ABYSS-Lite:
A radar altimeter for bathymetry, geodesy and mesoscale oceanography

A mission concept submitted to the NRC Decadal Survey

Authored by:

Smith	Walter	NOAA	walter@raptor.grdl.noaa.gov
Raney	Keith	Johns Hopkins Univ., MD	Keith.Raney@jhuapl.edu
Sandwell	David	Scripps institution of Oceanography, UCSD	dsandwell@ucsd.edu
Anglin	Lyn	Geological Survey of Canada's Pacific Division	anglin@nrcan.gc.ca
Andersen	Ole	Danish Space Center	oa@spacecenter.dk
Andreasen	Chris	NGA Office of Global Navigation	AndreasenC@nga.mil
Arbic	Brian	Princeton University and NOAA GFDL	arbic@splash.princeton.edu
Blackman	Donna	Scripps Institution of Oceanography, UCSD	dblackman@ucsd.edu
Camarda	Tom	National Geospatial Intelligence Agency	Thomas.P.Camarda@nga.mil
Cande	Steve	Scripps Institution of Oceanography, UCSD	scande@ucsd.edu
Carron	Michael	NATO Undersea Research Center	carron@saclantc.nato.int
Cazenave	Anny	CNES	anny.cazenave@cnes.fr
Christie	David	Oregon State University	dchristie@coas.oregonstate.edu
Coakley	Bernie	Univ. of Alaska, Fairbanks	Bernard.Coakley@gi.alaska.edu
Cochran	James	Lamont Doherty Earth Observatory	jrc@ldeo.columbia.edu
Douglas	Bruce	University of Maryland	BruceD7082@aol.com
Drinkwater	Mark	European Space Agency Earth Observation	Mark.Drinkwater@esa.int
Driscoll	Mavis	Northrop Grumman Corporation	mavis.driscoll@ngc.com
Eakins	Barry	USGS, Menlo Park, CA	beakins@usgs.gov
Egbert	Gary	Oregon State University, Corvallis, OR	egbert@coas.oregonstate.edu
Emery	Bill	University of Colorado	emery@colorado.edu
Factor	John	National Geospatial Intelligence Agency	John.K.Factor@nga.mil
Falconer	Robin	NZ Institute for Geological & Nuclear Sciences	r.falconer@gns.cri.nz
Forsyth	Donald	Brown University	Donald_Forsyth@brown.edu
Friederich	Jim	National Geospatial Intelligence Agency	James.E.Friederich@nga.mil
Geli	Louis	IFREMER	Louis.Geli@ifremer.fr
Gille	Sarah	UCSD	sgille@ucsd.edu
Godin	Ray	Integrated Program Office	Ray.Godin@noaa.gov
Goff	John	Univ. of Texas, Austin, TX	goff@ig.utexas.edu
Gonzalez	Frank	NOAA PMEL Tsunami group	Frank.I.Gonzalez@noaa.gov
Hensel	Jerry	Chevron/Texaco	jhensel@chevrontexaco.com
Hunter	Peter	Southampton Oceanography Centre	cart@soc.soton.ac.uk
Jacobs	Gregg	Naval Research Laboratory	Gregg.Jacobs@nrlssc.navy.mil
Jakobsson	Martin	Stockholm University	martin.jakobsson@geo.su.se
Jayne	Steve	Woods Hole Oceanographic Inst., MA	sjayne@whoi.edu
Jensen	Bob	Johns Hopkins Univ., MD	Bob.Jensen@jhuapl.edu

Kappel	Ellen	Geosciences Professional Services, MD	ekappel@geo-prose.com
Karner	Garry	LDEO Columbia University	garry@ldeo.columbia.edu
Kenyon	Steve	National Geospatial Intelligence Agency	Steve.C.Kenyon@nga.mil
Kruse	Sarah	University of South Florida	skruse@chuma1.cas.usf.edu
Kunze	Eric	Univ. of Victoria SEOS	kunze@uvic.ca
Lillibridge	John	NOAA Lab for Satellite Altimetry	John.Lillibridge@noaa.gov
Llewellyn-Smith	Stefan	Mechanical and Aerospace Engineering, UCSD	sgls@mechanics.ucsd.edu
Lonsdale	Peter	Scripps Institution of Oceanography, UCSD	plonsdale@ucsd.edu
Luther	Doug	Univ. of Hawaii, Honolulu	luther@soest.hawaii.edu
Mariano	John	Exxon-Mobil	john.mariano@exxonmobil.com
Marks	Karen	NOAA Lab for Satellite Altimetry	karen.marks@noaa.gov
Massell-Symons	Christina	Geological Data Center, UCSD	csymons@ucsd.edu
May	Marvin	Navigation R & D Center, Penn State Univ	mbm16@psu.edu
Mayer	Larry	UNH Center for Coastal & Ocean Mapping	larry.mayer@unh.edu
McGuire	James	Integrated Program Office	james.mcguire@noaa.gov
McNutt	Marcia	Monterey Bay Aquarium Research Institute	mcnutt@mbari.org
Metzger	Joseph	Naval Research Laboratory	metzger@nrlssc.navy.mil
Miller	Stephen P.	Scripps Institution of Oceanography, UCSD	spmiller@ucsd.edu
Mitchell	Roger	Earth Satellite Corporation	rmitchell@earthsat.com
Mitchum	Gary	University of South Florida, St. Petersburg	mitchum@marine.usf.edu
Mofjeld	Harold	NOAA PMEL Tsunami group	Harold.Mofjeld@noaa.gov
Monahan	Dave	Chairman, IHO-IOC GEBCO	monahand@ccom.unh.edu
Munk	Walter	Scripps Institution of Oceanography, UCSD	wmunk@ucsd.edu
Naar	David	Univ. of South Florida	naar@seas.marine.usf.edu
Nerem	Steve	University of Colorado Aerospace Engineering	Nerem@colorado.edu
Neumann	Gregory	Goddard Space Flight Center, NASA	neumann@tharsis.gsfc.nasa.gov
O'Loughlin	Michael	National Geospatial Intelligence Agency	Michael.C.OLoughlin@nga.mil
Orcutt	John	Scripps Institution of Oceanography, UCSD	jorcutt@ucsd.edu
Oswald	John	National Geospatial Intelligence Agency	John.A.Oswald@nga.mil
Pavlis	Nikolaos	Raytheon ITSS Corporation	npavlis@atlas.stx.com
Phipps Morgan	Jason	Cornell University	jp369@cornell.edu
Polzin	Kurt	WHOI	kpolzin@whoi.edu
Porter	David L.	Johns Hopkins Univ., MD	David.L.Porter@jhuapl.edu
Rankin	William	Naval Oceanographic Office	william.e.rankin@navy.mil
Ray	Richard	Goddard Space Flight Center, NASA	richard.ray@gsfc.nasa.gov
Rodriguez	Ernesto	Jet Propulsion Laboratory, NASA	er@vermeer.jpl.nasa.gov
Ruder	Michal	Wintermoon Geotechnologies, Inc.	meruder@wintermoon.com
Ryan	Bill	Lamont Doherty Earth Observatory	billr@ldeo.columbia.edu
Salman	Richard	National Geospatial Intelligence Agency	Richard.D.Salman@nga.mil
Sawyer	Dale	Rice Univ., Houston, TX	dale@rice.edu
Schenke	Hans-Werner	Alfred Wegner Institute	schenke@AWI-Bremerhaven.de
Schrama	Ejo	Delft Technical University	E.J.O.Schrama@lr.tudelft.nl
Sharman	George	NOAA	George.F.Sharman@noaa.gov

