Bathymetry: Assessing Methods

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Abstract

Covering over 70% of the Earth's surface, the undersea landscape or bathymetry has been revealed only within the past century due to advances in technology for measuring the depth of the ocean. Current depth-measuring techniques employ vehicles ranging from near-bottom remotely operated vehicles to ships on the sea surface to satellites high above the Earth. Depending on vehicle and mission, these systems utilize acoustics, optics, or radar altimetry to either directly measure or infer bathymetry. Each method provides different spatial resolution and can probe depths ranging from shallow coastlines to the deepest trenches. Coastal estuaries and bays must also be evaluated in terms of tidal currents that can change bathymetry on hourly time scales. Improvements are continually made to the types of data and analysis methods used for estimating bathymetry across the global ocean.

INTRODUCTION

The term "bathymetry" most simply refers to the depth of the seafloor relative to sea level, but the concepts involved in measuring bathymetry are far from commonplace. The mountains, shelves, canyons, and trenches of the seafloor have been mapped with varying degrees of accuracy since the mid-nineteenth century. Today, the depth of the seafloor can be measured from kilometer- to centimeter-scale using techniques as diverse as multibeam sonar from ships, optical remote sensing from aircraft and satellite, and satellite radar altimetry. Various types of bathymetry data have been compiled and modeled into gridded matrices spanning the seafloor at 1 arc-minute spatial resolution per pixel (<2 km) or even finer resolution for portions of the globe (e.g., <100 m resolution for U.S. coastal waters).[1] Even so, errors are prevalent in these modeled datasets and remote regions of the global ocean have yet to be accurately mapped. Indeed, the topography of Mars and Venus may be better known than our own seafloor.

Bathymetry is measured using "remote sensing" methods that investigate the seafloor indirectly without making physical contact. The majority of methods for estimating are based on the concept of using time to infer distance. Specifically, sensors emit a beam of sound, light, or radio waves and measure the round-trip travel time it takes for the beam to be reflected from a surface and return back to the sensor. The time elapsed is then related to the distance the beam traveled and used to infer bathymetry. The longer the elapsed time for the beam to return, the greater the distance traveled. However, limitations are inherent with all of these methods and no single technique is ideal for measuring the diversity and complexity of the underwater landscape and coastline. In addition to collecting additional datasets across the global ocean, new techniques are required to measure bathymetry and to interpret and process the datasets that have already been collected.

METHODS FOR ASSESSING BATHYMETRY

This section outlines the primary modern techniques for estimating bathymetry from acoustics to the use of both the visible and radio wave portions of the electromagnetic spectrum. Measurements are made through the water medium in the case of acoustics, through the water and air for visible light measurements, and through the air medium alone for radar altimetry remote sensing to obtain an estimate of the seafloor depth. As will be outlined further, each method has its own advantages and disadvantages in terms of scale of feature observed, accuracy, and water depth that can be sensed (Fig. 1). Acoustics is applicable for determining centimeter- to kilometer-scale features and is the prevailing method used to validate optical and radar bathymetry. Because of limits to penetration of visible light in a water medium, measurements using active and passive

light are only applicable in shallow water (generally <60 m) and are the primary means for delineating coastlines. Radar altimetry measurements from satellites provide large-scale bathymetry across the deep ocean and are particularly valuable in remote regions of the world ocean with little ship traffic. Marine radars from ships and shore have also been used to map bathymetry of shallow seas. The platforms for measuring bathymetry are also variable and include satellites orbiting high above the Earth, suborbital aircraft, ships on the sea surface, and remotely operated vehicles hovering along the seafloor.

Bathymetry measurements are not static. The rise and fall of the tides can change bathymetry up to several meters in height, depending on when and where measurements are taken. For bathymetric maps seaward of the continental shelf, usually no tidal corrections are made to ship soundings. Most international navigational charts used over shallow areas such as the Great Bahama Bank commonly adjust soundings to the lowest astronomical tide while mean lower low water is the datum for United States charts. However, tidal models have not yet been made perfect for shallow water mapping and tidal forecasting is an active area of research.[2] Having accurate tidal models are required for delineating coastlines, planning for storm surges and flooding,[3] and assessing bathymetry from satellite altimetry.

