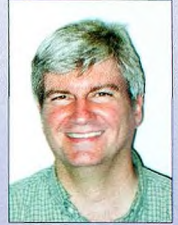


2,500m Isobath from Satellite Bathymetry Accuracy Assessment in Light of IHO S-44 Standards

By Karen M. Marks and Walter H.F. Smith, NOAA Laboratory for
Satellite Altimetry, Silver Spring, MD, USA



Abstract

We assess the vertical (depth) and horizontal accuracy of the 2,500m isobath from satellite-derived bathymetry. We find the satellite isobath meets IHO S-44 vertical accuracy standards 90% of the time in areas of smooth topography with good acoustic survey control, but only 31% of the time in a rugged, poorly surveyed area. A horizontal displacement of the satellite isobath with respect to the NGDC Coastal Relief Model offshore of New Jersey, USA, is due to the underlying depths being uncorrected for the velocity of sound in sea-water in the Model and corrected in the satellite-derived bathymetry data.



Résumé

Nous évaluons l'exactitude verticale (profondeur) et horizontale de l'isobathe des 2 500 m à partir de la bathymétrie dérivée par satellite. Nous trouvons que l'isobathe provenant du satellite répond à la norme de précision verticale de la S-44 de l'OHI, dans 90% des cas dans des zones à topographie lisse avec un bon contrôle des levés acoustiques mais, dans 31% des cas seulement, dans une zone rugueuse peu hydrographiée. Un déplacement horizontal de l'isobathe par satellite pour ce qui concerne le modèle de relief côtier du NGDC, au large du New Jersey, USA, est dû au fait que les profondeurs du modèle n'ont pas été corrigées en fonction de la vitesse du son dans l'eau de mer et corrigées dans les données bathymétriques dérivées par satellite.



Resumen

Nosotros valoramos la precisión vertical (profundidad) y horizontal de la isóbata de los 2.500m proveniente de batimetría derivada de satélite. Encontramos que la isóbata proveniente del satélite cumple la norma de precisión vertical de la S-44 de la OHI en un 90% de las veces, en áreas de topografía suave con buen control de levantamiento acústico, pero sólo cumple en un 31% en áreas rugosas pobremente levantadas. Un desplazamiento horizontal de la isóbata satelital con respecto al Modelo de Relieve Costero del NGDC en las afueras de Nueva Jersey, EE.UU de América, se debe a que las profundidades en el Modelo no han sido corregidas por la velocidad del sonido en el agua de mar y corregidas en los datos batimétricos derivados de satélite.

Introduction

Accurately locating the 2,500m isobath is a crucial component of a Coastal State's efforts to lay claim to its Juridical Continental Shelf under Article 76 of the United Nations Convention on the Law of the Sea (UNCLOS; United Nations 1983). The guidelines of the Commission on the Limits of the Continental Shelf (CLCS; United Nations 1999) refer to International Hydrographic Organization (IHO) S-44 standards (IHO 1998) for the expected accuracy in locating the 2,500m isobath in support of a claim. Ideally, one would have modern acoustic surveys with complete coverage in any area where one wanted to assess the potential for a claim. However, only a few percent of the deep ocean floor has been mapped by multibeam surveys. Bathymetry estimated indirectly by satellite (Smith and Sandwell 1994; 1997) can be a valuable tool in helping to locate the 2,500m isobath, but there is a trade-off: although the available satellite coverage is nearly global, it does not achieve the high resolution of state-of-the-art multibeam ship surveys. While satellite-derived bathymetry may be useful for planning traditional acoustic surveys and for preliminary reconnaissance of potential claims under UNCLOS, it remains to be seen whether such bathymetry will be acceptable to the CLCS.

In this paper we assess the vertical (depth) and horizontal accuracy of the 2,500m isobath from satellite-derived bathymetry in light of IHO S-44 standards. We look along the continental slope in the Gulf of Mexico to determine how well the satellite-derived bathymetry field predicts 2,500m depths in a region that has abundant ship sounding control. We also look at a region in the Woodlark Basin, east of Papua New Guinea, that had only sparse constraints from old ship surveys available when the satellite-derived bathymetry estimate was produced. Finally, we investigate a reported horizontal displacement of the 2,500m satellite isobath (Monahan 2004), when compared to the National Geophysical Data Center (NGDC) Coastal Relief Model (NGDC 2004; <http://www.ngdc.noaa.gov/mgg/coastal/coastal.html>) in a region offshore of New Jersey, USA.

Satellite-derived Bathymetry

Smith and Sandwell constructed their first predicted bathymetry grid in 1994, which covered the

southern oceans south of 30°S because satellite data north of 30°S latitude were classified at that time. After the remainder of the satellite data were declassified in 1995, Smith and Sandwell (1997) produced a global (72°N to 72°S) seafloor bathymetry grid. Over the years, as more ship data became available and as modelling techniques were improved, they periodically updated their bathymetric solution.

We use the most recent (November, 2000) version (8.2) of the Smith and Sandwell (1997) global seafloor bathymetry grid in our analysis (available online at http://topex.ucsd.edu/WWW_html/mar_topo.html, file "topo_8.2.img"); hereafter, unless stated otherwise, satellite-derived bathymetry refers to Version 8.2. This product is a two-arc-minute Mercator grid of global seafloor bathymetry that combines ship soundings, where available, with bathymetry interpolated from satellite gravity, where there are gaps. It is possible to determine which grid cells had ship measurements because this information is encoded: an odd grid depth value signifies the cell had ship control, an even depth value signifies it did not. The accuracy of the 2,500m isobath contoured from this grid depends on the number and quality of the ship soundings incorporated, the algorithms and assumptions used to derive bathymetry from satellite gravity, and the resolution that is a function of the grid spacing.

