

Global Shallow-Water Bathymetry From Satellite Ocean Color Data

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Knowledge of ocean bathymetry is important, not only for navigation but also for scientific studies of the ocean's volume, ecology, and circulation, all of which are related to Earth's climate. In coastal regions, moreover, detailed bathymetric maps are critical for storm surge modeling, marine power plant planning, understanding of ecosystem connectivity, coastal management, and change analyses. Because ocean areas are enormously large and ship surveys have limited coverage, adequate bathymetric data are still lacking throughout the global ocean.

Satellite altimetry can produce reasonable estimates of bathymetry for the deep ocean [Sandwell *et al.*, 2003, 2006], but the spatial resolution is very coarse (~6–9 kilometers) and can be highly inaccurate in shallow waters, where gravitational effects are small. For example, depths retrieved from the widely used ETOPO2 bathymetry database (the National Geophysical Data Center's 2-minute global relief data; <http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html>) for the Great Bahama Bank (Figure 1a) are seriously in error when compared with ship surveys [Dierssen *et al.*, 2009] (see Figure 1b). No statistical correlation was found between the

two bathymetry measurements, and the root-mean-square error of ETOPO2 bathymetry was as high as 208 meters. Yet determining a higher-spatial-resolution (e.g., 300-meter) bathymetry of this region with ship surveys would require about 4 years of nonstop effort.

Clearly, alternative methods are needed for estimating bathymetry in shallow coastal regions. A rapid and relatively robust method may be found through a new way of looking at satellite measurements of ocean color. This takes advantage of the fact that photons hitting the shallow ocean bottom and reflecting back to the surface modify the appearance of ocean color.

Retrieving Depth From Analyzing Spectral Data

It is well known that measurements of water color could help define bathymetry in

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shallow regions [Lyzenga, 1981; Polcyn *et al.*, 1970]. Earlier methods to estimate bathymetry from ocean color, however, were limited to approaches [Lyzenga, 1981; Polcyn *et al.*, 1970; Philpot, 1989] that require a few known depths to develop an empirical relationship, which then allows researchers to convert multiband color images to a bathymetric map. The resulting empirical relationships are generally sensor and site specific [Dierssen *et al.*, 2003; Stumpf *et al.*, 2003] and not transferable to other images or areas. Further, the approach is not applicable for regions difficult to reach, due to lack of in situ calibration data.

To overcome such a limitation, a physics-based approach, called hyperspectral optimization process exemplar (HOPE), has been developed [Lee *et al.*, 1999]. Basically, the spectral reflectance (R_{rs} , the ratio of water-leaving radiance to downwelling irradiance hitting the sea surface) is modeled as a function of five independent variables that include bottom depth. In a fashion similar to other spectral optimization schemes [e.g., Doerffer and Fischer, 1994; Klonowski *et al.*, 2007; Brando *et al.*, 2009], HOPE derives bottom depth by iteratively varying the values of the five unknowns until the modeled R_{rs} best matches the measured R_{rs} .

Unlike the empirical approaches used for retrieving depth from water color [Lyzenga, 1981; Stumpf *et al.*, 2003], the only required inputs for HOPE are the spectral reflectance data obtained from a remote sensor, thus eliminating the need for image-specific or region-specific algorithm tuning.

Application of the New Method

The HOPE method was applied to ocean color images of the Great Bahama Bank collected by the Medium-Resolution Imaging Spectrometer (MERIS) operated by the European Space Agency (ESA). The data collected 14 December 2004 by MERIS were fed to HOPE to derive properties of the water column and bottom. The derived bottom depth (no tidal correction is presented in Figure 1c) shows a range of about 1–10 meters across the main portions of the banks and a maximum depth of about 20 meters at the bank edges.

MERIS-derived depths were compared with ship surveys [Dierssen *et al.*, 2009], and it was found that the two data sets were highly statistically correlated, with a root-mean-square error of MERIS-derived bathymetry of about 3.4 meters (Figure 1d). Note that the errors factor in the ambiguity that results from differences in the spatial scale of the relative measurements (300 meters for MERIS and ~10 meters for ship) and the spatial heterogeneity in bathymetry over those scales.

