Along-Track Gravity Anomalies from Geostat and Seasat Altimetry: GEBCO Overlays

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Abstract. To provide easy access to the large number of Seasat and Geostat altimeter observations collected over the last decade, we have plotted these satellite altimeter profiles as overlays to the General Bathymetric Chart of the Oceans (GEBCO). Each of the 32 overlays displays along-track gravity anomalies for either ascending (southeast to northwest) or descending (northeast to southwest) altimeter passes. Where Seasat and Geosat profiles coincide, only the more accurate Geosat profiles were plotted. In poorly charted southern ocean areas, satellite altimeter profiles reveal many previously undetected features of the seafloor.

Introduction

The satellite altimeter data sets acquired by the Seasat (Lorell et al., 1980) and Geosat (Cheney et al., 1987) spacecraft now consist of more than 400 million observations covering most ocean areas between 72°N and 72°S. These data are largely inaccessible to most scientists since it takes a great deal of computer programming time and other human resources to process the data into a form that is suitable for detailed studies. Several investigators have interpolated/extrapolated the profiles onto uniform grids and published contour maps or gridded files of geoid height and/or gravity anomalies. While these displays reveal the overall characteristics of the marine gravity field, they lack the accuracy and detail needed for quantitative studies. The major limitation of the Seasat and Geosat (unclassified) data is that the along-track resolution of the Geosat profiles is about 10 km while the Geosat/Seasat profile spacing is about 60 km. Thus, the resolution is lost when the widely spaced profiles are gridded. In addition, the gridded maps no not distinguish between actual and interpolated values so the amplitudes and locations of small isolated features such as seamounts cannot be determined. Finally, the gridded maps do not convey information on the accuracy, repeatability and coverage of individual altimeter profiles.

To overcome these problems, we have produced 32 overlays for the GEBCO map series (Canadian Hydrographic Service, 1982) similar to the Seasat overlays produced by Sandwell (1984a) (see at the end of this article). Each overlay displays along-track gravity anomaly (computed from along-track sea surface slope) for either ascending or descending satellite altimeter profiles. Where Seasat and Geosat track-lines coincide, the more accurate Geosat profiles are plotted. These overlays, as well as the digital profile data, can be obtained from the Geological Data Center at Scripps Institution of Oceanography. An order form is provided at the end of this article. The digital data can also be obtained over the Internet using the GeoBase system (Menke et al., 1991). Sheets of the GEBCO bathymetric map series are available from the Hydrographic Chart Distribution Office, Ottawa, Ontario, Canada, K1G 3H6.

Data Processing

The overall objectives of our data processing were to extract the detailed information contained in the satellite altimeter profiles and to display this information so that it could be compared with bathymetry data collected by research vessels. Both Seasat and Geosat altimeter profiles were used because the Geosat data have better accuracy while the Seasat data have better coverage except near Antarctica where Geosat coverage is superior. The pre-processing (i.e. editing and averaging) of the Seasat and...
Geosat data is fully described in previous publications and thus only a brief outline is given here.

Seasat Geophysical Data Records (GDR's) were prepared and distributed by Lorell et al. (1980) who averaged the initial 10 Hz observations to 1 Hz observations. We edited these 1 Hz observations whenever the standard deviation of the average exceeded 0.2 m or whenever any of the editing flags was set. An additional 3-point median filter (Bendar and Watt, 1984) was applied to remove remaining outliers. The data were then corrected for path effects and instrument response using the correction factors provided with the GDR's (Lorell et al., 1980). After editing, the data were subdivided into ascending and descending sets and further subdivided into continuous passes. A pass consists of a series of data points with tie gaps of less than 5 seconds ($\sim 34$ km). Each pass was differentiated with respect to along-track distance using the first difference formula. This enhances the short-wavelength anomalies and also converts geoid height into along-track vertical deflection. We show below that 1.0 microradian ($\mu$rad) of vertical deflection is equal to 0.98 milligal (mgal) of along-track gravity disturbance.

