

MARINE GEOID, GRAVITY AND BATHYMETRY: AN INCREASINGLY CLEAR VIEW WITH SATELLITE ALTIMETRY

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ABSTRACT

Spaceborne radar altimeters have been profiling the ocean surface for over 30 years. These altimeter data have afforded the geoscience community a revolutionary and dramatically-improving view of the global marine gravity field - and geoid. These altimetric marine gravity fields have led directly to a greatly improved understanding of global bathymetry and marine tectonics. Over the past 15 of these 30 years, this altimetric profiling has been continuous, starting with ESA's ERS-1 launch in 1991 and followed by ERS-2 and Envisat both of which continue observing today. This retrospective paper chronicles the major progress realized in accurately mapping the static component of ocean surface topography and how as a result our knowledge of the global ocean floor's structure and tectonic history has dramatically increased.

1. INTRODUCTION

1.1. Altimetry's modern age

The modern age of satellite altimetric studies of ocean surface topography began with European Space Agency's (ESA's) launch of the European Remote Sensing satellite, ERS-1, in July, 1991. ERS-1 carried a single frequency (13 GHz) radar altimeter (RA) and employed it to make high-accuracy, ~3 cm precision (noise) [1] elevation measurements of the ocean surface topography as well as wave height and wind speed from a near-polar (98.5 degree inclination), 800 km elevation orbit continuously from 1991 through 1996. ERS's near polar orbit afforded nearly complete (99%) of the global ocean – covering all of the Southern Ocean and Antarctic seas (except very small portions underlying the southernmost limits of the Ross and Filchner floating ice shelves) and missing only the northernmost Arctic Ocean (latitudes north of 81.5°N).

For most of its operational lifetime, specifically from April 1992 until December 1994 and mid-1995 until its 1999 demise, ERS-1 was in a 35-day repeat orbit dubbed the Multi-Disciplinary Phase or what we shall refer to as the Exact Repeat Mission (ERM). During this 35-day ERM repeat phase ERS yielded moderately dense coverage of the oceans with a ground-track spacing of approximately 75 km at the equator (see Fig. 1).

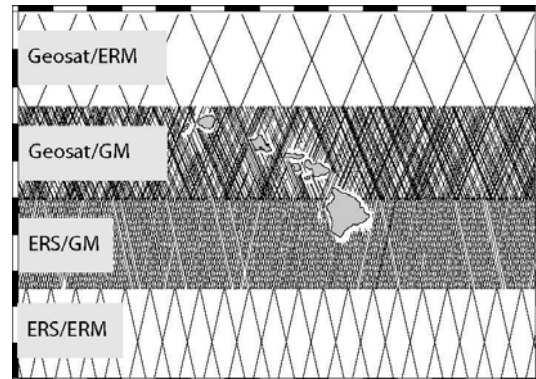


Figure 1. Sample ground-track pattern of various altimeter missions, e.g., ERS-1 and ERS-2. GM denotes Geodetic Phases for ERS-1 and Geosat. ERM denotes 35-day repeat for ERS-1 and ERS-2 and 17-day repeat for Geosat. Over Hawaiian Islands. Courtesy Dave Sandwell.

However of particular importance to marine geodesy and geophysics was ERS-1's Geodetic Phase (or Mission) GM which started in April 1994 and included two, successive 168-day repeat periods whose tracks were offset by 8 km producing a 366-day super-cycle.. This Geodetic Phase (ERS/GM) continued for a year until the launch of ERS-2 in April 2005 and produced a very dense coverage of the oceans (see Fig. 1) with a typical ground-track spacing of ~7 km at the equator. The ERS-1 GM produced that

which is arguably "...the most important marine geological and geophysical data set collected in the past (15 years)" [2] and enabled mapping of virtually the entire global marine gravity field to a two-dimensional, full-wavelength spatial resolution of 20 km or better [2, 3,13].

In April 1995 ERS-1 was joined in orbit by its successor mission ERS-2 which has operated now for more than ten years generally in the same 35-day repeat orbit as that of the ERS-1 Multi-Disciplinary Phase. ERS-2 was, in turn joined by Envisat in March 2002 which operates a two-frequency radar altimeter generally from this same 35-day orbit.

