Bathymetry from Space: White paper in support of a high-resolution, ocean altimeter mission

David T. Sandwell¹, Walter H. F. Smith², Sarah Gille¹, Steven Jayne³, Khalid Soofi⁴ and Bernard Coakley⁵

¹Scripps Institution of Oceanography, La Jolla, CA, 92093-0225
²Laboratory for Satellite Altimetry, NOAA, Silver Spring Maryland, 20910-3282
³Dept. of Physical Oceanography, Woods Hole Oceanographic Inst., Woods Hole, MA 02543
⁴Conoco Inc., 600 North Dairy Ashford, Houston, TX, 77252-2197
⁵Department of Geology, Tulane University, New Orleans, LA 70118

(A more complete version of this paper, with comprehensive appendices, can be copied from http://topex.ucsd.edu/marine_grav/white_paper.pdf.)
SUMMARY

“High-resolution” in this paper means something quite different than in other papers in this report. Most physical oceanographic applications require both high spatial (> 100 km wavelength) and temporal sampling to recover time-dependent variations in ocean topography. Our focus is on the recovery of the permanent ocean topography (geoid) signals with small horizontal spatial scales (12 km to 160 km full wavelength). These are caused by gravity anomalies related to geologic structure on and below the ocean floor, and in the deep ocean these reveal bathymetry. While nearly all areas of ocean science require bathymetric information, we focus on those applications where a new altimeter mission would provide the greatest benefit. These include:

- resolving the fine-scale (~15 km wavelength) tectonic structure of the deep ocean floor (e.g., abyssal hills, microplates, propagating rifts, seamounts, meteorite impacts, . . .);
- measuring the roughness spectra (15-100 km wavelength) of the seafloor on a global basis to better constrain models of tidal dissipation, vertical mixing, and mesoscale circulation of the oceans;
- and resolving the fine-scale (~15 km wavelength) gravity field of the continental margins for basic research and petroleum exploration.

Mission requirements for Bathymetry from Space are much less stringent and less costly than physical oceanography-type missions and it is probably not cost effective or even possible to enhance a repeat-pass oceanographic-type mission to meet our objectives. Long-term sea-surface height accuracy is not needed; the fundamental measurement is the slope of the ocean surface to an accuracy of ~1 µrad. This can be achieved without application of the usual environmental corrections. The main requirements are:

- **Improved range precision** -- A factor of 2 or more improvement in altimeter range precision, with respect to Geosat and Topex, is needed to reduce the noise due to ocean waves. The footprint of the radar should be less than 6 km to recover wavelengths as short as 12 km.
- **Fine cross-track spacing and long mission duration** – A ground track spacing of 6 km or less is required (non-repeat orbit for at least 1.2 years). The Geosat Geodetic Mission (1.5 years) provides a single mapping of the oceans at ~5 km track spacing. Since the measurement noise scales as the square root of the number of independent measurements, a 6-year mission would reduce the error by another factor of 2.
- **Moderate inclination** -- Current non-repeat orbit altimeter data have high inclination (72° Geosat, 82° ERS) and thus poor accuracy of the E-W slope at the equator. The new mission should have an inclination of ~50° or 125° degrees to improve E-W slope recovery.
- **Near-shore tracking** -- For applications near coastlines, the ability of the instrument to track the ocean surface close to shore, and acquire the surface soon after leaving land, is desirable.

The Wide Swath Ocean Altimeter concept cannot recover our signal with the required precision because the resolution cell size is 15 km and the off-nadir beams are less accurate than a conventional radar altimeter. A delay-Doppler altimeter (Raney, 1998) in a non-repeat orbit of moderate inclination (50 or 125 degrees) for more than 3 years would meet our science objectives.

INTRODUCTION

Detailed bathymetry is essential for understanding physical oceanography, biology, and marine geology. Currents and tides are steered by the overall shapes of the ocean basins as well as by the smaller sharp ocean ridges and seamounts. The interaction of flow with the rugged seafloor mixes the ocean. It has been proposed that variations in tidal amplitude modulate the mixing which may effect climate on decadal to millennial timescales. Sea life is abundant where rapid changes in ocean depth deflect nutrient-rich water toward the surface. Because erosion and sedimentation rates are low in the deep oceans, detailed bathymetry also reveals the mantle convection patterns, the plate boundaries, the cooling/subsidence of the oceanic lithosphere, the oceanic plateaus, and the distribution of volcanoes.

Topographic mapping with orbiting laser and radar altimeters has been the focus of current exploration of Venus, the Moon, and Mars and is providing very high resolution topographic maps of the Earth's land areas. However, since one cannot directly map the topography of the ocean basins from space, most seafloor mapping is a tedious process that has been carried out over a 40-year period by research vessels equipped with single or multibeam echo sounders [Smith, 1993]. So far only 0.1% of the oceans have been surveyed at the 100-m resolution. It has been estimated that the 125–200 ship-years of survey time needed to map the deep oceans (100-m resolution) would cost a few billion US$, and mapping the
shallow seas would take much more time and funding [Brown et al., 1995; M. Carron, U.S. Naval Oceanographic Office, pers. commun. 2001].