Results from another MERIS measurement (6 September 2008) show similar accuracy (see Figure 1d), indicating that this approach is robust and repeatable. Although the error of around 3 meters cautions against the use of these data for navigation, the retrieved

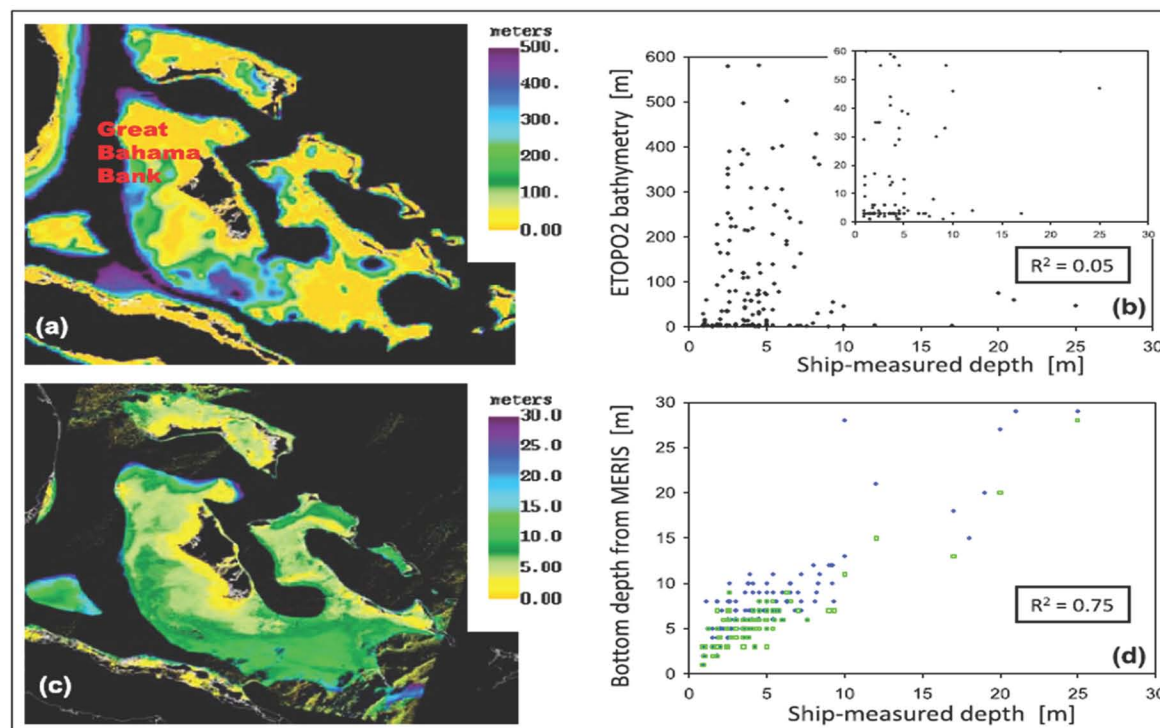


Fig. 1. (a) Depth of the Great Bahama Bank retrieved from the ETOPO2 bathymetry database. (b) Scatterplot between in situ depth and ETOPO2 bathymetry of matching locations (inset shows ETOPO2 bathymetry under 60 meters). (c) Bottom depth derived from Medium-Resolution Imaging Spectrometer (MERIS) measurements (14 December 2004) by the hyperspectral optimization process exemplar (HOPE) approach. (d) Like Figure 1b, a scatterplot between in situ depth and MERIS depths (rounded to nearest integer to match ETOPO2 format; blue indicates 14 December 2004, green indicates 6 September 2008). The coefficient of determination (R^2) represents all data points (281) in the plot. Note the color scale difference in Figures 1a and 1c. Black pixels represent land or deep waters.

bathymetry is substantially more reliable than that presented in ETOPO2.

Toward More Accurate Global Assessment of Shallow Waters

Because polar-orbiting sensors like MERIS and Moderate Resolution Imaging Spectroradiometer (MODIS) make measurements globally and near daily with a spatial resolution of hundreds of meters, the proof of concept seen through comparing remote sensing retrievals with ship surveys around the Great Bahama Bank demonstrates the great potential in deriving global, higher-resolution, shallow-water bathymetry from ocean color satellites. Such retrievals can complement information gained from surveys and altimetry results. Merging such data products with other bathymetry sources will provide unprecedentedly valuable information to scientists, commercial entities, coastal managers, and decision makers. To reach this highly desired goal, however, would require dedicated efforts to improve and mature algorithms for processing optically shallow waters from current and future ocean color satellite measurements.

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