Conventional Bathymetry, Bathymetry from Space, and Geodetic Altimetry

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This article offers a general introduction to those aspects of bathymetric mapping and satellite altimetry that are relevant to bathymetry from space. We begin with a review of some of the strengths and weaknesses of conventional bathymetric measurement and mapping. This context highlights the case for and value of space-based mapping: it is the only way to achieve globally uniform resolution within reasonable time and cost. However, a space mission cannot "see" the ocean floor directly; instead, it observes gravity anomalies that can be correlated with ocean floor topography. Geological factors and physical laws limit the resolution of this technique to a particular range of spatial scales (~100 km to ~5 km). While this is not perfect, it yields an enormous improvement in the resolution of global bottom roughness over traditional methods (Figure 1).

A satellite altimeter mission designed for bathymetric mapping is simpler and cheaper than one designed to monitor ocean currents, tides, or climate. It also yields information about Earth's gravity field that is independently useful for resource exploration and for compensation of the errors in inertial navigation systems. A new mission with a state-of-the-art altimeter could optimize the mapping of gravity and bathymetry and resolve a key element of bottom roughness—abyssal hill orientation—for only $100M.

More complete and technical reviews of these topics may be found elsewhere. Smith (1993) reviewed the problems and errors in conventional bathymetric data. Details on the processing of altimeter data to yield gravity and bathymetry may be found in Smith and Sandwell (1994; 1997), Sandwell and Smith (1997; 2001), and Smith (1998). Chelton et al. (2001) present a thorough treatment of satellite altimetry, with a view toward measuring ocean currents and climatic signals.

Conventional Bathymetric Measurements

Direct measurement of ocean floor depth is done by echosounding from a ship. This technique has become highly refined since the 1980s and now systems can map a swath of area beneath a ship's track with a width as much as twice the water depth in deep water. However, the speed of the ship is limited, and thus also the rate at which ocean area may be mapped. A complete swath survey of the deep ocean would take about 200 years of survey time, at a cost of billions of dollars (Carron et al., 2001); shallow coastal areas would take even longer.

Estimates of how much ocean floor is already mapped by swath bathymetry vary because some data are classified military secrets or proprietarily held by their collectors. Publicly available data cover only a few percent of the ocean floor, and there is general agreement that even if all data became public, they would still cover only a small fraction of the deep ocean area. If a complete global survey could be made by swath mapping, it would have much higher resolution and accuracy than what can be done from space. Until such a survey is a reality, however, we must work with the available data, which are primarily older, "low-tech" analog echosoundings.

Historically, the mandate for soundings has come from the need to chart hazards to navigation, that is, bottom features that are so shallow that a ship could run aground on them at low tide. This naturally concentrates mapping efforts very close to shorelines. More recently, there has also been some interest in mapping exclusive economic zones (EEZs), which extend outward 200 nautical miles from shore. The distribution of soundings in the ocean is relatively dense in shallow coastal areas and EEZs, but very sparse in the open ocean. As Figure 2 shows, the distribution of survey lines covers the South Pacific as coarsely as the Interstate Highway System covers the United States.

Echosounding data also have an uneven geographical distribution of technology and quality. Most of the soundings in remote oceans are old analog measurements geo-located using only celestial navigation (Smith, 1993). Modern digital swath systems with

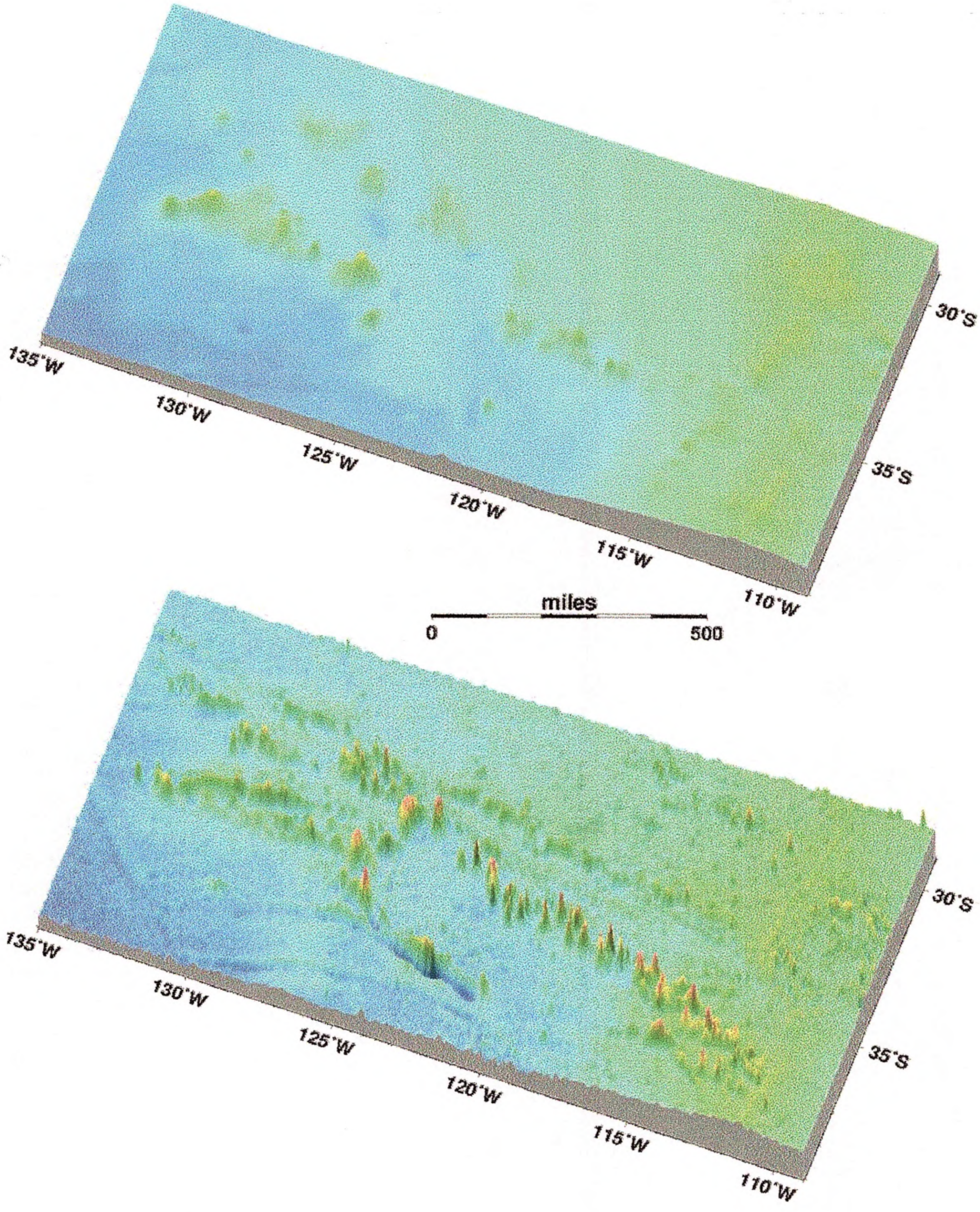

Figure 1. *Traditional bathymetric mapping (top) misses many important features of seafloor topography. Bathymetry from Space (bottom) reveals all the major seamounts, fracture zones, and troughs that are important habitats, obstacles to currents, sites of enhanced mixing and tsunami scattering, and clues to the motions of Earth's plates. The uncharted seamount chains found by satellite mapping prompted ship surveys which verified their existence. Figure 7 shows a profile along a ship survey across the trough and seamounts of the lower left part of the image. The area shown here is in the South Pacific southwest of Easter Island; the southern East Pacific Rise is near the right hand edge of the images. Data in the top image are from the ETOPO5 grid produced from hand-contoured charts; data in the bottom image are from Smith and Sandwell (1997).*

