Volume 1: Technical Proposal

1) ONR BAA 11-001

2) Title of Proposal: A Factor of 2-4 Improvement in Marine Gravity and Predicted Bathymetry from CryoSat, Jason-1, and Envisat Radar Altimetry: Arctic and Coastal Regions

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6) Duration of Effort: 3 years (10/01/11-09/30/14)

7) Proposed Costs: $157,076

1. Abstract

Marine gravity and bathymetry are foundational data, providing basic infrastructure for military, scientific, economic, educational, and political work. Naval operations require accurate gravity models for inertial navigation and fire control, and accurate bathymetry to assess navigational hazards in uncharted areas. In addition, coastal bathymetry is used for improving models of tides and currents. Over the next 3 to 5 years, a wealth of new marine gravity data will be provided by three currently operating satellite altimeters CryoSat, Jason-1, and Envisat. With careful processing of the new data, in combination existing altimetry and bathymetry data we propose to:

- **Improve global marine gravity maps by a factor of 2 in deep ocean areas and a factor of 4 in the Arctic areas and on shallow continental margins.**
- **Use these improved gravity maps along with our global compilation of soundings to refine a 30-arcsecond bathymetry model (SRTM30_PLUS).**
- **Prepare the next generation of scientists for ocean research.**

We will coordinate our research efforts with the Defense Mapping Agency, the Naval Oceanographic Office, and make these grids available to Navy labs, defense contractors, and the general public.

2. Relevance to ONR Objectives

***Current (known) Navy and defense users of our global marine gravity and bathymetry* -** Our global gravity anomaly and bathymetry products are used throughout the Navy and defense industry in unclassified applications. For example, the National Geospatial-Intelligence Agency (see support letter from Nikolaos K. Pavlis – sent separately to ONR) used our global marine gravity grid to create the Earth Gravitational Model 2008 (EGM2008; *Pavlis, et al*., 2008). Jim Braud could comment on how altimetric bathymetry is used to identify "Red Dots" for survey planning as part of the Submarine Navigation Improvement Program (SNIP) (also see support letter from Walter Smith). Paul Sartorius (see attached letter signed by his colleague Daniel Heins) could provide details on how SRTM30_PLUS V6.0 is being used in their Google Maritime Globe for the DoD and Intel community. Paul Elmore could provide details on how our cleaned global ship soundings are being used for their "Irregular Multiresolution Database Algorithm".

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***Global Navy Operations* -** Since the end of the Cold War, Navy operations have shifted from well-surveyed areas in the northern hemisphere to more global operations. For example, the Naval Meteorology and Oceanography Command (METOC) has the "*Global responsibility to provide operational meteorological, oceanographic (METOC), and mapping, charting and* *geodetic services to the operating forces of the Navy and the Department of Defense. - Anytime . . . Anywhere*". The northern hemisphere oceans were well surveyed under the Navy's Ocean Survey Program but coverage outside of the cold-war areas of operation is poor [*MEDEA Report*, 1995]. The inadequacy of global bathymetric charts, became apparent when the *USS San Francisco* crashed into an uncharted guyot in the Caroline Seamount province of the Western Pacific in January of 2005. The most alarming aspect of this incident was that the soundings on the Nautical Chart have depth errors of more than 1000 m. The depth predicted from gravity anomaly [*Smith and Sandwell,* 1997, V8.2] at the crash site is about 500 m although there is a shallow predicted point of 278 m about 4 nm to the east of the crash site. The availability of predicted depths may have provided some warning to the captain of the *USS San Francisco*. Since that incident, the Navy has instituted a "Red Dots" program to perform bathymetric surveys of gravity-predicted seamounts that could possibly be hazards to navigation.

Navy Ocean Modeling - In addition to this navigational use for this improved global bathymetry, the Navy and many other organizations around the world use predicted bathymetry for operational and scientific investigations (Table 1). Of particular relevance to the Navy is the use of bathymetry in real-time global ocean analysis and modeling [*Rhodes et al.,* 2002; *Hurlburt et al.,* 2008; http://www7320.nrlssc.navy.mil/global_nlom/]. The NRL has developed a 2-minute global bathymetry data set to support this modeling effort. The NRL DBDB2 is largely based on the Smith and Sandwell 2-minute grids (see http://www7320.nrlssc.navy.mil/DBDB2_WWW/). We believe our proposed refinement of the accuracy and resolution of the global grid would contribute to the NRL operational modeling.