Acoustics

Acoustic bathymetry or echo sounding came into play in the 1920s and was instrumental in determining the configuration of the seafloor as we know it today.[4] The initial technique was to emit a single pulse of sound and measure the elapsed time for it to travel to the seafloor and be reflected and be detected by a shipboard hydrophone. One-half of the round-trip travel time multiplied by the velocity

of sound in sea water equals the depth at a given point. As noted by Leonardo da Vinci in 1490 and later by Benjamin Franklin in 1762, sound travels far in water with little attenuation relative to air.[5] Sound also travels significantly faster in water than in air and great ocean depths can be probed acoustically without substantial degradation of the signal. The velocity of sound in seawater is ~1500 m/sec, but the precise velocity depends on ocean temperature, salinity, and pressure. In addition to the velocity of sound, the character of the seabed, vegetative cover, biota, and other particles in the water column, can affect the accuracy of the measured depth.

Today, high-resolution measurements of ocean depth and bottom reflectivity are produced by multibeam sonar. Each ping of a multibeam sonar emits a single wide swath of sound (up to 153°) that reflects off the seafloor (Fig. 2). The return echo is received by an array of transducers and then separated electronically into a number of individual beams for each of which a depth is calculated. Very high resolution is attainable in shallow water, but the swath width is decreased. Conversely, the efficiency of ship operation is increased in deep water as the swath width expands geometrically but resolution is decreased. A swath of the seafloor is acoustically imaged with each pass of a survey ship as it follows a pattern similar to "mowing the grass." A series of overlapping swaths produce a bathymetric map of the area being surveyed.

Various sound frequencies (e.g., 12–400 kHz) are employed for different depth ranges; the lower the frequency, the deeper the depth measurement possible, while higher frequency is associated with higher resolution but shallower depth. Bathymetry is now being estimated at levels of resolution and accuracy that were previously unattainable. For example, shallow-water multibeam systems can measure bathymetry roughly at a 10 cm scale in 10 m
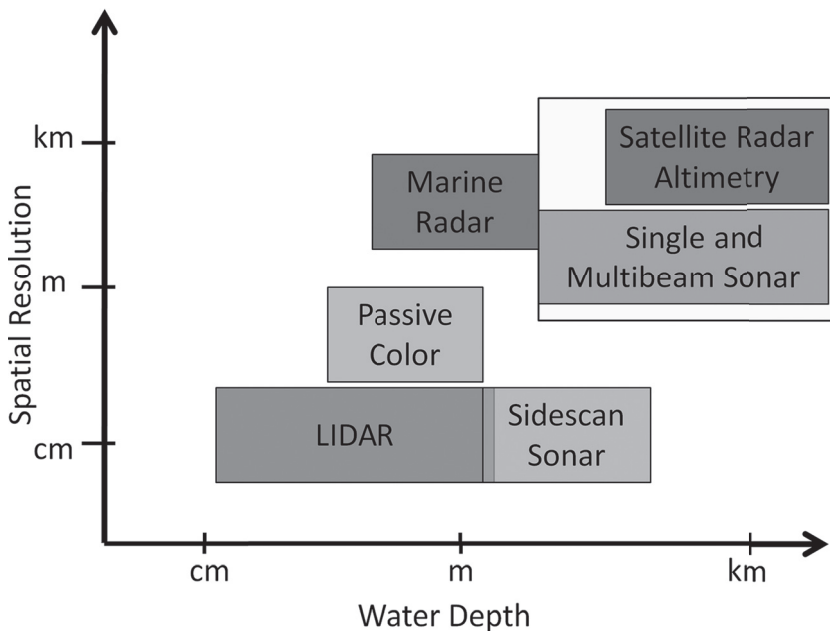

Fig. 1 Schematic showing the applicability of different techniques for estimating bathymetry in terms of spatial resolution of measurement and the range in water depths that can be sampled. The yellow box indicates the datasets that are integrated and interpolated to form the global gridded bathymetry datasets at 1 arcminute resolution.

of water and have been used to effectively map coastal waters of the United States.[6,7] Concentrated mapping programs also incorporate "sidescan" sonar for a qualitative view of seafloor reflectivity characteristics.[7] Acoustic sensors can also be placed on tethered remotely operated vehicles or autonomous underwater vehicles, such as gliders, that can maintain a constant position relative to the seafloor and provide high-resolution bathymetry.[8]

The primary disadvantages of acoustic measurements are the time and cost associated with making measurements from a ship in deep waters or a small vessel in shallow waters. In order to build up coherent images at a high resolution, many survey lines with overlapping tracks must be run. Because the swath width decreases in shallow water, many more ship or glider tracks are required in coastal estuaries and bays with shallower water. Hence, detailed surveys in coastal regimes require considerable time and effort to cover relatively small portions of the sea bed. In general, acoustic methods can be used throughout all oceanic depths from shallow estuaries to the deepest trenches. However, ship time is costly even in deep water, and because of increasing time and effort to operate in shallow waters, acoustic systems are not ideal for such tasks as monitoring bathymetric changes and shoreline configuration changes caused by such phenomena as tidal currents, storm surge, and sea-level change.