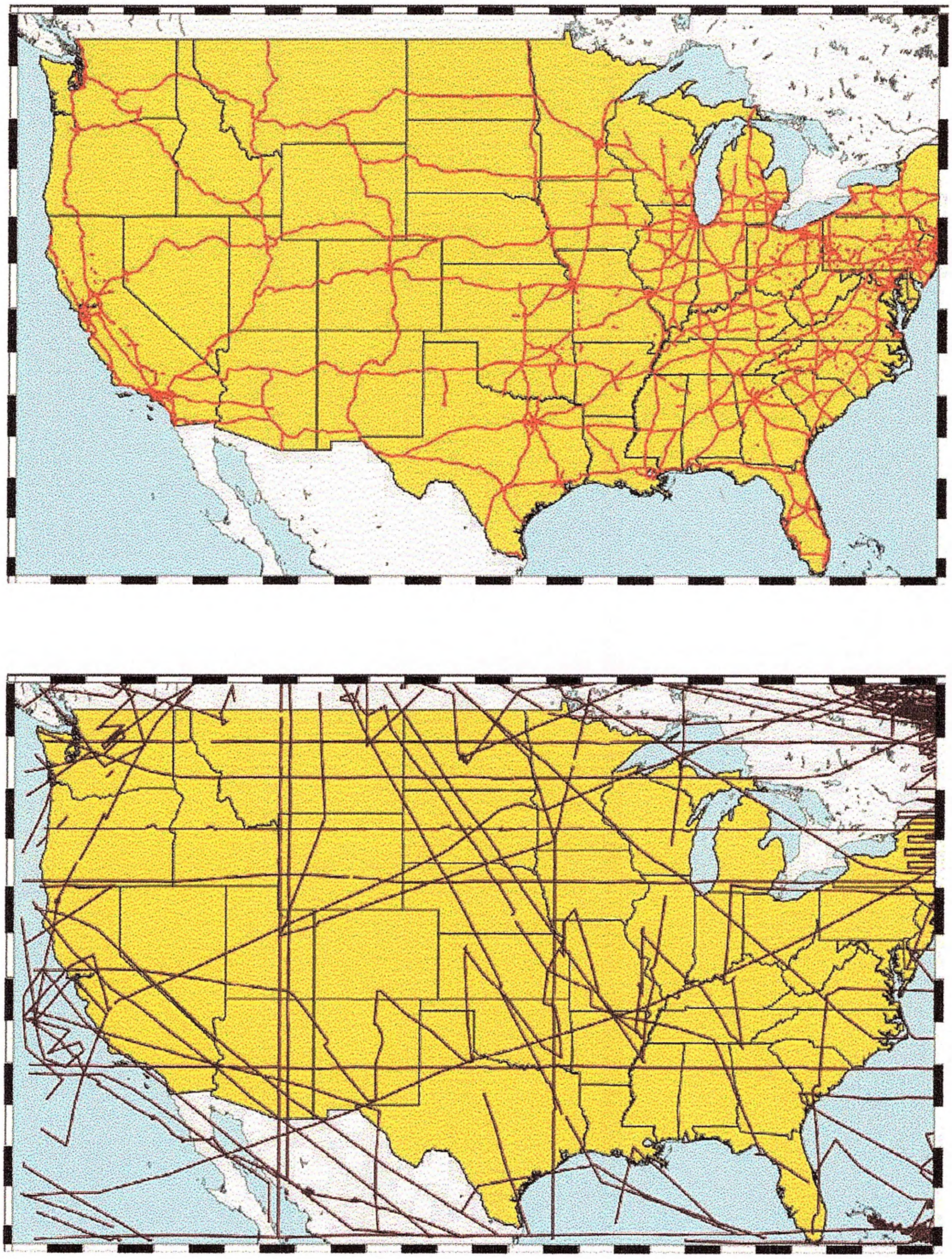

Figure 2. Imagine how poorly known the topography of the United States would be if survey data were confined to the U.S. Interstate Highway System (top). The remote ocean basins are just that poorly surveyed. The bathymetric survey lines in the South Pacific are shown (bottom) at the same scale as the Interstate highway map. The gaps between surveys are much larger than the bottom features of interest so conventional interpolation schemes fail to reveal the important features. Image courtesy of David Divins, NOAA.

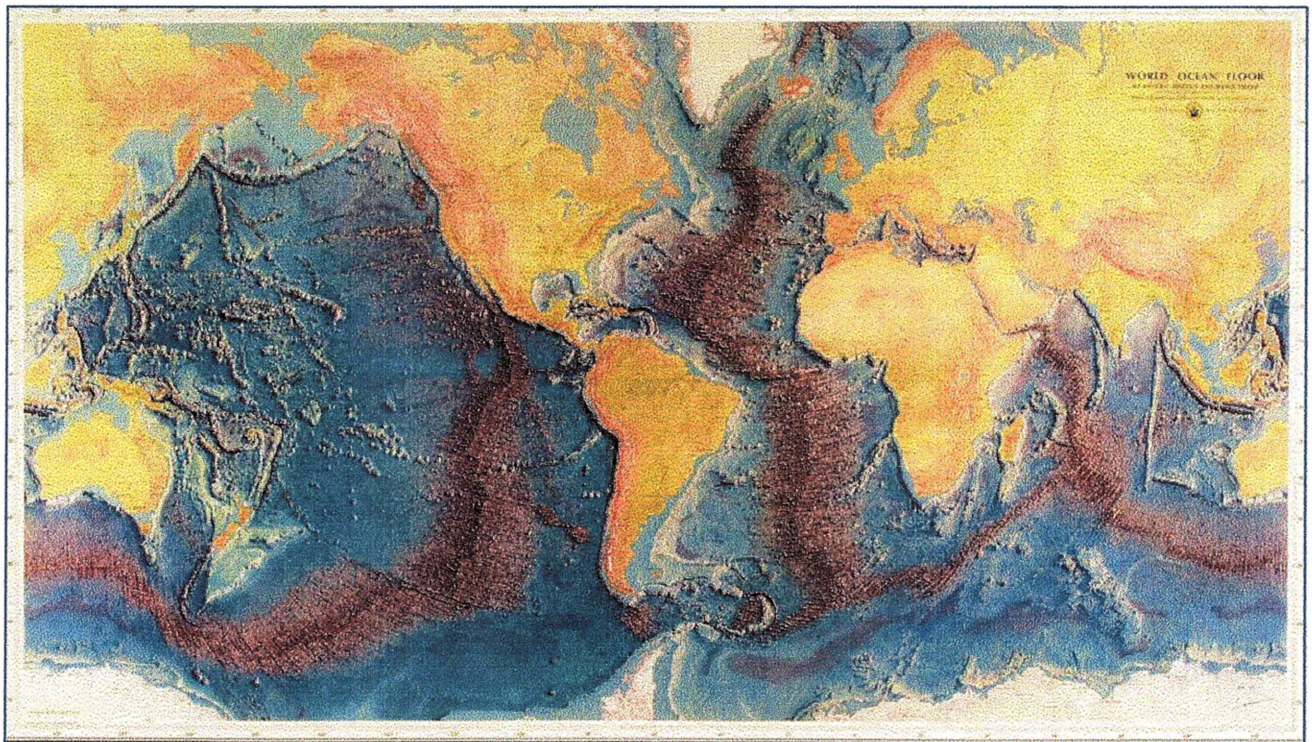

Figure 3. *The strengths and weaknesses of human artistic license in interpretation are shown in this beautiful physiographic diagram of the world's ocean floors made by Bruce C. Heezen and Marie Tharp in 1977. Maps portraying similar features and texture were widely distributed by the National Geographic Society. These maps show the major features of plate tectonics in approximately the right locations and are also aesthetically pleasing as works of art. Perhaps for these reasons this view of the oceans has become fixed in the public mind, creating the illusion that the entire ocean floor has been mapped. In fact, however, only a few percent of the ocean has been surveyed. The position of plate boundaries is approximately correct in these diagrams because the cartographers were guided by teleseismically determined earthquake locations. However, the portrayal of bottom shape is misleading. The "back of the alligator" texture is an apt metaphor for the very rough parts of the Mid-Atlantic Ridge and Southwest Indian Ridge, but the East Pacific Rise and Southeast Indian Ridge are actually much smoother. Compare the texture shown here with that of the map on the cover of this special issue. (Photograph courtesy of John Diebold. Map copyright 1977 by Marie Tharp. Used with permission. The printed map acknowledges support to Heezen & Tharp from the U.S. Navy's Office of Naval Research. The phrase "back of the alligator" is due to Tibor Toth, artist for the National Geographic Society.)*

satellite navigation are rarely deployed for exploratory mapping in unsurveyed areas.

Traditional Methods of Global Bathymetric Mapping

Since navigational charts exist to promote maritime safety, they often have a "shoal bias." They must portray any known bottom feature shallow enough to present a hazard to shipping, but they need not indicate any deeper aspects of bottom shape. (In fact, they need not exist at all in deep water areas.) Thus the depths indicated on these charts do not give a complete view of the seafloor.

In deep water areas of the open ocean, the gaps between survey lines are much larger than the size of features of interest. Prior to satellite altimetry, interpolation by machine algorithm proved unsatisfactory, and maps were drawn by hand, sometimes with a great deal of artistic license guided by plate tectonic theory and an understanding of seafloor fabric. This approach also allowed bathymetrists who had seen classified data to convey some of the essence of those data without revealing secret details. The most aesthetically pleasing maps also proved to have the greatest inspirational value and popular appeal. The justly celebrated "physiographic" diagrams of ocean basin shape produced by Bruce Heezen and Marie Tharp (Figure 3) seemed to satisfy an appetite for an illustration of plate tectonic features of the seafloor. This style of bottom portrayal was carried on and extended in a map series widely distributed by the (U.S.) National Geographic Society (NGS, a private organization). The NGS map series employed artists to paint the maps, ensuring their aesthetic appeal.