Applying IHO S-44 Standards to Bathymetric Model Isobaths

IHO S-44 distinguishes between hydrographic surveys and bathymetric models. A bathymetric model provides an estimate of depth information over the entire seabed surface interpolated from soundings at discrete points; it may be constructed when an area has not been completely surveyed (IHO 1998; Section 7.4.6). The standard for bathymetric models is in IHO S-44 Table 3; at a model depth of 2,500 metres the 'third order' standard applies, and the 95% confidence level error tolerance is ± 125 m.

In our study, both the satellite-derived bathymetry and the data from multibeam surveys are in the form of gridded models, and we derive 2,500m isobaths from these grids by machine contouring,

using the 'grdcontour' algorithm in GMT (Wessel and Smith 1998). Grdcontour fits piecewise linearly interpolated segments along parallels and meridians connecting the grid points, and then finds the intersection points between contour (isobath) levels and these segments. These points are connected by straight line segments to define the path of the isobath.

To compare an isobath derived from one grid to the model bathymetry in another grid, we take the point sequence defining the isobath and interpolate the other grid at these points using GMT's 'grdtrack' algorithm. We selected the default approach in this algorithm, which interpolates a grid to arbitrary points using piecewise bicubic surface elements as described in Lancaster and Salkauskas (1986; Section 9.3). The result is a point sequence with two depth values at each point: one value, from the first grid, is always 2,500m, while the second, from the other grid, is variable but near 2,500m. From the differences of these two depths along the sequence we construct a histogram, to show what percent of the differences lie within $\pm 125\text{m}$, the IHO S-44 standard. We can apply the above procedure to compare a 2,500m isobath from any gridded bathymetry model to any other gridded model.

In contrast, the method Monahan (2004) used to evaluate the 2,500m isobath is different. He applies a contouring algorithm to both the satellite-derived bathymetry and the reference grids, obtaining two versions of the 2,500m isobath, and he then computes the horizontal distance between these two isobaths at points along each. He uses an estimate of the local slope and applies a formula based on the cosine of that slope to the vertical standard in IHO S-44 and he thereby obtains an estimate of the permissible horizontal misplacement of the 2,500m isobath. The key difference between our method and Monahan's is that we are looking at vertical errors and he is looking at horizontal errors.

Accuracy of the 2,500m Satellite Isobath in a Region of Good Ship Control

We decided to examine the 2,500m isobath in the Gulf of Mexico because it is a region covered by dense ship survey data. Volume 4 of the NGDC

Coastal Relief Model (NGDC 2004), which is constructed from dense single- and multibeam surveys, covers the Texas-Louisiana Shelf, the Central Slope, and much of the Sigsbee Escarpment along which the 2,500m isobath lies (see Figure 1a). There is a good agreement in the location of the satellite isobath (red line in Figure 1a) and the Coastal Relief Model isobath (black line), but the satellite isobath does not quite resolve the sinuous twists that the Coastal Relief Model isobath does; these discrepancies are located mainly in narrow channels. This is expected because the 3-arc-second grid spacing of the Coastal Relief Model can resolve finer-scale topography than the 2-arc-minute grid spacing of the satellite grid.

As described in the previous section, to assess the vertical accuracy, we sampled the Coastal Relief Model depths along the satellite isobath and calculated the differences. The histogram in Figure 1b shows that the depth values are within 125 m of 2,500m 90% of the time. Thus, the satellite isobath very nearly meets the 95% confidence level for bathymetric model depth accuracy set in IHO S-44, in a region where the satellite-derived bathymetry solution incorporated abundant and good survey control.

Accuracy of the 2,500m Satellite Isobath in a Region of Poor Ship Control

We next examined the eastern portion of the Woodlark Basin, east of Papua New Guinea, that had only poor survey control available when Version 8.2 of the satellite-derived bathymetry grid was produced. Subsequently, a high resolution multibeam survey of this area (Goodliffe et al. 1999) was made available to us. By comparing the satellite isobath to a multibeam survey that was not incorporated into the satellite solution, it is possible to assess the accuracy of the satellite isobath in a case where predicted bathymetry dominates. This is typical of most of the ocean's seafloor because, as noted earlier, multibeam surveys cover only a few percent of the deep ocean bottom.

Figure 2a shows an image of the multibeam bathymetry data in the eastern portion of the Woodlark Basin. The red line in Figure 2a is the 2,500m satellite isobath, and the black line is the isobath from the multibeam survey. The satellite isobath is con-

siderably smoother than the multibeam isobath, and some canyons are not mapped by the satellite isobath at all.

We sampled the multibeam depths along the 2,500m satellite isobath, and calculated the differences. A histogram of these depth differences is shown in Figure 2b. In this region, only 31% of the depth differences are within 125m of 2,500m. Further, most of the depth differences range between -250 and 0m, indicating that multibeam depths are

deeper than the satellite-derived depths. This skewness towards negative values can be seen in Figure 2a as places where the 2,500m satellite isobath traverses seafloor that is deeper in the multibeam survey – as an example the satellite isobath crosses the mouths of several canyons rather than following the canyon walls inward.