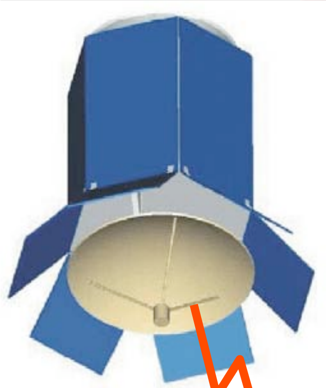
Shum	C.K.	Ohio State University, OH	ckshum@osu.edu
Simmons	Harper	International Arctic Research Center	harper.simmons@noaa.gov
Small	Chris	Lamont Dohergy Earth Observatory	small@ldeo.columbia.edu
Soofi	Khalid	Conoco	Khalid.A.Soofi@conoco.com
St.Laurent	Lou	Florida State University, Tallahassee	lous@ocean.fsu.edu
Stammer	Detlef	Inst for Meereskunde, Hamburg	stammer@ifm.uni-hamburg.de
Talwani	Manik	Rice Univ., Houston, TX	manik@rice.edu
Thurnheer	Andreas	Dept. of Oceanography, FL State Univ.	A.Thurnherr@ocean.fsu.edu
Titov	Vasily	NOAA PMEL Tsunami group	Vasily.Titov@noaa.gov
Tokmakian	Robin	Naval Postgraduate School, Monterey	robint@meeker.ucar.edu
Toohey	Joseph	National Geospatial Intelligence Agency	Joseph.L.Toohey@nga.mil
Trimmer	Ron	National Geospatial Intelligence Agency	Ronald.G.Trimmer@nga.mil
True	Scott	National Geospatial Intelligence Agency	Scott.A.True@nga.mil
Watts	Anthony	Oxford University	tony@earth.ox.ac.uk
Weatherall	Pauline	British Oceanographic Data Centre	paw@bodc.ac.uk
Wessel	Paul	Univ. of Hawaii, Honolulu, HI	pwessel@hawaii.edu
Wingham	Duncan	University College London	Duncan.Wingham@cpom.ucl.ac.uk
Young	Bill	Scripps Institution of Oceanography, UCSD	wryoung@ucsd.edu
Zlotnicki	Victor	Jet Propulsion Laboratory, NASA	vz@pacific.jpl.nasa.gov
Zumberge	Mark	Scripps Institution of Oceanography, UCSD	mzumberge@ucsd.edu

Acknowledgements and Additional Supporting Materials:

This mission concept has matured through its development as a NASA ESSP-3 proposal ("ABYSS: Altimetric Bathymetry from Surface Slopes"), in a NASA/NOAA/NSF funded workshop in 2002 (http://www.igpp.ucsd.edu/bathymetry_workshop), Navy workshops in 2003 and 2005, and articles in the 2004 "Bathymetry from Space" issue of *Oceanography* (http://www.tos.org/oceanography/issues/issue_archive/17_1.html). The concept presented here arranges these previously vetted materials to fit the NRC Decadal Survey outline. A website (http://topex.ucsd.edu/concept) holds additional supporting materials, including animated demonstrations of the effect of bathymetry in tsunami propagation and of the recovery of mesoscale eddies from a non-repeat orbit. Further discussion of the mission concept, resolving power, and applications to tsunami and seismic hazard, ocean circulation, ocean mixing, climate modeling, and the UN Law of the Sea can be found in peer-reviewed articles in *Oceanography* volume 17, number 1 (http://www.tos.org/oceanography/issues/issue_archive/17_1.html).

Disclaimer

The views, opinions and findings contained in this document are those of the authors and should not be construed as an official U.S. Government position, policy or decision. Co-authors of this report who are employees of U.S. federal agencies are acting in their capacities as scientific experts contributing to a science mission concept; they are not acting as advocates of U.S Government position, policy, or decision.



Fact Sheet

Abyss-Lite*

An altimeter for geodesy and mesoscale oceanography

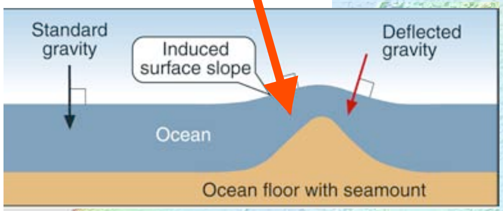
Method

• Radar measurement of sea surface slope reveals gravity anomalies & ocean flows

Themes

• The fine-scale (200-km to 5-km) ocean shape yields bathymetry, gravity anomalies, and deflections of the vertical (VD) unavailable by other means

• The non-repeat orbit monitors ocean currents and eddies unseen by other missions



Complements Related Missions

• GRACE, Champ and GOCE sense gravity at orbital altitude, where resolution is limited to ~200 km; Abyss-Lite measures gravity at sea level, where resolution down to ~ 5 km is available.