1.2. The early days of altimetry

Altimetry arguably got started in earnest with the 1969 NASA-sponsored Williamstown Conference and its report[4]. First among its four principal recommendations was development of satellites with "...10 cm accuracy altimeters...to measure the geopotential and mean sea level accurately enough to ...determine the general circulation of the oceans (and) to resolve the spatial variations in the gravity field to 100-km half wavelength." Note however that these same altimeter satellites were also envisioned to orbit drag-free at low (250 km) elevations and to include precise range-rate inter-satellite tracking from high-elevation (6000 km+) orbiters. So while the Williamstown Conference's entire vision of altimeter satellites did not fully and precisely become reality, it proved to be an extraordinary vision nonetheless. As we shall see, satellite altimetry's accuracy and impact on gravity and solid earth physics has far exceeded even the ambitious vision of this 1969 Conference. Within the nine years following this conference NASA launched three satellite altimeters: (1) S-193 SkyLab [5] in 1973, (2) the Geos-3 [6] in 1978 and (3) Seasat [7] in 1978. SEASAT yielded ocean elevation measurements in 1-s (or 6 km) averages which are precise to about 10 cm [7] and represented a dramatic improvement over Geos-3 or Skylab. Although SEASAT failed prematurely - only operating for about 3 months - it produced a data set that proved to be a landmark for marine geodesy and geophysics. This SEASAT data set yielded the first accurate maps of mean ocean topography, e.g. [8], substantially more precise than those from Geos-3 [9]. Moreover, W. F. Haxby (see Acknowledgements) and others [10, 11] computed accurate marine fields from these

SEASAT data and thereby imaged large-scale tectonic features on the ocean floor (see Fig 2).

2. WHY ALTIMETRY IS SO IMPORTANT FOR MARINE GEOPHYSICS AND GEODESY

2.1 Tectonic Fabric

The pioneering work of Haxby and colleagues [10, 11] involved computing and imaging marine gravity from SEASAT data and revealed - arguably for the first time - the actual large-scale tectonic fabric of the ocean floor. For example the mid-ocean ridge system can be traced around the globe in these SEASAT images (e.g. see the Southwest Indian ridge running from the center to lower left of Fig. 2; see also [13]). These SEASAT images were strikingly revealing in part because actual (sonar) surveys of the seafloor were, and are, sparsely distributed over the oceans [12,14]. Regions of the Southern Ocean roughly 500 km by 500 km (i.e., larger than the entire island of Ireland or US state of Colorado) still exist which are devoid of bathymetric soundings; in fact the topography of Mars and Venus are better mapped than our own seafloor.[15]. The 1600-km-long Foundation Seamount chain composed scores of undersea volcanoes was unknown before and discovered using SEASAT data [12]. Of course, our topographic knowledge gap results from the several kilometers of ocean which mask the seafloor. But fortunately the ocean's surface does not have a total "poker face". Subtle undulations (of amplitude millimeters to dekameters) in the marine geoid contain much information about the seafloor topography. Over the deep, mid-ocean where sediment cover is relatively thin (e.g., most mid-ocean ridge systems), these geoid undulations - or gravity anomalies - correlate strongly (at wavelengths < 300 km) with bathymetry [12]. Owing to this correlation, researchers [16] were able to detect roughly 1000 previously uncharted seamounts in the SEASAT data. The SEASAT data alone produced a seafloor mapping of 60 to 70 km resolution and led to the discovery of many major tectonic features such as the 1600-km-long Foundation Seamount chain as well the actual, full extent of 3500-km-long Louisville ridge [12, 15]. Moreover SEASAT marine gravity maps served as confirmation of the plate tectonic hypothesis. Corresponding images derived from ERS and Geosat/GM data reveal - as we will see below - substantially finer tectonic detail.

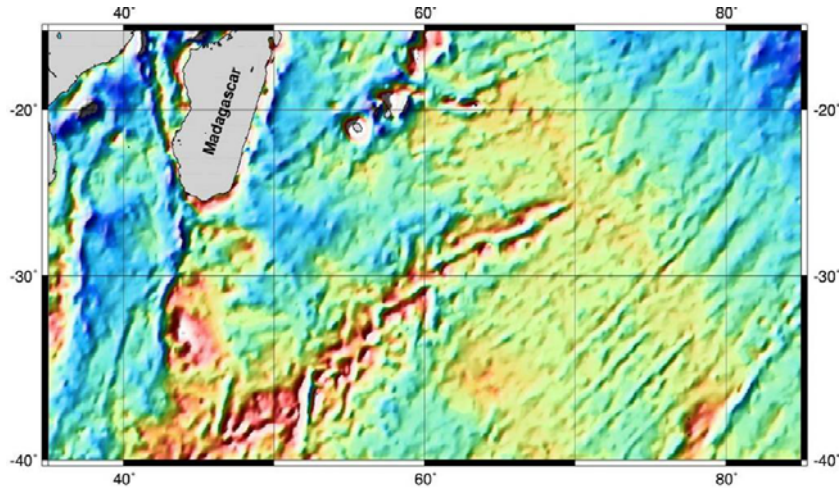


Figure 2. Marine gravity computed from SEASAT data over region of the Indian Ocean (Rodriguez) triple junction (70°E, 26°S) of three active seafloor spreading ridges (see Fig 3 and associated text). Recomputed but resolution is comparable to maps of Haxby [10,11]