The pre-processing of the Geosat profiles was slightly more involved because the Geosat ground track repeats every 17.05 days. Thus the repeat profiles were averaged to increase their signal to noise ratio. For our analysis, the first 44 repeat cycles of the Geosat (GDR) altimeter data from November 7, 1986 to November 27, 1988 were used (Cheney et al., 1987). Before averaging, individual repeat cycles were edited as described in Sandwell and McAdoo (1990). The 10 Hz observations along each repeat profile were then averaged into 2 Hz observations and the path length/instrument corrections were applied. As in the case of Seasat, the Geosat data were also subdivided into passes and each pass was differentiated along track. Finally the 44 repeat cycles were interpolated into uniform along-track bins and averaged together (Sandwell and McAdoo, 1990). When 3 or more repeat passes were available for averaging, the uncertainty of the average was also computed; data points were edited whenever the uncertainty exceeded 8 $\mu$rad (7.8 mgal). As a final step to suppress land reflections, a 3-point median filter was applied.

To illustrate the effects of the averaging and editing, we selected ascending Seasat and Geosat profiles along coincident ground tracks. The profiles begin in the southernmost Indian Ocean where seasonal ice sometimes obscures the ocean surface. They terminate at 45° S after intersecting a couple of prominent seamounts. In general, the noise for the 'raw' vertical deflection profiles (Figure 1, upper left) is much higher for Seasat than it is for Geosat because the Geosat profile is the average of up to 44 repeat cycles. Moreover, between 59° and 60° the noise level of the Seasat profile is very high because of erroneous radar reflections from the sea ice. After the 3-point median filter is applied (Figure 1, upper right), the general noise level of the Seasat data as well as the ice-induced noise is reduced significantly; the median filter has little effect on the Geosat profile.

The next step in the data processing was to bandpass filter both the Seasat and Geosat profiles. The long wavelengths (>1000 km) are first removed by subtracting a spherical harmonic model (Marsh et al., 1990) of the gravity field complete to degree and order 40 from the along-track vertical deflection. To suppress the short wavelength noise, a Gaussian shaped low-pass filter was convolved with each profile. The form of the filter is

$$
\exp \left( -\frac{s^2}{2\sigma^2} \right)
$$

where $s$ is distance along track and $\sigma$ the filter half-width. (6.7 km for Seasat and 3.4 km for Geosat). For Seasat profiles the $\sigma$ was selected to attenuate wavelengths of 36 km by 0.5 while for Geosat the 0.5 attenuation occurs at a wavelength of 18 km. The effects of this band-pass filter are illustrated in Figure 1 (lower left). After filtering, the noise level in the Seasat data is reduced to 4–8 $\mu$rad while the Geosat noise level is much lower (0.5–2 $\mu$rad).

**Along-Track Gravity Anomaly**

A modified version of the Fourier transform method described briefly in Haxby et al. (1983) and McAdoo (1990) was used to compute along-track gravity anomalies from along-track vertical deflections. To simplify the computations, a flat-earth approximation was used. This is a reasonable approximation because a spherical harmonic model, complete to degree and order 40, subtracted from the profiles before the along-track gravity is computed. (If desired, this model can be added back to the along-track gravity profiles.) Here we describe the method
Fig. 1. Ascending Seasat (shifted for display) and Geosat profiles from the southern Indian Ocean. Raw Seasat vertical deflection profiles are noisier than Geosat profiles (upper left). Median filter editing (upper right) removes outliers due to sea ice at 60° S. A low-pass filter (lower left) suppresses short wavelength noise. A Hilbert transform (i.e. 90° phase shift) converts vertical deflection to gravity anomaly.
in detail. To begin, one must relate the geoid height \( N(x) \) and other measurable quantities such as gravity anomaly \( \Delta g(x) \) to the gravitational potential \( V(x, z) \). In the following equations, the bold \( x \) denotes the coordinate \((x, y)\); similarly \( k \) denotes \((k_x, k_y)\) where \( k_x = 1/\lambda_x \) where \( \lambda_x \) is wavelength.