We attempted to discern why most of the differences are skewed towards negative values; in other words, why are most of the multibeam

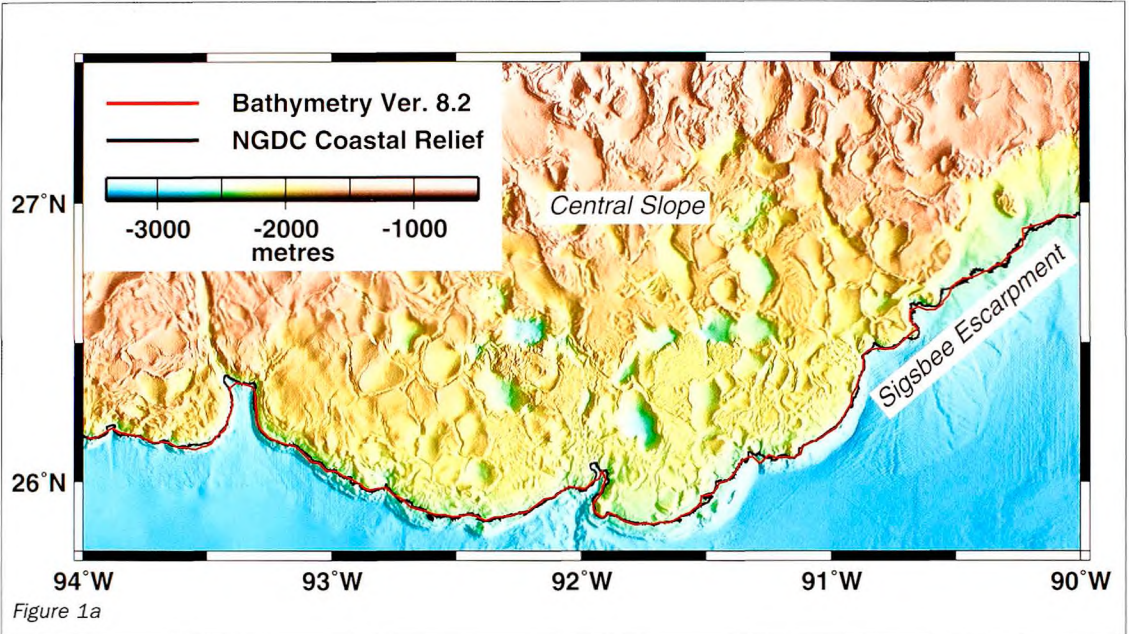


Figure 1a

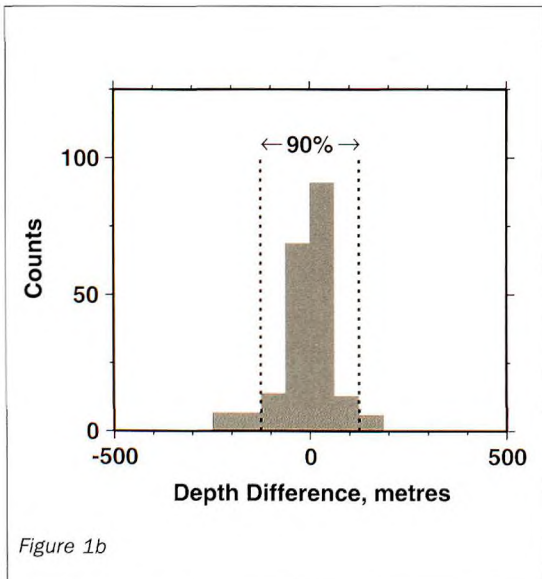


Figure 1b

Figure 1: (a) Colour shaded-relief image of bathymetry from the NGDC Coastal Relief Model (NGDC 2004), over the Central Slope in the Gulf of Mexico, USA. Depths range from 3,500m (blue) to 500 m (orange), and are 'illuminated' from the east. The red line is the 2,500m contour from Smith and Sandwell's Version 8.2 satellite-derived bathymetry grid (http://topex.ucsd.edu/WWW_html/mar_topo.html, file "topo_8.2.img"), the black line is the 2,500m contour from the NGDC Coastal Relief Model (<http://www.ngdc.noaa.gov/mgg/coastal/coastal.html>).

(b) Histogram of depth differences obtained by sampling the Coastal Relief Model along the 2,500m satellite isobath. Dotted lines at ± 125 m denote the 95% confidence level for bathymetric model vertical accuracy set in IHO S-44 (IHO 1998). Depth differences are within IHO S-44 standards 90% of the time.

depths deeper than 2,500m along the satellite isobath? We first compared both corrected and uncorrected depths from NGDC ship tracks in this region to the multibeam depths, and determined that the multibeam depths were properly corrected for the velocity of sound in seawater (Carter 1980), so this cannot account for the skewness.

We then tested whether the 2-arc-minute spacing of the satellite grid limits the resolution necessary for the 2,500m satellite isobath to adequately map the canyons in this rugged region. We averaged the .002 degree Woodlark Basin multibeam grid onto a 2-arc-minute grid and then calculated the depth dif-

ferences along the 2,500m isobath from the averaged grid. The histogram in Figure 3a shows that 78% of the depth differences are within 125m of 2,500m, and the depth values are symmetrically distributed. This indicates that the grid spacing alone cannot account for the skewness of the depth errors observed in Figure 2b.

To determine whether the filter used to predict bathymetry from satellite gravity could contribute to the skewness, we filtered the .002 degree Woodlark Basin multibeam grid with the same filter used by Smith and Sandwell (1994) to produce their satellite-derived bathymetry product. When we