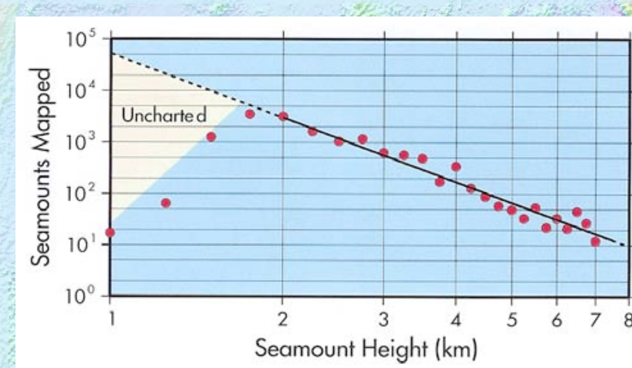
•Abyss-Lite's drifting orbit fills holes in the exact-repeat orbits covered by TOPEX/Poseidon, GFO, Envisat, and Jason-1, enabling fine-scale geodesy and detailed recovery of mesoscale eddies.

Implementation

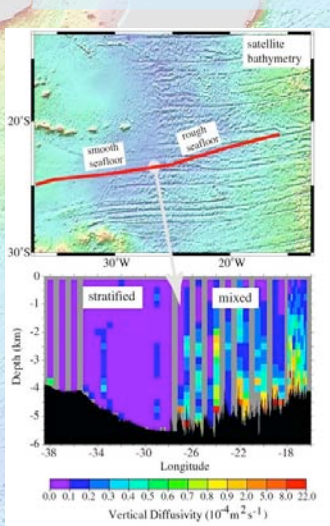
• ~800-km orbit, inclination ~120˚ (preferred) or ~60˚, non-repeat, ~22-day near-repeat, 6-y mission, small s/c

• Delay-Doppler radar altimeter w/ on-board processing for fine measurement precision, near-shore tracking, resistance to "wave noise"

•Low data rate; one ground station



A new Bathymetry from Space mission should find 50,000 unmapped seamounts (yellow area). A 2-fold improvement in seamount height precision should increase the total number of seamounts mapped by 18-fold. The proposed mission will yield a 20-fold improvement in areal resolution of the marine gravity field and bathymetry.



Science

• Ocean bottom shape and roughness control tsunami propagation, steering of flows, mixing rates, heat transport, global climate & sea level.

• Ocean floor structure answers fundamental science questions about Earth's magma budget, volcanism tectonics, and seismic hazards.

Applications

• Bathymetry aids habitat management, ecology, cable and pipeline routing, & Law of the Sea.

• Gravity field details enable precision inertial navigation and resource exploration.

• Real-time sea level anomaly observations enable operational oceanography.

Cost and Schedule

$75M (2-string altimeter, WVR, bus, integration and test)
Phase A/B FY 2006, Phase C/D FY 2007-9, Launch CY 2009

Participants and Endorsers

National Oceanic and Atmospheric Administration
University of California (San Diego)-Scripps
Johns Hopkins University Applied Physics Laboratory
~100 signatories from academia, civilian and military operational agencies, and international organizations

Points of Contact

Dr. Walter Smith, NOAA
Walter.HF.Smith@NOAA.gov

Prof. David Sandwell, UCSD-SIO
dsandwell@ucsd.edu

Dr. Keith Raney, JHU/APL
Keith.Raney@jhuapl.edu

*** A White Paper submitted to the NRC Decadal Survey**

May 2005

1. A summary of the mission concept, including the observational variable(s) to be measured, the characteristics of the measurement if known (accuracy, horizontal, vertical and temporal resolution), and domain of the Earth system (e.g. troposphere, upper-ocean, land surface).

This is a low-cost mission addressing the Study's themes of Earth Science Applications and Societal Needs; Ecosystem Dynamics and Biodiversity; Weather; Climate Variability and Change; and Solid Earth Hazards, Resources and Dynamics.

Data generated by a radar altimeter over large bodies of water are sufficient to support the generation of gravity anomaly and bathymetry maps. This paper outlines the conceptual design of a single-frequency high-precision radar altimeter hosted on a small dedicated Pegasus-class spacecraft whose mission would be to determine near-global bathymetry to a resolution of 6 km (half-wavelength) by measuring sea-surface slopes. The resulting data will extend the high-resolution end of the spectrum beyond the best existing global marine gravimetric and bathymetric data by a factor of 4 to 5 in horizontal scale, or 20 in area, and resolving at least 50,000 presently unknown seamounts.

The required measurement is the slope of the sea surface, rather than its height, and so absolute accuracy of height, and long-term stability of height accuracy are not required. Resolution of slope at short spatial scales is limited only by instrument precision, and a delay-Doppler radar altimeter for a six-year (baseline, three-year minimum) mission will meet the requirements. To support fine spatial resolution, the orbital ground track should not repeat for at least 1.5 years; however, the order in which the tracks are acquired is irrelevant to gravity and bathymetry purposes. Therefore, the orbit can be tuned to be rich in "near-repeats" enabling the observation of mesoscale ocean features for near-real-time applications such as in tropical cyclone intensification forecasts. (Observing the ocean mesoscale from a non-exact-repeat ground track is "thinking outside the box" but the supporting web material at http://topex.ucsd.edu/concept shows that this can be done; it works because of the near-repeats and because the mean sea surface is now well-known at mesoscale wavelengths.)

The proposed mission will map seamounts and other features of ocean bottom roughness that are critical controls on the propagation of tsunamis, the mixing rates in the deep ocean, the steering of flows, and hence the modeling and forecast of tsunami hazard and climate variability and change. The mission will reveal the fabric of abyssal hills on the ocean floor, opening new science frontiers in the process of seafloor spreading and the Earth's magma budget. The gravity and bathymetry data also will support inertial navigation, fisheries and habitat management and ecosystem studies, cable and pipeline routing, the evaluation of territorial claims under the Law of the Sea, and assessments of the seismic hazards and resource potential of offshore areas.

2. A description of how the proposed mission will help advance Earth science and/or applications, or provide a needed operational capability, for the next decade and beyond.

Bathymetry is foundational data, providing basic infrastructure for scientific, economic, educational, managerial, and political work. Applications as diverse as tsunami hazard forecasts, communications cable and pipeline route planning, resource exploration, habitat management, and territorial claims under the Law of the Sea all require reliable bathymetric maps to be available on demand. Fundamental Earth science questions, such as what controls seafloor shape and how seafloor shape influences global climate, also cannot be answered without bathymetric maps having globally uniform detail.