While shipboard surveys offer the only means for high-resolution seafloor mapping, moderate resolution (12-17 km wavelength) can be achieved using satellite radar altimetry at a fraction of the time and cost. Radar altimeters aboard the ERS-1 and Geosat spacecraft have surveyed the marine gravity field over nearly all of the world's oceans to a high accuracy and moderate spatial resolution (25-45 km; Figure 1). These data have been combined and processed to form a global marine geoid and gravity grid [Cazenave et al., 1996; Sandwell and Smith, 1997; Tapley and Kim, 2001]. In the wavelength band 10 to 160 km, variations in gravity anomaly are highly correlated with seafloor topography and thus, in principle, can be used to recover topography. There are ongoing efforts to combine ship and satellite data to form a uniform-resolution grid of seafloor topography [e.g., Figure 1] [Baudry and Calmant, 1991; Jung and Vogt, 1992; Calmant, 1994; Smith and Sandwell, 1994; Sichoix and Bonneville, 1996; Ramillien and Cazenave, 1997; Smith and Sandwell, 1997]. The sparse ship soundings constrain the long wavelength (> 160 km) variations in seafloor depth and are also used to calibrate the local variations in topography to gravity ratio associated with varying tectonics and sedimentation. Current satellite-derived gravity anomaly provides much of the information on the intermediate wavelength (25-160 km) topographic variations. The main limitation is the noise in the gravity anomaly measurements (i.e., sea surface slope) since this becomes amplified during the downward continuation process. The bathymetric models can only be improved through more accurate and dense measurements of the ocean surface slope.

**SCIENTIFIC RATIONALE FOR A BATHYMETRIC ALTIMETER MISSION**

While these satellite-derived maps of marine gravity anomaly and seafloor topography have sufficient accuracy and resolution for certain applications, there are several important science questions that can only be addressed with better accuracy and resolution (Table 1). Here we focus on three science issues but note that seafloor topography is fundamental to all aspects of ocean science.

- **What is the fine-scale tectonic structure of the deep ocean?**
- **How does seafloor depth and seafloor roughness affect ocean circulation and deep ocean mixing?**
- **What is the sedimentary and crustal structure of the continental margins?**

**Table 1. Applications of High Spatial Resolution Satellite Altimetry**

<table>
<thead>
<tr>
<th><strong>Topography Applications:</strong></th>
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<tbody>
<tr>
<td>fiber optic cable route planning (<a href="http://oe.saic.com">http://oe.saic.com</a>)</td>
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<tr>
<td>tsunami propagation and hazard models [Yeh, 1998]</td>
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<tr>
<td>hydrodynamic tide models and tidal friction [Egbert and Ray, 2001]</td>
</tr>
<tr>
<td>coastal tide model improvements [Shum et al., 1997; 2000]</td>
</tr>
<tr>
<td>ocean circulation models [Smith et al., 2000; R. Tokmakian, pers. commun.]</td>
</tr>
<tr>
<td>tidal role in ocean mixing [Jayne and St. Laurent, 2001]</td>
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<tr>
<td>understanding seafloor spreading ridges [Small, 1998]</td>
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<tr>
<td>education and outreach (i.e. geography of the ocean basins)</td>
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<tr>
<td>law of the sea [Monahan et al., 1999]</td>
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<td>fisheries management [Koslow, 1997]</td>
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<tr>
<th><strong>Gravity Applications:</strong></th>
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<tbody>
<tr>
<td>inertial guidance of ships, submarines, aircraft, and missiles</td>
</tr>
<tr>
<td>planning shipboard surveys</td>
</tr>
<tr>
<td>mapping seafloor spreading ridges and microplates (<a href="http://ridge.oce.orst.edu">http://ridge.oce.orst.edu</a>)</td>
</tr>
<tr>
<td>continental margin structure (<a href="http://www.ldeo.columbia.edu/margins/Home.html">http://www.ldeo.columbia.edu/margins/Home.html</a>)</td>
</tr>
<tr>
<td>petroleum exploration (below)</td>
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<tr>
<td>plate tectonics [Cazenave and Royer, 2001]</td>
</tr>
<tr>
<td>strength of the lithosphere [Cazenave and Royer, 2001]</td>
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<tr>
<td>search for meteorite impacts on the ocean floor [Dressler and Sharpton, 1999]</td>
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</table>
Satellite altimetry has revealed the large-scale manifestations of plate tectonics such as seafloor spreading ridges, transform faults, fracture zones, and linear volcanic chains [Haxby et al., 1983; Gahagan et al., 1988] and ridges [Smith and Sandwell, 1994], allowing refinement of the history of plate tectonic motions [e.g., Shaw and Cande, 1990; Mayes et al., 1990; Müller and Smith, 1993]. While altimetry has furnished a spectacular confirmation of the plate tectonic theory, the dense altimeter data available since 1995 have also shown that there are many complex details of plate tectonics that are poorly understood. Here we focus on those processes that produce smaller scale sea floor topography and structure in the oceanic crust.

Until dense altimeter data over ridges became available, many seafloor spreading studies were focused on the East Pacific Rise (EPR) and the Mid-Atlantic Ridge (MAR) and the differences in their bathymetric morphology. The EPR has an axial summit and relatively smooth flanks, while the MAR has a deep median valley and rougher flanks (Figure 2 – left) [Menard, 1967]. The lengths of axis segments and their offsets at transform faults also differ from one ridge to the other [Abbott, 1986]. The differences are manifest in gravity anomalies as well [Cochran, 1979; Macdonald et al., 1986]. Analysis of repeat-track Geosat profiles over ridges revealed an abrupt transition in ridge-axis gravity with spreading rate which occurs at a full-rate of about 80 mm/yr (Figure 2-right) [Small and Sandwell, 1989; 1992].

A number of models have been proposed to explain this contrast in terms of spreading-rate-dependent material strength and the transience or permanence of a magma supply [Sleep, 1969; Tapponier & Francheteau, 1978; Phipps Morgan et al., 1987; Chen & Morgan, 1990a, 1990b; Phipps Morgan & Chen, 1992, 1993]. Studies of shipboard bathymetric profiles [Malinverno, 1991; Small, 1998] were limited by the limited geographical distribution and heterogeneity in these data, and altimeter data provided a more uniform and systematic view (Figure 3).

