FINAL REPORT
Improvement of Predicted Bathymetry for Naval Operations and Scientific Applications

David T. Sandwell
University of California, San Diego
Scripps Institution of Oceanography, IGPP
9500 Gilman Drive, Dept. 0225
La Jolla, CA 92093-0225

phone: (858) 534-1709 fax: (885) 534-2902 email: dsandwell@ucsd.edu

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LONG-TERM GOALS

(1) Improve global bathymetric charts and provide uncertainties on predicted depths.
(2) Assemble and edit all unclassified depth soundings.
(3) Prepare the next generation of scientists for ocean research.

OBJECTIVES

Our primary objective is to improve bathymetric charts of the global oceans using a combination of ship soundings and satellite-derived gravity anomalies. More importantly, we plan to assign depth uncertainties to our global charts. These charts will serve as cautionary overlays for navigation, and will have numerous other scientific and practical applications. This work is performed in collaboration with the National Geospatial Agency (NGA), the Naval Meteorology and Oceanography Command (METOC, NAVO), and the National Oceanic and Atmospheric Administration (NOAA). Our role at SIO is to: 1) retrack all radar altimetry data for gravity field improvement; 2) edit/rescue bathymetry data from 5700 archive cruises; 3) construct a 1 minute global bathymetry grid for delivery to the parties of the MOU; and 4) perform scientific studies with the improved data

APPROACH

Task 1. - Improved gravity from satellite altimetry (Year 1, complete) - This 3-year effort was funded by National Science Foundation, NASA, ConocoPhillips, and ExxonMobil. Work was performed by David Sandwell and Walter Smith (NOAA). This involved retracking all of the raw radar altimeter waveforms from the ERS-1 and Geosat altimeters and constructing a new global marine gravity model. Before this effort, the satellite-derived gravity models had accuracies of 4-7 mGal in comparison with shipboard profiles [*Sandwell and Smith*, 1997]. The new models have accuracies of better than 3 mGal. This accuracy was confirmed through a blind test in March of 2006. Using proprietary data, Marcia Maia at IFREMER [Maia, 2006] performed a blind test of the accuracy and resolution of our gravity model (V16) as well as a competing model KMS20 [*Anderson and Knudsen*, 1997]. The results can be found at: http://earth.esa.int/cgi-bin/confalt15y.pl?abstract=1204

Task 2. - Cleanup of unclassified ship soundings (Years 1, 2, and 3) - We are evaluating and editing bathymetry profiles from nearly 5700 cruises of archive ship data; approximately 1800 of these cruise data were not used in our previous global bathymetric grids because they failed statistical tests. These data come from a variety of sources including: 4900 cruises from the National Geophysical Data Center (NGDC); about 500 cruises from the SIO and Lamont archives; and 104 cruises from IFREMER. This data cleanup effort involves: 1) hand editing of the soundings in the 5700 cruises to flag bad data; 2) separating the cruise data into well-navigated and poorly-navigated groups; and 3) constructing trial bathymetry grids to identify additional outliers. The initial editing was performed by Scott Nelson (UCSD undergraduate student) under the supervision of Joseph Becker (graduate student) and David Sandwell. Scott Nelson graduated from UCSD in September of 2006 and we found two replacement students to continue the editing effort. Seung-Hee Kim is a junior UCSD physics major who as worked for the past year as a volunteer while he waits for his work permit so we can hire him. He began his paid employment October 1, 2007. Breanna Binder, a senior UCSD physics major, was hired in August of 2007. Both are editing data as well as using the results as student research projects.

Task 3. - Construct new global bathymetry at 1 minute resolution (Years 2 and 3) - This task is being performed in collaboration with NOAA, METOC, and NGA. Here we are using the 1 minute gravity grid from Task 1 and all available edited soundings to develop the regional variations in topography/gravity transfer function that are used to map band-pass filtered gravity into bathymetry [*Smith and Sandwell*, 1994]. Two topography/gravity transfer functions will be developed - one based only on unclassified soundings will be used for development of trial global grids and scientific studies. The second transfer function will be developed at NOAA, NGA and METOC and will utilize classified soundings (not an SIO task). This predicted-depth grid will ultimately become the cautionary overlay for NGA's navigational charts. In addition to constructing predicted bathymetry, the grids will be "polished" to agree with trusted soundings and reformatted into the more widely used SRTM30 format. This work will be performed by David Sandwell, Walter Smith (NOAA), and Joseph Becker.