Despite the fundamental nature of bathymetry, we have much better maps of Earth's Moon, Mars, Venus and some asteroid surfaces than we have of Earth's ocean floors. Seafloor maps are inadequate for many of the purposes above because there has been no systematic ocean mapping effort. Existing surveys cover only a small fraction of the ocean floor and in an irregular pattern (Figure 1). The most detailed mapping possible would employ ships or robotic vehicles equipped with acoustic swath mapping systems, but a complete survey would take hundreds of years of vessel time at a cost of billions of dollars [Carron, M. J., P. R. Vogt, and W.-Y. Jung, *Intl. Hydr. Rev.* 2(3), 49-55, 2001].

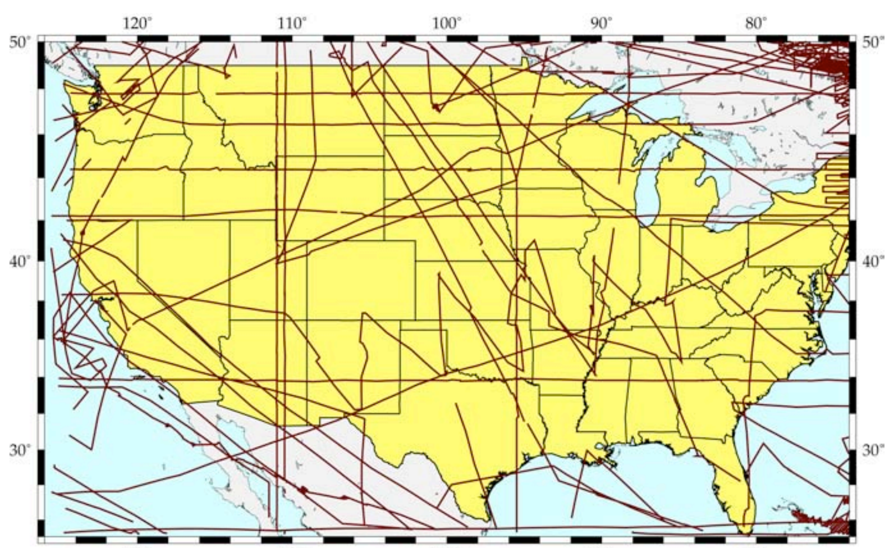


Figure 1. The topography of the United States would be very poorly known if surveyors took data only along the U.S. interstate highways. Our knowledge of the topography of remote ocean basins is similarly limited because the distribution of survey lines is just as sparse. Shown here are the bathymetric survey lines in the South Pacific (top) mapped at the same scale as the U.S.

Seafloor topography can be mapped globally from space in six years and at a cost under $100M. A radar altimeter mounted on an orbiting spacecraft can measure slight variations in ocean surface height, which reflect variations in the pull of gravity caused by seafloor topography. A new satellite altimeter mission, optimized to map the deep ocean bathymetry and gravity field, will provide a global map of the world's deep oceans at a resolution of 6-9 km. This resolution threshold is critical for a large number of basic science and practical applications, including:

- Understanding the geologic processes responsible for ocean floor features unexplained by simple plate tectonics, such as abyssal hills, seamounts, microplates, and propagating rifts (Figure 2).
- Improving tsunami hazard forecast accuracy by mapping the deep ocean topography that steers tsunami wave energy (Figure 3).
- Determining the effects of bathymetry and seafloor roughness on ocean circulation, mixing, climate, and biological communities, habitats, and mobility (Figure 4).
- Mapping the marine gravity field to improve inertial navigation and provide homogeneous coverage of continental margins.
- Providing bathymetric maps for numerous other practical applications, including reconnaissance for submarine cable and pipeline routes, improving tide models, and assessing potential territorial claims to the seabed under the United Nations Convention on the Law of the Sea.

Because ocean bathymetry is a fundamental measurement of our planet, there is a broad spectrum of interest from government, the research community, industry, and the general public.

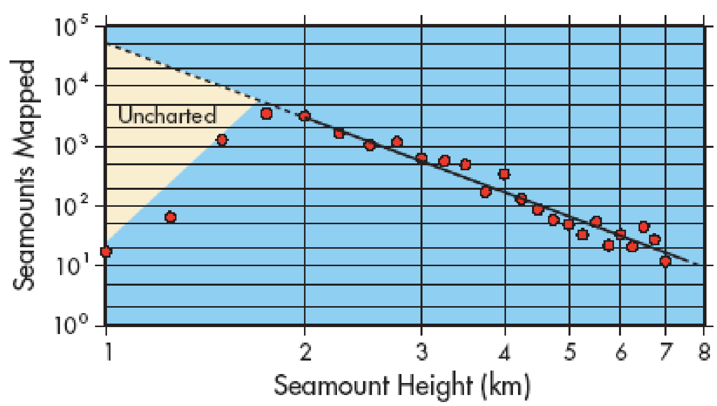


Figure 2. Seamounts come in a range of sizes. The red dots shown here indicate the number of seamounts found with existing satellite altimeter data, as a function of seamount size [Wessel, P., *J. Geophys. Res.*, 106, 19431-19441, 2001]. For seamounts 2 km tall and larger, the data are explained by a scaling rule (solid line). For heights less than 2 km, the red dots fall off the line because these more numerous small seamounts fall below the resolution of existing data. **A new Bathymetry from Space mission should find these unmapped seamounts.** Every improvement in height resolution by a factor of 2 should increase the total number of seamounts mapped by 18-fold. The newfound seamounts will have important applications in tsunami hazard (Figure 3), physical oceanography, marine ecology, fisheries management, and fundamental science questions about Earth's magma budget and the relationship between volcanism and

tectonics.