Table 1. Applications of Global Gravity and Bathymetry

Gravity Applications:
inertial guidance of ships, submarines, aircraft, and missiles
planning shipboard surveys
mapping seafloor spreading ridges and microplates
continental margin structure
Bathymetry Applications:
identification of navigational hazards
tsunami propagation and inundation models [*Mofjeld et al.,* 2004]
tide models and tidal friction [*Egbert and Ray,* 2001, *Metzger and Hurlburt*, 2001]
coastal tide model improvements [*van Norton et al., 2008]*
ocean circulation models [*Rhodes et al.,* 2002; *Gille et al*., 2004*]*
tidal role in ocean mixing [*Kunze and Llewellyn Smith, 2004*]
understanding seafloor spreading ridges [*Small,* 1998]
identification of linear volcanic chains [*Wessel and Lyons*, 1997]
education and outreach (i.e. geography of the ocean basins)
law of the sea [*Monahan 2004*]

3. Statement of Work

Background and Objectives - Marine gravity and bathymetry are foundational data, providing basic infrastructure for military, scientific, economic, educational, and political work (Table 1). Fundamental Earth science questions, such as what controls seafloor shape and how seafloor shape influences ocean currents and mixing, also cannot be answered without bathymetric maps having globally uniform detail. Over the next 3 to 5 years, a wealth of new marine gravity data will be provided by three currently operating satellite altimeters CryoSat, Jason-1, and Envisat. With careful processing of the data, in combination with data from past Geosat and ERS-1/GM altimeter missions, we propose to dramatically improve the accuracy of the global marine gravity field. This will result in matching improvements in bathymetry in areas devoid of ship soundings. Our proposed research has 3 main tasks:

- **Improve global marine gravity maps by a factor of 2 in deep ocean areas and a factor of 4 in the Arctic areas and on shallow continental margins.**
- **Use these improved gravity maps along with our global compilation of soundings to refine a 30-arcsecond bathymetry model (SRTM30_PLUS).**
- **Prepare the next generation of scientists for ocean research.**

The accuracy of the global marine gravity field depends primarily on two factors - spatial track density and altimeter range precision. Current models, having accuracies of 3-5 milligals (e.g., S&S V18 and DNSC08), are based on the non-repeat data collected by Geosat (US Navy - 18 mo.) and ERS-1 (ESA - 12 mo.), which use altimeter technology from the 70's and 80's, respectively (Figure 1). The next major advance in mapping the marine gravity will come from new satellite altimeter measurements having dramatically improved spatial track density combined with improved range precision. The **Technical Approach** section below provides details on the data from the new altimeters.

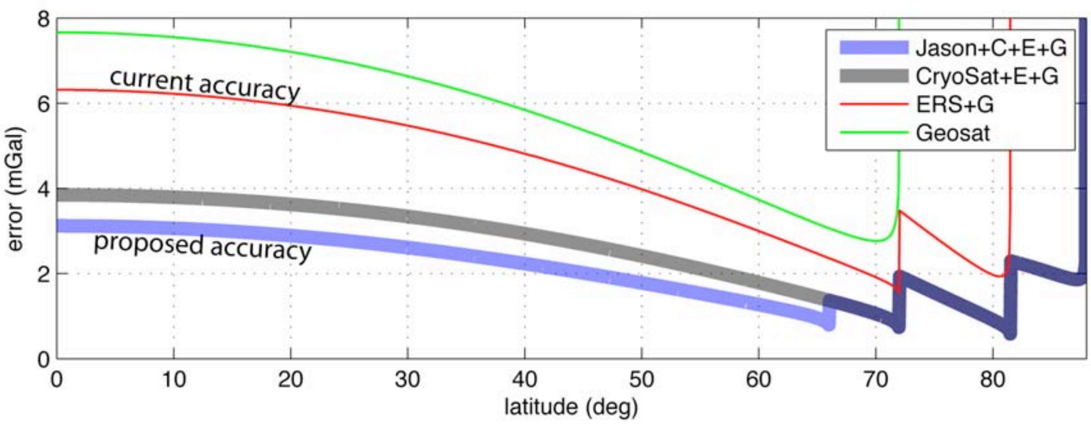


Figure 1. Theoretical gravity field accuracy versus latitude showing relative improvements as new altimeter data become available. Green curve shows the gravity field accuracy based on retracked Geosat only which has maximum latitude of 72˚. Accuracy improves with latitude to 72˚ as tracks become more orthogonal and track density increases. Red curve shows the present-day gravity accuracy from V18.1 [*Sandwell and Smith*, 2009], which also includes retracked ERS-1 data, which has maximum latitude of 81.5˚. The thick black and blue curves show improvements by adding CryoSat (3 years retracked, 88 degrees maximum coverage) and Jason (1.15 year retracked, 66 degrees maximum coverage).