As dense altimeter data became globally available they revealed details in the seafloor spreading process, including propagating rifts [Phipps Morgan & Sandwell, 1994], non-transform ridge offsets [Lonsdale, 1994], ridge-hotspot interactions [Small, 1995], disorganized back-arc spreading [Livermore et al., 1994], small (20 km) ridge jumps [Marks & Stock, 1995], and small scale (circa 25 km) spreading-rate-dependent tectonic fabric [Small & Sandwell, 1994; Marks & Stock, 1994; Phipps Morgan & Parmentier, 1995; Sahabi et al., 1996]. Phipps Morgan & Parmentier [1995] interpret a new fabric they call "crenulated seafloor" as evidence for stationary and/or migratory localized centers of upwelling magma beneath ridges. Many of these kinds of features are symmetric across ridge flanks.

Seafloor structure at quite small spatial scales (0.2-10 km wavelength) has also been imaged in acoustic swath bathymetry but only in a few small patches totaling less than 0.1% of the deep ocean floor area. To assess the capabilities of current and future bathymetric prediction from a new satellite altimeter mission, we have assembled three 200 km by 200 km areas where multibeam bathymetry data are available. The current and future capabilities will be discussed below. Here we illustrate the major differences in seafloor characteristics in these areas (Figure 4 - upper). The Mid-Atlantic Ridge (MAR) is characterized by an axial valley with relatively rugged surrounding seafloor abyssal hills (493 m rms). The hills are very anisotropic with the long-axis perpendicular to the seafloor spreading direction and visually have a characteristic wavelength of about 10 km. The Pacific Rise (EPR) has quite different seafloor morphology with a more isotropic pattern that formed in response to buoyancy instabilities of salt domes. Spectra for the MAR and EPR are provided in Figure 4 (lower). The lengths of axis segments and their offsets at transform faults also differ from one ridge to the other [Abbott, 1986]. The differences are manifest in gravity anomalies as well [Cochran, 1979; Macdonald et al., 1986]. Analysis of repeat-track Geosat profiles over ridges revealed an abrupt transition in ridge-axis gravity with spreading rate which occurs at a full-rate of about 80 mm/yr (Figure 2-right) [Small and Sandwell, 1989; 1992].

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Tidal dissipation and deep ocean mixing

Tides are the major process responsible for mixing the deep ocean. Astronomical calculations suggest that tidal mixing should dissipate 3.7 terawatts (TW) of energy throughout the global ocean. Munk and Wunsch [1998] estimated that about 1.9 TW of this tidal energy is required to maintain the observed deep ocean stratification. While tidal processes are known to be important in coastal regions and marginal seas
Shum et al., 1997; 2001], tidal dissipation due to shallow ocean boundary layer effects does not account for all tidal dissipation. Egbert and Ray [2000] estimated that 25% to 30% of total tidal dissipation takes place in the open ocean, and is generally associated with ridges and other rough topography.

Recent observational efforts have attempted to measure the effect of open ocean tidal dissipation and its corresponding impact on vertical diffusivities in the ocean. In microstructure measurements in the Brazil Basin (Figure 5), Polzin et al. [1997] found elevated levels of vertical diffusivity over rough bathymetry. Diffusivity levels appear to be modulated by the fortnightly and monthly tidal cycle [Ledwell et al., 2000]. These results are consistent with the idea that tidal motions over rough bathymetry generate vertically propagating internal waves that dissipate tidal energy and vertically mix the ocean.

To test the impact of bathymetric roughness on tides, Jayne and St. Laurent [2001] implemented a roughness dependent internal-wave drag term in a barotropic tide model. The inclusion of internal-wave drag results in substantially more dissipation, particularly in the middle of ocean basins. Jayne and St. Laurent found that the rms difference between observed and modeled tides was 40% smaller when they included a roughness dependent dissipation term. In addition, in agreement with Egbert and Ray's [2000] observations, deep-ocean tidal dissipation due to the roughness term was about 30% of total dissipation.

In this model, viscous drag in the deep ocean is primarily due to generation (and subsequent dissipation breaking) of internal waves. A more complete description of this process will require bathymetric roughness spectra over wavelengths of 10 to 30 km [St Laurent and Garrett, 2001]. Note that these are the wavelengths that are not currently resolved in existing bathymetry, and this band includes the ubiquitous abyssal hill topography and the corner wavenumbers described above. While these mixing models are still under development and there is some debate about the physics of the internal-wave generation process, numerical simulations are hampered by the lack of high-resolution seafloor bathymetry.

The role of topography in tidal mixing and internal wave generation remains an active area of research in physical oceanography. Underway now is the Hawaii Ocean Mixing Experiment (HOME) [http://chowder.ucsd.edu/home/home.html], a large field program with two dozen investigators. HOME specifically focuses on observing and modeling mixing along the Hawaiian Ridge. HOME is directed towards understanding specific processes, including the impact on tidal conversion of critical bottom slopes over length scales of 1 km or less [R. Pinkel, personal communication]. Although such length scales are beyond the reach of altimetry, the lessons learned in HOME appear likely to translate into ways to characterize ocean mixing on the basis of larger scale bathymetry.

The new higher-resolution altimetric bathymetry (10-30 km wavelength) would offer the potential to better refine ocean mixing estimates, extending the results from the Brazil Basin, HOME and other field programs to give them global applicability and making the existing global roughness estimates more reliable. Of particular interest is the western Equatorial Pacific, near the Solomon Islands, a region that is not well mapped but where seamounts and ridges associated with the island chains may substantially influence mixing processes.