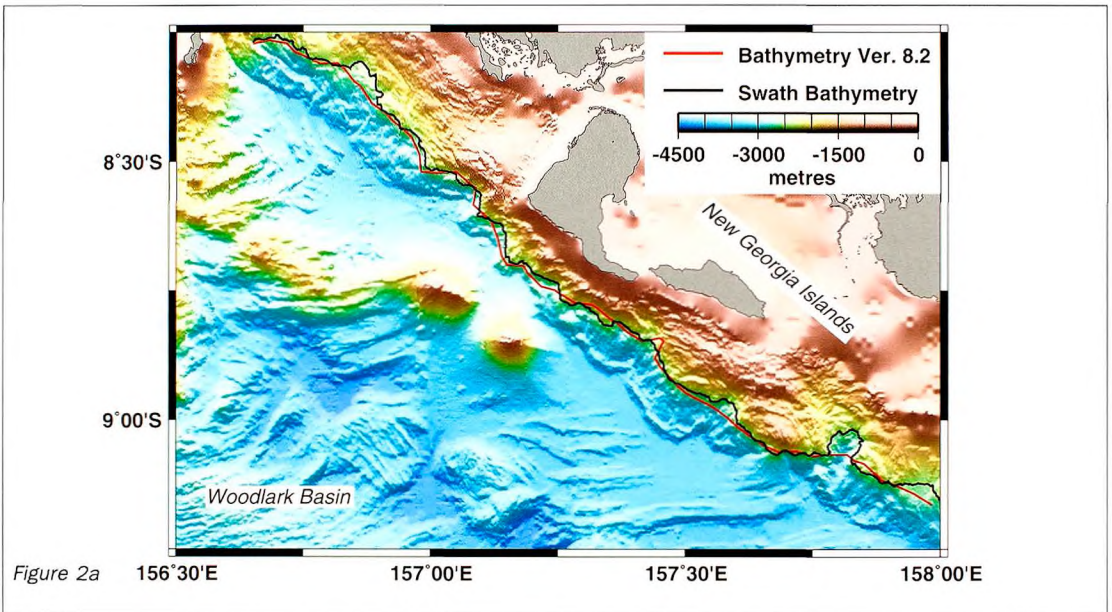


Figure 2: (a) Colour shaded-relief image of multibeam bathymetry (Goodliffe et al. 1999) in the eastern Woodlark Basin, east of Papua New Guinea. Depths range from 4,500 m (blue) to 0m (orange), and are 'illuminated' from the north. The red line is the 2,500m contour from the satellite-derived bathymetry grid, the black line is the 2,500m contour from the Woodlark Basin multibeam bathymetry grid.

(b) Histogram of depth differences obtained by sampling the multibeam grid along the 2,500m satellite isobath. Depth differences are within IHO S-44 standards (dotted lines) 31% of the time, but most are between -250 m and 0m. The multibeam depths are deeper than the 2,500m satellite isobath, particularly across the mouths of canyons.

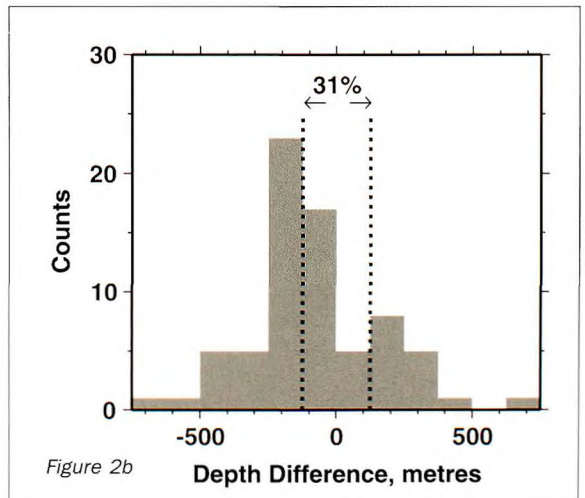


Figure 2b

calculated the depth differences between the 2,500m isobath from the filtered multibeam grid and the original multibeam grid (Figure 3b), we find that 56% of the depth values are within 125m of 2,500m, and they are symmetrically distributed.

Since neither the grid spacing nor filtering accounts for the skewness, we decided to inspect the ship survey data used in this area. We found it was collected by 3.5kHz single-wide-beam (30-degrees) precision depth recorders (analogue) hull-mounted on vessels navigated by dead-reckoning between Transit satellite fixes. Such navigation can be expected to be in error by one nautical mile or so, which could contribute to the observed skewness.

Finally, we considered whether the extreme ruggedness of the seafloor in this region can contribute to the observed skewness. The echo from a single-beam echo sounder will bounce back first from the closest location on the seafloor, which is not necessarily the seafloor directly beneath the ship. If the seafloor has a large slope, a shallower depth can be incorrectly mapped directly beneath the ship rather than off to the side where the echo is actually reflected. If the ship surveys incorporated into the satellite solution contained this error, it could explain why most multibeam depths are deeper along the 2,500m satellite isobath.

Based on our results described above, we think that the poor quality of the ship data in this region that were incorporated into the satellite-derived bathymetry solution are the most likely explanation for the skewness observed in Figure 2b.

A Reported Offset of the 2,500m Isobath Offshore of New Jersey, USA

In Monahan's (2004) study (and in an earlier conference presentation by Monahan and Mayer (1999)), the 2,500m isobath from Smith and Sandwell's Version 6.2 predicted bathymetry grid was plotted against that from the NGDC Coastal Relief Model (NGDC 2004), over a region offshore of New Jersey, USA. Because the Coastal Relief Model was constructed from recent multibeam surveys conducted using good positioning equipment, it was assumed to map the true location of the 2,500m isobath, and the horizontal distance between it and the predicted bathymetry contour

was measured. Monahan observed a systematic, seaward, 2-3km offset of the satellite isobath when compared to the NGDC isobath, but still found it to lie within the horizontal accuracy limits he derived from IHO S-44.