Gravity Field Tasks and Timeline

Year 1 – We will modify our waveform retracking software and altimeter processing software to be used with the CryoSat waveform data product in all three of its operational modes LRM, SAR and ocean InSAR (Figure 2). We have already evaluated a few passes of CryoSat over ocean areas to determine the signal-to-noise characteristics of the multi-looked waveform data. Through comparisons with high-resolution geoid models we will refine waveform-tracking algorithms that are optimized for the open ocean and sea ice areas. We expect that the algorithm development will continue into the second year of the investigation.

Year 2 - We will construct a new global marine gravity grid (1-minute resolution) based on all available satellite altimeter data. The methods and computer codes for constructing the vertical deflection, gravity anomaly, and geoid height grids are published in [*Sandwell and Smith*, 1997; 2009]. If we can automatically re-track CryoSat SAR data in areas of sea ice, we will extend the grid to +88° latitude. The gravity field construction will be repeated at 1-year intervals until the end of the CryoSat mission (3 – 5 years). The long-wavelength reference field for this grid will be based on the best available spherical-harmonic gravity models from EGM2008 and the updates from CHAMP, GRACE, and GOCE. The altimeter-derived gravity models are most accurate between wavelengths of 20 km and 2000 km while the satellite-derived models are most accurate between wavelengths of 400 km and 40,000-km. The overlap part of the spectrum will be used to validate both approaches as well as to isolate the false gravity signals that will be apparent in the altimeter-derived gravity along the fronts of the major currents.

Year 3 – If Jason-1 is still operational after it is placed into a 419-day repeat cycle phase in mid-2012, we will develop a waveform retracker that is optimized for gravity recovery. We hope to receive 419 days of Jason-1 data from the planned Geodetic mission by mid-2014. We will add these data to the gravity field to improve the lower latitude gravity accuracy by another milligal. The major benefit of Jason-1 data will be to better constrain the E-W gravity field so N-S features such as the East Pacific Rise can be better resolved. In addition to Jason-1 we expect some new gravity information from the drifting phase of Envisat. However, the extent and duration of this drifting phase are not yet known. ESA hopes to keep the envelope of the drifting Envisat tracks to less than 20 km so repeat-track InSAR and altimetry is still sometimes possible.

Bathymetry Tasks and Timeline

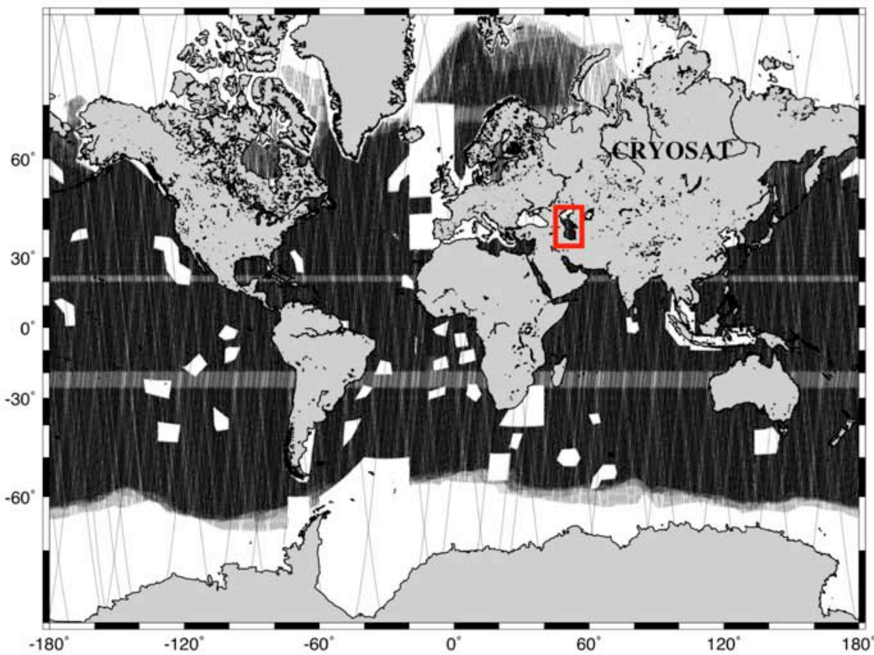
Years 2 and 3 **-** The second aspect of our proposed research is to continue the construction of global bathymetry models at 1-minute and 30-arc seconds. Using funding from a previous ONR contract (N00014-06-1-0140, 11/2005 to 9/2008, $243,265) as well as funding from the National Science Foundation, we have assembled arguably the largest set of cleaned unclassified soundings [*Becker et al.,* 2009]. Currently, we are adding all available multibeam data to this 500-m compilation, working with the US academic fleet data [*Carbotte et al*., 2004] and, through GEBCO and the IHO, obtaining data from hydrographic surveys globally. We use these soundings to constrain the long-wavelength (> 200 km) shape of the ocean basins as well as to calibrate the ratio of short wavelength topography to gravity for predicting seafloor depth in the data voids [*Smith and Sandwell*, 1994; 1997].