Ocean circulation and mesoscale eddies

Ocean circulation is influenced by seafloor topography in a variety of ways, particularly at high latitudes, where stratification is low. Bathymetry can steer the path of currents, determine where upwelling occurs (and supply iron-rich sediment to upwelled water allowing phytoplankton to bloom at the ocean surface), generate topographic lee waves downstream of topography, and dissipate eddy kinetic energy.

Theoretical constraints on vorticity suggest that large-scale barotropic flows in the ocean should be directed along lines of constant $\phi/H$, where $\phi$ is the Coriolis parameter and $H$ is the ocean depth. At high-latitudes where changes in $\phi$ are small, barotropic oceanic flows should nearly follow bathymetric contours. Although real flows include baroclinic components and are expected to deviate from $\phi/H$ lines, bathymetry is nonetheless a good predictor for large-scale circulation patterns. LaCasce [2000] showed that in both the Atlantic and Pacific Oceans, floats were more likely to travel along $\phi/H$ contours than across them. Holloway [1992] has even suggested that topography should be used as an a priori guess to determine large-scale dissipation in ocean circulation models.

Specific current flow patterns are clearly determined by bathymetry [Schulman, 1975]. For example, the path of the wind-driven Antarctic Circumpolar Current (ACC) has long been known to be steered by
deep seafloor topography [e.g., Gordon and Baker, 1986] (Figure 1). Altimetric investigations suggest that the jets that comprise the ACC are tightly steered around bathymetric obstructions in the Southern Ocean. Figure 1 shows that the paths of the Subantarctic Front and Polar Front (as estimated from altimetry) pass through the Eltanin and Udintsev Fracture Zones, respectively, in the Pacific-Antarctic Ridge [Gille, 1994]. Similar effects occur downstream of Drake Passage and south of New Zealand, where the ACC is steered through troughs between a series of islands. Detailed study of the role that bathymetry plays in controlling ocean circulation has been limited by the lack of accurate bathymetry, particularly in the Southern Ocean where areas as large as 2x10^6 km² are unsurveyed [Sandwell and Smith, 2001] and where current altimetric bathymetry cannot resolve all of the details of the bathymetry.

Ridges can generate topographic lee waves [e.g. McCartney, 1976]. Altimeter observations have consistently shown elevated levels of eddy kinetic energy downstream of ridges and seamounts, in the Gulf Stream [Kelly, 1991] and particularly in the ACC [Sandwell and Zhang, 1989, Chelton et al., 1990; Morrow et al., 1992; Gille and Kelly, 1996]. In an analysis based on sea surface height variability estimates from altimeter data, Stammer [1998] found evidence for high meridional eddy heat fluxes in locations of high eddy kinetic energy, suggesting that high variability regions associated with topography are potentially important in the global heat budget.

Topography also plays a role in vertical motions in the ocean. Horizontal flow that encounters topography can be deflected vertically rather than around topography. At George's Bank, tidal forcing over topography upwells water to the surface. In the equatorial Pacific, topography plays a slightly different role: upwelling is driven by a wind divergence at the equator rather than topography. Near the Galapagos, upwelled water entrains iron rich volcanic sediments resulting in a phytoplankton bloom downwind of the Galapagos [Feldman et al., 1984]. Careful study of high resolution bathymetry in comparison with ocean color data may yield other nutrient blooms associated as much with sediment and bathymetry as with current motions or wind.

Finally, just as tidal dissipation may be linked with bottom roughness, mesoscale motions in the ocean may also be controlled by roughness. A preliminary study by Gille et al. [2000] compared bottom roughness (Figure 3) with upper ocean mesoscale variability (Figure 6). Results showed that eddy kinetic energy (EKE) is greatest in the deeper ocean areas and over smooth seafloor. This anti-correlation between roughness and variability is strongest at higher latitudes suggesting a communication of the surface currents with the deep ocean floor in locations with low stratification. Rough bathymetry may transfer energy from the 100-300 km eddy length scales resolved by altimetry to smaller scales or to vertically propagating motions resulting in an apparent loss of EKE. Since numerical ocean models do not yet account for spatial variations in bottom friction and moreover, since they incorporate ad-hoc dissipation mechanisms, improvements in seafloor depth and roughness may ultimately lead to a better understanding of deep ocean mixing. The link between seafloor roughness and spreading rate provides an interesting possibility that vertical mixing of paleo-oceans depended on the average spreading rate of the ocean floor and thus the waxing and waning of the mantle convection patterns.

Structure of continental margins and exploration of offshore sedimentary basins

Continental Margins

All continental margins either were or are active plate boundaries. The transition from oceanic to continental crust is structurally complex and often obscured by thick layers of sediment shed from the continent. The various sedimentary layers and basement are of contrasting composition and density. Changes in the thickness and elevation of these layers can be tracked with gravity anomaly data. The continuous high-resolution data set of altimetric gravity anomalies that would be collected during a high resolution altimeter mission would dramatically improve our understanding of the variety of continental margins. These data would help complete understanding of the processes (plate tectonic and sedimentary) that create and modify these features over geologic time, facilitating more accurate predictions of the location and extent of economically significant oil and gas fields.

Understanding of continental margins has come slowly, through independent surveys pursued by many scientific organizations, governments and corporations over the past fifty years. Each of these surveys has focused on a particular segment of a continental margin with a particular purpose in mind; scientific, legal or commercial. While these data sets have built our understanding, the accumulation of data has not resulted in a complete or systematic characterization of continental margins worldwide. An altimetric
gravity anomaly dataset, continuous along and across the submerged margins of the continents, would provide a means for systematic exploration and inter-comparison of the complex transition from continental to oceanic crust. A high-resolution altimeter mission would provide this dataset.