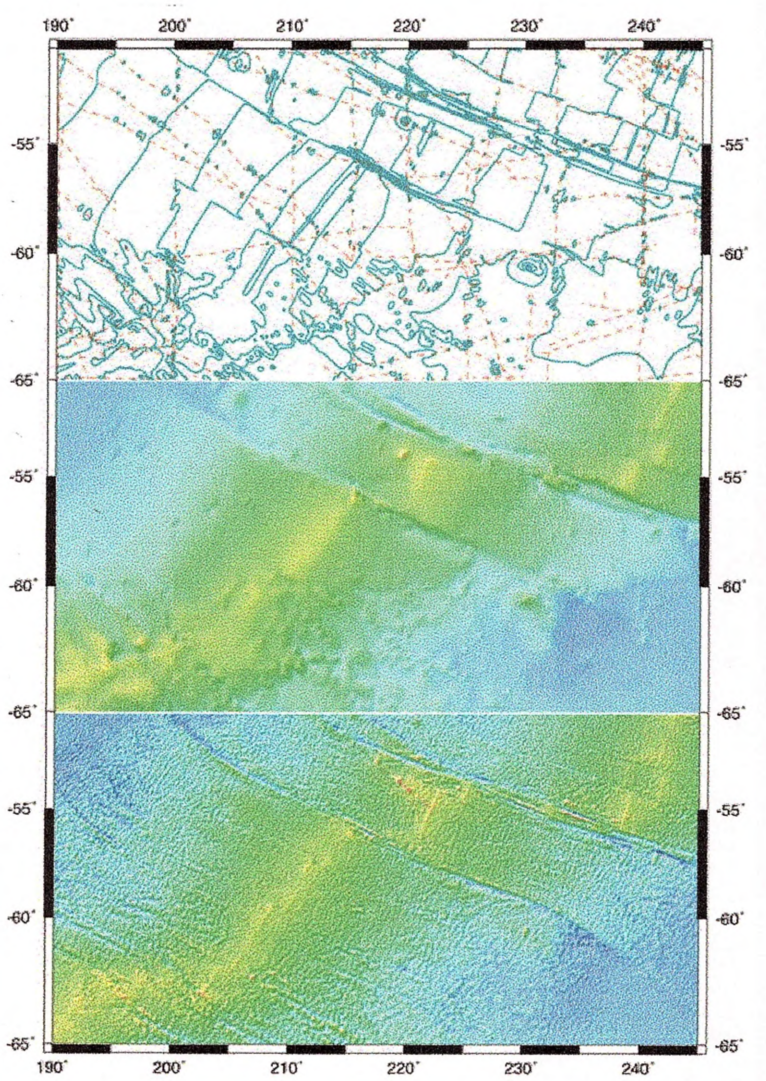

Figure 4. *Human artistic license is evident in traditional bathymetric maps and gridded products. (Top): The General Bathymetric Charts of the Oceans (GEBCO) show a change in texture in the southwest Pacific Ocean, with roughness sharply increased south of 60°S. The solid lines are depth contours at 500 m intervals and the dashed lines indicate the locations of sounding surveys used by GEBCO bathymetrists to draw the contours. Close inspection shows that there are extra contours south of 60°S that are not required by the surveys and not included north of 60°S. Different people drew the contours in the two places, with different styles. Their influence extended to the ETOPO5 bathymetric grid (middle) that was produced from contours. Bathymetry from Space (bottom) uniformly and correctly portrays the ocean bottom texture. (Contours and tracklines in the top panel are from the GEBCO Digital Atlas, available from the British Oceanographic Data Centre.)*

Hand-drawn maps also allowed intelligent synthesis of ancillary information in the era before easy computing. For example, knowing the plate tectonic theory, one could draw plate boundaries in unsurveyed areas by following teleseismically located earthquake epicenters. Assuming that depth should increase away from mid-ocean ridges approximately as the square root of distance from the ridge, and understanding the abrupt nature of fracture zones, one could guess where to place depth contours. These considerations led to a reorganization of the venerable Committee for the General Bathymetric Charts of the Oceans (GEBCO) to include marine geologists as well as hydrographers in the production of its 5th Edition chart series, begun in the 1970s.

All traditionally produced maps show the influence of human choices in the portrayal of seafloor texture. This is true throughout the ocean basins, not just at mid-ocean ridges. For example, the GEBCO charts show what appears to be a change in ocean floor roughness along some geographical boundaries (Figure 4, top panel). What changes at these boundaries is not the true ocean floor texture but the human beings who drew each chart.

The GEBCO and other contour charts, even with these artifacts in texture, ultimately had more impact on research than did the Heezen & Tharp and NGS maps because the contours could be digitized and fed into a machine algorithm to produce a grid yielding numerical values for depth estimates on a regular lattice of points. Such grids greatly facilitate a wide variety of research applications. The U. S. Naval Oceanographic Office produced a grid known as "DBDB-5" (digital bathymetric data base at five arc-minute spacing) in the 1970s and it was eventually widely distributed by the U.S. National Geophysical Data Center as part of "ETOPO-5" (Earth topography at 5 arc-min) in 1988. One can find in it the same artificial texture boundaries (Figure 4, middle panel) that appear in the original contours (Figure 4, top panel), as well as other artifacts (Smith and Wessel, 1990; Smith, 1993).

Regardless of the gridding scheme used, grids produced from contours are subject to a statistical bias known as "terracing": numbers in the grid are much more likely to be equal to or near to contour values than to other values in between

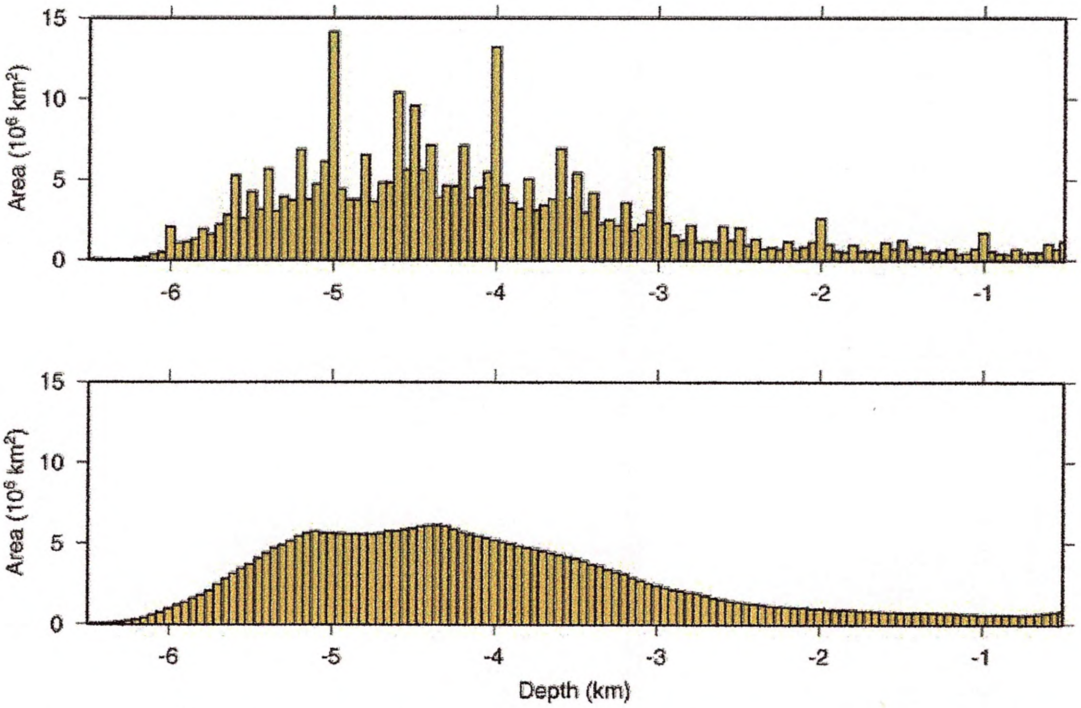

Figure 5. *A "terracing" problem plagues traditional bathymetric grids produced from contours. Terracing causes a grid to have values equal to contoured values much more frequently than it has any other values. These hypsometric diagrams show histograms of the area of the ocean floor lying at depth intervals of 50 m. A grid produced from contours (top panel, ETOPO5 data) has spikes at multiples of 1000, 500, and 200 m, indicating that contoured depths occur more often than they should in that data set. This artifact leads to biases in physical models fitting the data by regression, and also prevents the grid from yielding useful calculations of bottom slope or roughness. Bathymetry from Space produces a smooth curve (bottom panel).*

