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Ocean Gravity Models From Future Satellite Missions

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Over the past 3 decades, satellite altimetry has been a key tool for dynamic ocean studies and for accurately estimating sea surface heights. The geodetic reference surface—the "geoid"—can be approximated as the mean sea surface height of an ocean corrected for dynamic terms such as tides and currents. It is an equipotential surface of the gravity field; and variations of this field are quantified as free-air anomalies, from which density heterogeneities of the oceanic basement can be inferred.

Using such data in combination with other geophysical data, scientists have improved their knowledge of the nature of submarine relief and underlying structures. In solid Earth geophysics, major breakthroughs came from the development of high-resolution marine gravity models based on closely spaced altimetry profiles collected during the U.S. Navy's Geosat satellite geodetic mission (launched in 1985) and the first version of the European Remote Sensing satellite geodetic mission (ERS 1, launched in 1991). These were combined with other repetitive profiles from the international TOPEX/POSEIDON satellite (launched in 1992); ERS 1; TOPEX/POSEIDON's successor, Jason (launched in 2001); and the European Space Agency's (ESA) Envisat missions (ERS's successors [see, e.g., *Sandwell and Smith,* 1997; *Andersen and Knudsen,* 1998]).

These missions helped scientists to quantify free-air anomalies. Such satellite-derived free-air anomalies, combined with existing bathymetric data, allowed the calculation of a global predicted bathymetry, of great use for planning cruises and other geodynamic and lithospheric studies [*Smith and Sandwell,* 1997; *Calmant et al.,* 2002; *Ramillien and Cazenave,* 1997]. Further, knowledge of the fine-scaled variations in bathymetry and sea surface heights through analyzing free-air anomalies have improved the study of ocean circulation, maps of the continental shelves near coastlines, surveys of natural resources, predictions of tectonic plate reorganizations, and the detection of earthquakes and tsunami.

Recent advances in technology promise geodetic analysis using satellite altimetry on a very fine scale. This has forced scientists to evaluate their needs in light of ever tightening governmental and institutional science budgets. From community discussions, two mission scenarios, the Surface Water and Ocean Topography (SWOT) project and the Gravity From Altimetry (GRAL) project, have emerged to help advance marine geophysical studies in the 21st century (see Figure 1).

The Need for a Dedicated Satellite Altimetry Mission

Satellite altimetry data are typically fed into gravity models that have been thoroughly tested against shipborne marine gravity data [*Rapp,* 1998; *Rapp and Yi,* 1997; *Featherstone,* 2002; *Denker and Roland,* 2003; *Small and Sandwell,* 1992]. Differences between these data sets average about 12 milligals, equivalent to a few centimeters in mean sea level depending on the geographical areas, the proximity to coasts, the presence of permanent currents, etc.

Initial gravity models were able to resolve features as small as 25 kilometers. Newer models, using retracking (i.e., repicking arrival times of radar pulses and recalculating orbit heights), improved this resolution to 16 kilometers. However, this quality decreases considerably near coastal shelves or in rough bathymetric areas, where the resolution remains no better than in the initial models. These values represent the upper quality limits of the models currently available (e.g., the Sandwell V16.1 [*Sandwell and Smith,* 2009] or Andersen and Knudsen DNSC08 models).

Such limitations are partly due to altimetric technology, which prevents the exploitation of measurements close to the coastlines

