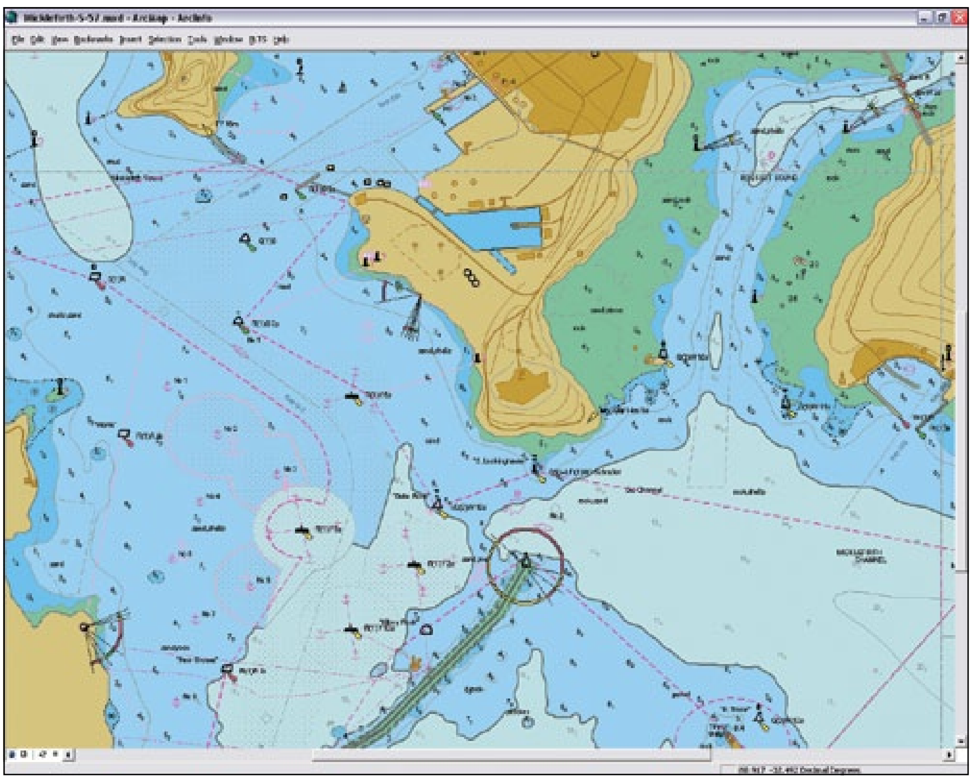

Figure 32. An electronic navigational chart (ENC) is used with an ECDIS for all commercial shipping and navigation. Courtesy of ESRI.

100 major submarine cable systems crisscross the ocean floor today, and many more are planned (Cookson 2003).

The first submarine communications systems carried telegraph messages, while the next generation of cables handled telephony traffic; then came data communications. All of the modern cables use optical fibers to carry telephone, Internet, and private data-transfer traffic. By 2003, deep-sea cable linked every continent except Antarctica. The history of the transoceanic cables is an interesting one that began in 1842 when Samuel Morse (of Morse code fame) sank a cable insulated with tarred hemp and rubber.

Today commercial cables stretch from land, down the continental slopes, across the ocean floor through the deepest parts of the ocean—the abyssal planes where no light penetrates—and back up again, cutting across steep sections of continental shelf to reach land. The planning and selection of the routes used for transoceanic cables is an important part of the process of laying submarine utilities. Survey vessels, using a variety of sensors such as multibeam, single-beam, magnetometers, and seismic profilers, traverse the intended route collecting data. Using many of the techniques and products described earlier, a variety of analysis and bathymetric models are generated from the data. Geophysicists and engineers from utility companies examine bathymetric and geomorphologic characteristics of the seafloor to determine the exact paths that the submarine cables or pipelines should follow. They use 3D visualization and analysis, contour isobaths, cross-sectional profiles, and traditional nautical charts to help in their decision making. It is imperative that existing infrastructure and seafloor features influence the selection process. New submarine utilities must avoid bottom trawling equipment, military exercise areas, existing cable and pipeline infrastructure.