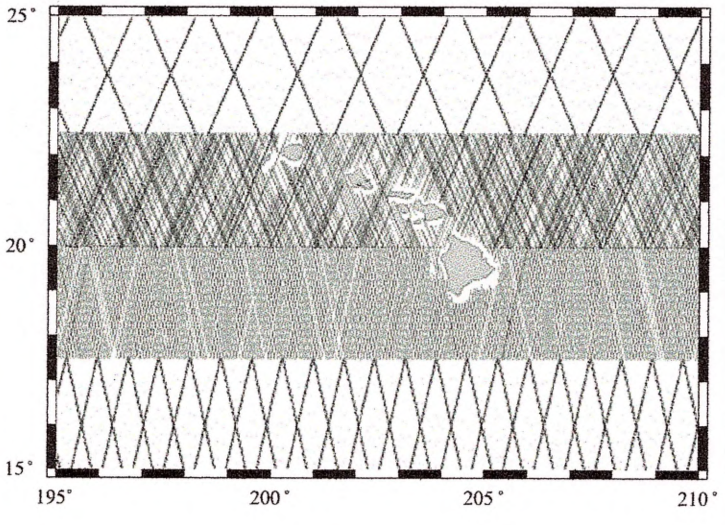

Figure 6. *Satellite altimeter survey tracks cover the globe much more densely than the bathymetric survey tracks shown in Figure 2. This map shows the Hawaiian Islands for scale, and the track density of four orbital patterns. Each orbit produces continuous tracks, but only narrow strips of each track pattern are shown here for clarity. The middle two strips show the dense track patterns of "geodetic" orbits suitable for Bathymetry from Space; the top and bottom strips are "oceanographic" orbits used to monitor currents, tides, and climate. Top, the Geosat Exact Repeat Mission; 2nd from top, the Geosat Geodetic Mission; 2nd from bottom, the ERS-1 geodetic mission ("Phases E and F"); bottom, the ERS-1/ERS-2/Envisat 35-day repeat track. Not shown is the 10-day repeat track of the Topex/Poseidon and Jason "oceanographic" missions; those tracks are even more widely spaced than the tracks in the top strip shown here. Geosat was a U.S. Navy mission and ERS-1 a European Space Agency mission.*

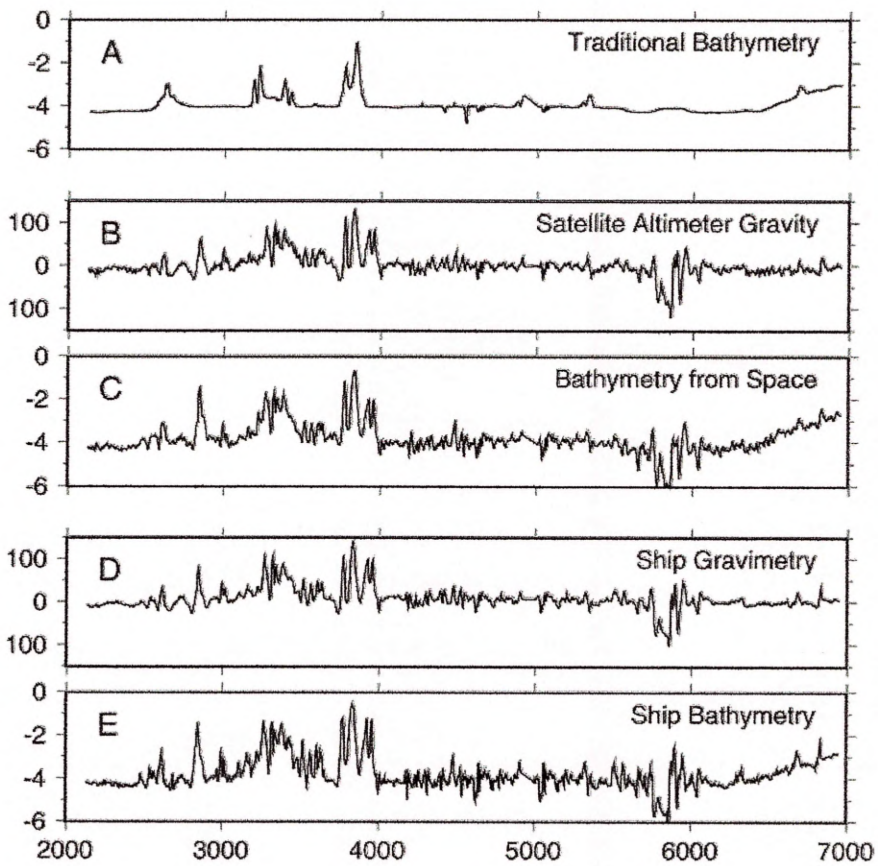

Figure 7. *These profiles of gravity and bathymetry lie along a ship survey line in the southwest (lower left) part of Figure 1. Traditional bathymetry (A) shows a smooth seafloor with only a few seamounts of simple shape. Satellite altimeter data reveal gravity anomalies (B); these may be used to estimate bathymetry (C). The differences between (A) and (C) prompted a survey by a ship, yielding "ground truth" measurements of gravity (D) and bathymetry (E). Quantifying the cross-correlation between pairs of data types allows one to explore the signal-to-noise and limiting resolution of altimetric data. Correlations between space-based and ground-truth profiles are high at scales longer than 12 km in both gravity and depth; root-mean-square differences are about 5 mGal in gravity and 120 m in depth. At fine scales, the satellite gravity has a higher noise level than the ship gravity, while the space bathymetry is smoother than the true bathymetry. Ship gravity is correlated with ship bathymetry down to about 5 km scales, implying that a more-precise satellite mission with better signal-to-noise between 5 and 12 km half-wavelengths could yield higher-resolution bathymetry. Very-long-wavelength trends in bathymetry, such as the upward tilt in the profiles near the right hand edge, are not reflected in the gravity anomalies due to "isostasy." The horizontal scale is in km along the survey; vertical scales are in km of depth and mGal of gravity anomaly. Data sources: A, ETOPO-5 gridded from contour charts; B and C, Smith and Sandwell, 1994; D and E, 1997 cruise of the French research vessel* Atalante.

(Figure 5). Terracing inhibits realistic calculation of bottom slopes from grids, and leads to biases when geophysical models are fit to gridded data by least-squares regression (Smith, 1993). Despite these problems, grids continue to be produced from hand-contoured charts. The Centenary Edition of the GEBCO Digital Atlas (British Oceanographic Data Centre, 2003) includes a grid made from hand-drawn contours, even though in some areas (such as the South Pacific) those contours have not been updated since the 1970s.

Satellites and Ships are Highly Complementary Mapping Tools

Satellites offer rapid global coverage at lower resolution while slower ships provide targeted high-resolution surveys. The speed at which the sub-satellite point moves over Earth's surface is more than 1000 times the speed of an oceanographic vessel, and a satellite can survey the ocean with a dense (order 5 km apart) network of ground tracks in a little over a year's time

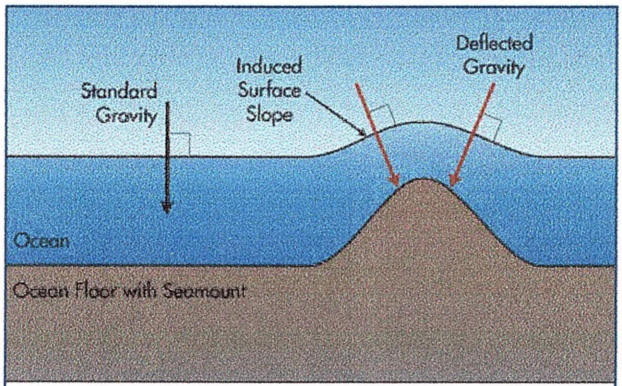

Figure 8. *Topography on the ocean floor adds its own attraction to Earth's usual gravity. This additional gravity pulls extra water up around a seamount and tilts the direction of gravity. The slope of the sea surface is nearly perpendicular to the pull of gravity. A space-based radar cannot "see" the ocean bottom but it can measure the tilts of the ocean surface. These reveal gravity deflections and from these the ocean bottom topography may be inferred. Note that the overall sea level is irrelevant; only the local tilt over the length scales of bathymetric features such as seamounts is important. This means that the radar doesn't need absolute height accuracy, and tides, El Niño, and other large-scale sea-level events may come and go; the local tilt remains steadily detectable.*

(Figure 6). The total cost of a satellite mission designed for bathymetry from space, including a suitable altimeter instrument, host spacecraft, launch, and operations, is slightly under $100M, according to a Johns Hopkins University Applied Physics Laboratory design study contracted by the National Oceanic and Atmospheric Administration (Raney et al., 2003).