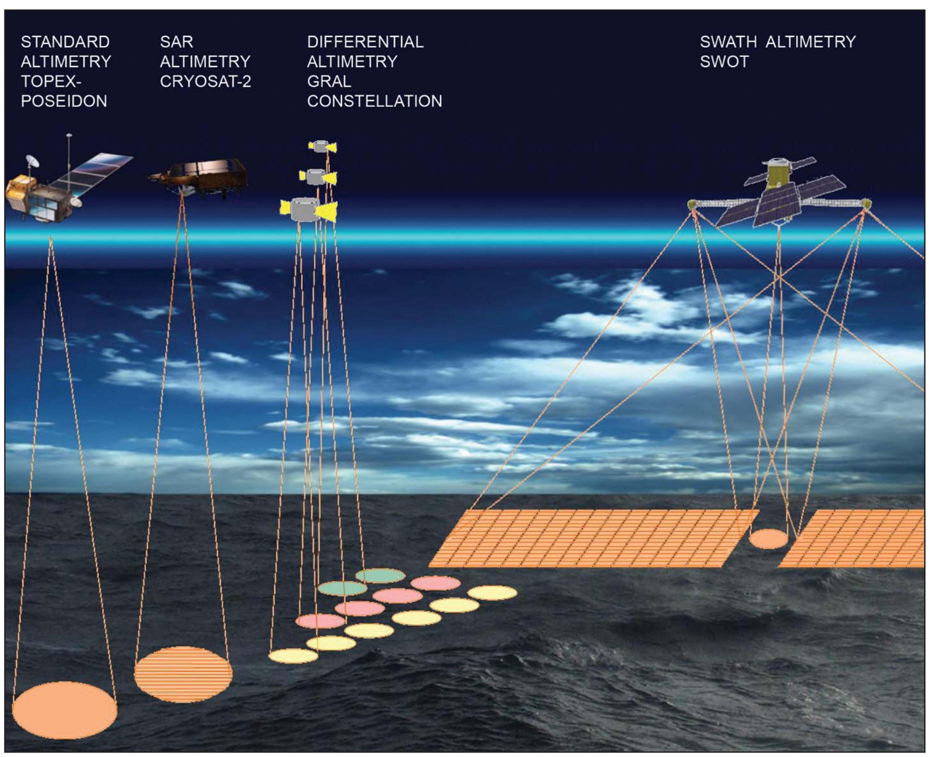

Fig. 1. Standard altimetry on the TOPEX/POSEIDON satellite and synthetic aperture radar (SAR) satellites (such as the upcoming CryoSat 2) traces out discrete footprints on the Earth's surface. The proposed Gravity From Altimetry (GRAL) project modifies this footprint approach, whereas the proposed Surface Water and Ocean Topography (SWOT) project traces out a swath. Image compiled from the European Space Agency and Rodriguez *[2008].*

and limits the space resolution along the satellite tracks to 7 kilometers after reprocessing. The resolution across track remains unchanged. In addition, the altimetry missions were mostly designed for oceanography purposes, which prioritized short-time repetitiveness of the orbits (i.e., large track spacing) over spatial coverage (i.e., nonrepetitive orbits) and thus degraded the spatial resolution of the whole.

As a result, except for geodetic missions with drifting orbits, altimetric missions have been generally dedicated to accurate dynamic oceanic studies, with highly repetitive tracks spaced some 100 kilometers apart. Other missions are subject specific (such as the soon-to-be-launched CryoSat 2, an ESA mission to study sea ice). So despite significant improvements in the accuracy of altimeters, the spatial coverage remains largely inadequate for geodetic purposes.

In an attempt to overcome these limitations, a mission called Altimetric Bathymetry From Surface Slopes (ABYSS) was proposed in the early 2000s [*Smith et al.,* 2001], with the goal of reaching the ultimate resolution allowable by the laws of physics to predict bathymetry from space (about 8 kilometers, or twice the ocean average depth). Spurred by a white paper published in 2001 [*Sandwell et al.,* 2001] and a workshop in 2002, the geodetic community agreed that such satellite-borne radar altimetry appeared as the least expensive and most realistic way to obtain a global high-resolution gravity model over the world's oceans. However, the ABYSS proposal was rejected by funding agencies.

Spatial gravity missions such as the ESA's Gravity Field and Steady-State Ocean Circulation Explorer (GOCE), launched in March 2009 with an onboard gradiometer, will directly provide global gravity field and geoid data but with a spatial resolution no better than 100 kilometers. The GOCE data will especially improve the standardization of the world geodetic references [*Johannessen et al.,* 2003].

Nonetheless, a dedicated satellite altimetry mission still remains the best means to bridge the resolution gap between spacecraft and shipborne gravimetry. It can usefully take advantage of the long-wavelength gravity from the GOCE mission and fill in short-wavelength information. Scientists are now seeking to rally the scientific community around an altimetric mission with the primary objective being to provide a high-resolution mean sea surface and geoid, with SWOT and GRAL as the leading candidates.

Requirements and Inherent Limitations

The objective of a new high-resolution altimetry mission is to reach the quality level of shipborne gravity surveys and get as close as possible to a resolution of 1 kilometer. This spatial resolution corresponds to the size of the smallest cell within gravity models. Thus, a high resolution is directly linked to a small altimeter footprint. Most current missions have a ground footprint of nearly 60 square kilometers, whereas frequency delay–Doppler and single-aperture radar technologies or data retracking provide a better resolution.

Currently, the smallest achievable measurement cell size for gravity models ranges from 4.2 to 5.3 kilometers on a side, depending on the specifications of the satellite altimetry data that feed the model. This size may be reduced to a promising 1 kilometer using swath altimetry [*Fu and Ferrari,* 2008], but the signal still needs to be integrated over a larger surface to increase the signal-to-noise ratio. Moreover, the ranging precision has to be improved by a factor of 2. A requirement of 1 milligal roughly corresponds to the instrument being able to measure 1 centimeter in height over as much as 10 kilometers in distance [*Sandwell et al.,* 2001].

The data coverage, required to be as uniform as possible over the whole oceanic surface, depends on the repeatability of the satellite orbits and on their inclination. Considering a classical altimeter, only a nearly drifting orbit with low repetitiveness will produce ground tracks not spaced more than the size of the footprint. Further, the orbit inclination must be as high as possible (>85°) to cover the polar regions.

The SWOT Project

Given these requirements and limitations, the SWOT project [*Fu and Ferrari,* 2008] may represent a unique opportunity for solid Earth sciences. Similar to how swath bathymetry echo sounding revolutionized seafloor surveys in the early 1980s, the ambitious and revolutionary SWOT project seeks to perform swath altimetric measurements. Hence, instead of averaging over the whole footprint surface, it will rake the oceans and determine the height along the width of the swath. The principle of swath altimetry relies on across-track measurements of radar reflectance and interference patterns. By illuminating a wide strip perpendicular to the satellite's track and by receiving the signal on two antennas sufficiently distant, the altimeter will be able to measure in stereo the height of the ocean surface.