2.2. The ERS-1 – GEOSAT GM Synergy

2.2a Tectonic Details

The densely spaced altimeter data from the ERS-1's 168-day Geodetic Mission (see text above) and from GEOSAT/GM are clearly very important to marine geodesy and geophysics. They are particularly important for mapping the

marine tectonic details, and refining models of plate motion, e.g., precise details how seafloor spreading (between tectonic plates) has varied in space and time in the past 180 million years. Indeed transient (non-steady) details of plate motion can be delineated by tracing fine-scale structures (e.g., propagators, etc) in the seafloor. For example, in Fig. 3, we see three major

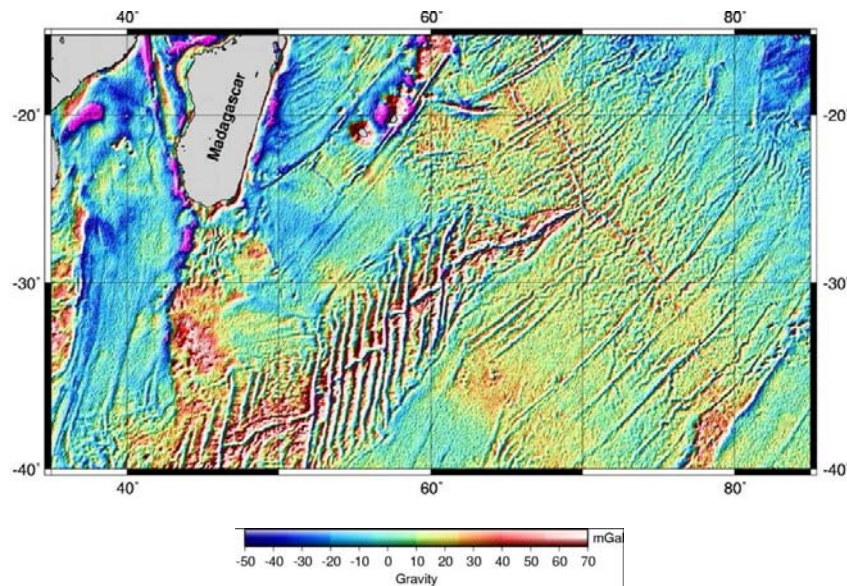


Figure 3. Marine gravity computed from GEOSAT and ERS data by Sandwell and Smith [2,18] (see also [19]) over region of the Indian Ocean (Rodriguez) triple junction (70°E, 26°S). See text. Compare with Figure 2.

spreading centers: the Southwest Indian Ridge (SWIR), the Central Indian Ridge (CIR), and the Southeast Indian Ridge (SEIR) all meeting at the Rodriguez Triple Junction (RTJ, at 70°E, 26°S). The SWIR is the locus of seafloor spreading between the Antarctic and African plates and extends from the lower left in Fig 3 northeast to the Rodriguez Triple Junction (RTJ) in the Central Indian Ocean. The SWIR's central (axial) valley can be seen very clearly in Fig 3. Note also in Fig 3 the 'V' pattern which flanks the SWIR's axial valley and whose vertex is at the RTJ.. This "V" opens to the southwest and the north-south lineations within the "V" define the SWIR Fracture Zones (FZ). The "V" itself traces the past loci of RTJ. The northern leg of the 'V' traces the RTJ's locus on the African plate and the southern leg traces RTJ's locus on the Antarctic Plate.

So the detailed ERS/Geosat gravity (Fig 3) confirms that – and exactly how – the RTJ has been migrating to the northeast at about 3.6 cm/yr for past 43 million years (see [20] for details).

While the comparable marine gravity (Fig 2) derived from SEASAT data does show the large scale tectonic fabric it does not contain the important fine-scale details. e.g., the "V" trace of the Rodriguez Triple Junction; RTJ. The preceding is just one example of how the recent ERS/Geosat-GM marine gravity fields reveal important details in the tectonic structure of ocean basins and help refine tectonic models including trace the non-steady components of relative plate motions.