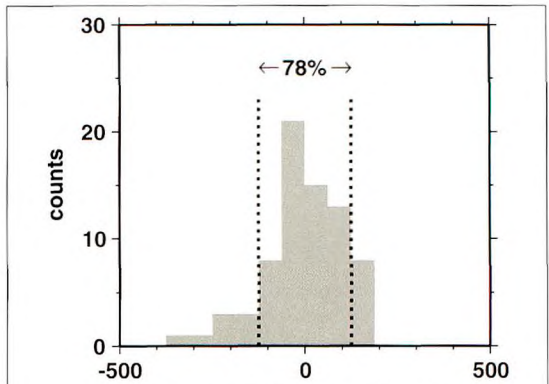


Figure 3a

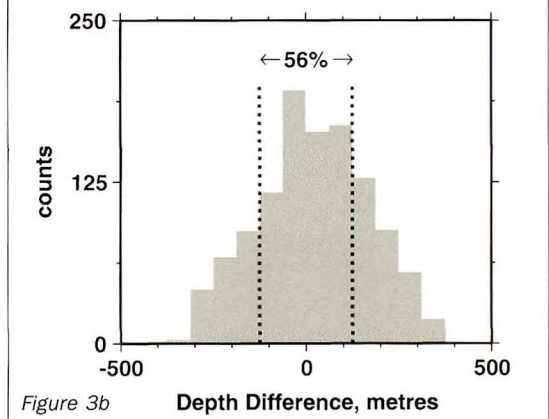


Figure 3b

Figure 3: (a) Histogram of depth differences between the 2,500m contour from the Woodlark Basin multibeam grid averaged to 2-arc-minute grid spacing, and the original .002 degree multibeam grid. Depth differences are within 125m (dotted lines) of 2,500m 78% of the time and are symmetrically distributed, indicating that the grid spacing alone does not account for deeper multibeam depths along the 2,500m satellite isobath seen in Figures 2a and 2b.

(b) Histogram of depth differences between the 2,500m contour from the multibeam grid filtered to pass wavelengths from satellite gravity (see text), and the original .002 degree multibeam grid. Depth differences are within 125m of 2,500m 56% of the time and are symmetrically distributed. Filtering does not account for the deeper multibeam depths either.

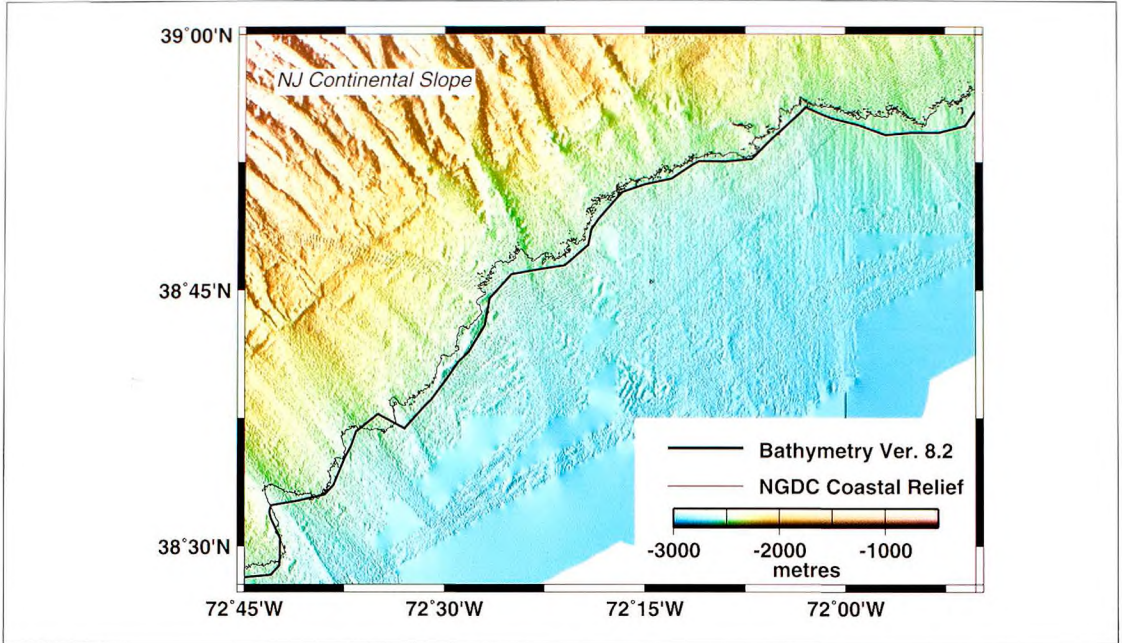


Figure 4: Colour shaded-relief image of bathymetry from the NGDC Coastal Relief Model, over the continental slope offshore of New Jersey (NJ), USA. Depths range from 3,000m (blue) to 500m (orange), and are 'illuminated' from the east. The underlying density of soundings from which the model is constructed is evident as image roughness (high density) or smoothness (low density). The thin, sinuous black line is the 2,500m contour from the NGDC Coastal Relief Model. The thick black line is the 2,500m contour from the satellite-derived bathymetry grid.