Such technology would allow scientists to reach a kilometric resolution for the first computed cells of gravity models [*Rodriguez,* 2008]. SWOT's expected performance of 1-centimeter resolution in height for every 5 kilometers on the ocean heavily depends on how precisely the distance and the attitude between the antennas, about 20 meters apart, can be monitored. The instrument's proposed 78° orbital inclination will ensure coverage of most of the polar regions and will leave no gaps in track coverage while ensuring convenient time sampling, with an approximate repetitiveness of 11 days. However, the first 3 months will be a calibration and validation phase, in which spatial coverage will be ignored but repetitiveness will be tested at 3 days to improve resolution calibration [*Rodriguez,* 2008]. SWOT's launch is envisioned for 2016.

The GRAL Proposal

SWOT is ambitious, and given current tight science budgets for government institutions and universities, a simpler alternative might be necessary. Fortunately, there is a less expensive and technologically robust alternative to the ambitious SWOT project to measure accurately the mean sea surface. Reviving the Water Inclination Topography and Technology Experiment (WITTEX) [*Raney and Porter,* 2001], the GRAL mission concept consists of a constellation of three nanosatellites weighing less than 10 kilograms each and equipped with classical footprint altimeters that follow each other along the same near-polar orbit. The principle is to obtain instantaneous differential altimetric or slope measurements, both along and across track, thanks to the constellation configuration.

The expected performance of GRAL matches that of SWOT. These satellites would be launched together, and the high ratio of performance to cost would make GRAL a tractable alternative for acquiring a high-resolution geoid (Figure 1).

Next Steps: Picking a Project

It is clear that improvements in both the accuracy and the spatial resolution needed to uniformly describe short-wavelength anomalies of the mean sea surface, geoid, or derived gravity field require a new high-resolution altimetric mission as a complement to the GOCE mission. For a comparison of SWOT and GRAL with past and future missions, in terms of repeat cycles, inclination, and data resolution, please see the electronic supplement to this *Eos* issue (http://www.agu.org/eos_elec/).

Of the two leading satellite altimetry mission scenarios, SWOT is the most likely to meet community requirements, but GRAL has the benefit of being a simpler, lower-cost alternative. GRAL perhaps could be a first guess to high-resolution gravity modeling, with SWOT following later, depending on new technology, designs, and financial costs.

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NEWS

McNutt Outlines Priorities for the U.S. Geological Survey

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For Marcia McNutt, the new director of the U.S. Geological Survey (USGS) and science advisor to the secretary of the interior, the clock is ticking. "Everyone feels that we have perhaps 3 years in which a very ambitious agenda needs to be accomplished," McNutt told *Eos* in a recent exclusive interview. "We want to make sure by the end of [U.S. President Obama's] first term we have got significant accomplishments on issues such as climate change, environment, and energy, and other things that are important to the president."

"Everything is on a fast track to move quickly," she said. "Everything had to be done yesterday, if not last week." While the political process often requires immediate scientific information, the scientific process can take a bit longer, McNutt said, noting that it is fortunate research at the USGS has persisted in many areas.

McNutt comes well prepared for the task to head the USGS. She was president and chief executive officer of the Monterey Bay Aquarium Research Institute, Moss Landing, Calif., from 1997 to 2009. In addition, she chaired the Ocean Exploration Panel convened by former U.S. President Bill Clinton; was a professor of geophysics at the Massachusetts Institute of Technology and at Stanford University, California; worked at the USGS on earthquake predictions from 1979 to 1982; and was chief scientist on many oceanographic expeditions. Her education includes a doctorate in Earth sciences from the Scripps Institution of Oceanography, La Jolla, Calif., and completion of a U.S. Navy SEALS underwater explosives training course.

In addition, she was AGU president from 2000 to 2002 and received AGU's Macelwane Medal in 1988 for research accomplishments by a young scientist and the Maurice Ewing Medal in 2007 for her significant contributions to deep-sea exploration.

McNutt has indicated that her priorities at the USGS include making progress regarding climate change and renewing the agency's workforce. "The time is right to make climate change a top priority within the USGS," McNutt said. Even with the restrictions on resources due to the federal deficit and the war in Afghanistan, "this is going to be one of the very few areas where we will see some growth in the budget and some creative ways that we can work with other agencies to get some traction on this problem." McNutt said the two parts of the USGS science strategy that mesh best with the White House's and the

Marcia McNutt

interior secretary's priorities concern climate change and developing renewable energies.

Renewing the USGS workforce is important, she said, because about 40% of the workforce will be at or beyond retirement age in the next 5 years.

"The erosion in the USGS has been because over the years, [the agency] has been strangled by year after year after year of flat budgets in the face of increasing costs, and the inability to hire," McNutt told *Eos*. "To put us back on top again, we need to be able to renew our workforce, and we need the budget to execute our mission."

McNutt said the workforce needs to better reflect the nation's diversity and the "full