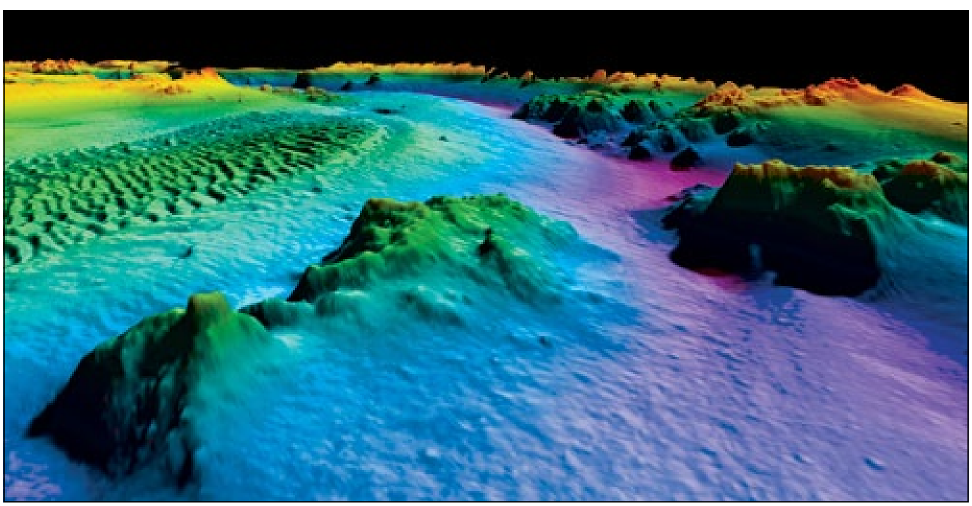

Figure 33. A high-resolution model of the seafloor is generated from multibeam echo sounder data in Portsmouth Harbor, New Hampshire. Courtesy of IVS-3D and the University of New Hampshire Center for Coastal Ocean Mapping.

GIS plays an integral role in planning surveys and deploying and maintaining of undersea cable installations. While many applications can provide a high-resolution ocean floor, only GIS adds the capacity to fuse meaningful information related to physical characteristics such as slope, aspect, rugosity, contours, and many other information layers not limited to the ocean floor. The image of the Hawaiian Islands is a timeless example of how high-resolution seafloor can be merged with geophysical data to produce a meaningful map that depicts the relationship of the seafloor with the land mass above sea level (figure 34).

International law

The structure of the ocean floor is important for many reasons beyond the traditional applications of bathymetry. It influences the legal definition of jurisdictional boundaries for coastal nations. The United Nations Convention on the Law of the Sea (UNCLOS) defines the guidelines for the use