It would seem that satellite surveys are about 2 x 10^4 times more efficient than vehicles in the water, with three orders of magnitude coming from speed and one from cost. However, the satellite method also has much lower resolution. State-of-the-art acoustic swath-mapping systems can image seafloor area "pixels" on the order of 100 m by 100 m in deep water, whereas the presently available satellite altimeter maps of the oceans do not easily resolve areas much smaller than about 10 km by 10 km (half-wavelength). A new space-based bathymetry mission would improve the resolution, but if cost-effectiveness is measured as resolution divided by cost, space bathymetry can beat acoustic bathymetry by perhaps only a factor of 8 or more.

While satellites may be more efficient and cost-effective mapping tools, their greatest virtue lies in their uniform and comprehensive global coverage. Satellites cannot be denied access to territorial waters. They also make no noise in the water column and so do not disturb marine life. By carrying the same sensor everywhere they yield a uniform level of detail across the globe. Thus if a satellite map shows a change in bottom texture, one can be sure it is real. Later, it can be investigated in greater detail with an accurately targeted ship survey, if desired (Figure 7). Many of the applications of bathymetric mapping, including all those in this special issue, require a globally uniform level of resolution and fidelity to spatial changes in texture or roughness.

Bathymetry via Altimetric Gravity

A space-based radar sensor cannot directly "see" the deep ocean floor. (In very shallow and very clear water the bottom may be visible to lasers or multi-spectral scanning systems.) Space-based ocean floor mapping is possible because topography on the seafloor creates gravity anomalies that tilt the ocean surface in ways that are measurable with a radar altimeter (Figure 8). These ocean surface tilts may be directly interpreted as an anomaly in the direction of gravity called a "deflection of the vertical." The vertical deflections of interest have amplitudes from 1 to a few hundred microradians, or 0.2 to 60 arc-seconds; a one microradian tilt of the sea surface is 1 mm of sea surface height change per km of horizontal distance.

Anomalies in the direction of the vertical are important information for compensating errors in inertial navigation systems (INS). Without such a correction, an INS mistakenly interprets a deflection anomaly as an acceleration of the vehicle. INS systems used on some submarines during the Cold War employed an error-compensating scheme requiring a map of vertical deflections at a fairly high level of precision. This limited the geographical range of operation of those subs to areas the U.S. Navy had covered with precise gravity surveys (satellite navigation signals cannot be received by a submerged antenna). Today, many military and civilian vehicles employ INS as a backup to GPS, and there is a need for worldwide operability. Current global altimeter data are about a factor of two too noisy to meet the one-arc-second precision goal set recently by the U.S. Air Force and the National Imagery and Mapping Agency. A new space bathymetry mission would be a factor of four better than current data and thus would meet the USAF-NIMA goal with a safety margin of a factor of two.

The gravity anomaly field at the sea surface obeys a mathematical equation (Laplace's differential equation) that allows one to recover anomalies in the magnitude of gravity (simply called "gravity anomalies") from the deflections of the vertical (Haxby et al., 1983; Sandwell, 1984). This is useful because the gravity anomalies are more easily interpreted and correlated with seafloor structure, and because they also can be checked against independent measurements made by ships carrying gravimeters (Figure 7). Roughly speaking, a one microradian vertical deflection can be related to a 1 milliGal anomaly in the acceleration of gravity. A milliGalileo is 10^{-5} m/s^2; since standard gravity is

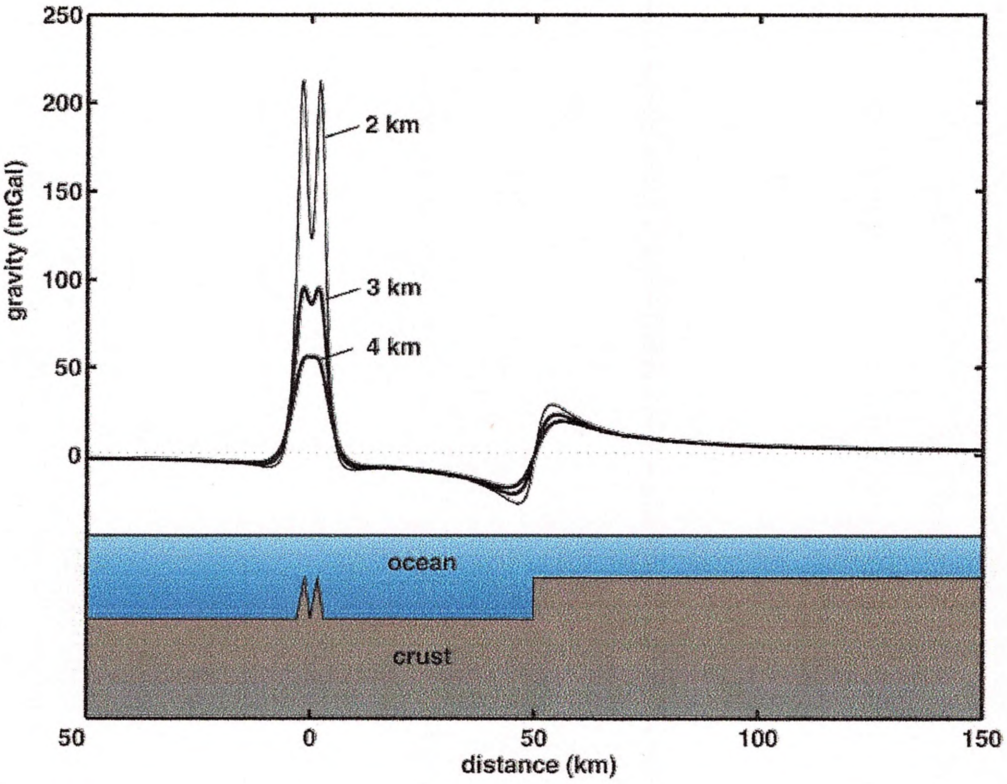

***Figure 9.** The gravity anomaly at the ocean surface does not exactly mimic the topography of the ocean floor below it at all length scales. Instead, it resembles a "band-pass-filtered" version of the topography. Very-broad-scale (longer than 100 km or so) changes in depth are in "isostatic balance" and so these contribute no gravity anomaly. However, if there is a sharp step from one regional level to another, such as at a plateau edge as suggested in this cartoon, then the gravity field may show an "edge anomaly," the zero-crossing of which locates the edge of the plateau. The shortest scales that gravity can see are limited by "upward continuation," which attenuates horizontal scales that are short compared to the average depth of the region. For example, two small seamounts that are 4 km apart and 1 km tall will create a gravity anomaly with two peaks if the water depth is less than 4 km but the anomaly will blur into one broad peak if the depth is 4 km. This "upward continuation" also makes the proportionality between gravity amplitude and topography amplitude a strong function of water depth for small-scale features. Therefore, the resolution of small-scale features in deep water requires precise gravity. Optimizing the signal-to-noise ratio at very short length scales is the key to detailed Bathymetry from Space.*

about 9.8 m/s^2, both the microradian and the milliGal represent parts-per-million-sized anomalies.

Once the deflections have been converted to gravity, bathymetric mapping follows by exploiting the correlation of bathymetry with gravity, using the available sounding data to calibrate the correlation and maintain the accuracy of the map. In effect, this means that bathymetry from space is yet another interpolation scheme for filling in the gaps between surveys. However, this technique replaces human choices and artistry with an empirically determined cross-covariance between gravity and bathymetry, embodying real physical laws. The ocean floor texture so derived is in marked contrast to traditional maps (see Figure 1 and the cover of this special issue). Because satellites provide uniform and unbiased coverage, the only limitations on the technique come from the nature of the gravity-topography correlation, and the errors in the altimeter measurements.

