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14. ABSTRACT
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.

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A New Approach for Exploring Ice Sheets and Sub-Ice Geology

Active seismic measurements were an important part of geophysical traverses on the Antarctic ice sheet as far back as the 1920s. These methods lost their leading role for ice thickness measurements to much faster ground-based and airborne radar surveys because of the considerable logistical effort necessary for seismic data acquisition. However, new achievements with a vibrator source in active seismics (vibroseis for short) could open new prospects and foster future geological and glaciological surveys in Antarctica and Greenland and on ice caps and glaciers.

Active seismic methods have the unique ability to image sub-ice geology and remotely obtain its physical properties. Friction at the basal interface of an ice sheet plays a pivotal role in controlling ice dynamics and is largely determined by the presence of water and/or sediments underneath the ice. High-quality seismic reflection measurements came in demand as scientific interest in the dynamics of ice streams (e.g., West Antarctic ice streams) increased and as site surveys were needed for optimum sampling of sub-ice sediments for paleoclimate studies (e.g., Cape Roberts Project, Antarctic Geological Drilling (ANDRILL)). Nevertheless, the available literature demonstrates that seismic studies on ice sheets are not widespread and are only carried out on small, local scales over a few tens of kilometers. Prominent examples of such seismic studies are the observation of transient processes in bed geology driven by ice flow [*Smith et al.*, 2007] and the long record of seismic exploration of subglacial lake environments, for example, around Lake Vostok and more recently around subglacial Lake Ellsworth. Seismic properties of the ice sheets remain only an occasional topic [*Horgan et al.*, 2008], often complementary to radar.

The Firn-Layer Problem

The upper tens of meters of an ice sheet consist of a highly porous layer of firn (snow that is more than 1 year old), which acts as an acoustic waveguide, or trap, making the excitation of seismic waves from a surface source difficult. Soft firn causes large inelastic energy losses for impulsive sources. During most seismic surveys in Antarctica, researchers have used explosives in 10- to 20-meter-deep boreholes to overcome signal attenuation caused by the steep velocity gradient in the surface layer between soft firn and harder ice. The boreholes are drilled by different techniques, requiring considerable time and energy for each hole. With the seismic source below the surface, surface ghost reflections are commonly present in the data. Despite these difficulties, explosives sources in shallow boreholes are still the simplest way to obtain acceptable data quality. Even with this approach, involving minimal efforts, the necessary logistical requirements have discouraged the acquisition of longer seismic profiles, for example, as part of overland traverses.

The Vibroseis Surface Source

During the 2009–2010 Antarctic field season the Linking Micro-Physical Properties to Macro Features in Ice Sheets With Geophysical Techniques (LIMPICS) project aimed to make seismic vibrator measurements for the first time in Antarctica [*Kristoffersen et al.*, 2010]. In contrast to an impulsive surface source of millisecond duration, a controlled vibrator source emits energy as a finite-amplitude pressure pulse over many seconds. Energy losses by inelastic behavior are thus much less because of reduced ground pressure.

The project used a truck-mounted Failing Y-1100 vibrator (peak actuator force equivalent to 12 tons) on skis towed by a Pisten Bully snowcat on the floating Ekström Ice Shelf near the German research station Neumayer III. Sweeps of 10-second duration with a linear increase in frequency over the range of 10–100 hertz were compared to shots of 300-gram explosive charge fired in 10-meter-deep boreholes (Figure 1). Both types of data were recorded with a snow streamer (i.e., geophones towed on a cable across the snow surface), and the data show the primary reflection from the ice-water interface, its multiples, and the reflections from and within the seafloor. The explosives source is clearly rich in higher frequencies (up to 300 hertz), while the energy in the vibroseis record is limited to the sweep frequencies. The vibrator excites slightly more surface waves than the explosive charge, but the total energy level is higher relative to an explosive charge at 10-meter depth. Identifiable reflections are present over a two-way travel time of more than 2 seconds.

With the current vibroseis–snow streamer setup, seismic data production is about 10 kilometers per day for single-fold coverage, with peak production rates up to 3 kilometers per hour. Optimization should enable a doubling of the production rate to 20 kilometers per day even for multifold coverage, comparable to onshore vibroseis surveys. Surface properties do not impose a problem, as the vibrator pad (2.5 square meters) generally sank no more than a total of 10–20 centimeters in dry snow after three consecutive sweeps.