Optics

Remote sensing by visible light has also been used to estimate shallow water bathymetry, where acoustic methods become limited. Bathymetry has been quantified using passive methods, which measure only the natural light reflecting from the seafloor, and active methods, which use lasers to measure the distance to the seafloor.

Passive ocean color remote sensing

Of the sunlight that hits the ocean surface, only a small percentage is scattered back out again and can be remotely detected by aircraft or satellite. Passive ocean color sensors measure this small amount of solar radiation that has entered the water column and been scattered back out.[9] In waters that are shallow and clear enough for light to reach the bottom (called "optically shallow"), the color of the seafloor also contributes to the water leaving radiance in a way that depends on the bathymetry, substances in the water column, and bottom composition. In the clearest natural waters, bright sandy bottoms can be detected in 30 m or more. In most coastal areas, water is clarity is reduced by algae, sediment and other colored substances and generally depths less than 10 m can be measured. As the water becomes more turbid with sediment or dense phytoplankton, much of the light entering the water column is absorbed in the top layer of the water and the sea becomes "optically deep" at only a few meters in depth.

In sufficiently shallow and clear water, the magnitude and spectral quality of light reflected from the seafloor can be interpreted from remotely sensed ocean color. Methods to retrieve shallow water bathymetry from passive ocean color reflectance measurements have been either empirical [10] or radiometrically based using iterative modeling or look-up
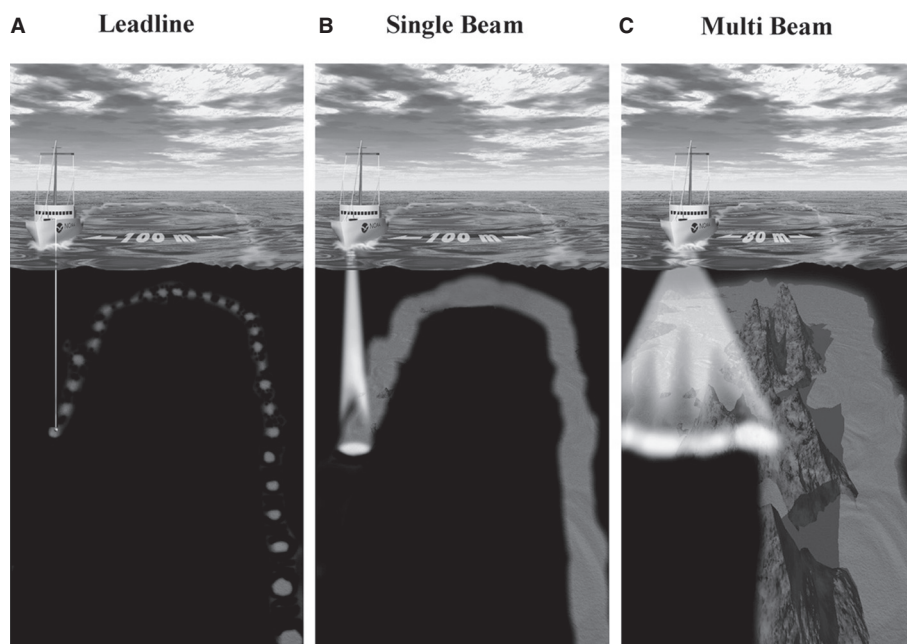

Fig. 2 Illustration of different methods for measuring bathymetry from A) line and sinker technology; B) echo sounding using single-beam acoustics; and C) multibeam acoustics providing the highest spatial resolution of seafloor features.

tables.[11] Many of the empirical approaches use far red or near-infrared wavelengths where water is highly absorbing and the signal is less influenced by phytoplankton, sediments, and other absorbing and scattering material in the water column.[12] Radiometrically based approaches generally use most of the visible spectrum and require many wavelengths of data (i.e., hyperspectral) to retrieve bathymetry. In addition, the radiometric methods also solve for the color of the seafloor (i.e., benthic reflectance), as this is a key component of the water-leaving radiance signal. Using passive ocean color, bathymetry has been mapped with high spatial resolution from aircraft [12] to regional scales from satellites [13] (Fig. 3).

