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COMPARISON OF MARINE GRAVITY FROM SHIPBOARD AND HIGH-DENSITY SATELLITE ALTIMETRY ALONG THE MID-ATLANTIC RIDGE, 30.5°-35.5°S

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Abstract. We compare new marine gravity fields derived from satellite altimetry with shipboard measurements over a region of more than 120,000 square kilometers in the central South Atlantic. Newly declassified satellite data were employed to construct free-air anomaly maps on 0.05 degree grids [Sandwell and Smith, 1992; Marks et al., 1993]. An extensive gravity and bathymetry dataset from four cruises along the Mid-Atlantic Ridge from 30.5-35.5°S provides a benchmark for testing the two-dimensional resolution and accuracy of the satellite measurements where their crosstrack spacing is near their widest. The satellite gravity signal is coherent with bathymetry in this region down to wavelengths of 26 km (γ^2=0.5), compared to 12.5 km for shipboard gravity. Residuals between the shipboard and satellite datasets have a roughly normal distribution. The standard deviation of satellite gravity with respect to shipboard measurements is nearly 7 mGal in a region of 140 mGal total variation, whereas the internal standard deviation at crossovers for GPS-navigated shipboard data is 1.8 mGal. The differences between shipboard and satellite data are too large to use satellite gravity to determine crustal thickness variations within a typical ridge segment.

Introduction

Three-dimensional analysis of gravity and bathymetry provides a unique look at the density structure of crust and upper mantle at mid-ocean ridges [Kuo and Forsyth, 1988; Lin et al., 1990; Blackman and Forsyth, 1991; Morris and Detrick, 1991]. Maps of the marine gravity field [Sandwell, 1992; Sandwell and Smith, 1992; McAdoo and Marks, 1992; Marks et al., 1993; Smith et al., 1993] based on Seasat, ERS-1, and recently declassified Geosat Geodetic Mission (GM) altimetry in the southern hemisphere from 30°S-72°S, together with improvements in the density and quality of the marine bathymetric database, will enhance the study of gravity variations on the global ridge system. The purpose of this note is to assess the current state of the art in marine gravimetry by a two-dimensional (2-D) comparison of the free-air gravity anomaly (FAA) field derived from satellite altimetry with that obtained from shipboard measurements, in an area extending nearly five degrees in latitude and longitude.

Satellite Altimetry and Shipboard Gravity Datasets

Sandwell (Eos, Jan. 19, 1993, p.35; updated Mar.18, 1993) has generated a global marine gravity field using 20 pixels per degree in longitude, with the same pixel dimensions in latitude, on a Mercator projection. The spacing of this grid is about 4.5 km over the Mid-Atlantic Ridge (MAR) from 30.5°-36.5°S and 12°-17°W. The vertical gravity gradient is calculated using Laplace's equation for gravitational potential from gridded maps of the vertical deflection (i.e. sea surface slope) in the east and north directions, as described in Sandwell [1992]. The gravity anomaly, relative to a spherical harmonic model, is then generated via Fourier analysis, using a flat-earth approximation. These steps are aided by an efficient POCS-like interpolation algorithm [Menke, 1991] for the along-track vertical deflections.

Marks et al. [1993] also produced a gravity field for the southern oceans, using Geosat data only, spaced 0.05° in longitude, 0.04° in latitude, registered on grid lines. The accuracy of this grid is somewhat improved over their earlier version by the optimal filtering techniques of Smith et. al. [1993], which cannot as yet be applied to data from ERS-1. This grid is now available from NOAA through the National Geophysical Data Center (NGDC Data Announcement 93-MGG-01, Global Relief Data on CD-ROM, 1993).

Figure 1 shows the satellite tracks now available, as well as the ship tracks in the area used for the comparison. The