This comprehensive data set, a uniform survey of the continental margins, has not been obtained during previous altimetric missions, could not be collected from a ship and will not be collected by any of the geopotential satellite missions planned by either NASA or the ESA. Previous and future altimetric missions have and will collect relatively lower resolution data. The increase in resolution with the new mission will greatly increase our ability to image crustal scale structures of scientific and commercial interest. Shipboard surveys, which can collect high-resolution data, are expensive and particularly difficult to execute in the shallow waters that would be sampled during a high-resolution altimeter survey.

The altimetric gravity anomaly data set will be unique and immensely valuable for science and exploration:

- A complete data set which will facilitate comparisons between continental margins.
- An exploration tool which will direct oil and gas exploration and permit extrapolation of known structures from well-surveyed areas.
- A uniform, high-resolution data set continuous from the deep ocean to the shallow shelf which will make it possible to follow fracture zones out of the ocean basin into antecedent continental structures, to define and compare segmentation of margins along strike and identify the position of the continent-ocean boundary. Conversely the continuity of geological features on land can be traced on to the Continental Margin.
- An image of the gravity field useful for the study of mass anomalies (eg sediment type and distribution) and isostatic compensation at continental margins.

**Hydrocarbon exploration**

More than 60% of the Earth's land and shallow marine areas are covered by > 2 km of sediments and sedimentary rocks, with the thickest accumulations on rifted continental margins. Sedimentary basins are the low-temperature chemical reactors that produce most of the hydrocarbon and mineral resources upon which modern civilization depends. The science and technology for the discovery and production of these resources will remain vital to the world's economy for at least the next several decades.

Free-air marine gravity anomalies derived from satellite altimetry are able to outline most of these major basins with remarkable precision. Gravity and bathymetry data derived from altimetry are also used to identify current and paleo submarine canyons, faults and local recent uplifts, active in modern time. These geomorphic features provide clues to where to look for large deposits of sediments. Figure 7 shows the paleo submarine canyons associated with the Indus (left, offshore Pakistan) and Ganges Rivers (offshore right, Bangladesh).

While current altimeter data delineate the large offshore basins and major structures, they do not resolve some of the smaller geomorphic features and they cannot be used to detect some of the smaller basins (Table 2 and Figure 7). Wavelengths shorter than 40 km in the presently available data cannot be interpreted with confidence close to shore, as the raw altimeter data are often missing or unreliable near the coast. The exploration industry would like to have altimeter data with as much resolution as possible and extending as near-shore as possible. The 2-D seismic survey standard in the industry uses a track line spacing of 5 km, yielding structure maps with a 10 km Nyquist wavelength. Altimetry with a similar resolution is desirable.

<table>
<thead>
<tr>
<th>Target</th>
<th>Wavelength</th>
<th>Amplitude</th>
<th>not resolvable from space</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buried cavities, tunnels, tanks</td>
<td>1 – 10 m</td>
<td>5-100 µGal</td>
<td></td>
</tr>
<tr>
<td>Pediment and seismic weathering layer thickness, shallow gas pockets, karst</td>
<td>10 – 200 m</td>
<td>0.05 mGal – 0.2 mGal</td>
<td></td>
</tr>
<tr>
<td>Shallow salt domes and cap rock</td>
<td>200 – 1000 m</td>
<td>0.1 – 0.3 mGal</td>
<td></td>
</tr>
<tr>
<td>Anticlines, faults deep salt, and overhang</td>
<td>500 – 4000 m</td>
<td>0.2 – 2.0 mGal</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Wavelength and amplitude resolution required for typical geologic targets [Yale et al., 1998].
Sedimentary basin structure. [Resolution commensurate with grid spacing (5-10 km) of seismic surveys for frontier basins.]

<table>
<thead>
<tr>
<th>Resolution (km)</th>
<th>Gravity (mGal)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 – 20</td>
<td>5</td>
<td>new mission</td>
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Sedimentary basin outlines and boundaries, plate tectonic structures

<table>
<thead>
<tr>
<th>Resolution (km)</th>
<th>Gravity (mGal)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 – 100</td>
<td>10</td>
<td>current resolution of Geosat and ERS is 24-45 km</td>
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</table>

LIMITATIONS OF PAST, CURRENT, AND PLANNED GRAVITY MISSIONS

There are three approaches to measuring marine gravity anomaly. Shipboard surveys provide the most direct approach. However, like bathymetric surveys, the marine coverage is sparse and inadequate for assessing the global roughness of the ocean floor or exploring the offshore sedimentary basins. The second approach is to measure variations in gravitational acceleration at satellite altitude. Three new satellite gravity missions CHAMP [Reigber et al., 1996], GRACE [Tapley et al., 1996], and GOCE will provide extremely accurate measurements of the global gravity field and its time variations [Tapley and Kim, 2001]. However, because these spacecraft measure gravity at altitudes higher than 250 km, they are unable to recover wavelengths shorter than about 160 km. Although these new missions offer little short-wavelength information, they provide the ideal reference field for shorter wavelength surveys.

The third approach to measuring marine gravity is satellite altimetry, in which a pulse-limited radar measures the altitude of the satellite above the closest sea surface point. The radar pulse reflects from an area of ocean surface (footprint) that grows with increasing sea state [see Stewart, 1985]. There are several sources of error in these measurements but most occur over length scales greater than a few hundred kilometers [Sandwell, 1991; Tapley et al., 1994]. For gravity field recovery and bathymetric estimation, the major error source is the roughness of the ocean surface due to ocean waves (Figures 8). Thus the only way to improve the resolution is to make many more measurements.