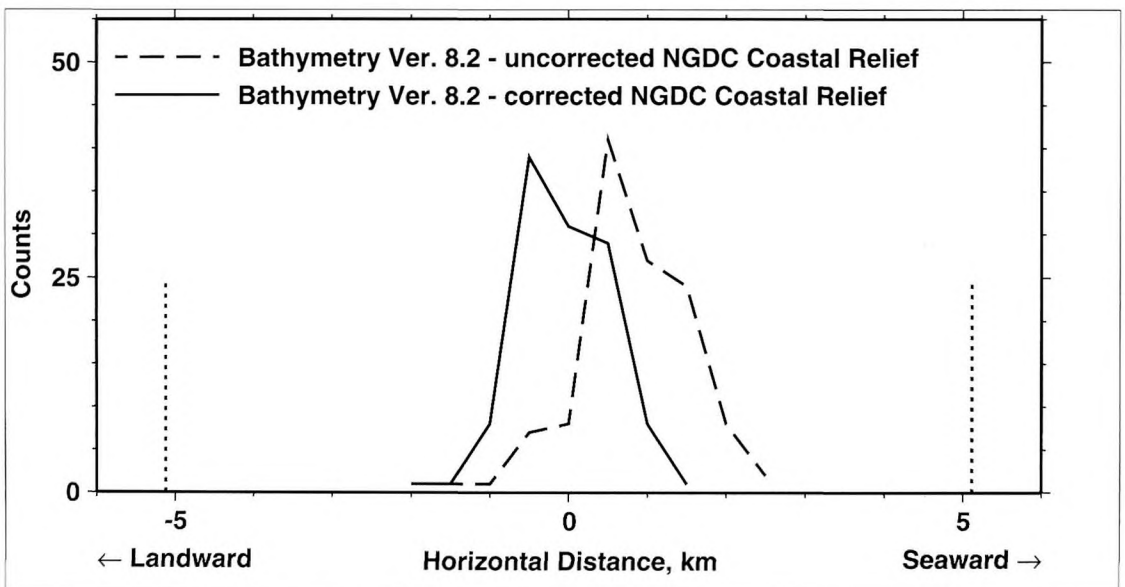


Figure 5: Histogram of horizontal distance between 2,500m contours from satellite-derived bathymetry and the NGDC Coastal Relief Model shown in Figure 4. When the satellite-derived bathymetry position is measured against the uncorrected NGDC Coastal Relief isobath (dashed line), there is a 0.5-1.5km seaward offset. When the location is instead reckoned to the Carter-corrected Coastal Relief Model isobath (solid line), there is no offset. Both histogram curves lie within the IHO S-44 horizontal uncertainty limits (see text) of ± 5.114 km (dotted lines) derived by Monahan (2004).

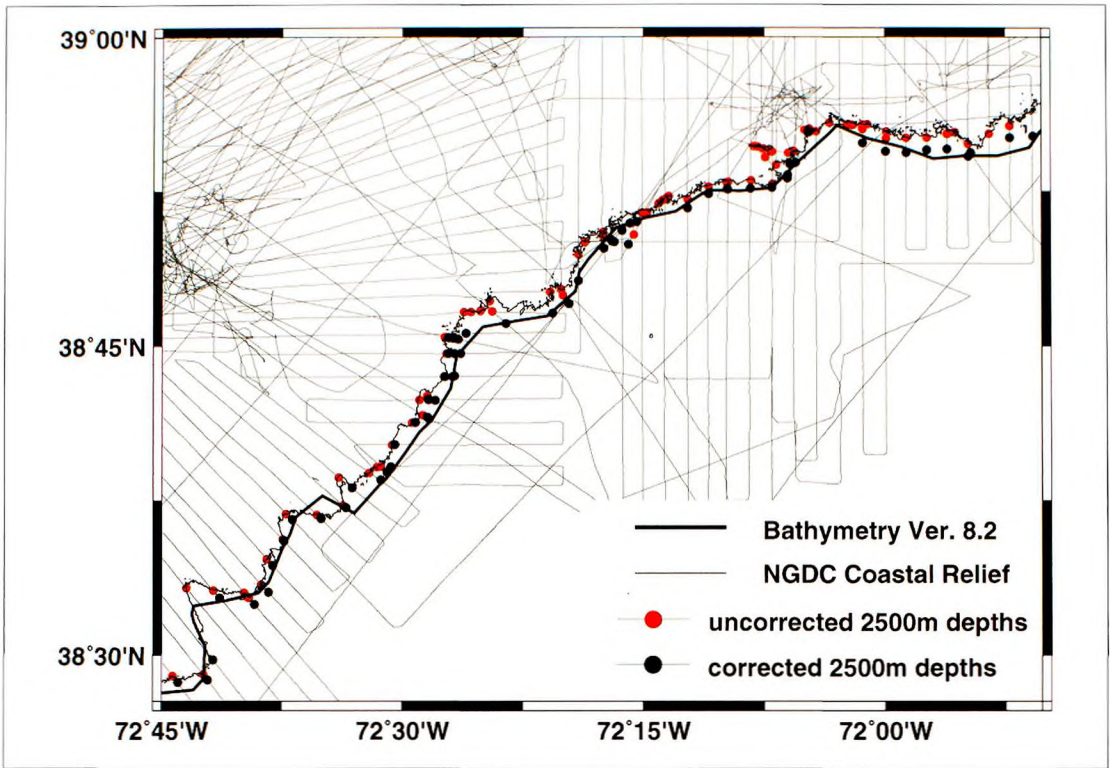


Figure 6: Ship tracks (gray lines) and depths from the NGDC GEODAS Marine Trackline Geophysics database (NGDC 2003). The 2,500m depths corrected for the velocity of sound in water (Carter 1980) (black circles) lie on the 2,500m satellite isobath (thick black line), and uncorrected 2,500m depths (red circles) lie on the NGDC Coastal Relief Model isobath (thin black line). This indicates the NGDC Coastal Relief Model assimilated uncorrected depths in this area, while the satellite-derived bathymetry depicts corrected depths.

In our present investigation of the origin of this offset, we use Version 8.2 of the satellite-derived bathymetry grid. Figure 4 shows a colour-shaded relief image of the NGDC Coastal Relief Model offshore of New Jersey, with 2,500m isobaths from the Coastal Relief Model and from the satellite-derived bathymetry grid. We find the same apparent offset of the satellite isobath that Monahan did.

To quantify the horizontal distance between the two 2,500m isobaths, we first had to smooth the sinusoidal Coastal Relief Model contour. This was accomplished by resampling the 3-second Coastal Relief Model onto a 1-minute grid, and then contouring a 2,500m isobath from that. The smoothed isobath was then sampled at 1km intervals, and the horizontal distances between these points and the satellite isobath were calculated using the Haversine Formula (Sinnott 1984). We were able to automate this process by iteratively searching for the

shortest distance at each point. Figure 5 shows a histogram of the horizontal distances determined (dashed line). The displacement of the peak in the dashed line indicates there is about a 0.5-1.5km seaward offset of the 2,500m satellite isobath from that of the Coastal Relief Model. This result seems to be consistent with the result that is shown in Figure 6 of Monahan (2004).