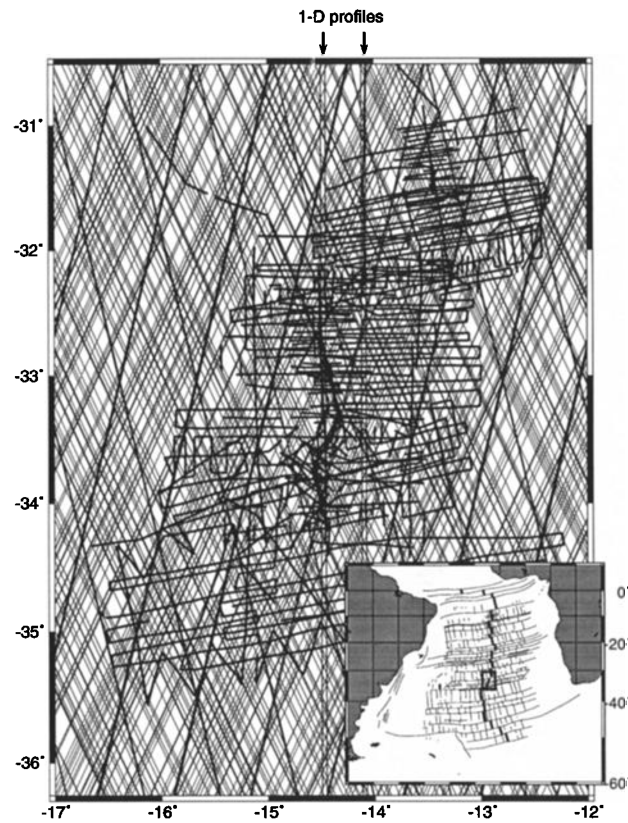

Fig. 1. South Atlantic ship tracks providing gravity data, from Marathon 10 and 13 (1984-85) and Plume 4 and 5 (1990) cruises, superimposed on Geosat (densely spaced) and ERS-1 (higher angle) satellite tracks. Arrows locate two profiles with high quality shipboard data for 1-D comparison.

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somewhat uneven, cross-track spacing of altimetric profiles, mainly Geosat, increases from 72°S to 30°S, and thus these new gravity fields have their poorest resolution at the latitude of this study. To stabilize mapping and interpolation of the along-track sea-surface slopes to evenly-spaced grids of east and north vertical deflections, and to reduce high-frequency noise, Sandwell [1992] incorporates a filter simulating the effects of upward-continuation of anomalies to a height z of 1.6 km above sea level, so that the corner wavelength (half power) of this filter is $4 \pi (1.6)/\ln(2)$, or 29 km.

Figure 2 shows Sandwell's [1993] map of FAA contoured at 5 mGal intervals. The troughs trending 079° with amplitude of 40 mGals or more delimit the active portions of the 69-km-offset Cox and 220-km-offset Montevideo Fracture Zones, as well as smaller offsets at the Meteor Fracture Zone and the 33°30' discontinuity [Kuo and Forsyth, 1988; Fox et al., 1991]. These features are identified on the inset to Figure 3.

Figure 3 shows gravity collected on the Marathon 10 and 13 (1984-1985) and Plume 4 and 5 expeditions (1990) of the R/V Thomas Washington [Neumann and Forsyth, 1993]. Tracklines are shown in Figure 1. These ship tracks, generally closer than 10 km, represent the densest mid-ocean gravity survey south of 30°S. The 1990 cruises not only filled in and extended the coverage from 1984-85, but employed a modern, stable Bell gravimeter and were navigated with nearly full GPS coverage. Internal consistency at crossovers for the 1990 data was 1.8 mGals standard deviation (s.d.). The accuracy of these values is assured by portside ties to the 1967 IGRF, and by careful drift corrections [Smith et al., 1988]. Residual drift between cruise legs, after shipboard correction, was negligible (<0.5 mGals). Navigational precision after satellite and bathymetric crossover correction [Nishimura and Forsyth, 1988; Neumann et al., 1990] is better than 125 m. The improved navigation model and inertial corrections, combined with a least-squares adjustment at over 600 crossings, reduced crossover errors in the 1984-85 data to 3.8 mGals S.D. Such precision was not possible with the original

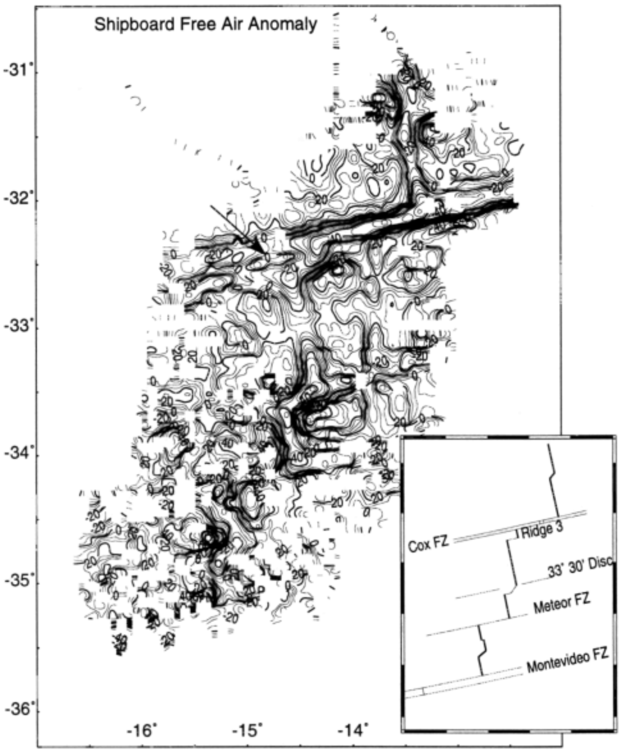

Fig. 3. FAA from shipboard gravimetry, after Neumann and Forsyth [1993]. Inset shows eight ridge segments and four major fracture zones on the southern Mid-Atlantic Ridge..

dataset [Kuo and Forsyth, 1988] because of cross-coupling errors on the gravimeter and navigational uncertainty.