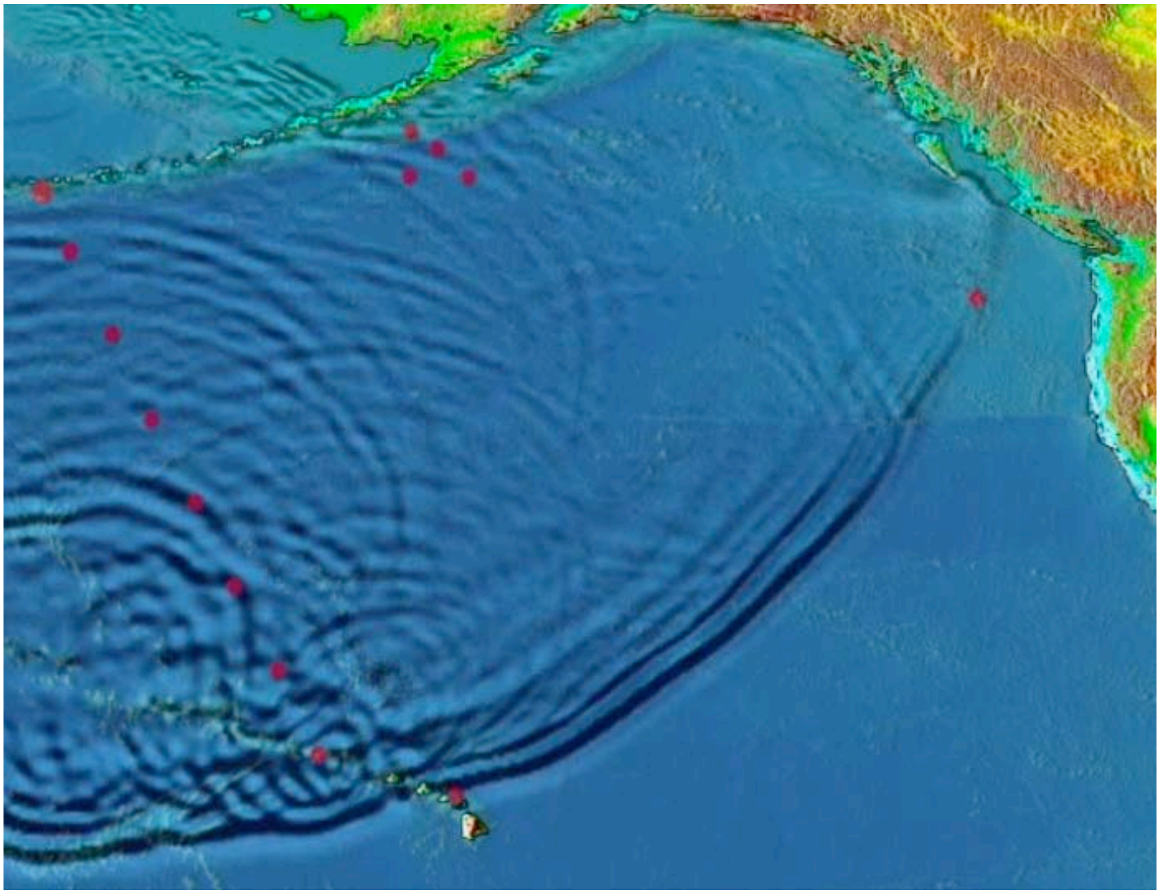
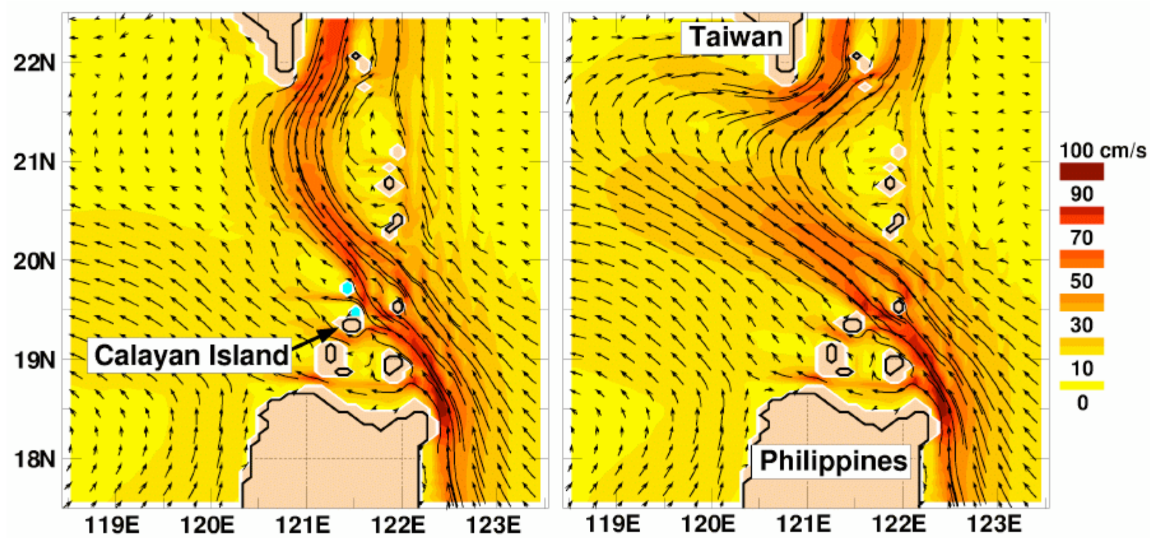


Figure 3. Tsunamis are catastrophic shock waves that can flood coastal areas after a submarine earthquake, volcanic eruption, or landslide. A submarine event on one side of an ocean basin can flood the coasts on the other side in a matter of hours. Careful modeling of the propagation and refraction of these waves is a key component of hazard mitigation. Shown here is a still image from an animation of the propagation of a tsunami in June of 1996 caused by a M7.9 earthquake in Adak, Alaska. The tsunami was 1 meter high in Alaska and 0.5 meters high in Hawaii. It was recorded at tide and bottom pressure gauges, allowing detailed studies of the effects of seamounts on its propagation. Please view the complete animation at http://topex.ucsd.edu/concept One can see here the general scattering effect of seamounts and the "wave guide" action of the Mendocino Fracture Zone to the west of California, but viewing the animation makes these effects clearer and also illustrates that the most energetic arrival may not be the first one, and that two nearby coastal areas may receive very different amounts of energy as a result of the effect of deepwater bathymetry on propagation. Based on the experience shown here, pre-computed tsunami scattering models are being implemented in the Pacific warning system, but these could be much better and might allow more localized hazard warnings if the seamounts on the ocean floor could be mapped in more detail. Model studies have shown that lack of information about the small-scale bathymetry of the ocean floor makes the estimated height of the flooding wave uncertain by 100% or more. We must map the ocean floor in order to correctly forecast the arrival times and energies of tsunamis. This is something a space mission can do, and it is perhaps the only real contribution to tsunami hazard that can be made from space.