Task 4. - Scientific analysis: Seamounts, detailed tectonics, and seafloor roughness (Years 2, and 3) - We are using the trial grids and edited trackline data for a variety of scientific analyses. In addition to improving our scientific understanding of the deep oceans, these analyses provide important feedback on data quality. Graduate student (Joseph Becker) is examining seafloor roughness along trackline data and study gravity topography ratios at seamounts and spreading ridges. Karen Luttrell is using topographic loads to investigate 3-D stress fields around volcanic features and relate the stress to tectonic processes. Part of the support for this scientific work is funded by NASA.

WORK COMPLETED - FINAL

Task 1. - Improved gravity from satellite altimetry - This task is complete [*Sandwell and Smith*, 2009].

Task 2. - Cleanup of unclassified ship soundings – This task is complete. The final set of raw ship soundings was distributed to the partners of the MOA on December 29, 2008. See attached Letter *Appendix A*.

Task 3. - Construct new global bathymetry at 1 minute resolution – This task was completed on September 16, 2008. We completed the construction of two global bathymetry grids. They are publically available for ftp at the following ftp sites (Figure 1).

(1) Global bathymetry:
topo_11.1.img - ftp://topex.ucsd.edu/pub/global_topo_1min
One minute global bathymetric prediction between latitudes of +/-81 degrees in a spherical Mercator grid format. This format has roughly square cells, which are needed for the Fourier analyses of the grids.

SRTM30_PLUS V5.0 - ftp://topex.ucsd.edu/pub/srtm30_plus
Thirty arc second global data set was constructed and distributed in the SRTM30 grid format that divides the Earth into 33 areas. There are 33 matching files containing the source identification number of the data in each grid cell.

(2) Uncertainty Grid:
This task was not completed. NAVO did not provide information on the uncertainties in the global grid based on a comparison with their classified soundings.

(3) Raw data exchange: This task was completed and all the raw data were sent to the partners of the MOA (See *Appendix A*). Our working group has agreed on raw data exchange format(s) that will include both vertical and horizontal sounding uncertainties.

Task 4. - Scientific analysis: Seamounts, detailed tectonics, and seafloor roughness (Years 2, and 3) - Becker and Sandwell have published a paper in JGR oceans on Global Estimates of Seafloor Slope from Single-Beam Ship Soundings [*Becker and Sandwell*, 2008].

RESULTS

Results achieved during the four years of the effort can be summarized as follows:
FY06
- We have completed the construction of a marine gravity field based on re-tracked waveforms of ERS-1 and Geosat radar altimeter data. These data cover all ocean areas between latitudes of +/-81 degrees. A blind test performed by IFREMER shows the accuracy of this field is generally better than 3 mGal and the ½ wavelength resolution is as short as 8 km.
- We have completed the hand editing of the 4900 cruises of single-beam soundings from the NGDC data base and are gathering and assessing all other publicly-available soundings.

FY07
- We have formed a working team of scientists from NOAA, NAVO, NGA, and SIO to construct global bathymetric grids at 1 minute and 30-arc second resolution. In addition, we are devising methods to construct a companion uncertainty grid. This group holds bi-monthly teleconferences and had a meeting at SIO in February of 2007 to review the first draft of the grids.
- Joseph Becker (graduate student) is using the edited sounding data to prepare a Ph.D. thesis on the deep ocean mixing produced by tidal flow over rugged abyssal hill topography. A first paper on the fraction of seafloor having slope exceeding the critical slope needed to generate internal waves has been sent for review at *Journal of Geophysical Research*.
- We have completed a draft version of the global grid at 1 minute resolution. This version includes globally dense shallow water (< 300 m) soundings provided by the NGA. These new data have dramatically improved the accuracy of our global grids in the 0-300 m depth range.