Because ocean color sensors are already up in space for oceanographic research with data freely available,[14] the use of satellites to derive shallow water bathymetry is quite effective and cost-efficient compared to acoustic methods. However, cloud cover masks the ocean color and only clear sky imagery can be analyzed. In addition, only a few percentage of the incident light that reaches the ocean is reflected back to a satellite. When viewed remotely, the ocean color is observed through a thick atmosphere containing gases and aerosols which also reflect sunlight back to the sensor. The atmosphere contributes more photons to a satellite sensor than the ocean surface itself and accurate "atmospheric correction" is one of the many challenges to obtaining an accurate water-leaving radiance required for estimating shallow water bathymetry. If too much signal is removed from the atmospheric correction, the ocean will appear too dark and bathymetry can be overestimated and vice versa.[15] Most methods also require some a priori knowledge of the benthic reflectance in the region and such measurements are difficult to make and integrate over the appropriate scales required for remote sensing. Bathymetry estimated with passive ocean color methods are generally not accurate enough for navigational purposes, but they provide much better results than gravimetric measurements (see further) over shallow basins (Fig. 3C) and the spectral information can also provide an estimate of the seafloor composition.

Active lidar

At present, the most effective means to map shallow water bathymetry is with active lidar systems. Active sensors produce and sense their own stream of light (e.g., light detection and ranging, or LIDAR) and are generally flown on aircraft, although several space-based lidars have been launched. Similar to acoustic measurements, LIDAR uses the round-trip travel time of a pulse of light to estimate the distance to the seafloor. Aircraft-mounted lasers pulse a
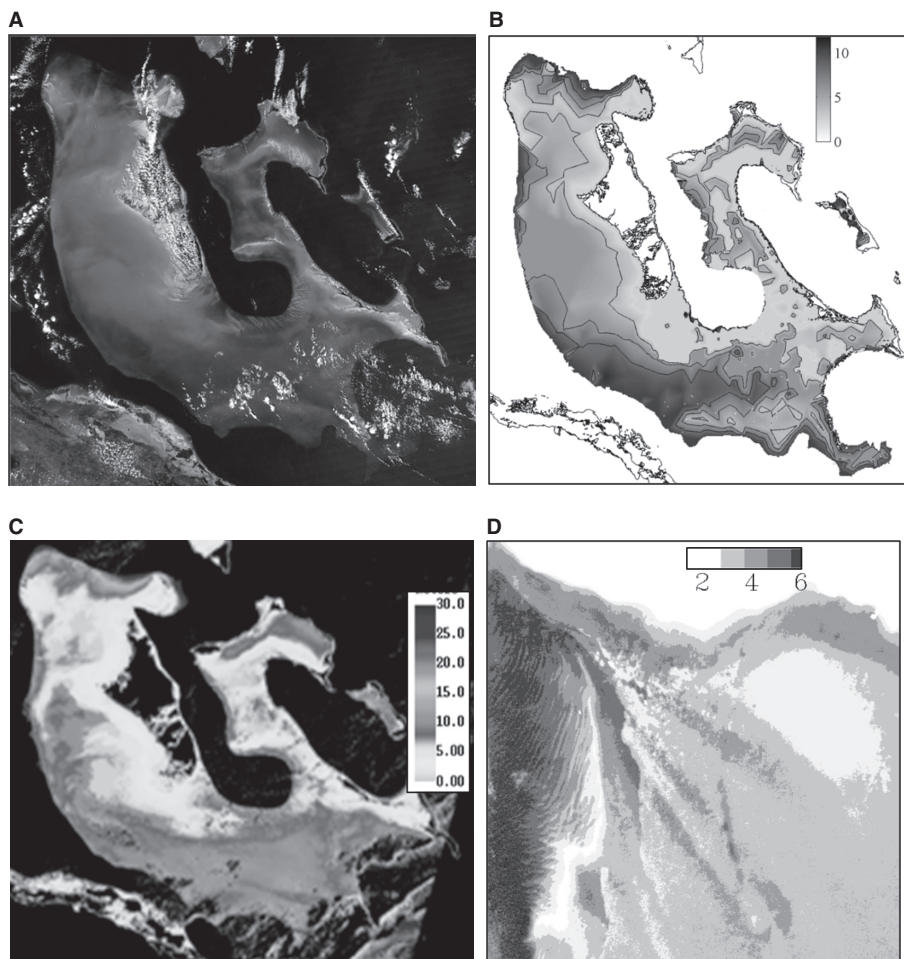
Fig. 3 The Great Bahama Bank is a large optically shallow bank that can be mapped with passive ocean color techniques. A) A pseudo-true-color image from the MODIS Aqua sensor at 250 m resolution from 6 March 2004 shows the bright reflected color off of the shallow Bank; B) bathymetry gridded using selected soundings from navigational chart;[26] C) bathymetry modeled from the MERIS ocean color sensor;[13] D) shallow water bathymetry mapped from a hyperspectral sensor on an aircraft for a small region south of Lee Stocking Island, Bahamas.[27] All bathymetry is in units of meters (m).