2.2b Geopolitical Aspects

In 1992 when ERS-'s 168-day Geodetic Mission was first proposed and openly discussed [17] at the first ERS-1 Symposium in Cannes, France, almost all Geosat/GM data (all data north of 30°S) remained classified by the US Navy. [13]. In fact Anny Cazenave [17] and colleagues who helped propose the ERS-1 GM expressed concerns that the US would never declassify the Geosat GM data, and in fact the US Navy might be unhappy with the ERS-1 GM. It seems now that ERS-1 GM ultimately caused the US to declassify in 1995 all the Geosat GM data. We now have BOTH the ERS-1/GM and Geosat/GM datasets! This happy ERS-1 – Geosat/GM

"synergy" has proved a boon for marine geophysics.

3. ALTIMETRIC GRAVITY IN POLAR SEAS

Because the of their higher orbital inclination (-81.5° for ERS and Envisat as opposed to -72.0° for Geosat and SEASAT) ERS and Envisat altimetry are the predominant source of altimetry for mapping the Arctic and Southern Ocean. Researchers [21, 22,23] have reprocessed ERS return echoes and then computed detailed marine gravity in the ice-covered polar seas. The resulting detailed gravity revealed previously uncharted tectonic fabric, e.g., a lineated low down the middle of the Arctic Ocean's Canada Basin (see Fig. 4) locating the extinct spreading ridge which gave rise to the Basin's seafloor [22,23] as well as similar structures in the seafloor of the Southern Ocean [21]. Note: because height trackers on board ERS altimeters are optimized for open ocean - as opposed to ice-covered ocean - operation, the computation of,

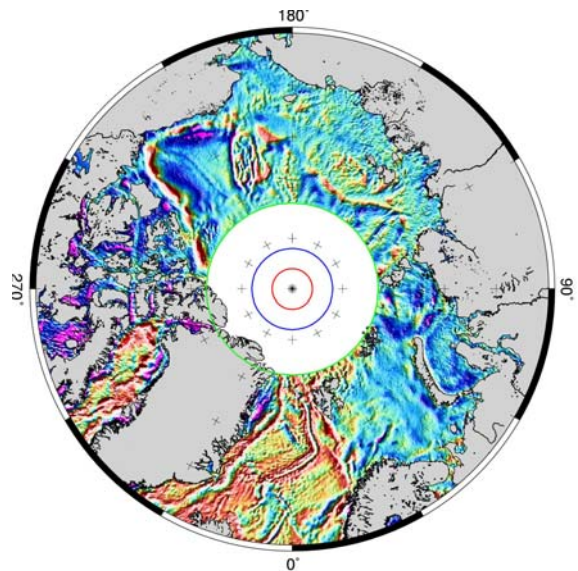


Figure 4. Marine gravity of the Arctic computed from retracked ERS altimetry [22]. Red circle at 88° denotes the northern limit of CryoSat's anticipated coverage. Note among other tectonic details the north-south trending lineation (at ~216° E longitude)in the Canada Basin north of Alaska which denotes an extinct spreading ridge.

polar marine gravity is particularly challenging and requires reprocessing of ERS return echoes to correct on-board tracker errors.

4. BATHYMETRIC MAPPING USING ALTIMETRY

Researchers [12] have constructed bathymetric mappings of most of the oceans with a 12 to 20 km resolution by combining the available depth soundings collected over the past 30 years with high-resolution marine gravity information provided by the ERS and GEOSAT satellites. Figs 5a and 5b show an example for the Atlantic Ocean, Mediterranean and other European seas.