Shipboard data, consisting of 78,000 samples taken at one-minute time intervals, were gridded at 0.05° intervals using a Gaussian weighted average with a standard deviation of one half grid spacing and a cutoff of one grid spacing. No other interpolation was performed. The resulting grids have the same position and sampling density as the satellite maps. This dataset, representing 72 days at sea in the area, has numerous large-amplitude features and provides excellent ground-truth for recent satellite studies.

Figure 4 shows Sea Beam bathymetry collected on the same cruises. Depths along the MAR are about 2600 m at zero-age, and range from less than 800 m to more than 5 km. Rift flanks are very mountainous at slow-spreading ridges. The 1400-2300 kg m^{-3} density contrast of crust and mantle relative to seawater contributes to variations in the FAA across the survey of up to 140 mGals (Figures 2 and 3), and leads to high coherence between the FAA and bathymetry at short to moderate (<200 km) wavelengths.

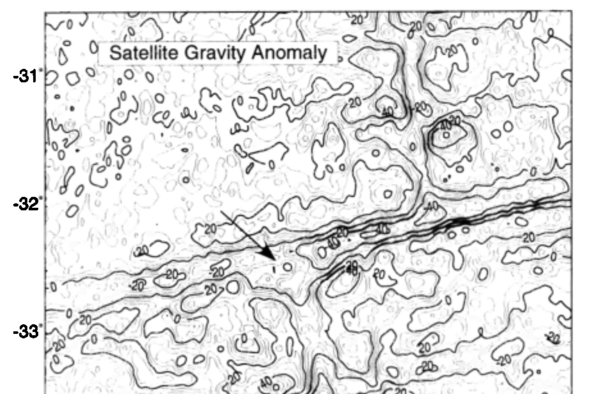

Fig. 2. Free-air gravity anomaly (FAA) from a worldwide grid by D. Sandwell [Eos, Jan. 19, 1993, p. 35]. Contour interval 5 mGal (50 gu). Arrow points to an uplifted rift flank at the limit of resolution in Figures 2-4.

Data Comparison

The ship's FAA map visually shows higher resolution (Figure 3). The geometry of individual ridge segments is delineated by gravity lows. The flanking highs, especially near plate offsets, stand out as sharp, uncompensated features producing positive gravity anomalies. Gradients are steeper, particularly along the edges of fracture zones where very short wavelength features are seen in the bathymetry. Features such as the 19 km long ridge segment 3 south of the Cox Fracture Zone, and its uplifted flank to the west, easily visible in the shipboard gravity and bathymetry (see arrows in Figures 3 and 4), are not well resolved in the satellite map (Figure 2).

To quantify the differences in gravity fields, we gridded the shipboard data separately to match the satellite maps, limiting our comparison to the region covered on shipboard, consisting of about 5600 points for the Sandwell grid, and 5800 points for the NOAA grid. The mean values of the satellite maps were

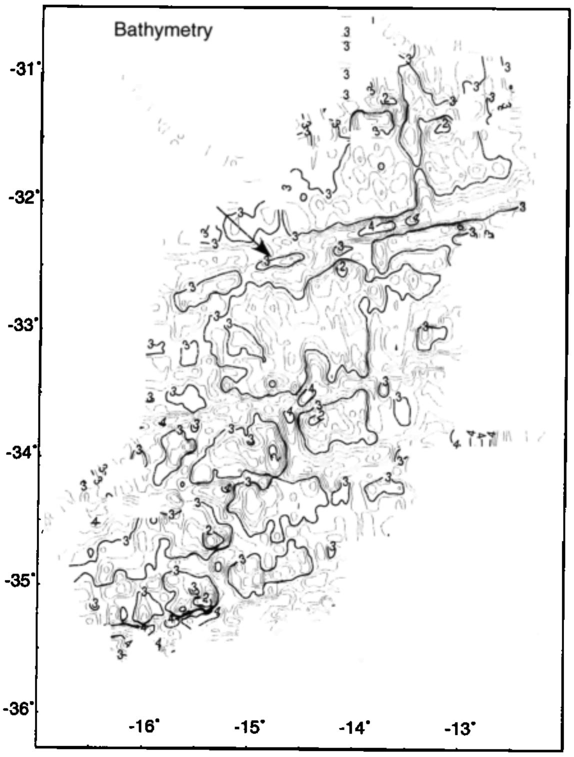

Fig. 4. Bathymetry from four cruise legs, as in Figure 3, contoured at 200 m intervals. The three-dimensional attraction of density contrasts at the water-crust and crust-mantle interfaces is responsible for much of the FAA.