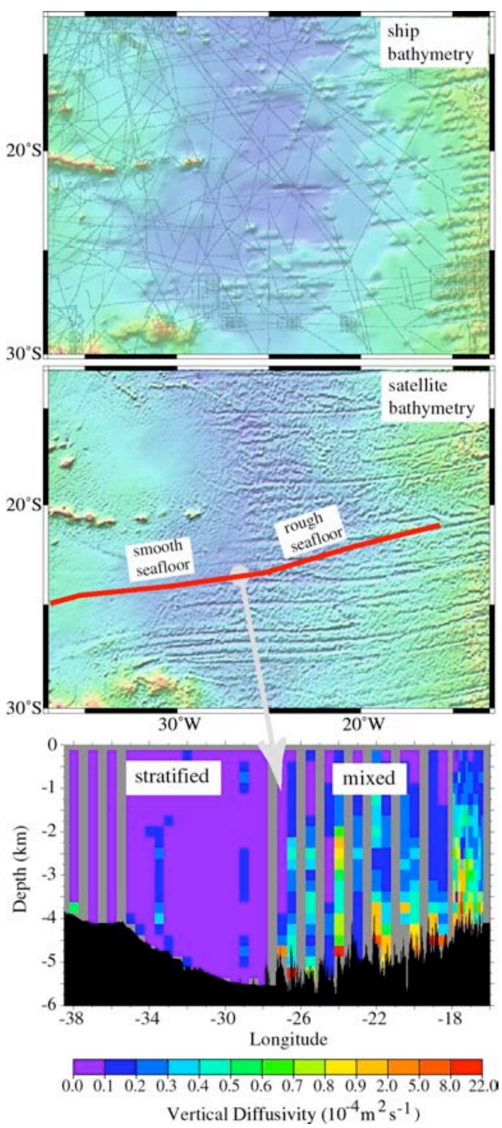


Figure 4a (above). The availability of accurate bathymetric data at ~10 km scale is critical for modeling the ocean's major current systems. Shown here is the behavior of the U.S. Navy's Layered Ocean Model simulating the mean flow of the Kuroshio Current in the North Pacific. In the left panel, the model correctly simulates the flow, while in the right panel the flow intrudes unrealistically far into the South China Sea. The bathymetry in the two model runs is different at only three grid points shown by the blue dots north of Calayan Island in the left panel. These small shoals in the Luzon Strait are required to correctly model this major flow in the Pacific. From Metzger, E.J. and H.E. Hurlburt, 2001, *Geophys. Res. Lett.*, 28, 1059-1062.

Figure 4b (at left). Mixing rates in the ocean govern the rate at which the ocean absorbs heat and greenhouse gases, moderating climate. Global climate change forecasts are uncertain in part due to uncertainty in the global average ocean mixing rate. Mixing rates in the ocean vary geographically depending on bottom roughness. (upper) Bathymetry of Brazil Basin, South Atlantic derived from ship soundings lacks the resolution needed to distinguish between rough and smooth seafloor. (center) Bathymetry derived from satellite altimetry and ship soundings resolves the rough seafloor associated with fracture zones but not abyssal hills. (lower) Mixing rates observed during an oceanographic survey across the Brazil Basin in the South Atlantic Ocean. Low mixing rates (purple) were found over the smooth topography to the west, and higher mixing rates (multiple colors) over the rough topography to the east. Modified from *Mauritzen et al.*, 2002, *J. Geophys. Res.*, 107(C10), 3147. For more discussion of the connections between the ocean bottom and mixing rates and global climate, please see the articles in *Oceanography*, 17(1), 2004 at www.tos.org

Mission Requirements

The resolution of the altimetry technique is limited by physical law, subject to instrument capability. Every bathymetric feature that might be mapped from space could be mapped now if a suitably configured instrument and mission were implemented. There is no gain in waiting for technological advances. Mission requirements for this task are much less stringent and less costly than typical physical oceanography missions. Long-term sea-surface height accuracy is not needed; the fundamental measurement is the slope of the ocean surface to an accuracy of ~1 microradian (1 mm per km). The main mission requirements are:

Improved range precision. A factor of two or more improvement in altimeter range precision with respect to current altimeters is needed to reduce the noise due to ocean waves.

Improved along-track spatial resolution. The missing seamount and bathymetric data are in the 6-km to 25-km range. The shorter scales can be mapped only if the along-track resolved footprint of the altimeter is ~ 6 km or less. This requirement cannot be met by conventional radar altimeter data, especially in areas of large prevailing significant wave heights such as are typical of the southern Pacific ocean.

Fine cross-track spacing and long mission duration. A ground track spacing of 6 km or less is required. A six-year mission would reduce the error by another factor of two.

Moderate inclination. Existing satellite altimeters have relatively high orbital inclinations, thus their resolution of east-west components of ocean slope is poor at low latitudes. The new mission should have an orbital inclination close to 60° or 120° so as to resolve north-south and eastwest components almost equally while still covering nearly all the world's ocean area.

Near-shore tracking. For applications near coastlines, the ability of the instrument to track the ocean surface close to shore, and acquire the surface soon after leaving land, is desirable.

3. A rough estimate of the total cost (large, medium, or small as defined above) of the proposed mission over ten years. For operational missions the costs should include one-time costs associated with building the instrument and launch and ongoing operational costs.

This is a "small" mission as defined by the Decadal Survey. The ROM cost of the spacecraft, two-string (redundant) altimeter, and water-vapor-radiometer (WVR) is $75M, based on a Phase A/B start in FY 2006, and a launch in CY 2009. The spacecraft will fit the mass and size constraints of a Pegasus launch vehicle reaching the desired orbit. Thus, the ten-year cost, including implementation, launch, on-orbit operations, one ground station with embedded ground support, and science, is much less than $200M.