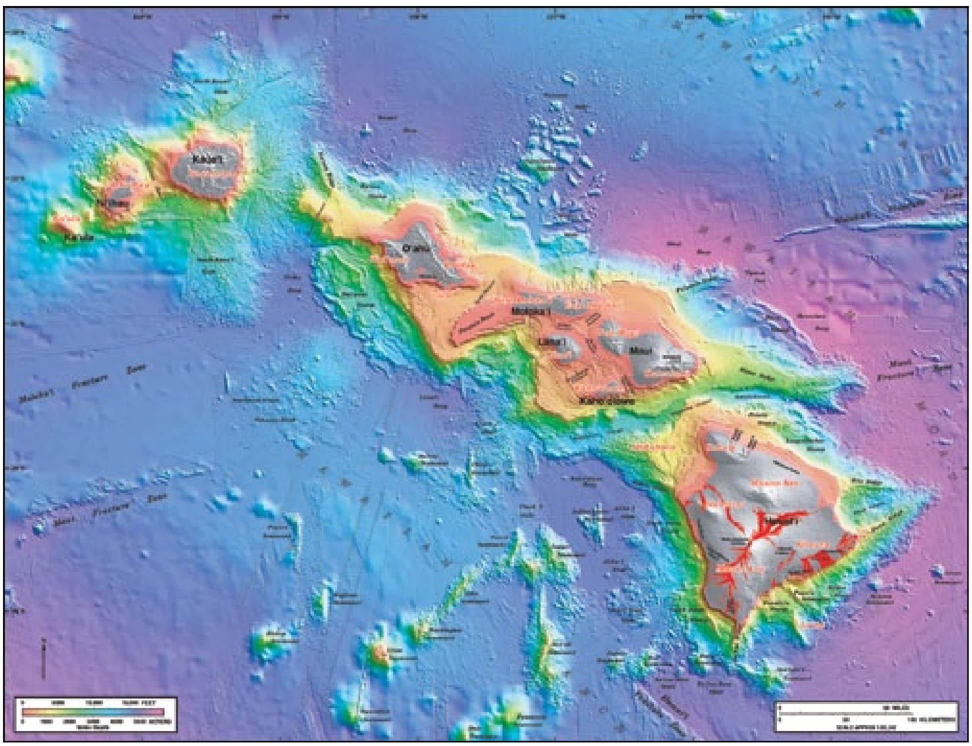

Figure 34. An image of the Hawaiian Islands ocean floor and geomorphology with volcanic activity highlighted. Courtesy of USGS; Data sources include: Japan Agency for Marine-Earth Science and Technology, Monterey Bay Aquarium Research Institute, National Geophysical Data Center, Scripps Institute of Oceanography, Smith and Sandwell Radar Altimetry, University of Hawaii, U.S. Geological Survey.

of the world's oceans and management of marine natural resources. The 1994 convention allows nations to claim an Exclusive Economic Zone (EEZ) extending 200 nautical miles from their coastlines. These nations also have the right to explore and exploit resources on and below the seabed for up to 350 nautical miles, or 100 nautical miles beyond the 2,500-meter isobaths.

Advanced geospatial analysis plays a crucial role in the submission of claims to delineate the outer limits of the continental shelf. The continental shelf can be described as the natural prolongation of territory from the land to the outer limit of the continental margin. This is the region of the seafloor where thick continental crust transitions into thinner oceanic crust. UNCLOS includes a detailed set of scientific and mathematical guidelines that coastal nations must follow to identify their respective outer limits of the continental shelf (figure 35).

The analyses required to delineate the legal boundary depend on clearly understanding the depth and structure of the seafloor. Fundamental to the process is the ability to identify the foot of the continental slope. Single-beam and multibeam bathymetric data can identify not only depth but also the microstructures and sediment types that make up the ocean floor. Geospatial technologies such as GIS can evaluate and visualize bathymetric data to provide insight into the submarine processes of the ocean bottom. The use of these technologies helps coastal nations define their legal rights to explore and exploit the submarine resources, both living and non-living, and more proactively manage marine resources.

Ocean power and renewable energy

Bathymetry has many applications for the renewable energy industry that emphasize ocean power among other alternative energy sources. Every continent is surrounded by a cleaner and more

Figure 35. Bathymetric measurement of the seafloor and definition slope foot of the continental shelf plays a large role in defining a nation's sovereign limits under UNCLOS. Courtesy of ESRI.

efficient means to supply our global energy needs with power generated by wave, current, swell, and temperature dynamics. New ways to tap the power of the ocean are emerging, and incentives are driving this industry to new levels of growth. Among the many innovations is a giant underwater orb for farming fish in the open ocean. Now in prototype development, the Oceansphere structure is one way that aquaculture is looking beyond standard nearshore farming techniques used to raise fish in a natural environment (figures 36, 37). Powered to move through the ocean in various depths by ocean thermal energy conversion technology (OTEC), unanchored orbs the size of football fields would create a new way to produce seafood in an environmentally responsible and economically viable manner. The OTEC technology works by extracting energy from the differences in temperature between the ocean's shallow and deep waters. Placing aquaculture spheres near regions of benthic complexity—where small fish like to hide, feed, and reproduce on a rough ocean floor—would offer the best of both worlds. Because of growing consumer appetite, the supply of tuna, especially blue fin and big eye, is rapidly declining worldwide and in some regions may not recover. Larger pelagic fish such as tuna prefer to swim in schools in the open water column above the ocean floor, where water high in nutrients is also known to cycle through ecosystems supported by benthic complexity (Garrison 2007). The success of these spheres in the open ocean would enable the commercial farming of tuna inside a nutrient- and oxygen-rich environment. This would mean more