Anticipated Project Results - During the investigation we will construct interim models of global marine gravity at 1-minute resolution and global bathymetry at both 1 minute and 30-arc second resolution. Data will be available from the web site http://topex.ucsd.edu. At the end of the investigation we will publish the data, the waveform retracking methods, and any scientific discoveries from the new gravity and bathymetry grids.

4. Technical Approach

New Satellite Altimetry Data From CryoSat, Jason-1 and Envisat - The marine geophysics community (unclassified) has been waiting for 15 years for a new source of densely spaced radar altimeter measurements. Current gravity fields are based primarily on 18 months of Geosat/GM data collected in 1985-86 and 12 months of ERS-1/GM collected in 1995-96. Since then there have been several advances in radar altimeter technology but all the newer satellites have been placed in the repeat orbit configuration that is optimal for recovering changes in ocean surface height associated with currents and tides [*Fu and Cazenave*, 2001] but provide little new gravity information. The repeat orbit altimeters include Geosat/ERM, 1986-1989; ERS-1, 1991-1995; Topex/Poseidon, 1992-2006; ERS-2, 1995-2010; GFO, 1998-2008; Jason-1, 2001-present; Envisat, 2002-present; and Jason-2, 2008-present. Over the past year there have been three developments related to radar altimeter missions with dense track spacing. First, CryoSat-2 was successfully launched in February of 2010 and has routinely collected altimetry data over ice, land, and ocean since July 2010 (Figure 2 - upper). Second, the Envisat satellite, which has been in continuous operation since 2002, is running low on the fuel needed for maintaining a repeating ground track. Beginning in October, 2010 the orbit was allowed to drift while still collecting altimetry data. Envisat will remain in this drifting orbit at least until the 2013 launch of the replacement satellite Sentinel-1. Third the Jason-1 altimeter was replaced by Jason-2 in 2008 so to avoid a potential collision and to provide new gravity information, it will be maneuvered into an orbit with a 419-day repeat cycle (Figure 2 - lower) in early 2013 which is optimal for gravity field recovery [*Morrow et al*., 2010]. In their normal operating modes all three of these "new" altimeters have range precision approximately the square root of two times better than Geosat and ERS because they operate at 2 times higher pulse repetition frequencies of about 2000 Hz. More important, the CryoSat altimeter can also be operated in a synthetic aperture radar mode over the oceans to achieve perhaps a factor of 2-4 improvement in range precision [*Raney et al*., 2003; *Smith and Sandwell*, 2004; *Gilles et al*., 2010]. Figure 2 shows the planned modes of operation for CryoSat as well as the actual standard-mode (LRM) data collected for 6 months. We currently have 13 months of LRM and SAR data at SIO. A zoom of the Caspian Sea area shows 6-mo. coverage as well as planned coverage from CryoSat and Jason-1. The planned Jason-1 trackline is too dense to see individual tracks on this figure.

A preliminary analysis, discussed below, shows that the CryoSat altimeter has better range precision than Geosat by a factor of 1.4. If CryoSat operated for 3 years or longer, then the combined gravity field improvement will be nearly a factor of 2 over most of the ocean and a factor of 4 at high latitudes (> 72˚ Arctic and Antarctic) as shown in Figure 1. One negative feature of CryoSat is that the high orbital inclination results in mostly N-S track orientation so at low latitudes the E-W component will not be resolved as well as the N-S component. At low latitudes, the data from Jason-1 will be important for gravity field improvement. The tracks will be very dense if the satellite can operate for a full 419 day repeat cycle.