Other sources of error include tide-model error, ocean variability, dynamic topography, ionospheric delay error, tropospheric delay error, and electromagnetic bias error (Table 3). Corrections for many of these errors are supplied with the geophysical data record. However, for gravity field recovery and especially bathymetric prediction not all corrections are relevant or even useful. For example, corrections based on global models (i.e., wet troposphere, dry troposphere, ionosphere, and inverted barometer) typically do not have wavelength components shorter than 1000 km, and their amplitude variations are less than 1 m so they do not contribute more than 1 µrad of error. Yale [1997] has examined the slope of the corrections supplied with the Topex/Poseidon GDR and found only the ocean tide correction [Bettadpur and Eanes, 1994] should be applied. The dual frequency altimeter aboard Topex/Poseidon satellite provides an estimate of the ionospheric correction, however, because it is based on the travel time difference between radar pulses at C-band and Ku-band, the noise in the difference measurement adds noise to the slope estimate for wavelengths less than about 100 km [Imel, 1994]. The most troublesome errors are associated with mesoscale variability and dynamic topography [Rapp and Yi, 1997]. The variability signal can be as large as 6 µrad [Figure 6] but fortunately it is confined to a few energetic areas of the oceans and given enough redundant slope estimates from nearby tracks [Sandwell and Zhang, 1989], some of this noise can be reduced by averaging. Dynamic topography typically has slopes of less than 0.1 µrad. However, along a few areas of steady intense western boundary current, the slopes can be up to 6 µrad; this will corrupt both the gravity field recovery and the bathymetric prediction over length scales of 100-200 km.

<table>
<thead>
<tr>
<th>Signal or Error source</th>
<th>Length (km)</th>
<th>Height (cm)</th>
<th>Slope (µrad)</th>
<th>Mission-avg. slope (µrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity Signal</td>
<td>12–400</td>
<td>1–300</td>
<td>1–300</td>
<td>1–300</td>
</tr>
</tbody>
</table>

**Table 3 Signal and Maximum Error in Sea Surface Slope**

<table>
<thead>
<tr>
<th>Measurement error sources:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit errors¹</td>
</tr>
<tr>
<td>Ionosphere²,³</td>
</tr>
<tr>
<td>Wet Troposphere³</td>
</tr>
</tbody>
</table>
An important remaining issue is the anisotropy in the accuracy of the current marine gravity fields derived from Geosat and ERS [Sandwell and Smith, 1997]. Note that the current Topex/Poseidon mission, in its 10-day repeat configuration, provides almost no additional gravity field information because of the wide ground track spacing (315 km). As shown in Figure 9 (left panel), the E-W component of gravity field error at the equator is currently 3.5 times worse than the N-S error. There are two reasons for this. First, it has been shown that estimating sea surface slope by differencing heights on adjacent tracks results in slope estimates that are much less accurate than the along-track slope estimate [Olgiati et al., 1995]. This is because the adjacent tracks, which are acquired at different times, have different environmental path delays and different orbit errors that cannot be entirely corrected with a crossover adjustment. In contrast, height measurements along the satellite tracks have common errors that are largely eliminated by computing the along-track slope. The second reason is simply that, at the equator, the Geosat and ERS tracks run mainly in the N-S direction. The situation is quite different at the turnover latitude of Geosat (72° latitude), where the tracks are oriented in an E-W direction. The current Geosat/ERS configuration provides adequate control on the E-W slope for latitudes greater than about 60° latitude [Figure 9 – left panel].

What is the optimal inclination for gravity field recovery given availability of the passed (Geosat/GM, ERS/GM) and planned (Cryosat) non-repeat radar altimeters? The upper-right panel in Figure 9 shows the area of ocean covered as a function of orbital inclination. Of course about 1/2 of the ocean area lies south of 30°. The lower-right panel shows the area-averaged degree of anisotropy as a function of orbital inclination for both prograde (solid) and retrograde (dashed). The optimal prograde inclination (Op) is 50° while the optimal retrograde (Or) is slightly higher 55° (125° inclination). Geosat and Topex inclinations provide about the same area-averaged inclination although a more detailed evaluation shows Topex tracks are more orthogonal in the low latitudes (< 20°) where the current gravity fields suffer from poor E-W control. The International Space Station (ISS), which has a non-repeat orbit, is nearly optimal for this application. The east components shows greater improvement than the north component and the final error level after 6 years is 1 to 1.5 µrad. The desired noise level of about 1 µrad or 1 mGal can be achieved with a new if the mission duration exceeds about 6 years.

The final issue in gravity field recovery from the Geosat and ERS altimeters is related to the coastal data (Figure 10A). The issues for Geosat and ERS are different but both are illustrated in Figure 10B showing the available ground tracks in the Caspian Sea. The ERS-1 geodetic mission data are absent in this inland sea because the altimeter was switched to the ice mode where the ranging resolution is optimized for land or ice topography but inadequate for gravity field recovery. Many of the Geosat tracks over this sea are short or absent because the Geosat altimeter sometimes had trouble re-acquiring the sea surface when transitioning from land to water. Figure 10C shows the track density that would be acquired in 1.5 years in the ISS inclination with perfect ocean tracking. The differences are significant and in this particular area, just 1.5 years of non-repeat coverage would provide a factor of 2 improvement in accuracy.