Using Brun’s formula, we relate the geoid height \( N \) to the potential \( V \)

\[
N(x) \simeq \frac{1}{g_o} V(x, 0)
\]

where \( g_o \) is the average acceleration of gravity. The gravity anomaly \( \Delta g \) on the ocean surface is the vertical derivative of the potential. The free-air correction term is not included in this flat earth approximation because it is largely accounted for in the spherical harmonic model

\[
\Delta g(x) = -\frac{\partial V(x, 0)}{\partial z}
\]

The east component of vertical deflection is the slope of the geoid in the x-direction.

\[
\eta(x) \equiv -\frac{\partial N}{\partial x} \simeq -\frac{1}{g_o} \frac{\partial V}{\partial x}
\]

and the north component of vertical deflection is the slope of the geoid in the y-direction.

\[
\zeta(x) \equiv -\frac{\partial N}{\partial y} \simeq -\frac{1}{g_o} \frac{\partial V}{\partial y}
\]

These quantities are related to one another through Laplace’s equation.

\[
\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0
\]

Substitution of (3), (4) and (5) into Laplace’s equation (6) yields

\[
\frac{\partial \Delta g}{\partial z} = -g_o \left( \frac{\partial \eta}{\partial x} + \frac{\partial \zeta}{\partial y} \right)
\]

The derivative property of Fourier Transforms along with the upward continuation property of the gravitational potential is used to reduce the differential equation (7) into an algebraic equation. The forward and inverse Fourier transforms are defined as

\[
F(k) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x)e^{-i2\pi(k \cdot x)} \, dx \, dk
\]

\[
f(x) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(k)e^{i2\pi(k \cdot x)} \, dk \, dx
\]

The Fourier transform of equation (7) is

\[
\frac{\partial \Delta g(k, z)}{\partial z} = -i2\pi g_o [k_x \eta(k) + k_y \zeta(k)]
\]

From the solution to Laplace’s equation in the wavenumber domain the upward continuation formula relates the gravity anomaly at the surface of the earth to the gravity anomaly at some elevation \( z \).

\[
\Delta g(k, z) = \Delta g(k, 0)e^{-2\pi|k|z}
\]

where \( |k| = (k_x^2 + k_y^2)^{1/2} \).

Taking the derivative of (11) with respect to \( z \) and evaluating the result at \( z = 0 \) one arrives at an algebraic formula relating the Fourier transform of the gravity anomaly to the sum of the Fourier transform of the two components of vertical deflection.

\[
\Delta g(k, 0) = \frac{ig_o}{|k|} [k_x \eta(k) + k_y \zeta(k)]
\]

To compute gravity anomalies from a dense network of satellite altimeter profiles of geoid height, one constructs a uniform grid of geoid height and calculates the east \( \eta \) and north \( \zeta \) components of vertical deflection by differentiating the grid in the \( x \) and \( y \) directions respectively. In practice, it is best to first differentiate the geoid profiles in the along track direction before gridding them. The along-track slopes are then converted into east and north components of vertical deflection using the formulas in Sandwell (1984b). One then computes the 2-dimensional Fourier transform of \( \eta \) and \( \zeta \), and uses equation (12) to calculate the Fourier transform of the gravity anomaly \( \Delta g(k) \). Finally one takes the inverse Fourier transform of \( \Delta g(k) \) resulting in the gravity anomaly. At this point one could also add the spherical harmonic gravity model back to the gridded gravity values in order to recover the long wavelength gravity field.