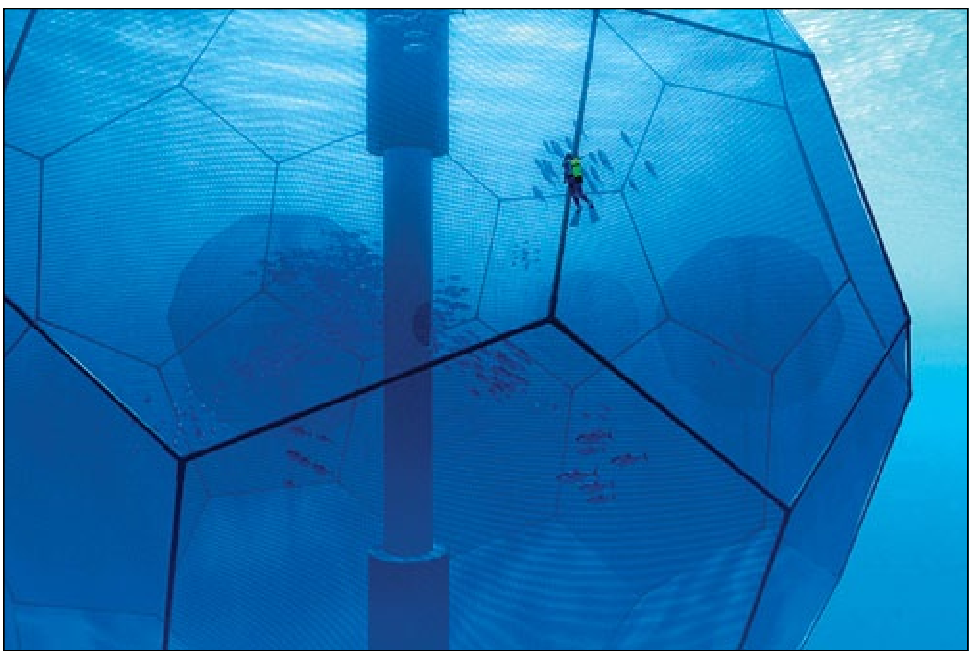

Figure 36. The Oceansphere is an innovation that seeks to combine aquaculture with ocean power to raise tuna in an underwater sphere the size of a football field. In this image you can see the relative size of an envisioned sphere dwarfing the diver next to it. Courtesy of Bill Spencer and Hawaii Oceanic Technologies.

farmed fish on a smaller environmental footprint where water temperatures and circulating currents dissolve effluent and promote fish health.

Other technologies, which mostly focus on generating electricity from waves, tides, and currents, have been implemented successfully in the past few years. Each of the innovations has a strong bearing on the importance of seafloor mapping, and bathymetry to the future implementation of new forms of sustainable energy.

Electrical power generated from the ocean and at the interface between ocean and land is key to meeting the needs of independent power producers, utilities, and the public sector (Milne 1995). PG&E's wave-power project off the coast near Humboldt, California, is one example of how power utilities and other companies are looking beyond traditional fuel sources for energy. Another device called the open-center turbine is envisioned for the ocean floor to harness electricity from currents (figure 37). Farms of underwater turbines would provide a silent and renewable source of electricity at depths that cause no navigational hazard. Most ocean-power technologies, including buoys that convert the rise and fall of waves into electricity, are either anchored to the seafloor, suspended above it, or have cables that span large stretches of ocean floor for the transmission of energy. The use of bathymetry and GIS to clearly depict the ocean floor, determine accurate depths, and collect substrate composition data will lead to more capable decision support for engineering and design