| Oceanographic error sources: |  |  |
|-------------------------------|-----------------|-----------------|-----------------|-----------------|
| Sea-state bias 5              | > 20            | < 0.6           | < 0.3           | < 0.1           |
| Inverse barometer 6           | > 250           | < 5             | < 0.2           | < 0.1           |
| Basin-scale circulation (steady) 7 | > 1000         | 100             | < 1             | < 1             |
| El Niño, inter-annual variability, planetary waves 8 | > 1000          | 20              | < 0.2           | < 0.1           |
| Deep ocean tide model errors 4,10 | > 1000         | 3               | < 0.03          | < 0.01          |
| Coastal tide model errors 4,10 | 50–100          | < 13            | < 2.6           | < 1.1           |
| Eddys & Mesoscale Variability 9 | 60–200          | 30–50           | 2.5–5           | 1–2             |
| Meandering jet (Gulf Stream) 4,11 | 100–300        | 30–100          | 3–10            | 2–4             |
| Steady Jet (Florida Current) 4,11 | 100            | 50–100          | 5–10            | 5–10            |

MISSION REQUIREMENTS

How should a new ocean mapping mission be designed? What could it resolve?

We argue that understanding tidal dissipation and ocean mixing may ultimately require sea floor roughness on very short spatial scales, even those too short to be measured by altimetry. However, we have also shown (Figure 4), the roughness at these scales is well-modeled by a self-affine (fractal) surface, so that seafloor topography may be characterized statistically at wavelengths which are shorter than the corner wavenumber [Goff and Jordan, 1988]. Thus if one could map the oceans with enough resolution to establish the total power and the corner wavenumber, the statistical properties of the shorter part of the spectrum would follow from the self-affinity.

The corner wavenumber for the two patches we have examined (MAR and EPR) are both 20 km. However, it should be noted that other major complications on the seafloor such as fracture zones and seamounts can change both the total power and corner wavenumber. Moreover, the spectrum of the seafloor is usually anisotropic with fracture zones oriented parallel to the spreading direction and abyssal hills perpendicular to the spreading direction. The important point is that if one could map the full topography of the ocean floor to better than a 20 km wavelength, one could extrapolate the full anisotropic roughness spectrum; the anisotropy is important because deep tidal currents interact with the bottom only along their direction of flow. Current bathymetric prediction can capture wavelengths of only 40 km on smooth seafloor and about 25 km on rough seafloor. A new mission with sufficient accuracy to recover 15-km wavelengths would capture essentially all the interesting geophysics of the seafloor spreading process, and in addition, the statistical properties of the finer-scale roughness.

To achieve significant contributions in several areas of geophysics, physical oceanography, and climate research, an altimeter mission having the following characteristics is needed:

- **Altimeter Precision** - The most important requirement of this new mission is improvements in ranging technology to achieve a factor of 2 improvement in range precision (with respect to Geosat and Topex) in a typical sea state of 3 m. In shallow water, where upward continuation is minor, and in calm seas where waves are not significant (e.g. Caspian Sea), it will also be important to have an along-track footprint that is less than 1/4 of the resolvable wavelength of about 12 km. This footprint is smaller than the standard pulse-limited footprint of Geosat or Topex.

- **Mission Duration** - The Geosat Geodetic Mission (1.5 years) provides a single mapping of the oceans at ~5 km track spacing. Since the measurement noise scales as the square root of the number of measurements, a 6-year mission will reduce the error by a factor of 2. This combined with the factor of 2 improvement due to instrumentation results in an overall factor of 4 improvement.

- **Moderate inclination** - Current non-repeat orbit altimeters have high inclination (72˚ Geosat, 82˚ ERS) and thus poor accuracy of the E-W slope at the equator. The new mission should have an inclination of ~50˚ or 125˚ degrees to improve E-W slope recovery (Figure 9).

- **Near-shore tracking** - For applications near coastlines, the ability of the instrument to track the ocean surface close to shore, and acquire the surface soon after leaving land, is desirable (Figure 10).

Finally, it should be stressed that the basic measurement is not the height of the ocean surface but the slope of the ocean surface. The height differences over horizontal distances from a few km to a few hundred km must be measured with sufficient accuracy and precision that the horizontal slope of the sea surface along the satellite track can be calculated with a precision of about 1 microradian (6 mm height change over 6 km horizontal distance). The band of wavelengths we need to resolve is from 12 to a few hundred km (full wavelength). This requires careful processing of the radar pulse data at high sampling rates.

The need to resolve height differences, and not heights, means that the mission can be much cheaper than other altimeter missions and can take advantage of spacecraft platforms which are less stable than other missions require. This is because the absolute height, and any component of height which changes only over wavelengths much longer than a few hundred km, is irrelevant, as it contributes negligible slope (Table 3). Therefore one can tolerate large spacecraft motions, and errors modeling them, so long as they vary slowly with distance. Also, one need not measure the radar propagation delays in the ionosphere and troposphere, as the slopes of these corrections are also negligible.


Dressler, B.O., Sharpton, V. *Large Meteorite Impacts and Planetary Evolution; II*, Special Paper 339, Geological Society of America, Boulder, CO.


Figure 1 Data needed for predicting bathymetry. (a) Tracks of stacked Geosat/ERM (17-day repeat cycle), Geosat/GM, ERS-1 Geodetic Phase (168-day repeat cycle) and stacked ERS-1 (35-day repeat). (b) Ship tracks in area of the Eltanin and Udintsev transform faults. Track density is sparse except along the Pacific-Antarctic plate boundary. (c) Gravity anomaly (mGal) derived from all 4 altimeter data sets. (d) Bathymetry (m) estimated from ship soundings and gravity inversion. Red curves mark the sub-Antarctic and polar fronts of the Antarctic Circumpolar Current [Gille, 1994]. The Sub-Antarctic Front (SAF-red) passes directly over a NW-trending Hollister ridge which has a minimum ocean depth of 135 m [Geli et al., 1997]. The Polar Front (PF) is centered on the 6000m deep valley of the Udintsev transform fault.