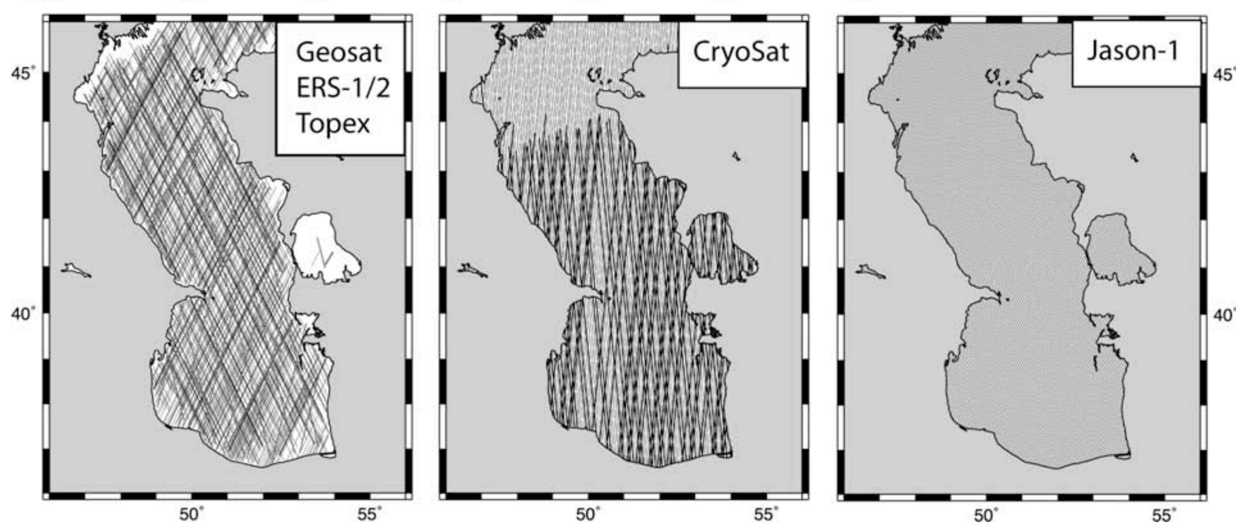


Figure 2. (upper) planned radar operating modes for CryoSat; LRM – standard mode used by all previous altimeters; SAR – synthetic aperture radar mode may provide 2-4 times better range precision. SARIN – uses two receive antennas to also measure cross-track slope over ice. We propose to process the data from all three modes for complete ocean coverage.
(middle) Actual CryoSat data collected in the LRM mode for 6 months basically follows the acquisition plan. Missing bands at +/- 22 latitude are due to calibration which ended in February, 2011 so these gaps will be filled.

(lower) Ground tracks for the Caspian Sea region. (left) actual tracks used in V18.2 global gravity [*Sandwell and Smith*, 2009]. (center) CryoSat tracks for 6 months (dark lines) as well as planned 1-year tracks (light lines). (right) planned Jason-1 tracklines (light lines). We have an investigation, approved by the European Space Agency, to obtain all the CryoSat waveform data (LRM, SAR, and InSAR) over the oceans at no cost (see letter from Tommaso Parrinello).

***Why Retracking is Essential* -** Satellite altimetry data are provided to the user community at different levels of processing. Most users begin with the level-2 products where the raw waveform data have been tracked and averaged into 1 Hz or 7 km along-track spacing. Standard waveform tracking estimates 3 to 5 parameters, the most important being arrival time, rise time, and the return amplitude [*Amarouche et al.*, 2004; *Brown*, 1977]. Through calibration, these 3 parameters are transformed into sea surface height, significant wave height (SWH), and wind speed, respectively. Most users of level-2 data average these parameters for about 30 km in the along-track direction to further reduce noise. However, this standard processing is inadequate for optimal recovery of the marine gravity field. The marine gravity field is a measure of ocean surface slope so high range precision over the shortest possible along-track distance is needed.