FY08-09

- We finished the assembly and editing of the raw ship soundings and distributed the data to the partners of the MOA.
- We constructed a new global 1-minute gravity anomaly model based on retracked Geosat and ERS-1 altimeter data. This model uses EGM2008 as a reference.
- We completed and distributed a final 1-minute global bathymetry grid (V11.1).
- We completed and distributed a final 30-arc second global bathymetry grid (5.0). This effort is published in Marine Geodesy [*Becker et al.*, 2009]

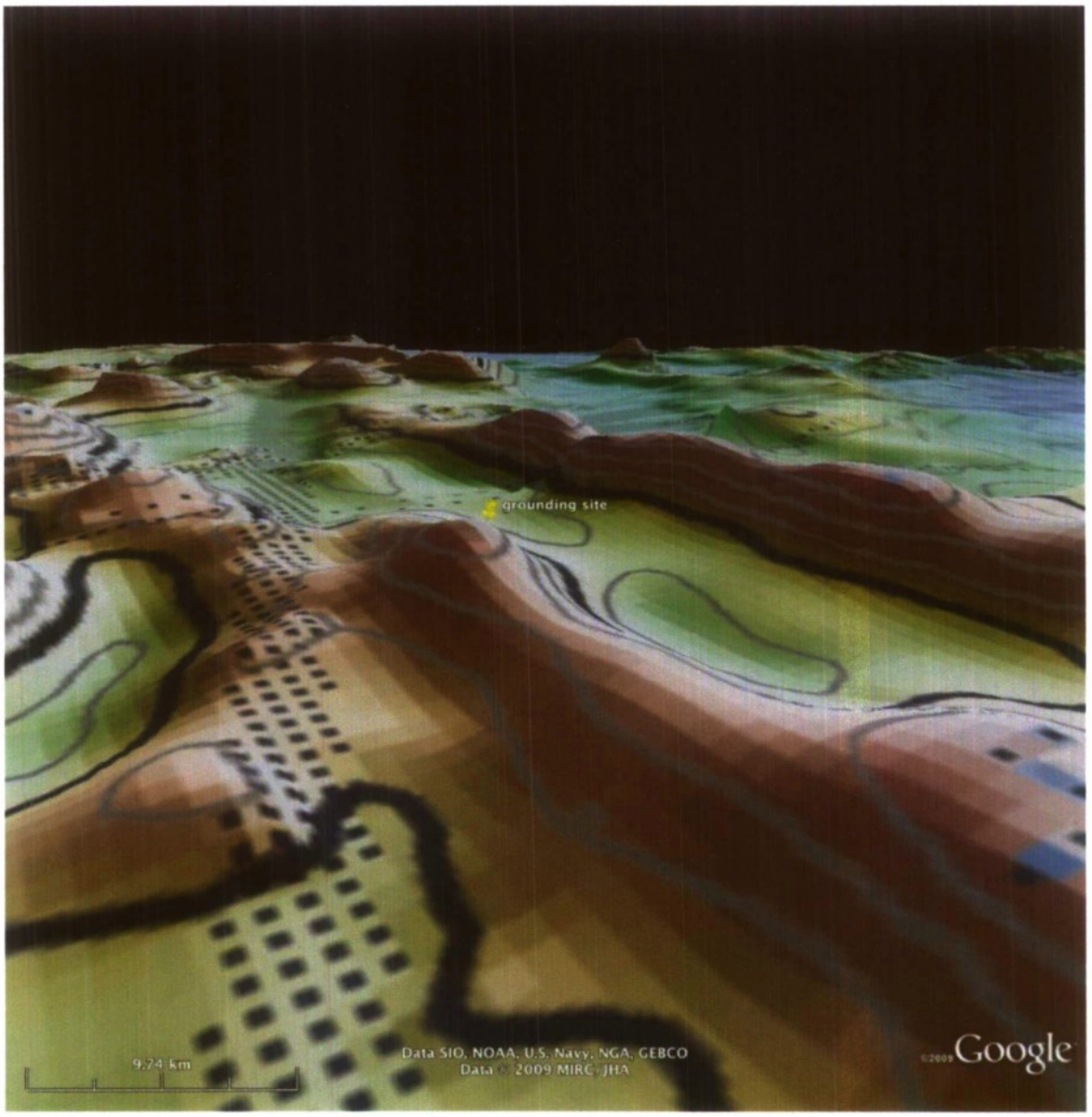

Figure Bathymetry around the grounding site (2005) of the USS San Francisco. Contour interval is 500 m. Black squares slow locations of ship soundings. This overlay for Google Earth is available at: ftp://topex.ucsd.edu/pub/global_topo_1min/global_topo_1min_V12.1.kmz