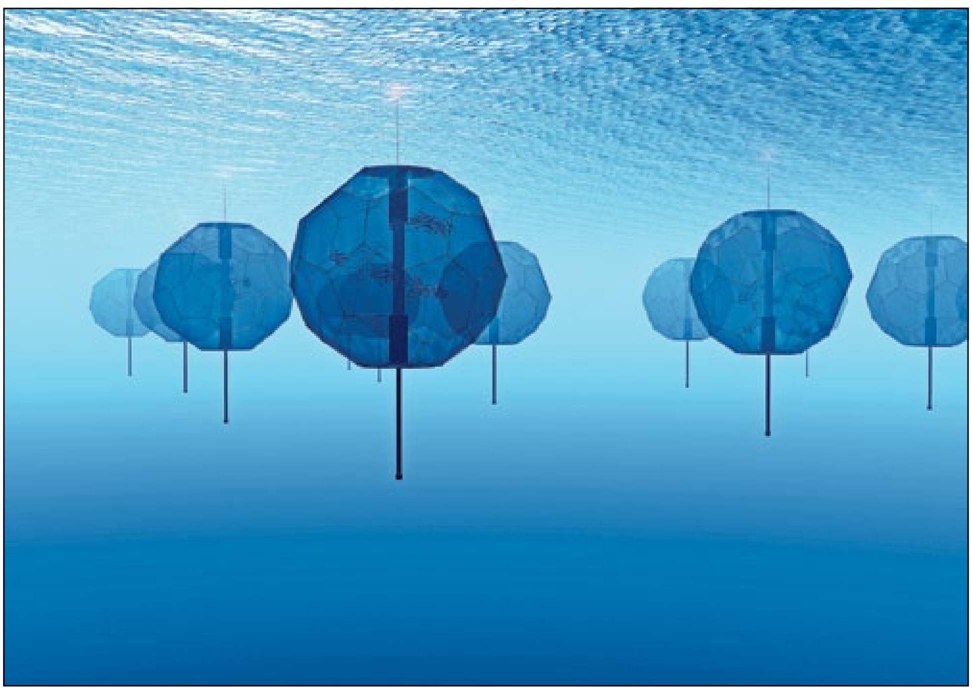

Figure 37. One new method of aquaculture would farm fish in spheres and float in place using ocean thermal energy conversion technology (OTEC). Courtesy of Bill Spencer and Hawaii Oceanic Technologies.

work. This information is essential for locating infrastructure, transmission cables, and maintenance facilities. Ocean power companies are responsible for planning, building, and operating their technologies in ways that do not harm marine ecosystems (figure 38).

It is widely accepted that the extensive burning of fossil fuels and the release of carbon dioxide gases are contributing to global climate change. With global energy demands set to increase, there is an undeniable and urgent need to develop new renewable energy technologies. The clear representation of the ocean floor and more detailed and accurate ways to depict it can help these and other industries to develop and flourish.

Figure 38. A schematic image of an open-center turbine designed to generate energy from underwater currents at the ocean floor. Courtesy of Open Hydro.

Defense

The applications of bathymetric data for military and naval uses are varied and have far-reaching implications for training exercises and warfare. Navigation, route-survey planning, identification of amphibious landing sites, mine detection and placement, and understanding the benthic environment are critical to the mission. Building a comprehensive tactical and strategic picture for military purposes requires the integration of high-resolution bathymetric data with other GIS-based information.

The U.S. Navy is developing a much broader GIS capability that includes many layers and services, including bathymetry. The Navy and other branches of the military are using advancements in Earth-viewer software, including ArcGIS Explorer, Google Earth, and NASA World