Factors Limiting the Gravity-Topography Correlation

The gravity anomalies caused by topography have been discussed in the scientific literature since the 18th century, and a 19th century paper (Siemens, 1876) suggested using gravity to estimate depth, although this was a fanciful notion given the difficulty of measuring gravity at sea in that day. The last three decades have seen a vast literature on gravity-topography correlations, exploiting linear filter theory and a spectral approach. In fact, the expected relationship is not quite

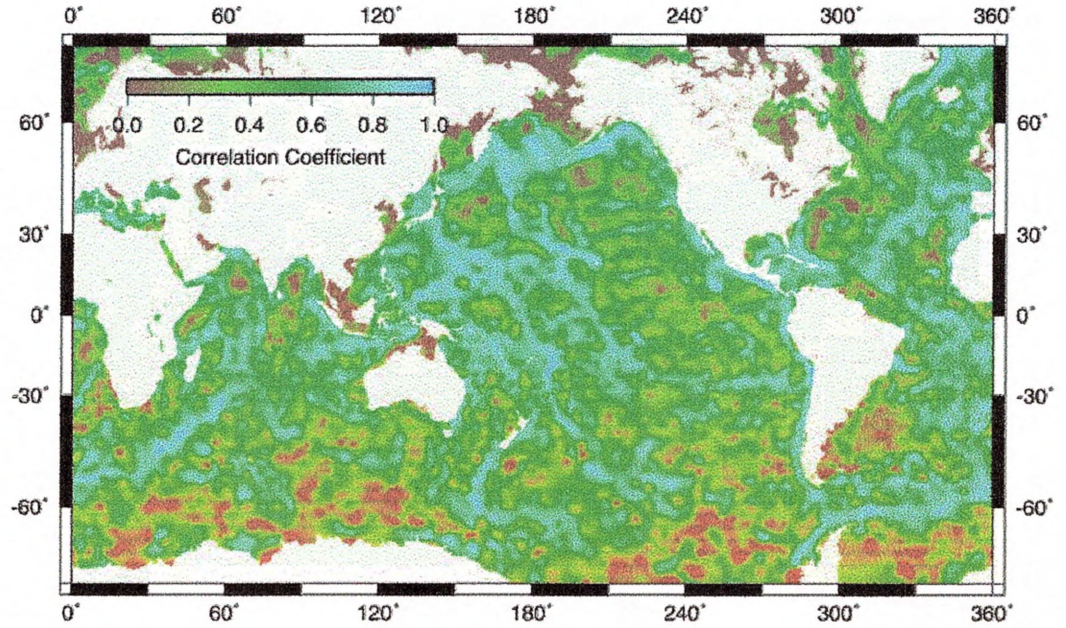

Figure 10. *The Bathymetry from Space technique takes into account varying sub-bottom geology. Altimetric gravity and depth soundings are filtered to isolate the length scales over which they may be correlated. The correlation must then be determined empirically because it depends on seafloor geology. The correlation is high over large-amplitude seafloor topography, such as at the major seamount chains and the Mid-Atlantic and Southwest Indian Ridges. It is low over continental margins and abyssal plains where the seafloor is flat and there is essentially no topographic signal at scales shorter than ~100 km. Note that this doesn't mean bathymetry from space won't work in these areas; the method has correctly detected that the seafloor is flat. Correlations are intermediate over relatively smooth seafloor, such as in the central Pacific Ocean. Here altimetry is of some value in mapping topography but the signal strengths are small and so noise in the measurements has reduced the correlation. With a new mission having a better signal-to-noise ratio, these areas would show higher correlations. (Adapted from Smith, 1998.)*

linear (Parker, 1973). Non-linearities are a significant fraction of the total effect only where the amplitude of the topography approaches the mean depth of the water and the slopes grow steep, as may occur at some very tall seamounts.

Gravity-topography correlation research was stimulated by a phenomenon called "isostasy," which reveals the mechanics of Earth's tectonic plates. The subject is thoroughly reviewed by Watts (2001). Earth's outer layers have finite strength and can only hold up topographic masses of limited size; larger objects are "isostatically compensated" and in effect contain less mass than their surface topography would suggest. The result is that long-wavelength (greater than a few hundred kilometers) topography is supported by buoyancy and generates essentially zero gravity anomaly (Figure 7). There are long-wavelength gravity anomalies, but these come from deeper inside Earth, not from the surface topography. Thus the long wavelengths in a bathymetric map must come from interpolation of soundings; they cannot be estimated from gravity. Features as large as oceanic plateaus cannot be fully mapped with gravity, although gravity may accurately locate their edges (Figure 9); however, medium-sized seamounts and smaller features are too small to be isostatically compensated and may be mapped with gravity (Smith and Sandwell, 1994; 1997; Smith, 1998).

While the long-wavelength resolution of bathymetry from space is limited by isostasy, the short-wavelength (about 10 km) resolution is limited by a phenomenon known as "upward continuation." This results from Newton's law that the strength of gravity falls off with the square of the distance between the source and the perceiver. Upward continuation of the gravity field to the sea surface from its source at the seafloor imposes a scale-dependent attenuation of the anomalies. Anomalies with wavelengths that are long compared to the mean water depth will suffer little attenuation, while those that are much shorter than about π times the water depth will be strongly attenuated.

Some readers may have heard of "space gravity" missions such as GRACE (Gravity Recovery and Climate Experiment) and GOCE (Gravity and Ocean Circulation Explorer) that measure Earth's gravitational field in space at ~400 km altitude. Upward continuation affects them too; they cannot resolve gravity anomalies much shorter than ~400 km scales. Because Earth topography is isostatically compensated at these wavelengths, these missions cannot do bathymetry from space. The virtue of satellite altimetry is that, by measuring ocean surface tilts, it measures gravity at the sea surface, not at orbital altitude. With altimetric gravity anomalies, there is 4 km of upward continuation, not 400 km, making bathymetry from space possible.

The limitations on long- and short-wavelengths are summarized in Figure 9. In effect, the sea surface gravity field is missing some information about the topography at both short and long wavelengths; the gravity effect of topography appears as a band-pass-filtered version of the topography. To predict topography from gravity one must stay within the band of wavelengths where gravity and topography may be correlated. The smallest feature that can be resolved depends on the integrated effect of the band-pass-filter, the signal-to-noise ratio in the altimetry, and the signal strength spectrum of the seafloor topography feature to be imaged. The paper by Goff et al. in this issue offers a more thorough investigation of the limiting resolution, for both currently available altimeter data, and data that could be obtained by a new mission. An important result of that paper is that a new mission would be able to resolve the fine-scale seafloor fabric known as abyssal hills, even in the smoothest seafloor areas.

In addition to the limitations on length scale, the gravity-bathymetry correlation is also influenced by sub-seafloor geology, primarily because of variations in sediment thickness. Areas of high and low correlation are easily detected by simply filtering the gravity field with a band-pass filter and then checking the resulting data for correlations with similarly filtered soundings (Smith and Sandwell, 1994; Smith, 1998). The results are shown in Figure 10. Interested readers may wish to compare Figure 10 to a map of sediment thickness currently under compilation at the U.S. National Geophysical Data Center (http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html). One should bear in mind that sediment thickness is known even more poorly than bathymetry. Monahan (this issue) speculates that the strength of the topography-gravity correlation may be useful as a proxy for sediment thickness.

Seafloor spreading creates oceanic crustal rocks with fairly uniform density and simple layering. Faulting and volcanism associated with the spreading process create abyssal hills, the "original" topography of the ocean floor. Later, sedimentation may alter the bottom shape by partly or completely burying this original topography.

Far from land the sedimentation rate in the ocean is very low, and the total accumulation of sediment is usually small. A thin layer of sediment is draped over the original topography but follows it closely. Under these conditions, the gravity-topography correlation is high. Since these conditions prevail in most of the deep ocean, the space bathymetry technique works well over most areas.

The sub-seafloor geology of continental margins can be quite complicated, with a heterogeneous mix of rock densities in complex shapes. Continental margins and nearby abyssal plains usually have thick sediments supplied to them by continental erosion. Significant gravity anomalies come from sub-seafloor geology in these areas, and consequently there is little correlation between gravity and seafloor topography.

This is actually not a problem, however, because bathymetric soundings are more common near land, and so there are enough sounding data to detect the lack of correlation. Then the bathymetry from space algorithm will correctly predict no seafloor topography over the length scales on which it operates, and this produces the correct result: the seafloor is essentially flat on continental margins and abyssal plains. Perhaps surprisingly, altimetric bathymetry also seems to correctly locate the 2500 m isobath midway up the continental slope (Monahan, this issue). Furthermore, the gravity anomalies in these uncorrelated areas are independently useful for exploring the sub-seafloor geology and its resource potential.

Geodetic Versus Oceanographic Altimetry

Applications of satellite altimeter data, and space missions or mission phases designed to furnish data for these applications, can be described as either "oceanographic" or "geodetic." Though both can employ the same space hardware, the two applications examine different signals, have different space and time sampling requirements, and different sensitivities to errors of various types. Bathymetry from space is a geodetic application.