narrow, high-frequency laser beam toward the earth and are capable of recording elevation measurements at rates of hundreds to thousands of pulses per second. Because they do not rely on sunlight, LIDAR systems can be operated at night.
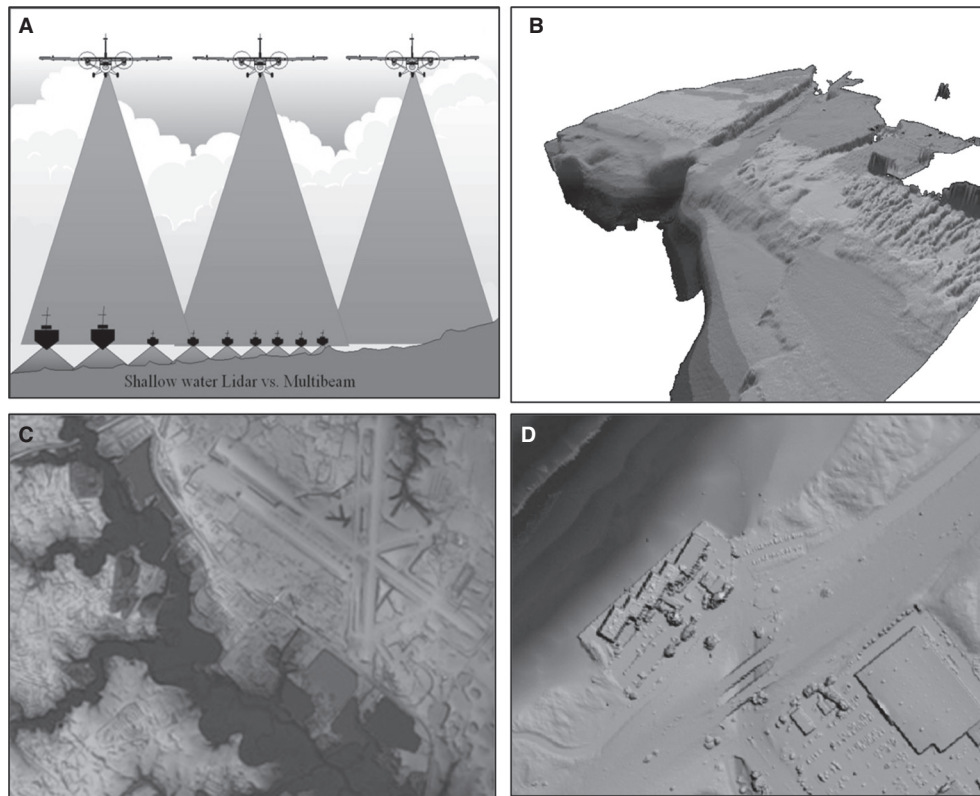
Generally, two lasers are employed to estimate bathymetry: 1) an infrared laser (1064 nm), which does not penetrate water, is used to detect the sea surface and 2) a green laser (532 nm) is used to penetrate into the water column and provide a return signal from the seafloor.[16] In coastal waters, green light is the least absorbed and generally penetrates the deepest into the water column. Similar to passive ocean color measurements, the green laser is attenuated by the absorbing and scattering particles in the water column, and the maximum depth of measurement is determined by a combination of the optical properties of the water column and seafloor. In ideal conditions, depths up to 60 m have been measured with LIDAR systems,[17] but most applications are limited to depths <40 m.