Cost estimates are based on the ABYSS ESSP-3 proposal for the ISS instrument (peer-reviewed by NASA) and a NOAA-funded internal study at JHUAPL [Raney, R. K., Smith, W. H. F., and Sandwell, D. T., Abyss-Lite: A high-resolution gravimetric and bathymetric mission (AIAA-2004-6006), in *Proceedings, Space-2004*, AIAA, San Diego, CA, 2004] that considered spacecraft trade-offs including those in the GSFC Rapid Spacecraft Development Office catalog.

Abyss-Lite Design

A delay-Doppler altimeter [Raney, R. K., The delay Doppler radar altimeter, *IEEE Transactions on Geoscience and Remote Sensing* 36 (5), 1578-1588, 1998] meets the requirements cited above for lower noise level, robustness of noise in the presence of large surface waves, fine-scale resolution, and better nearshore tracking. Abyss-Lite, comprised of a single-frequency Ku-band radar, on-board processor, and essential subsystems, is a relatively simple, low-cost, small-satellite design. This instrument and signal processing has proven heritage. Under NASA Instrument Incubator funding, the Johns Hopkins University Applied Physics Laboratory developed and proved through airborne trials an airborne prototype that emulates the innovative features central to the delay-Doppler concept. Thanks to signal processing techniques adapted from the field of synthetic aperture radar, the resulting delay-Doppler radar altimeter has significantly better measurement precision than is possible with any conventional radar altimeter [Jensen, J. R. and Raney, R. K., Delay Doppler radar altimeter: Better measurement precision, in *Proceedings IEEE Geoscience and Remote Sensing Symposium IGARSS'98*ed, IEEE, Seattle, WA, 1998, pp. 2011-2013]. Furthermore, its canonic post-processing footprint is ~250 meters along-track; several of these can be accumulated to generate ~5 km spatial resolution, a dimension that does not expand with increasing wave height. The precision and spatial resolution of this instrument are ideally suited to meet the demands of high resolution gravimetry and bathymetry.

The altimeter in principle is similar to current conventional oceanographic instruments, and virtually identical to the SAR-mode of the SIRAL altimeter on CryoSat [Raney, R. K. and Jensen, J. R., An Airborne CryoSat Prototype: The D2P Radar Altimeter, in *Proceedings of the International Geoscience and Remote Sensing Symposium IGARSS02*, IEEE, Toronto, 2002, pp. 1765-1767]. However, unlike CryoSat, the Abyss-Lite altimeter payload includes a real-time processor, which has been true for all ocean-viewing radar altimeter satellites since Seasat. Consequently, the data storage and down-link rates are very small. (The inherent data rate from the instrument is less than 30 kHz.) Thus only one ground station is required to support the Abyss-Lite mission, with a factor of two reserve. Further, on-board processing sorts reflections by Doppler (along-track angle of the arrival), which is the basis for "smart" range-gate tracking to assure reliable near-shore operation.

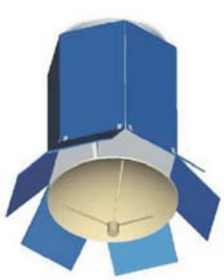


Figure 5. Abyss-Lite on-orbit configuration

The instrument payload and bus hardware required is all space-qualified, having strong heritage and low risk. The Abyss-Lite altimeter would be assembled on a dedicated honeycomb deck. Once integrated, the instrument would be environmentally tested, and calibrated before delivery to the spacecraft's integration facility. The integration with the spacecraft would occur toward the end of spacecraft assembly. The design study concluded [Raney, R. K., Smith, W. H. F., and Sandwell, D. T., Abyss-Lite: A high-resolution gravimetric and bathymetric mission (AIAA-2004-6006), in *Proceedings, Space-2004*, AIAA, San Diego, CA, 2004] that the spacecraft would fit the mass and size constraints of a Pegasus launch vehicle. A copy of the design study is at http://topex.ucsd.edu/concept

The two key parameters are: (1) instrument precision (which implies a delay-Doppler radar altimeter), and (2) the orbit, which must be non-repeating or a repeat period longer than one year), and at a moderate inclination (either prograde or retrograde). Spacecraft and instrument cost are not sensitive to these parameters, although the launch cost and launch vehicle mass limits do depend on inclination.

4. A description of how the proposed mission meets one or more of the following criteria, which will be used to evaluate and prioritize the candidate proposals:

4a. Identified as a high priority or requirement in previous studies, for example NRC and WMO reports and existing planning efforts such as the International Working Group on Earth Observations (IWGEO: http://iwgeo.ssc.nasa.gov);

ABYSS-Lite will deliver gravity and bathymetry that have been identified as needs in the National Research Council's review of NASA's Solid Earth Science Working Group strategic plan, in the NASA High-resolution Ocean Topography Science Working Group report, in the NASA/NOAA/NSF Bathymetry from Space workshop report, and in the American Geophysical Union's report to the United Nations on the Sumatra Tsunami.

4b. Makes a significant contribution to more than one of the seven Panel themes;

Theme 1 - Earth Science Applications and Societal Needs: Gravity anomalies from this mission would supply data on deflections of the vertical that are needed in military and civilian inertial navigation systems. Bathymetry from this mission will aid fisheries and habitat management, ecological studies, cable and pipeline route planning, assessment of seabed territorial claims under the UN Law of the Sea, and many other applications; bathymetry is foundational data for all ocean science, management, and policy.

Theme 2 - Land use change, ecosystem dynamics, and biodiversity: Seamounts host important ecosystems in the oceans, and fish living on deep sea seamount flanks, such as Oreos and Orange Roughy, have become economically important. Existing maps poorly resolve seamounts and their summit depths. The proposed mission will vastly improve the mapping of seamounts, providing foundational data for ecology and biology.

Theme 3 - Weather: The proposed mission will furnish spatially detailed near-real-time observations of warm- and cold-core eddies, data used in forecasts of tropical cyclone intensification. (Recovery of the eddy field from a geodetic orbit is demonstrated in the supporting material at http://topex.ucsd.edu/concept) Tsunami hazard forecasts for the United States are under the National Weather Service and thus may be considered a "weather" issue; however, this Concept Paper takes these under Theme 7 – Hazards.