If the wind ceased to blow and the currents ceased to flow, and the sun and moon vanished so there were no tides, then the ocean would come to rest in hydrostatic equilibrium on the solid Earth. In this situation, the ocean surface would lie on a gravitational equipotential surface called the "geoid." (In geodesy, "gravity" and its potential include both the Newtonian attraction and the centrifugal effect of a uniformly rotating Earth.) Mass redistribution associated with post-glacial rebound and climate change alters the geoid only at very long wavelengths and only at rates much less than 1 mm/yr. The geoid is essentially time-invariant on the length scales of concern in this paper. When the term was coined in the 19th century, geodesists imagined that the geoid was synonymous with "mean sea level." In fact the time-averaged "mean sea surface" is not quite on the geoid; the difference is due to the time-average of tidal deformations and dynamical displacements associated with the mean ocean circulation.

The gravity vector is perpendicular to the geoid; therefore deflections of the vertical at sea level are angles equal to geoid slopes (Figure 8). Because gravity

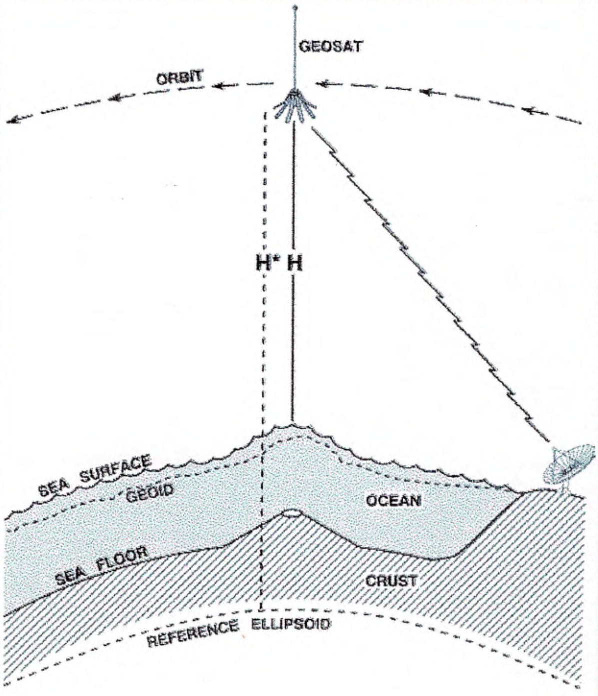

Figure 11. *In satellite radar altimetry of the ocean surface, an Earth-orbiting spacecraft measures the distance between its antenna and the ocean surface, H, by precise timing of the round-trip of a radar pulse. The radar pulse samples enough ocean area to average out most of the effects of waves. The spacecraft's latitude, longitude, and height above a reference ellipsoid, H* are determined by combining tracking data with a model of the forces on the satellite. The height difference H* minus H yields the height of the ocean surface above the ellipsoid. This surface is not quite on the "geoid," the equipotential surface of Earth's gravity field, due to various dynamical displacements. There are also errors in H and H* so that the altimeter data do not exactly yield the true sea surface height. However, all these effects are correlated over long enough distances that the local tilt of the surface as measured by the satellite is usually within 1 microradian of the slope of the geoid on bathymetric length scales, and hence the bathymetric gravity anomaly signal can be easily recovered in the presence of these error sources and oceanographic signals. Errors that might present a problem in other applications, like monitoring global sea level rise, are inconsequential to a geodetic altimeter mission like Bathymetry from Space.*

anomalies may induce deflections of the vertical from 1 to a few hundred microradians, the geoid may change by as much as a few meters vertically over 10 km horizontally.

The actual ocean surface departs from the geoid due to the dynamics of geostrophic flow and the ocean's response to tidal and meteorological forcing. In the open ocean in deep water, these departures are on the order of a few decimeters. Oceanographers want to observe a time series of these departures, and require an "exact repeat orbit" (Figure 6) that periodically revisits the same network of ground tracks and hence the same mean sea surface. The time series is only useful if all measurement errors and calibrations that might vary in time at the few centimeter level can be accounted for. Observing global sea-level rise requires stability in all the calibrations and error compensations at the mm/yr level; current research is investigating this possibility.

The altimetric measurement scheme is shown in Figure 11. Errors in the measurement are of three kinds. First, there is a random error due to ocean surface waves. Second, there is "orbit error" (error in H*) due to mis-modeling the spacecraft's trajectory. Third, there are errors in the range measurement, H. Some of these are accounted for by engineering calibrations, but there remain important "environmental corrections" for delay of the radar propagation by the ionosphere and troposphere. (Altimeters primarily use Ku-band radar that can "see" through clouds; the environmental problem is one of propagation speed, not attenuation.) The most accurate altimeters carry auxiliary instruments to measure these propagation delays *in situ*, with consequent increased complexity and expense of the mission. For geodetic and bathymetric purposes, these are not needed.

The altimetrically measured sea surface height is thus not the geoid height but rather the ocean surface height plus the measurement errors. Yet it happens that the slope of the measured height is almost exactly the slope of the geoid, and hence gives the vertical deflection and, in turn, the gravity anomaly and seafloor topography. This is because almost all the non-geoidal components of the height are of small amplitude (order of decimeters) and are correlated over long length scales (hundreds of km) and so have negligible slopes, well under one microradian.

There are some exceptions. The most energetic western boundary currents and their eddies produce dynamic signals of several decimeters with correlation scales of ~100 km (Jacobs et al., 2001) and so introduce an error of a few microradians. The tides can have significant slopes in shallow seas such as the North Sea, Yellow Sea, and Patagonian Shelf; however, tide models are usually good enough to remove most of this signal. In extreme cases in the Inter-Tropical Convergence Zone one may find water vapor delay gradients around 1 microradian.

To demonstrate that the slope of the altimetrically measured height profile is essentially the geoid slope, we use Exact Repeat Mission data from the U.S. Navy's Geosat. Geosat did an excellent job of mapping the marine gravity field despite the fact that it had no *in situ* measurement of ionosphere or troposphere delays. We did not apply any models for these delays to the data; however, we did subtract a modeled tide. We

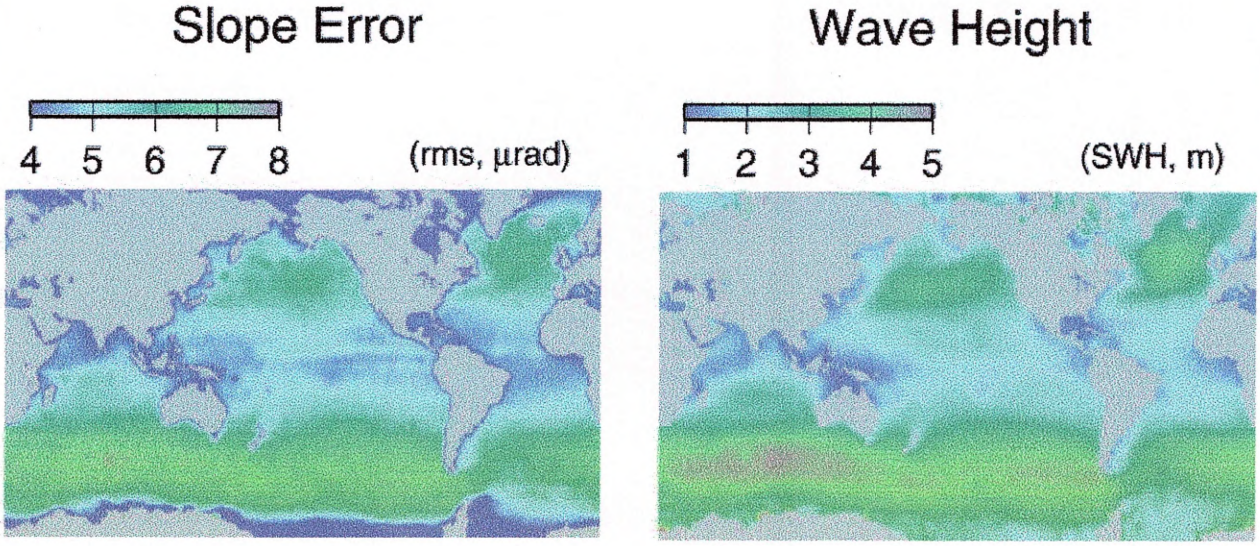

Figure 12. A map of the magnitude of the error in deflections of the vertical determined altimetrically (left) resembles a map of the average wave height (right). Just as significant, the error map pattern does not look like the map pattern expected for errors due to tides, ocean currents, or radar path delays in the ionosphere or troposphere. This confirms that the only important error source in geodetic altimetry is the random error induced by surface waves. A geodetic altimeter mission does not need expensive and complicated systems for measuring ionosphere or troposphere effects. Wave height data courtesy of P. D. Cotton (pers. comm.)

time-averaged all the repeat profiles along each repeated track, and then subtracted the average from each individual profile. The residual after subtraction is the height signal that cannot be repeated from one measurement to the next; this is the error plus the time-varying dynamical ocean signal.