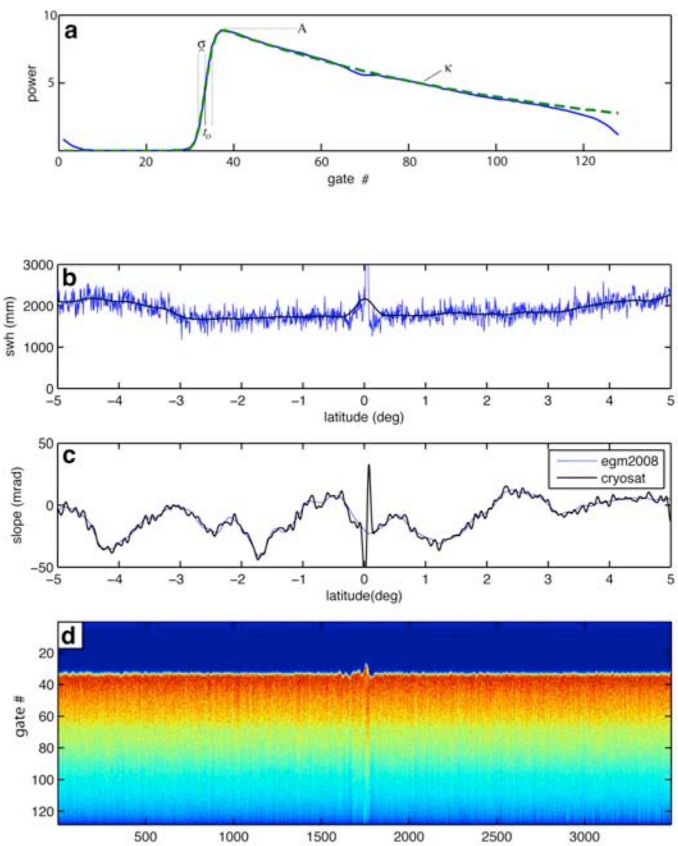


Figure 3. Short segment of a CryoSat LRM track across the Indian Ocean.
(a) Average of 27,000 CryoSat radar waveforms (solid) and a simplified model (dashed) with four adjustable parameters: A-amplitude, t_o – arrival time, σ – rise time, and κ – trailing edge decay.
(b) Significant wave height (SWH) derived from 4-parameter retracking model (blue curve) has unrealistic short wavelength jitter. Smoothed SWH (black curve) was provided to a 2-parameter retracker to constrain the shape of the leading edge of the waveform so the arrival time is more accurately estimated.
(c) Arrival time converted to along-track slope (black curve) compared with slope from the EGM2008 model (blue curve, essentially V18.1 gravity). Both were low-pass filtered at 18 km wavelength for direct comparison with previous analyses of Geosat and ERS-1 data. The slope differences have a median absolute deviation of 2.48 microradian – part of this difference is gravity signal and part is altimeter noise.
(d) CryoSat waveforms used for the analysis. The anomaly at the equator is perhaps due to a rain cell. Further algorithm development is needed to identify and remove these bad data.

The accuracy of the recovered gravity field depends primarily on the accuracy of the arrival time parameter. One way of improving the gravity field is to retrack the raw altimeter waveform using an algorithm that is optimized for arrival time estimation. Arrival time error and SWH error are inherently correlated because of the noise characteristics of the return waveform [*Maus et al.*, 1998; *Sandwell and Smith*, 2005]. Two previous studies have demonstrated up to 40% improvement in range precision by optimizing the retracking algorithm to achieve high range precision at the expense of recovering small spatial scale variations in significant wave height [*Maus et al.*, 1998; *Sandwell and Smith*, 2005]. For this proposal, we have modified the ERS-1 retracking software to work with CryoSat LRM data. Our preliminary analysis based on 8 profiles across the Indian Ocean reveal the following (Figure 3). First the quality of the raw waveform data are excellent. The EGM2008 model was used to assess the accuracy of slope estimated from retracked CryoSat. The standard 3-parameter retracking has a median absolute deviation (MAD) of 3.14 μrad. The optimized 2-parameter retracking reduces the MAD to 2.48 μrad. A similar analysis using retracked Geosat and ERS-1 data shows MADs of 3.19 μrad and 3.56 μrad, respectively. **We attribute the 1.4 reduction in noise level of CryoSat with respect to the previous altimeters to its 2 times higher pulse repetition frequency. This preliminary analysis suggests that a factor of 2 improvement of global marine gravity is feasible with 3 years of data and optimized waveform retracking.** The European Space Agency has no plans to retrack CryoSat data using this optimized approach. Our proposal is to develop optimal retracking methods for CryoSat, Jason-1, and Envisat. One year of CryoSat data has 500 million waveforms so the retracking algorithms must be computationally efficient.