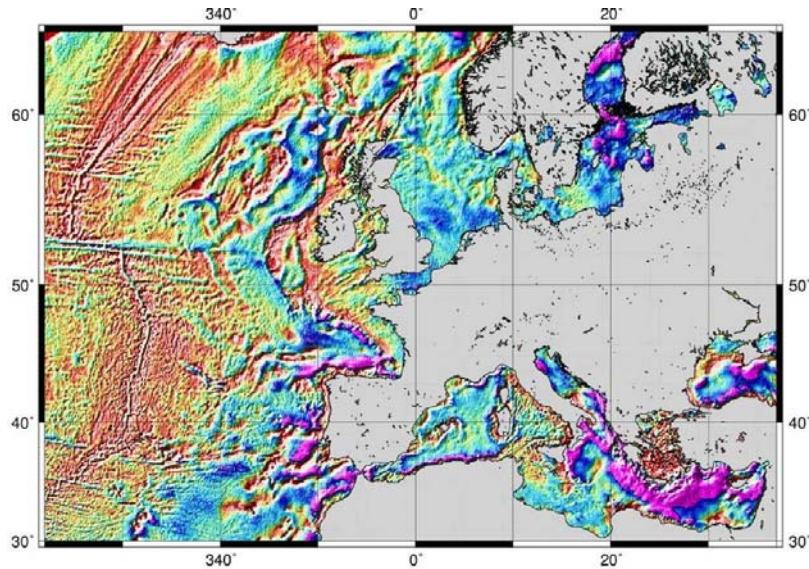


Figure 5a. Marine gravity computed from GEOSAT and ERS data [2,18] over European region.

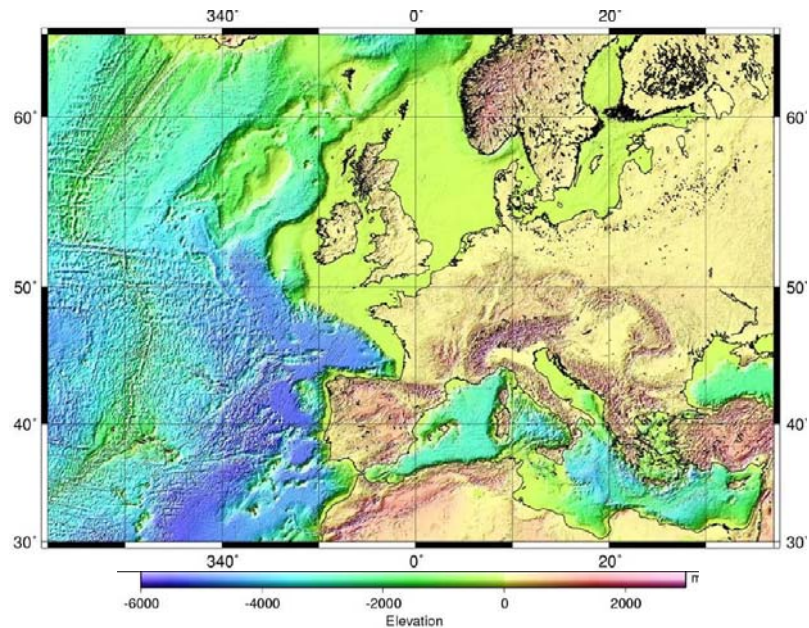


Figure 5b. Sea Floor topography for European region from altimetry and depth soundings[12,18].

Note the detail along the Mid-Atlantic Ridge in both gravity, Fig 5a, and bathymetry, Fig 5b.

Also in both 5a and 5b note the Ampere Seamount at 37°N, 348°E or 600km west of

Gibraltar. The Ampere is one a group, the Horseshoe Seamounts comprising part of the Gibraltar-Azores structure which runs west roughly along the 37°N parallel to meet the Mid-Atlantic Ridge at the Azores and delineates the hard-to-trace tectonic boundary between the Eurasian and African plates.

5. SUMMARY

We have seen how altimetric marine gravity fields have benefited, increasingly, marine geology and geophysics. By revealing large-scale tectonic fabric of the seafloor these gravity fields serve to test and confirm plate tectonics regionally and globally. Recently, higher resolution (20 km or better) gravity fields have been computed from ERS(GM) as well as Geosat data which are dramatically increasing our knowledge of the global seafloor's detailed structure and tectonic history as well as bathymetry. Fine scale details revealed in these new fields help refine tectonic models, delineate microplates, detect large numbers of new seamounts and improve digital bathymetric maps. Future prospects for continued large improvements center on a proposed new satellite altimeter mission detailed by Sandwell et al. [24] in this symposium.

6. ACKNOWLEDGMENTS

William F. (Bill) Haxby is gratefully acknowledged for his pioneering work on the use of satellite altimetry to image the global seafloor. Bill died in January of 2006 just two months before this Symposium.** As a scientist and friend, he is greatly missed. I also thank Karen Marks, Dave Sandwell, Walter Smith, Seymour Laxon and Ole Anderson for their help and input. Contents of this manuscript are solely the opinions of the author and do not constitute a statement of policy, decision, or position on behalf of NOAA or the U. S. Government.

**www.ldeo.columbia.edu/news/2006/01_06_06.htm

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