Origin of the 2,500m Isobath Offset

Our first step in investigating the origin of this offset was to plot 2,500m depths obtained from soundings along ship tracks on top of the isobaths. We used sounding data from the NGDC GEODAS Marine Trackline Geophysics database (accessible on website http://www.ngdc.noaa.gov/mgg/gdas/gd_sys.html and also available on CD-ROM (NGDC 2003)). We downloaded ship bathymetry data covering the study area both with the correction for

velocity of sound in seawater (Carter 1980) applied, and also as uncorrected depths. Both these corrected and uncorrected depths are plotted in Figure 6. The corrected 2,500m depth soundings (black circles) lie along the 2,500m satellite isobath, and the uncorrected depth soundings (red circles) lie on the NGDC Coastal Relief Model 2,500m isobath. This indicates that in this region, the Coastal Relief Model 2,500m isobath follows uncorrected depths, even though the documentation states that the Model is in corrected depths. The 2,500m satellite isobath follows corrected depths. We conclude the 0.5-1.5 km offset between the isobaths in Figures 4 and 5 is due to the underlying data being uncorrected in the NGDC Coastal Relief Model, and corrected in the Smith and Sandwell satellite-derived bathymetry grid.

We examined the underlying ship coverage in more detail and identified R/V *Atlantis II* legs A121 and A124 as comprising almost all of the surveys plotted in Figure 6 (ship tracks are thin gray lines). We suspect that uncorrected R/V *Atlantis II* multibeam data were incorporated into the NGDC Coastal Relief Model, and that these uncorrected data dominate the Coastal Relief Model in this region offshore of New Jersey. Subsequently, the use of uncorrected R/V *Atlantis II* multibeam data was confirmed by John Campagnoli (personal communication, 2005) at NGDC. In our comparisons of the NGDC Coastal Relief Model 2,500m isobath to the Smith and Sandwell isobath in the Gulf of Mexico reported in this paper, and also in other regions including off the USA west coast, we found no offset between the isobaths, indicating they both follow corrected depths in their respective underlying grids. Volume 2 of the NGDC Coastal Relief Model extends from 31°- 40° N. The isobaths are offset to the north offshore of New Jersey, but they match up and there is no offset to the south offshore of North Carolina. This demonstrates an inconsistency in depth corrections in Volume 2 of the Coastal Relief Model.

We made a 'corrected' version of the NGDC Coastal Relief Model by applying Carter's corrections to each depth point in the 3-second grid covering our study area offshore of New Jersey. We used the same procedure described above to calculate the horizontal distances between the 'corrected' NGDC Coastal Relief Model 2,500m isobath and that from the Smith and Sandwell

predicted bathymetry grid. The solid line in Figure 5 shows the histogram of these horizontal distances. The peak is centered on zero, indicating there is no systematic offset between the isobaths. This is because both isobaths follow corrected depths in their underlying grids. For reference, Figure 5 also shows the horizontal accuracy limits for the 2,500m isobath location as reckoned by Monahan (2004) from IHO S-44 standards and the mean slope in the region. Our 'corrected' Coastal Relief Model result only strengthens Monahan's earlier conclusion that the satellite isobath location meets his interpretation of horizontal accuracy implied in the S-44 guidelines.

How Can a Multibeam Survey Be in Uncorrected Metres?

Readers of this journal understand that multibeam swath surveys cannot be made without knowledge of the actual vertical profile of sound velocity in seawater, as this information is required to calculate the refracted path of the slant-ranging (side-looking) sonar beams. One wonders then how it is possible that multibeam survey data could be ingested into a model without correcting the depths for the variable sound speed. We speculate that the answer lies in an accident of history surrounding the use of early SeaBeam swath mapping systems by the North East Consortium for Oceanographic Research (NECOR, an umbrella group of academic institutions in the north eastern United States sharing SeaBeam resources).

The original contract from the U.S. Navy under which SeaBeam was developed required that the system should report nominal depths in uncorrected units, in order that the results could be compared with traditional fathometer readings, which were also uncorrected for sound velocity variations. Thus the system was configured to use the sound velocity profile in internal calculations of slant range refractions but to then 'uncorrect' the true distance units so that they were reported as nominal depths only. On the R/V *Conrad* in the 1980s, it was standard practice to use expendable bathythermographs (XBTs) to obtain a sound velocity profile and to enter this into the SeaBeam computer; however, when the depths were reported out of the system, they came as 'uncorrected depths', meaning two-way vertical travel time to the bottom

scaled by 750 metres per second. R/V *Conrad* was operated by the Lamont Geological Observatory but the SeaBeam data from R/V *Conrad* were processed at a NECOR facility at the University of Rhode Island. We suppose that a similar practice was used for the *Atlantis II* data which caused the confusion identified in this paper.

It should be noted that the sense of the displacement (landward or seaward) of an isobath caused by a sound velocity error depends on the prevailing acoustic conditions in the water column. Inspection of the sound velocity correction tables (Carter 1980) shows that the sense of displacement of the 2,500m isobath changes sign as one crosses the Gulf Stream, for example.

Summary

We have shown how well satellite-derived bathymetry can map the 2,500m isobath in two disparate areas – one where the satellite solution incorporated abundant, good control data, the other where the control data were sparse and poor and predictions from satellite gravity dominate. In the former area the satellite isobath very nearly meets the 95% confidence level for bathymetric model depth accuracy set in IHO S-44, and in the latter it meets the requirements 31% of the time. Because Smith and Sandwell constrain the satellite-derived bathymetry solution to agree with acoustic sounding control data wherever such data are available, it is no surprise that their product performs best where detailed ship data are publicly available. In the case where seafloor topography is rough and control data are poor and sparse, the satellite-derived bathymetry field may still perform well enough to be used for reconnaissance purposes, though it will not meet IHO standard S-44.