How will improved gravity enable new science? One of the main drivers for an improved gravity field is the ability to resolve new structures on the ocean floor (Figure 4). The scientific rationale for such a mission is mature and a set of papers related to this topic was published in a special issue of *Oceanography* [*Smith*, 2004], entitled *Bathymetry from Space*. The global ocean floor could be mapped to about 200 m horizontal resolution acoustically by ships carrying multi-beam echo-sounders, at an investment of around 200 years of ship time [*Carron et al*., 2001]. A global ocean mapping program by a satellite altimeter operated in SAR mode would be cheaper by an order of magnitude, but would also have a more limited resolution (about 6 km). This limitation is imposed by physical law (upward continuation of gravity anomalies from the sea floor to the sea surface) and not by altimeter technology. Studies by the ABYSS science team, [*Smith*, 2005] found that an altimeter mapping sea surface slope to 1 microradian with a half-wavelength resolution of 6 km would be sufficient to resolve the abyssal hill fabric of the oceans [*Goff,* 2010]. Although not as detailed as acoustic bathymetry, mapping to this resolution threshold would be a critical advance for a large number of basic science and practical applications, including: determining the effects of bathymetry and seafloor roughness on ocean circulation [*Gille et al.*, 2004], mixing [*Kunze and Llewellyn Smith*, 2004], climate [*Jayne et al.*, 2004], tides [*Arbic et al.*, 2004], and biological communities, habitats, and mobility [*Koslow*, 1997]; understanding the geologic processes responsible for ocean floor features, such as abyssal hills, seamounts, microplates, and propagating rift [*Sandwell et al.*, 2006; Sandwell and Wessel, 2010]; improving tsunami hazard forecast accuracy by mapping the deep ocean topography that steers tsunami wave propagation [*Mofjeld et al.*, 2004]; assessing potential territorial claims to the seabed under the United Nations Convention on the Law of the Sea [*Monahan*, 2004].

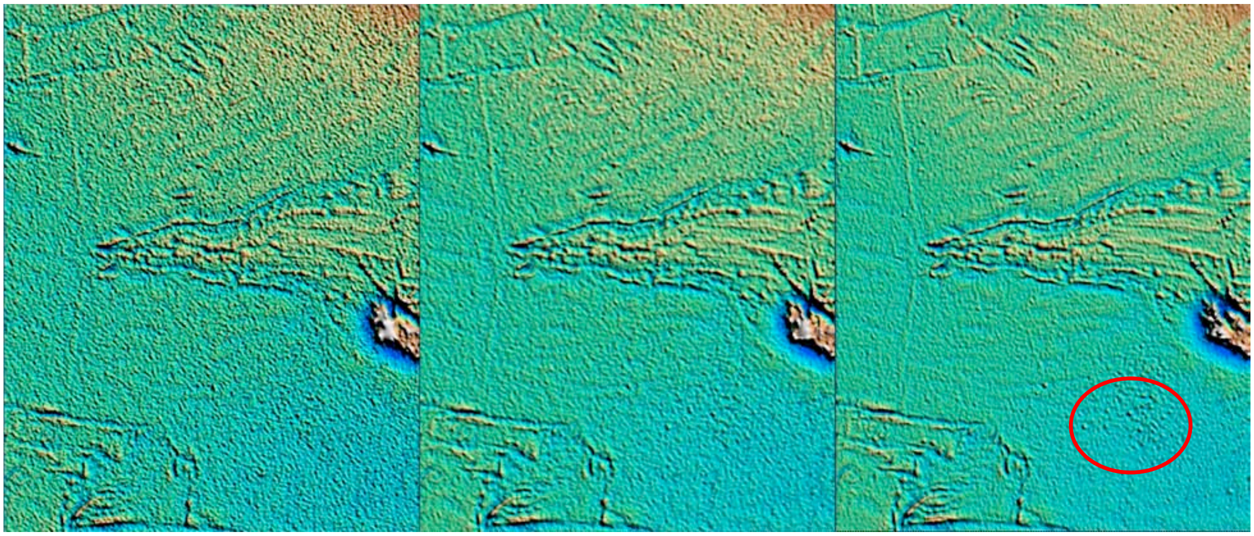


Figure 4 Shaded gravity anomaly for a large region in the Central Pacific Ocean centered at the Galapagos Triple Junction (latitude 11˚ to –8˚, longitude 255˚ to 270˚). Colors saturate at +/- 60 mGal. The visual noise level decreases as one moves from V9.1 (left) to V11.1 (center) to V18.1 (right). The axis of the East Pacific Rise is well defined in V18.1 but more difficult to trace in V9.1 because of the higher noise level. The red oval outlines a patch of small uncharted seamounts not apparent in V9.1. The evolution from V9.1 to V18.1 corresponds to a factor of 2 improvement in gravity field accuracy. **Our proposed investigation will improve the accuracy by another factor of 2 at lower latitudes and a factor of 4 in some Arctic and coastal areas. This will reveal significant unknown details in seafloor morphology.**

These studies of the new science are related to a gravity accuracy of better than 1 mGal. Note that 1 mGal accuracy in gravity translates into 1 microradian accuracy in ocean surface slope. Current gravity models have accuracies of 3-5 mGal over a 9 km length scale. With CryoSat we hope to reduce this error to 1.5-2.5 mGal over a 9 km length scale (Figure 1). Achievement of better than 1 mGal over a 6 km length scale will require an altimeter operating in SAR mode. So we see CryoSat as an important milestone in demonstrating the ultimate accuracy and resolution threshold. Moreover, as shown in Figure 2, CryoSat will be operated in the SAR mode over the Arctic Ocean as well as some small test regions in the lower-latitude oceans. As part of this proposal we will assess the gravity improvement that can actually be achieved by operating in the SAR mode and will incorporate these SAR-mode data in our global gravity models.