The root-mean-square (rms) amplitude of the slope of this residual is shown in Figure 12. The geographical distribution of these errors does not resemble the expected pattern for errors due to water vapor, ionosphere delays, or the ocean circulation or tides. However, it does resemble the spatial pattern of the long-term average of wave height. This demonstrates that random errors in the altimeter measurement induced by waves are the dominant error source in geodetic altimetry. The slope error seen in Figure 12 in low wave height regimes is about 4 microradians. This level is to be expected, given that conventional altimeters orbit at about 7 km/s and have a random error of around 2 cm in a one-second averaged height in calm seas.

Prospects for Higher Resolution

Can bathymetry from space yield higher resolution in the future? The simple answer is yes! However, one must consider what limits the present resolution, what signal, if any, remains to be measured, and whether there is a technology to make the measurement.

The topography of the ocean floor at yet-to-be-resolved scales is made up of abyssal hills (see article by Goff et al. in this issue). These are self-affine (quasi-fractal) so that their amplitudes decrease with decreasing horizontal scale length. The sea-surface gravity signal of these hills diminishes even more rapidly due to upward continuation. It is probably impractical to attempt bathymetric estimation from sea surface gravity at scale lengths shorter than the mean depth of the ocean, or 4 km.

The self-affine nature of abyssal hills means that bottom slope and roughness statistics may be extrapolated to extremely small scales if the characteristic hill parameters can be resolved. Detailed modeling by Goff et al. (this issue) shows that the rms noise level in current altimetric gravity is about 4 mGal, and that these data allow extraction of hill parameters in only those areas where the bottom topography is particularly rough. They find that extraction of hill parameters typical of very smooth bottom would require a noise level around 1 mGal.

Other independent lines of evidence support the noise level estimates of Goff et al. (this issue). Slope error noise levels (Figure 12) and rms differences between altimetric gravity and ship gravity (Figure 7) confirm the 4 mGal estimate of the current noise floor. The expected noise level for state-of-the-art ship gravimetry is about 1 mGal and such data are correlated with ship bathymetry down to about 5-km scales.

This confirms that a lower noise level would allow altimetric gravity data to resolve smaller features.

These lines of evidence suggest that a new mission to optimize bathymetric resolution should achieve about a factor of four lower noise than at present, that is, 1 mGal of gravity noise, or on the order of 1 microradian of slope noise. In doing so, it would measure gravity as well as a ship can, and it would resolve bathymetry down to ~5 km scales (half-wavelength). Greater precision would not effect further resolution gain, as the signal rapidly becomes vanishingly small around this point, due to upward continuation. The spatial sampling characteristics of the mission would also have to support recovery of data at ~5 km scales.

Since the ERS-1 geodetic data have a higher noise level, wider track spacing, and a shorter mission duration than the Geosat geodetic data, the present 4 mGal noise level is determined mostly by Geosat. A new mission with a Geosat-quality altimeter could reduce the noise by a factor of four through averaging, but only with a 16-fold redundancy in data coverage. Because the new mission would need to have ground tracks spaced 5 km apart or closer, its orbit should not repeat for at least 18 months; to achieve 16-fold redundancy would mean a prohibitive 24-year-long mission. Thus improved resolution will have to employ a new technology. We consider here only radar technologies, as laser altimeters have a footprint much smaller than ocean waves and removing the wave height signal is a problem.

One new ocean altimeter technology in development is the Wide Swath Ocean Altimeter ("WSOA;" Rodriguez and Pollard, 2001; Fu, 2003). It is planned as an experimental payload on the successor satellite to the *Topex/Poseidon* and *Jason* series, expected to launch in late 2007 or 2008. That satellite will follow the same orbit as its predecessors, a 10-day exact repeat with 315 km between ground tracks at the equator. The WSOA will employ two antennae, each extending 3.5 m to either side of the spacecraft, and will operate the pair interferometrically as a real-aperture radar, to image a swath of area as much as 100 km on either side of the ground track. This instrument was designed to monitor temporal variability in ocean surface heights associated with the dynamics of mesoscale ocean currents. The designed data product will have a resolution of 15 to 25 km and will be given on a 15 km by 15 km grid of points within the swath. The error budget for these heights is ~5 cm, slightly worse than a conventional altimeter.

These specifications suggest that the WSOA cannot improve on existing geodetic altimetry, since the current resolution is already ~10 km. However, by designing a special processing of the WSOA interferometric signal, it may be possible to reduce the sample spacing in the "look direction," that is, along the line connecting the two outrigger antennae. Given a long-enough mission duration, one might achieve a higher resolution in the look direction of the time-averaged sea surface height.

Additional factors will also limit the WSOA's ability to measure geodetic signals. Even if the resolution in the look direction can be customized, there remains a limit of ~10 km resolution in the direction of flight due to averaging required in the space hardware. The swath will cover only 60% of the ocean at low latitudes, where most ocean area lies. Finally, there is the complication of "yaw steering." The spacecraft that carries the WSOA will be steered around its yaw axis to maintain good illumination of its solar panels, and consequently the WSOA's look direction will be steered as well. The look direction will be in the favorable direction, perpendicular to flight, only part of the time. (This problem applies only to the WSOA planned for the follow-on to the Jason mission. Some other satellite farther in the future could be designed to avoid a yaw steering problem.)

The other new ocean altimeter technology is the delay-Doppler altimeter ("DDA;" Raney, 1999). This instrument adapts some innovations of synthetic aperture radar and employs them in a nadir-looking instrument. Whereas conventional ocean radar altimeters pulse only fast enough to support incoherent processing, the DDA sends many more radar pulses and processes these coherently. It exploits Doppler shifts in the coherent reflections to slice the footprint into strips that are very narrow in the direction of flight (~250 m) and independent of any yaw of the spacecraft. This narrowing and slicing, when combined with the faster pulsing, yields several improvements over a conventional instrument that are ideal for a new bathymetry from space mission.

The European Space Agency's CryoSat mission, intended to launch late this year or in 2005, will carry a hybrid altimeter into polar orbit to measure the topography of Earth's polar ice caps and sea ice. It will use a high pulse rate near the poles for later DDA processing on the ground; it will not carry enough on-board computing power to do DDA processing in "real time." Over ice-free ocean water it will operate primarily as a conventional altimeter with a conventional pulse rate. Its data storage and telemetry capabilities will not permit it to operate in high-pulse-rate mode over the entire ocean, unfortunately. However, it may collect high-rate data during portions of a few selected orbits to support demonstration of the DDA technique over ocean water.

For geodetic purposes, the most important virtue of the DDA is that it is much less sensitive to random errors induced by ocean surface waves (Figure 12). On a flat, wave-free ocean, the random noise level in the DDA is about a factor of two less than that of a conventional altimeter. In both DDA and conventional instruments, the random noise level increases as the wave heights on the ocean surface increase, as in Figure 12, but with the DDA the rate of growth of this error is much slower than that of a conventional instrument. Thus the DDA would reduce the noise level most where the reduction is most needed.

Another virtue is better surface-following than a conventional instrument. If the DDA processing is done in real time by an on-board computer, then the surface-following algorithm (the "tracker") can exploit the narrow footprint slices to maintain "lock" on the ocean surface quite close to shore. Conventional instruments often suffer data losses near shore, particularly as the direction of flight leaves land and heads out to sea, when it can take the tracker a relatively long time to "find" the ocean surface and begin to follow it.

A DDA needs to transmit less power, so its electronics can be smaller and, for a given design life, cheaper than conventional hardware. Because the DDA is small and has low power requirements, and because a geodetic mission doesn't need auxiliary instruments to measure water vapor and ionosphere delays, a new space bathymetry mission could be small enough and light enough to use a Pegasus launch vehicle, among the least expensive of alternatives.

A design study for a mission of this kind ("ABYSS-Lite;" Raney et al., 2003) has been underwritten by NOAA. The mission employs on-board computing of Doppler processing to achieve all the benefits of a fully functional real-time DDA. The design considers the effects of wave height error and so conservatively assumes that the DDA performance will be only a factor of two better than Geosat. It uses a non-repeat orbit so that after 18 months, the ground track spacing is ~5 km. The noise level in the slopes so derived is so good that it should meet the NIMA-Air Force goal of 1 arc-second after only the first 18-month data collection cycle. However, the mission has a design life of six years, to furnish a four-fold redundancy. This will guard against losses and may permit the improvement of tide models in coastal areas; it also will allow averaging to remove some of the oceanographic error associated with western boundary currents. Averaging over the four-fold redundancy will cut the noise by a factor of two. This plus the two-times-better altimeter allows this low cost ($100M) mission to realize all the achievable resolution for bathymetry from space.

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