IMPACT/APPLICATIONS

The impact of this research it twofold. First, our global bathymetric grid is used for a variety of purposed ranging from cautionary overlays of NGA navigation charts to popular applications such as Google Earth. Google Earth acknowledges the MOA efforts at the bottom of their display window: as "Data: SIO, NOAA, U.S. Vavy, NGA, GEBCO". The addition of the shallow ocean data (< 300 m) may be useful for global studies of coastal processes. Second, we are using the edited sounding data to assess the roughness of the seafloor for understanding the tectonics of the deep oceans as well as the effects of seafloor roughness on deep-ocean mixing.

RELATED PROJECTS

Most of the gravity field improvement was funded by NASA and the National Science foundation. The NASA grant has expired and we are in the last year of our NSF funding.

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Appendix A.

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CECIL AND IDA GREEN
INSTITUTE OF GEOPHYSICS AND PLANETARY PHYSICS
SCRIPPS INSTITUTION OF OCEANOGRAPHY
LA JOLLA, CALIFORNIA 92093-0225

Tel: (858) 534-7109
email: dsandwell@ucsd.edu

December 29, 2008

Dear MOA Collaborators,

The MOA expired September 2008 so we should bring this official effort to some closure. Although we did not accomplish everything outlined in the MOA we did make some significant progress, especially on the accumulation and cleaning of raw sounding data. An important final step in this process it to confirm which soundings are "releasable" and therefore become public domain data. The data come from a variety of sources as shown in the table below and some of these data are "owned" by agencies outside of our group such as IFREMER and JAMSTEC so they are not all in the public domain but we should strive to make as much data open as possible. There are a few official approvals that we need before making the MOA-contributed raw sounding data freely available by ftp. Here are the items of the proposal for data release:

1) release edited files in the uniform cm-format;
2) the data labeled NGA_DNC shall **not** be released as they were marked proprietary data when submitted by NGA;
3) the data labeled IFREMER shall **not** be released under a verbal agreement with IFREMER.

There are two other data sets where clarification is needed. First, NGA contributed 7089 files of trackline data with names such as "SU197332.xyz". These data largely overlap with the NGDC_GEODAS data. One task for 2009 is to identify the unique tracks from this set, edit the files, and convert them to cm-format. Shall all of these data be releasable? Second, GEBCO (through NOAA) contributed shallow water soundings from ENC charts as well as contributions from the UKHO. Shall these data be releasable? I will ask JAMSTEC if they will allow the unrestricted distribution of the cm-files derived from their multibeam data available by ftp.

There are two data files (MOA_public.tar and MOA_private.tar) that have been placed on a temporary ftp site for your download. This represents a snapshot of all the data used to construct V11.1 of the 1-minute Mercator global topography grid as well as V5.0 of the ½ minute SRTM30_PLUS grid. I will also send each MOA partner one copy on DLT tape since the files are very large.

Sincerely,

David T. Sandwell

David T. Sandwell

REPORT DOCUMENTATION PAGE

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Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The impact of this research it twofold. First, our global bathymetric grid is used for a variety of purposes ranging from cautionary overlays of NGA navigation charts to popular applications such as Google Earth. Google Earth acknowledges the MOA efforts at the bottom of their display window: as "Data: SIO, NOAA, U.S. Navy, NGA, GEBCO". The addition of the shallow ocean data (< 300 m) may be useful for global studies of coastal processes. Second, we are using the edited sounding data to assess the roughness of the seafloor for understanding the tectonics of the deep oceans as well as the effects of seafloor roughness on deep-ocean mixing.

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