Future Prospects

A vibrator has the advantage of being a known and repeatable source signal and

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Global Shallow-Water Bathymetry From Satellite Ocean Color Data

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 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.

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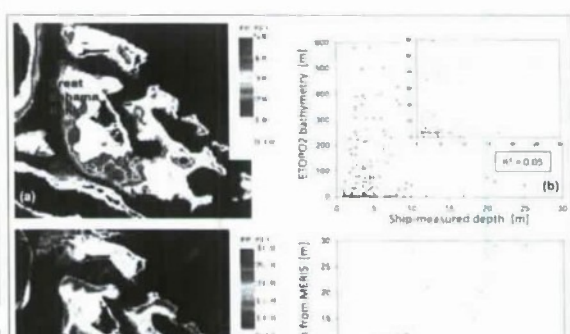

Fig. 1. (a) Depth of the Great Bahama Bank retrieved from the ETOPO2 bathymetry database. (b) Scatterplot between in situ depth and ETOPO2 bathymetry of matching locations (inset shows ETOPO2 bathymetry under 60 meters). (c) Bottom depth derived from Medium Resolution Imaging Spectrometer (MERIS) measurements (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.

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also of having reduced logistics costs, higher production rates, and less impact on the environment than explosives. Further investigations should address appropriate selection of vibrator size (commercially available vibrators range from 50 kilograms to more than 10 tons) for a trade-off between resolution and penetration depth depending on target objectives and the applicability of vibrator types (inducing shear or pressure waves) to sophisticated analysis methods such as amplitude variation with offset. Logistical limitations require improved implementations such as mounting a vibrator directly on a sled (instead of on a truck on skis) and modular systems for deployment with smaller airplanes.

The vibroseis–snow streamer configuration used presents a tool suitable for traverses of several hundred kilometers and thus for target-oriented surveys for specific objectives such as (1) exploring the subice sediment structure suitable for sampling by scientific drilling and analysis for climate information; (2) investigating the physical properties of the ice-bedrock interface; (3) exploring grounding line processes like internal basal ice structures and water-routing systems; (4) conducting surveys of subglacial lake settings, especially water depth and sediment information; (5) complementing radar in exploring the physical properties of the lower part of the ice sheet; and (6) tying together offshore and onshore seismic data for geological interpretations.

Photos of the vibrator truck and the measurement setup are available in the online supplement to this *Eos* issue (http://www.agu.org/eos_elec/).

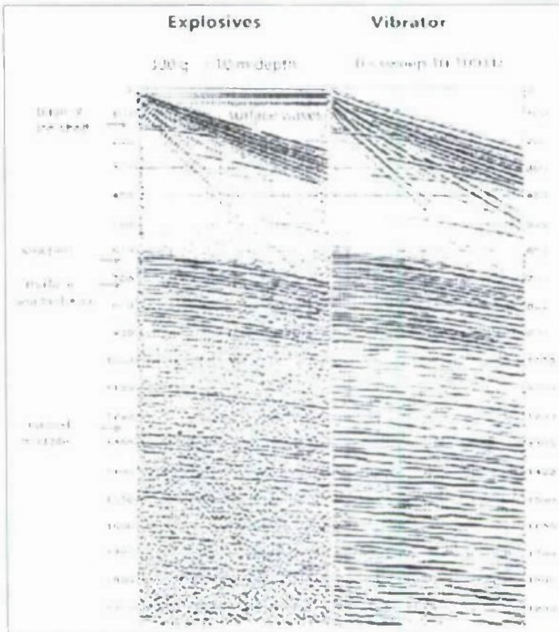

Fig. 1. Comparison of shot gathers sampled at 1-millisecond intervals. Signals recorded on 60 geophone channels over a distance of 725 meters along the streamer from the explosives source are shown at left, and signals from the vibrator source are shown at right. Vertical axes indicate two-way travel time, in milliseconds. The origin of several reflection signals is indicated.

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Bathymetry

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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 1.1 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 2 meters cautions against the use of these data for navigation, the retrieved 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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