within a mGal or less of that of the ship. After a DC shift, RMS differences were about 7.2 and 8.2 mGals for Sandwell's and NOAA's, respectively.

Systematic errors account for some of the difference between satellite and shipboard gravity. A visible lack of registration between the images leads to substantial errors near the plate boundary, where horizontal gradients are as large as 10 mGals km^{-1}. The ship's data were therefore shifted before gridding to obtain the best match by linear regression, which should have a correlation coefficient near 1 and a slope of unity. For Sandwell's map, the correlation improves to a maximum of 0.9485 when the satellite data are shifted by -0.004° in latitude and 0.005° in longitude. The NOAA dataset has a best correlation of 0.9442 when satellite data are shifted by -0.010° in latitude and 0.024° in longitude. Sandwell's gravity field was then scaled by a factor of 1.09 to obtain the best linear fit, with a residual of 6.7 mGals S.D. The NOAA dataset had a slightly higher amplitude than the shipboard gravity, with a residual of 7.0 mGals after scaling by 0.99. Residuals are only slightly long-tailed: about 1% are larger than 20 mGals, 3 standard errors, compared with 0.27% expected for a normal distribution.

We also compared the bathymetry, shipboard and satellite data in the wavenumber domain. Shipboard data were interpolated onto a 128-by-128 grid covering the sampled area (Figure 3), tapering exponentially toward the mean value away from known data points. Gravity data were interpolated in similar fashion, supported by the same set of constrained points. Grids were then mirrored about the x and y axes, to eliminate an implied discontinuity at the edges prior to the FFT. The spectral power density (the amplitude squared of complex Fourier coefficients, normalized by number of samples), averaged over radial wavenumbers at geometrically spaced intervals, ten or twenty per decade, is plotted in log-log space in Figure 5a. A peak at the lowest wavenumber represents the dominant wavelengths of the ridge axis running diagonally across the study area. The spectra also contain features related to ridge segmentation. The downward slopes with increasing wavenumber reflect the power law scaling of topography [Bell, 1975] and the decay of gravity fields with upward continuation from their source to sea level. Flattening of the gravity spectrum, beginning at wavelengths longer than about 57 km, results from nearly full isostatic compensation of topography with plate flexure. There are slight offsets between the ship and the satellite spectra. The steeper slope of the satellite gravity spectra at high wavenumbers results from