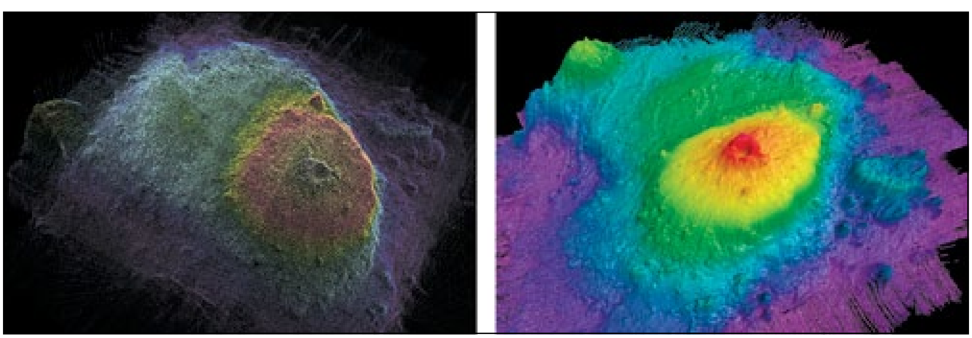

Figure 39. This subsurface shoal could pose a threat to submarine navigation. Traditional hydrographic data collection techniques would typically miss this feature; however, modern, continuous coverage provided by multibeam systems can reveal these kinds of seabed structures. Image courtesy of Kongsberg Maritime AS. Courtesy of Kongsberg Maritime AS.

Wind. In the globe-viewing software currently available, bathymetric representations of seafloor are composed of datasets from a variety of sources, including low-resolution bathymetry. The U.S. Defense Department is adding high-resolution coastal bathymetry to these databases, but accidents can still happen. Three nuclear submarines in U.S. waters have collided with pinnacles, rocks, and the seafloor itself since 2005. According to publicly aired news reports, the accidents have caused hundreds of millions of dollars in damage, risked the lives of crew onboard, and endangered nearby civilians. Reasons cited for these accidents that cost lives included human error, poor navigational standards, and a lack of vital information (AP 2009) (figure 39).

Web services

Organizations worldwide are transitioning from desktop environments to network-based systems using enterprise GIS. During the past several decades, an enormous amount of data has been collected throughout the world in a variety of formats, platforms, and knowledge domains. The challenge is to migrate more of these data from local repositories to federated systems in a Web-services environment that includes enterprise GIS. Bathymetric data form just one category of oceanographic information that demonstrates this need for migration. Slow methods for acquiring, processing, and creating bathymetric models limit the exchange and distribution of data. This lack of an organized approach to share data and products across a wide range of users reduces cross-departmental use of bathymetric information and illustrates the need for a modern, standards-based approach.

Data collectors and providers will no longer pass data and products in a stove-pipe approach for distribution. They can share Web services with specific or wide sets of users. Even just taking advantage of Web services within the hydrographic community will have far reaching effects for consumers of bathymetric data. In the past few years, many online GIS service systems have used the client/server model in which a client submits a request to the server, the server processes the request, and the client receives the result. These systems mainly feature the dissemination of data, or geodata services. In addition to data display and query, geoprocessing functions in these systems provide a complete set of GIS functions via Web-accessible services (figure 40).

Figure 40. Web services can leverage information collected from a wide variety of sources distributed across a network of servers and accessed by diverse end users, including desktop clients. Courtesy of ESRI.

The core technology is distributed GIS, where both data components and functions, or methods, can be distributed across the network as published models. GIS software no longer needs to be a single proprietary system. It can be divided into many interoperable functional components and distributed online with packaged models, or geoprocessing services. Use of these services enables clients to access GIS data and functional resources distributed anywhere in the network. This technology can be used to create seafloor models from a network of data distributed globally. The bathymetric data supporting these seafloor models can assist other GIS-based services, such as spatial analysis, route planning, and environmental mapping. For example, one can look at one of the first and most common popular uses of Web services (driving directions), and apply it to the ocean. In the same way that route queries can provide the best driving directions between two points, queries sent across a different network can suggest a ship route that identifies seafloor hazards, meteorological and oceanographic conditions, and any shipping restrictions. When it can take more than 20,000 gallons to fill the fuel tanks of an average ocean liner (Maxtone-Graham 2004), avoiding a headwind can save thousands of dollars and reduce the risk of running aground.