Current LIDAR measurements with an elevation accuracy of 10–30 cm can provide point measurements from 0.1 to 8 pixels per m^2. They have been successfully used to map bathymetric features, beach erosion, coral reefs, and coastal vegetation. Unlike acoustic sensors on ships, the imagery is provided in fixed-width swaths independent of water depth and can provide high area coverage rates of up to 70 km^2 hr^{-1} (Fig. 4A). The method is particularly effective in shallow water where larger ships are excluded and acoustic surveying is least efficient. Another major advantage of LIDAR is that it can map land and water in the same mission and provide continuity of shoreline mapping. Such combined land and water measurements have been used by environmental managers to map coastlines and conduct city planning for storms and potential changes in sea level (Fig. 4B–D). Airborne systems are also useful in shallow waters with reefs or in regions where tidal flows make ship-based measurements difficult if not impossible. Often LIDAR systems are coupled with passive hyperspectral imagers to assess both the bathymetry and seafloor composition simultaneously.

Radar Systems

Marine radars can be used from satellite to detect large-scale changes in bathymetry that are related to sea-surface height. Imaging radar systems from ships and shore have been used to measure wave fields and deduce shallow water bathymetry from wave theory.

Fig. 4 A) Airborne LIDAR provides a large sampling swatch for collecting bathymetry data compared to ship-based sonar systems and B) can seamlessly blend water and land elevations in one image for precise coastline delineation. LIDAR data collected in C) coastal Delaware can be used for mapping projected sea-level rise; and D) Monterey Bay for evaluating erosion patterns along a seawall jutting into the coastal zone. Images in Panel A and Panel B provided courtesy of Optech Industries. Images from Panel C and Panel D are available from the NOAA Coastal Services Center Digital Coast project.

Satellite altimetry

The presence of bathymetric features, such as ridges and troughs, create changes in Earth's gravity field that produce small fluctuations in the height of the sea surface. The sea surface bulges slightly upward in response to a seamount, for example, as water is attracted to the greater mass (Fig. 5). Satellite-mounted radar altimeters orbiting the Earth can measure these slight variations in the sea surface-height by sending out radio wave pulses at high frequencies, usually in the range of 13 GHz, for determining sea-surface height variations. The radar pulse scatters off of the sea surface and the round-trip travel time of the signal is measured. If the satellite's position in orbit is well-characterized, then the round-trip travel time of the pulse can be related quite precisely to the height of the sea surface relative to the satellite sensor and can be estimated to within a few centimeters (Fig. 5). At wavelengths from 1–200 km, gravity anomaly variations are highly correlated with sea-floor topography and have been used to gravimetrically map bathymetry of the world oceans with a spatial resolution of ~10 km resolving features ~20 km in scale.[18]d

Sea-surface heights are not impacted by bathymetry alone, but also by oceanographic factors such as waves, currents, and tides, as well as the underlying density of the seafloor. To effectively use altimetry for bathymetric purposes, the sea-surface height that would exist without any perturbing factors or "geoid" must be modeled (Fig. 5). Determining the geoid over the oceans is an active area of research. The footprint of the pulse must be large enough to average out the local irregularities in the surface due to
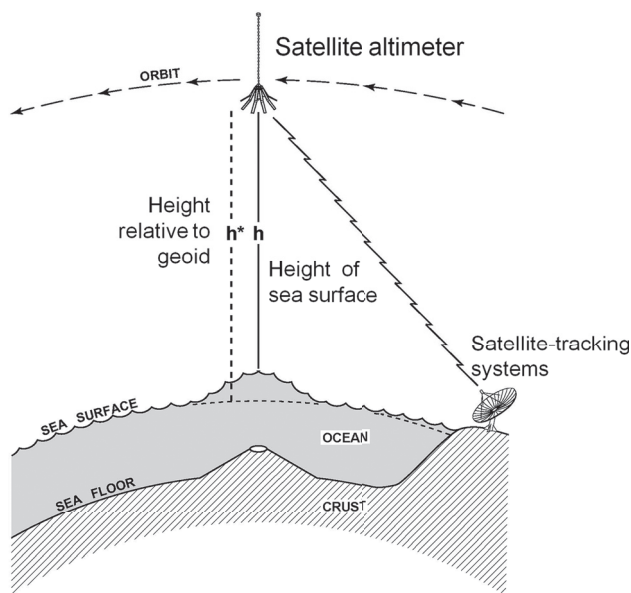