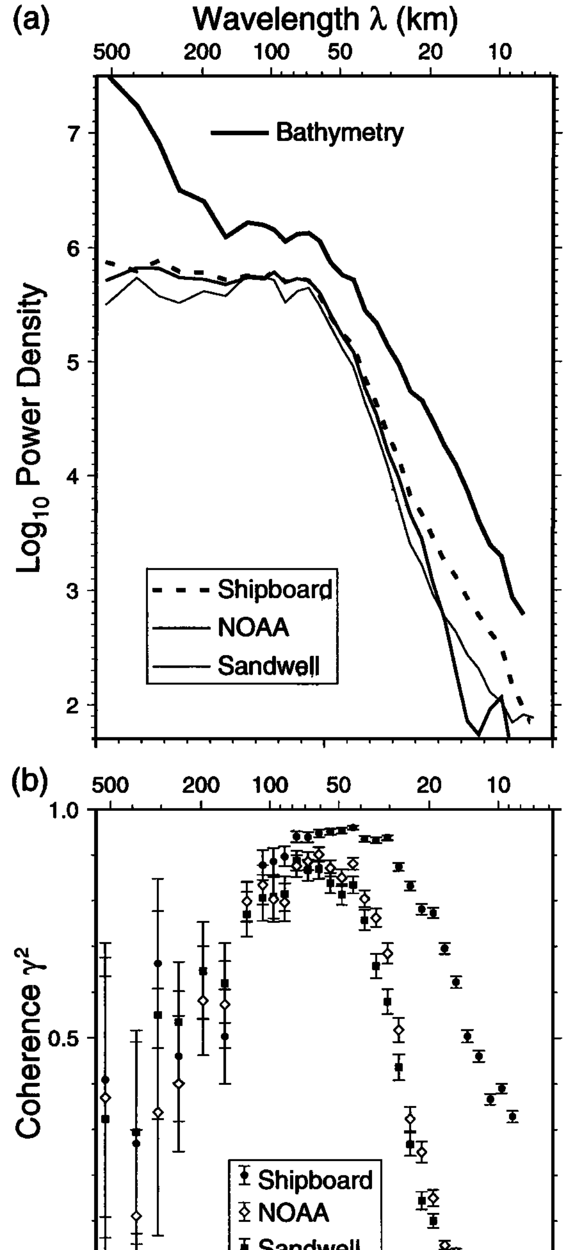

Fig. 5. Power spectra and coherence of bathymetry and gravity for the region covered by Figure 3, as a function of wavenumber k. a) Spectral density in squared units per reciprocal degree. b) Coherence of Sea Beam bathymetry with gravity fields from shipboard and satellite data.

the naturally "red" spectrum of sea-surface gravity, further convolved with the smoothing filters used to interpolate the vertical deflection datasets. The long wavelength amplitude of the NOAA field is in good agreement with the ship's, while Sandwell's amplitude is lower, apparently due to techniques used to combine disparate datasets from Geosat and ERS-1.

A plot of coherence (γ^2) with bathymetry (Figure 5b) indicates that the satellite gravity is almost incoherent below a wavelength of 20 km. The coherence indicates the fraction of power in the gravity that can be predicted by a linear filter operating on the bathymetry at a given wavenumer. In the absence of noise it should be nearly unity at short wavelengths, where the gravity signal is dominated by the attraction of the rock/water interface. Some coherence remains in the shipboard gravity down to the 9 km Nyquist limit, whereas none remains in the satellite gravity. The coherence of the NOAA gravity field is slightly higher than Sandwell's at wavelengths < 70 km. The long-wavelength (>130 km) coherence of Sandwell's map, which incorporates additional data from ERS-1 tracks, is marginally better. The NOAA field is coherent (γ^2=0.5) to wavelengths of 26 km, versus 27.5 km for the Sandwell field and 12.5 km for the ship's gravity.

The ship gravity/bathymetry coherences could be higher than the altimetric gravity/bathymetry coherences due to the fact that they were taken along the same path, but this advantage is probably minor. An echosounder swath is wide enough (2-4 km) to sample the majority of seafloor over the area from which gravity samples were taken, and coverage over fracture zones and rift valleys where most of the signal is generated is nearly complete. Thus bathymetry should be a fairly good predictor of gravity along any track. The increase in residual resulting from the 1-2 km misregistration discussed above was only 1.2 mGal, suggesting that, in any case, the ship's "coherence advantage" is slight.

The 1984-85 shipboard gravity data, collected using an older gravimeter and corrected with cross-ties, may have substantial errors. Our most reliable benchmarks are the quasi-1D profiles shown by arrows in Figure 1 along densely surveyed regions near the ridge axis, where almost all gravity is constrained by several tracks of the 1990 Plume cruise data. Profiles from Sandwell's map at 345.53° and 345.93° longitude, after removing the mean, have RMS residuals of 6.0 and 5.6 mGals. The largest differences occur near short-wavelength features, suggesting that some of this residual is due to spatial aliasing, and will improve with the denser coverage obtained from future satellite data.

The noise level and filtered nature of satellite marine gravity measurements necessarily limits their utility in studies of crustal thickness and density variations. When residual gravity anomalies are interpreted in terms of crustal thickness variations by downward continuation to the moho at typical depth of 9 km, the practical limit has been wavelengths of about 25 km [e.g., Kuo and Forsyth, 1988]. Figure 5b demonstrates that significant information is lost in the 25 to 75 km wavelength range using satellite data alone. For anomalies at wavelengths shorter than 25 km arising from density variations within the crust, such as the presence of magma chambers, shipboard gravimetry is essential. When the difference between the satellite and shipboard gravity fields is downward continued in the same way as residual gravity anomalies, it creates erroneous variations in crustal thickness with an RMS amplitude of 700-800 m. This exceeds the amplitude of variation in crustal thickness, about 650 m RMS, inferred in our survey area [Neumann and Forsyth, 1993]. Clearly shipboard gravity measurements are required for determination of local variations in crustal thickness.

This comparison verifies the accuracy of satellite gravity for quantitative regional and global studies of the mid-ocean ridges. The apparent noise level in the present data set is too large to be able to resolve the existence of the smallest ridge segments, or crustal thickness variations on a typical segment scale, so shipboard gravimetry remains an essential tool, complemented by the extensive and rapidly improving results from satellite missions.

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