Large servers manage the data for geoprocessing on the Internet. Many servers are load balanced with a detailed file structure containing tiles of data. Thin clients, or desktop computers, provide a visualization environment into which end-users consume preprocessed imagery and data. As this applies to bathymetry, seafloor models can be generated locally from any available data. End users can find a Web-based browser and application to select the polygonal area they want for a new seafloor model. Their query is sent over the network to the servers and compared against available sounding data. The results are packaged and sent to the user, or the server creates a geoprocessing model. The model is generated based on the end users' requirements (spatial resolution, age of survey, type of surface, etc.) and returned for consumption in their visualization or analysis software (figure 41).

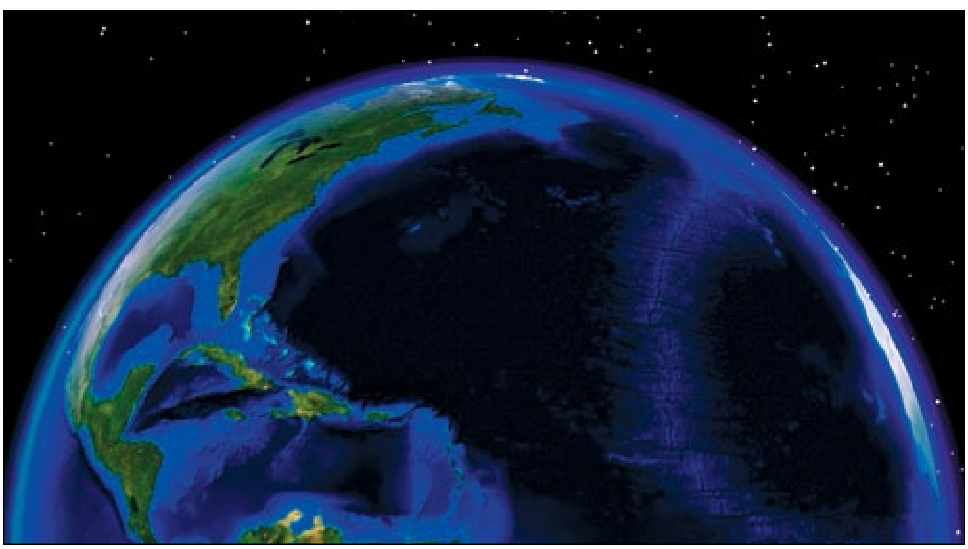

Figure 41. Survey coverage information, the soundings themselves, and derived models are just some of the bathymetry data that can be served across an open architecture. Courtesy of ESRI.

This approach to support online geoprocessing services is based on distributed open-object architecture. It allows the assembling of geoprocessing components distributed across the network and then enables a transfer to the client whenever geoprocessing is requested. This architecture improves the performance of client-server communication and opens the entire geoprocessing framework to all Internet users. An online application framework that enables this sharing of data and information can help us better understand characteristics of the underwater environment.

Conclusion

As we extend our reach into other areas of information technology, the global situational awareness we have for our planet also grows to include the ocean floor. We know more than ever before that the seafloor is a place that harbors life, governs currents, gives waves their formation, and provides an environment that interacts with all other parts of the ocean. The collection of new datasets and the tools available to create high-resolution seafloor are giving rise not only to a renewed and growing appreciation for the underwater terrain but also to what we can gain from learning more about it.

Modern data-collection techniques have given marine scientists, military planners, and engineers the ability to capture high-resolution bathymetry. However, it is the advancement and GIS-based systems through server- and client-based processing and visualization techniques that have enabled end users with little or no specific bathymetric knowledge to view the submarine environment and integrate these data with other oceanographic information.

Whether the depth information we use for seafloor analysis and visualization comes from satellites, aircraft, submersibles, or surface vessels, the technical evolution of how these data are processed, shared, and consumed is inevitable. Now, a diverse set of users can gather data from shallow coastlines and ocean trenches and derive a comprehensive picture of the benthic environment for many applications. It is the collection, modeling, and consumption of this bathymetric data in an open, Web-based, GIS architecture that demonstrate the opportunities for visualization and analysis that are before us.

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