Figure 2 Typical ridge axis relief and gravity amplitude versus spreading rate [Small, 1994]. The EPR has a smooth gravity profile with a positive anomaly over the axis of 10 or more mGal, while the MAR has a rougher gravity profile with a negative anomaly over the axis exceeding 30 mGal in magnitude.
Figure 3  Seafloor roughness from altimeter-derived, high-pass filtered topography (24-160 km wavelength). Because of noise in the gravity field, the smaller-scale seafloor roughness associated with abyssal hills is not captured in this estimate. Analysis of high-resolution bathymetry suggests that the ratio of rough-to-smooth seafloor is at least two times greater than shown in this figure. Detailed bathymetry of the MAR, EPR, and Gulf of Mexico (GOM) are shown in Figure 4. The roughness contrast in the Brazil Basin (BB) is shown in Figure 5.
Figure 4 (upper) Measured bathymetry (right column) and predicted bathymetry (left and center columns) for representative areas on the Mid-Atlantic Ridge, the East Pacific Rise, and the Gulf of Mexico. The Mid-Atlantic Ridge and East Pacific Rise show the characteristic abyssal-hill signature of slow and fast spreading ridges, respectively. While the current predicted bathymetry in the Gulf of Mexico is unable to resolve the salt-related mini-basins (outlined), the future predicted bathymetry reveals some of the more important structures; a global data set would be beneficial in frontier reconnaissance studies.

(lower) East-west spectra of the Mid-Atlantic Ridge and the East Pacific Rise area bathymetry. For both areas, the corner wavenumber and roll-off exponent are 20 km and –2.8, respectively. The total power is 493 m for the MAR and 209 m for the EPR. The noise spectra (dotted curves) for current and future bathymetric prediction is discussed in the following section. A signal to noise ratio of 1 defines the resolution limits of current and future bathymetric prediction. The current resolution for rough and smooth seafloor is 25 km and 45 km, respectively. Assuming a factor of 5 noise reduction in a future mission, the resolution improves to 12 and 17 km, respectively. Note this improvement captures the corner wavenumber of 20 km.
Figure 5  (upper) Bathymetry of Brazil Basin, South Atlantic derived from ship soundings lacks the resolution needed to distinguish between rough and smooth seafloor.  (center) Bathymetry derived from satellite altimetry and ship soundings resolves the rough seafloor associated with fracture zones but not abyssal hills.  
(lower) Vertical diffusivity represents vertical mixing of stratified seawater.  Mixing rates are an order of magnitude greater over rough topography (abyssal hills and fracture zones) than they are over smooth topography.  Enhanced mixing over rough topography extends from depths of about 1500 m to the bottom of the ocean (> 4000 m).  Mixing effects the vertical stratification which in turn influences deep currents and their horizontal and vertical stability to perturbations (after Polzin et al. [1997]).
Figure 6  Mesoscale slope variability from Topex and ERS repeat-pass altimetry. Note regions of highest ocean variability are concentrated in ocean areas greater than 3000 m deep (contour lines). A comparison with Figure 3 also that, in the deep ocean, the highest variability occurs over smooth seafloor.

Figure 7  Submarine canyon associated with Indus River, Pakistan (left) Ganges River, Bangladesh (right).
Figure 8  The along-track resolution of three radar altimeters Geosat, ERS1 and Topex, [Yale et al., 1995]. Two areas were selected for analysis. Area 1 over the equatorial Mid-Atlantic Ridge has a high signal due to the rugged seafloor and relatively low wave-height noise. Area 2 over the Pacific-Antarctic Ridge has a lower gravity signal but a much higher noise level because it is an area of large wave height. The two curves in each plot show coherence between individual cycles (dashed) and independent stacks (solid). The resolution of the stacked profiles is better than the individual cycles. Topex and Geosat have generally better resolution than ERS1. The grey vertical box marks the resolution desired from a new altimeter mission. The range of desired resolution reflects the limiting factors of ocean depth and wave height.

Figure 9  (left -red curves - Current) Propagation of along-track slope error from 1.5 years of dense Geosat coverage and 1 year of dense ERS-1 coverage into east (solid) and north (dashed) components of sea surface slope recovery versus latitude. At the equator, the Geosat and ERS tracks mainly run N-S so the N-S component is well determined (dashed red curve) while the E-W component of sea surface slope is poorly determined (solid red curve). The black curves show the improvement in E-W (solid) and N-S (dashed) slope error resulting from a new delay-doppler altimeter in an ISS (52˚) orbital inclination for 6 years. We assumed the new delay-doppler altimeter has one half the noise level of Geosat (Keith Raney, personal communication, 2001).

(right) Trade-off analysis to establish the average N-S to E-W anisotropy as a function of orbital inclination (solid – prograde, dashed – retrograde). The optimal inclinations are 50˚ (Op) and 55˚ (Or), respectively. The ERS (E), Geosat (G) and Topex (T) inclinations are good at higher latitudes but suffer from poor E-W slope recovery at low latitudes where the area of ocean (right-upper) is maximum.
Figure 10 (A) Gravity anomaly of the Caspian Sea (10 mGal contour interval) derived from all available satellite altimeter data (Geosat, ERS and Topex). Major oil fields are sketched in red. Future exploration will focus on the northern Caspian near the outlet of the Volga River. (B) Tracks of available altimeter data show less-than-optimal coverage because ERS data are not available (land mask) and many Geosat profiles are missing due to problems with the onboard tracker re-acquiring the water surface. (C) Tracks from 1.5 years of a new satellite altimeter in an ISS orbital inclination.