We investigated the apparent seaward offset between 2,500m isobaths derived from the NGDC Coastal Relief Model (NGDC 2004) and the Smith and Sandwell (1997) predicted bathymetry grid offshore of New Jersey, USA, that was reported by Monahan (2004). We determined that this offset is due to the incorporation of uncorrected depths into the NGDC Coastal Relief Model in this vicinity. When an isobath from uncorrected data (the NGDC model) is compared to an isobath from corrected data (satellite-derived bathymetry), there will be an offset. We found that uncorrected depths from R/V

Atlantis II legs A121 and A124 were inadvertently incorporated into the NGDC Coastal Relief Model.

Acknowledgements

David Monahan and Hans-Werner Schenke provided helpful reviews. We thank Larry Mayer and John Campagnoli for helpful discussions, and David Monahan as well. We thank Andrew Goodliffe for kindly providing us with multibeam data in the Woodlark Basin. Graphics and analyses were created using the Generic Mapping Tools (GMT) software package (Wessel and Smith 1998). GMT is available on the internet at <http://gmt.soest.hawaii.edu>. The views, opinions, and findings contained in this report are those of the authors and should not be construed as an official National Oceanic and Atmospheric Administration or U.S. Government position, policy, or decision.

References

- Carter, D. J. T. (1980). *Echo-Sounding Correction Tables*. (3rd Ed.) Hydrographic Department, Ministry of Defense, Taunton, United Kingdom
- Goodliffe, J. A., Taylor, B., and Martinez, F. (1999). Data Report: Marine geophysical surveys of the Woodlark Basin Region. In: Taylor, B., Huchon, P., Klaus, A. et al., Proc. ODP, Init. Repts., 180, 1-20 [CD-ROM]. Available from: Ocean Drilling Program, Texas A&M University, College Station, TX, 77845-9547, USA
- International Hydrographic Organization (1998). IHO Standards for Hydrographic Surveys: Special Publication, 44, International Hydrographic Bureau, Monaco, 26pp
- Lancaster, P., and Salkauskas, K. (1986). *Curve and Surface Fitting: An Introduction*, Academic Press, London, 280 pp
- Monahan, D. (2004). Altimetry applications to continental shelf delineation under the United Nations Convention on the Law of the Sea, *Oceanography*, 17, 75-82
- Monahan, D., and Mayer, L. A. (1999). An examination of publicly available bathymetry data sets using digital mapping tools to determine their applicability to Article 76 of UNCLOS. In: Proceedings of the International Conference on Technical Aspects of Mar-

itime Boundary Delineation and Delimitation, International Hydrographic Bureau, Monaco, 183-190

National Geophysical Data Center. (2004). Coastal Relief Model CD-ROMs/DVD-ROM, Data Announce. 04-MGG-01, U.S. Dept. of Commerce, Natl. Oceanic and Atmos. Admin., Boulder, CO, USA

National Geophysical Data Center. (2003). Worldwide Marine Geophysical Data, version 4.1.18 (Geodas CD-ROM), Data Announce. 2003-MGG-02, U.S. Dept. of Commerce, Natl. Oceanic and Atmos. Admin., Boulder, CO, USA

Sinnott, R. W. (1984). Virtues of Haversine. *Sky and Telescope*, 68, 159

Smith, W. H. F., and Sandwell, D. T. (1994). Bathymetric prediction from dense satellite altimetry and sparse shipboard bathymetry. *J. Geophys. Res.*, 99, 21,803-21,824

Smith, W. H. F., and Sandwell, D. T. (1997). Global sea floor topography from satellite altimetry and ship depth soundings. *Science*, 277, 1,956-1,962

United Nations. (1983). The Law of the Sea: United Nations Convention on the Law of the Sea, with Index and Final Act of the Third United Nations Convention on the Law of the Sea, UN Publication Sale No. E.93., V.16

United Nations (1999). Scientific and technical guidelines of the Commission on the Limits of the Continental Shelf, CLCS11, United Nations, 91 p

Wessel, P., and Smith, W. H. F. (1998). New, improved version of Generic Mapping Tools released, *EOS Trans. Amer. Geophys. U.* 79, 579

Biography of the Authors

Karen Marks has worked as a Geophysicist since 1990 at the NOAA Laboratory for Satellite Altimetry

of the U.S. National Oceanic and Atmospheric Administration in Silver Spring, Maryland, USA. Prior she worked on altimetry precision at The Analytic Sciences Corporation (TASC). She received a B.S. in Geology from the University of Florida, an M.S. in Geophysics from Boston College, and a Ph.D. in Geophysics from the University of Houston, with a dissertation on the geophysics of the Australian-Antarctic Discordance Zone. Her current research includes evaluating bathymetric datasets for United Nations Law of the Sea applications. Her research also encompasses marine tectonic and geodynamic applications of satellite altimetry with emphasis on plate tectonic histories and seafloor spreading. She advises the General Bathymetric Charts of the Oceans (GEBCO) Working Group on the Integration of Geoscience Data.

Walter H.F. Smith earned a B.Sc. at the University of Southern California in 1984, after which he attended a summer school at the French national space agency in Toulouse on the applications of satellites to solid-Earth geophysics. Following that he was a research assistant in the Gravity Department of the Lamont-Doherty Geological Observatory of Columbia University in New York, where he received his M.A. in 1986 and Ph.D. in 1990, with a thesis on the geophysics of seamounts in the Pacific Ocean basin. From 1990 to 1992 he was a Green Scholar at the Institute for Geophysics and Planetary Physics of the Scripps Institution of Oceanography at the University of California, San Diego. Since 1992 he has been a Geophysicist in the Laboratory for Satellite Altimetry of the U.S. National Oceanic and Atmospheric Administration in Silver Spring, Maryland, USA. Smith is the co-developer of the Generic Mapping Tools (GMT) software, and has taught Data Analysis and Inverse Theory at the Johns Hopkins University in Baltimore. Since 1993 he has advised the committee for the General Bathymetric Charts of the Oceans (GEBCO), which he now serves by chairing its Subcommittee on Digital Bathymetry.

E-mail: karen.marks@noaa.gov