Theme 4 – Climate Variability and Change: Ocean topography and bottom roughness mapped by this mission are needed for realistic models of ocean circulation and climatically important heat transport. Three articles making the connections between the ocean floor and climate modeling are at http://www.tos.org/oceanography/issues/issue_archive/17_1.html

Theme 7 - Solid Earth Hazards, Resources and Dynamics: This mission addresses seismic and tsunami hazards, marine petroleum and mineral resources, and fundamental science questions in the dynamics of sea floor spreading, plate tectonics, and Earth's magma budget. For details on the tsunami and seismic hazard applications, see the article at http://www.tos.org/oceanography/issues/issue_archive/issue_pdfs/17_1/17_1_Mofjeld_et_al.pdf and the animation at http://topex.ucsd.edu/concept

4c. Contributes to important scientific questions facing Earth sciences today (scientific merit, discovery, exploration);

The surfaces of Mars, Venus, Earth's Moon, and some asteroids are much better mapped than Earth's ocean floors, and many fundamental discoveries await the mapping of our home planet. Marine gravity anomaly and bathymetry maps obtained from existing altimeter mission data have revealed the global pattern of mid-ocean ridges, transform faults and fracture zones, trenches and linear volcanic chains that are the basic ideas of the plate tectonic theory. At the same time these data have revealed some enigmas in the details of plate tectonic processes. What controls the transition between smooth and rough seafloor generation at mid-ocean ridges? How and why do ridge discontinuities propagate? Are linear chains of very small seamounts caused by small-scale convection, hotspots, or the stretching or cracking of plates? Is there a speed limit to plate tectonics? What is the magmatic budget and thermal history of the Earth? The proposed mission will open new insights into these fundamental questions, by resolving the tectonic fabric of the ocean floors at the scale of abyssal hills and small seamounts.

4d. Contributes to applications and/or policy making (operations, applications, societal benefits);

Bathymetry is basic infrastructure for a variety of applications and policy issues from territorial claims to fisheries management. As one example, the location of the 2500 m isobath (depth contour) is one element in extended territorial claims to the seabed under Article 76 of the United Nations Convention on the Law of the Sea. Data from this mission can be used to evaluate potential territorial claims by any coastal nation. The non-living resource value alone in a possible United States claim was estimated at $1.3 trillion in 2000 dollars at 2000 oil prices [Murton, B., L. Parson, P. Hunter and P. Miles, Global non-living resources on the extended continental shelf: prospects at the year 2000, Intl Seabed Authority, Kingston Jamaica, 2000].

The mission will also furnish near-real-time sea level anomaly observations for operational oceanography applications in hurricane intensification, oil spill dispersal, search and rescue, and other activities.

4e. Contributes to long-term monitoring of the Earth;

Gravity and bathymetry at the scales mapped here do not change over human lifetimes, so the mission needs to be done only once; this will not lead into a perpetual series of monitoring missions. However, the mission will furnish near-real-time sea level anomalies for monitoring mesoscale ocean features. This will be an important contribution to monitoring the Earth, particularly if the mission is launched during a time gap in coverage by other missions, such as may occur in the 2008-2013 time frame. Recovery of mesoscale ocean variations from a non-exact-repeat orbit is thinking outside the box, but it works. Please see the demonstration at http://topex.ucsd.edu/concept

4f. Complements other observational systems;

This mission complements other gravity observing and ocean observing systems. Space-based gravity observing satellite programs such as GRACE, CHAMP and GOCE sense the gravity field at satellite altitude, ~400 km above the Earth, and so a physcal law called "upward continuation" in potential theory limits their spatial resolution to about 200 km and wider features. The proposed mission, by measuring how gravity anomalies distort the shape of the ocean surface, measures the gravity field at sea level and so suffers no loss of resolution. Thus this mission can fill in the spatial details unseen by GRACE, CHAMP and GOCE.

Eddy-resolving ocean circulation models have been shown to require satellite altimeter observations of sea level anomalies in order to fully resolve the mesoscale ocean flow; in situ observation programs such as the ARGO floats furnish inadequate sampling. Traditional exact-repeat mission oceanographic altimeters (Topex/Poseidon, Jason, OSTM, ERS-1, -2, EnviSat, Geosat Follow-On) leave large and permanent gaps in their spatial coverage. The proposed mission's orbit can be tuned so that its ground track has a near-repeat ideal for filling the gaps in mesoscale coverage.

The oceans are presently observed by four altimeters (Topex, Jason, EnviSat, GFO) but by 2008 there may be only one altimter (OSTM) in an orbit poorly suited to mesoscale observing, a situation not to be remedied until the launch of NPOESS C-3 in 2013. If the proposed mission flies in the 2008-2013 time frame, data from a mission such as proposed here are required for applications such as hurricane intensification forecasts.

4g. Affordable (cost-benefit);

This is a low-cost mission and the benefits extend across a wide variety of applications. To put the cost in perspective, a complete mapping of the oceans by ships will require ~100 years of survey time at a cost of ~10 billion dollars [Carron, M.J., P.R. Vogt and W.-Y. Jung, A proposed international long-term project to systematically map the world's ocean floors from beach to trench: GOMaP (Global Ocean Mapping Program), *Int. Hydr. Rev.*, 2(3), 49—55, 2001]. The cost of not mapping the ocean is also high. On January 8 2005 a billion dollar US nuclear submarine was wrecked when it ran at full speed into an uncharted seamount.

4h. Degree of readiness (technical, resources, people);

The concept has matured through the NASA ESSP process, NSF, NOAA, NASA and Navy workshops, NOAA-funded design studies, and numerous peer-reviewed publications. The instrument has been developed and flown in aircraft under NASA Instrument Incubator Program funding. There is space flight heritage of all the key technical components. Data processing algorithms, archiving, distribution, and customer service apparatus have already been developed and proven with previous missions. Human and other resources are in place. The cost is low and the NASA cost can be lower by leveraging NOAA, DoD or international agency interest.

4i. Risk mitigation and strategic redundancy (backup of other critical systems);

The proposed program has very low scientific, operational or technical risk, and will furnish new data not available by other means within a reasonable time and cost. The mission extends the resolution, and hence value, of other gravity and ocean observing programs. If launched in the "altimeter gap" of circa 2008—2013, it mitigates the risk of having zero sea level observing capability should OSTM fail.

4j. Fits with other national and international plans and activities.

In addition to the items mentioned under 4a above, there is NOAA and Navy interest in the mission and significant inter-agency contributions may be possible. There is a nascent science working team in France and Danish, Dutch and English investigators are also studying potential synergies.