Fig. 5 Illustration of the use of radar altimetry to estimate large-scale bathymetry of the deep ocean floor.[18] The radar pulse provides the height of the sea surface to centimeter-scale, *h*, which is combined with the height relative to Earth's geoid, *h**, and acoustic soundings in order to estimate bathymetry.

ocean waves. Tidal corrections must be applied. Corrections to the travel time of the pulse are also made for water vapor and electrons in the atmosphere. Profiles from many satellites, collected over many years, are combined to make high resolution images of the geoid showing major mass and density differences on the seafloor.

To produce reasonable estimates of bathymetry, the gravimetric anomaly measurements are combined with acoustically determined soundings to construct uniform grids of seafloor topography.[19,20] The methods work best in the deep-ocean basins, where sediments are thin and geological features can be mapped at coarser resolution. For example, gravimetric techniques are the primary method to locate seamounts >2000 m in height across the global ocean floor. However, errors arise in regions with sparse acoustic soundings and where thick sediments can bury the underlying "basement" topography. Gravimetric methods for estimating depth are of limited value over continental shelves, where sediments are thick and conventional bathymetric soundings are plentiful.

Comprehensive high-resolution bathymetry grids have been constructed from quality-controlled ship depth soundings with interpolation between sounding points guided by satellite-derived gravity data.[1,21] These data, freely available online, are used in a variety of applications, including tsunami path forecasting and ocean current models. However, such gridded datasets are not accurate enough to assess hazards to navigation, and in shallow water where other remote sensing techniques, such as LIDAR, would produce significantly better results.

Imaging radar systems

Wave theory has been used to deduce shallow bathymetry since the 1940s when sequences of aerial photographs were used by the Allied forces to map water depth along the Normandy coast of France.[22] As waves move into shallow water, their speed decreases and the wavelengths get shorter. Wave dispersion theory can be used to infer the bottom depth that would produce waves of a given speed (or celerity) and wavelength. Modern techniques rely on the same principles but use imaging radar systems to get accurate measurements of wavelength and speed of waves. The X-band radars, in particular, interact with the small sea-surface capillary waves and the backscattered signal can be used to resolve wave fields. A minimum degree of sea-surface roughness is needed to make such measurements with significant wave heights >1 m and wind speeds >3 ms^{-1}.[23] Water depth is calculated both from linear wave theory and from a nonlinear wave dispersion equation that approximates the effects of amplitude dispersion of the waves in the shallow water [24]

Marine radar systems mounted on coastal stations have been used to infer nearshore bathymetry.[25] The technique was recently expanded for radar measurements collected on moving vessel[23]. Over 64 km^2 of coastal seas were

mapped within a bay using radar data collected in 2 h using equipment already available on the ship.[23] The techniques were quite accurate down to 40–50 m water depth with a horizontal resolution of 50–100 m pixels. The practical limits of the technique vary by location and occur when the water depth is approximately one-quarter of the wavelength. Imaging radars measure a wide swath of sea in 360° around the vessel and, unlike acoustic systems, only a single pass is needed to estimate bathymetry over a wide area. Because ships already have radars for navigation, only a recorder is necessary to collect the data and the method is quite cost effective. The method does not resolve bathymetry at high enough resolution for most navigational purposes, but is especially useful for reconnaissance of coastal regions for military and scientific purposes and surveying migrating features such as interisland channels.

CONCLUSION

Knowledge of ocean bathymetry has progressed rapidly in the past century due to the advancement of techniques using acoustics, optics, and radar. The ocean has been mapped at a variety of spatial resolutions from kilometers to centimeters, but considerable work has yet to be done to accurately map the vast underwater landscape. More acoustic soundings are required to validate gravimetric bathymetry in remote regions of the world (e.g., the Southern Ocean), better characterization of the geoid is necessary for refining gravimetric techniques, more accurate tidal models are needed to assess nearshore bathymetry, and higher spatial resolution data are vital to assess shallow water bathymetry to delineate coastlines for storm surges and potential changes to sea level. The seafloor may be considered one of the last largely unexplored and most dynamic landscapes on Earth.

ACKNOWLEDGMENTS

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