Continued assembly and editing of all unclassified bathymetry data **-** The improved global gravity model will be used in combination with our expanding archive of cleaned bathymetry soundings to make a new global bathymetric prediction [*Smith and Sandwell*, 1994; 1997]. The accuracy of the prediction degrades with distance to the nearest depth sounding [*Marks et al*., 2010] so our focus will be to locate existing sounding data that will fill the largest data gaps. These "new" data do not come from the normal archives such as NGDC or the Marine Geosciences Data System. For example, the National Geospatial-Intelligence Agency has accumulated an archive of 1376 cruises that are not included in the NOAA GEODAS distribution [*Von Rosenberg*, 2006, personal communication]. In general the quality of these data are poor. Approximate 50% of these sounding data have significant blunders in depth or navigation. However, some of these tracks are valuable because they cover remote seafloor where there are large gaps. Undergraduate students in our lab visually examine every trackline using a tool that displays the sounding depth along with the predicted depth. Blunders and questionable data are flagged and not used in the next update of the global bathymetry. This is an iterative process where a new global map is constructed, the identity of conflicting points is recorded and the trackline is re-edited. Over the past 7 years we have assembled and cleaned 7800 files of bathymetry data from perhaps 100 different sources. The locations of all these soundings are easily visualized in our seamount discovery tool for Google Earth ftp://topex.ucsd.edu/pub/global_topo_1min/global_topo_1min_V14.1.kmz . Some of these data are proprietary but most have no restrictions and have been provided to other investigators (http://topex.ucsd.edu/WWW_html/mar_topo.html).

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5. Rationale for requested support of any facilities, equipment, or materials.

We have requested support for the purchase of a desktop computer (year 1) as well as IGPP Network computer support and communications costs (all three years). Our proposed activity is computer intensive and these items are needed to maintain the computing capability for this effort.

6. Related Proposal Pending at NSF

A similar marine gravity proposal was submitted to the National Science Foundation on February 15, 2011. That proposal is still pending. The program manager (Richard Carlson) cannot provide a time estimate for a decision on that NSF proposal so we are submitting this related proposal to ONR. We have discussed the possibility that NSF would fund 1/2 of the proposed effort. This ONR proposal would provide the other 1/2 support. One of the reviewers of our NSF proposal said *I consider this proposal a must fund no matter what deal - the community NEEDS the improvements to the altimetric gravity map that will be afforded by the new data becoming available*" . . ."*a factor of 2 improvement will constitute a "quantum leap" that is sure to excite a broad array of research endeavors (I'm already thinking about a proposal!)*. There is no question that we will analyze these data as proposed. The only issue is community support and open access.

7. Description of general and special facilities available for performing the proposed work.

Over the past 20 years we have developed specialized software for the analysis of radar altimeter data for constructing marine gravity models. In addition we have developed software for predicting bathymetry in areas where there are no depth soundings. We have assembled more than 8000 cruises of trackline and multibeam bathymetry and have edited these data. These cleaned sounding data are freely available on request. SIO/IGPP provides numerous facilities to be used during this investigation including: gigabit ethernet network to desktop computers; mass storage data facility to provide on-line backup and archiving of large data sets; and access to all shipboard data contained at the SIO Geological Data Center.

8. Biographical Information of Key Personnel

The research will be performed by SIO graduate student Emmanuel Garcia and SIO professor David Sandwell in collaboration with NOAA researcher Walter H. F. Smith. Emmanuel is a second-year graduate student and this proposed research will be used for the development of his Ph.D. thesis. Walter Smith will be involved in all aspects of this research. Smith and Sandwell have collaborated for almost 20 years on the development of methods for mapping the ocean basins using satellite altimetry and ship soundings. Funding for Walter's salary or research activities have not been included in the budget because he is a NOAA employee and does not need outside salary support. Walter has provided a letter of support describing his role in the project.

9. Pertinent bibliography of the investigators

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