This procedure should work well when high density satellite altimeter coverage becomes available. However, as mentioned above, the characteristic spacing of the Seasat and Geosat profiles is much greater than the resolution along individual profiles. Thus it is impossible to retain the full along-track resolution when the profiles are gridded and so the transformed gravity anomalies will suffer from lack of resolution. To overcome the gridding problem, we have constructed pseudo along-track gravity anomalies using individual vertical deflection profiles. First
one aligns the $x$-axis of our local coordinate system in the direction of the satellite ground track. Then one assumes that the curvature of the geoid in the cross-track direction is zero; this assumption eliminates the $y$-derivatives in equation (6) and (7) and the $k_y$ terms in equations (10) and (12). After simplification, the Fourier transform of the along-track gravity anomaly is related to the Fourier transform of the along-track vertical deflection by

$$\Delta g(k_z) = ig_x \frac{k_x}{|k_x|} \eta(k_z)$$

(13)

This procedure of Fourier transformation of the along-track vertical deflection, multiplication by $ig_x \text{ sgn}(k_x)$ and inverse Fourier transformation corresponds to the Hilbert transform of the vertical deflection profile scaled by the average acceleration of gravity. From equation (13) we see that 1 micro-radian ($\mu$rad) of vertical deflection corresponds to 0.98 milligal (mgal) of gravity anomaly. Figure 1 (lower right) shows the effect of the Hilbert transformation of the band-pass filtered vertical deflection profile. To minimize the edge effects associated with the Hilbert transformation of a finite length profile, the ends of the vertical deflection profiles are extended and cosine tapered to zero. As a final note because of the 2-D assumption, the along-track gravity anomalies presented here will not agree with shipboard gravity profiles. Moreover, they will have significant disagreements at crossover points. The only way to increase the accuracy of the profiles is to obtain denser coverage; the accuracy of the satellite altimeter measurements is not the major limitation.

On each overlay, either ascending or descending passes were plotted along the subsatellite track. The ascending and descending passes were not plotted together because the combination plots are confusing and difficult to interpret. Gravity anomalies are displayed at a scale of 40 mgal anomaly per degree of longitude as cross-track deviations from the ground track. Positive anomalies are connected to the ground track at regular intervals thus providing a partial fill. Between latitudes of $-46.6$ and $46.6$, the Geosat fill lines occur at intervals of about 10 km while the Seasat fill interval is about 13.4 km. At higher latitudes the Geosat and Seasat fill intervals are the same ($\sim 6.7$ km). All 32 overlays at 1/4 their actual size are included on the following pages. After locating the desired overlay, the full-size sheets can be ordered using the form on the last page of this report.

**Interpretation**

Examples of Geosat along-track gravity profiles over a variety of tectonic features are shown in Figure 3. The largest negative gravity anomalies on the Earth are associated with the deep ocean trenches. An ascending profile, which crosses the Kuril Trench ($55^\circ$ N, $153^\circ$ E), has a $-300$ mgal trench axis anomaly. Seaward (south) of the trench axis is a broad, positive outer-rise anomaly associated with the flexure of the oceanic lithosphere as it is subducted beneath the Kuril Arc. The large positive anomalies landward (north) of the trench axis correspond to the submarine back-arc volcanos.

Seamounts act as isolated volcanic loads on the oceanic lithosphere causing a downward flexure of the plate. Makarov Seamount, in the western Pacific ($29.5^\circ$ N, $153.5^\circ$ E), displays this characteristic gravity anomaly signature which consists of a large positive anomaly directly above the center of the seamount surrounded by broad negative anomalies adjacent to the seamount. The negative anomalies reflect the downward flexure of the lithosphere.

The gravity signatures of spreading ridges are quite diverse and depend primarily on spreading rate. Fast spreading ridges, such as the East Pacific Rise ($8^\circ$ S, $252^\circ$ E), have small amplitude positive anomalies about the ridge axis reflecting a relatively small ($\sim 200$ m) axial ridge in the seafloor. In contrast, slow spreading ridges, such as the Southwest
Fig. 2. Sixteen geographical regions for the GEBCO overlays. There are two overlays for each area, one for ascending passes and the other for descending passes.
Fig. 3: Examples of along-track gravity profiles across the Kuril Trench (upper left), Makarov Seamount (lower left), the fast spreading East Pacific Rise (upper right) and the slow spreading Southwest Indian Ridge.
Indian Ridge (52.8° S, 19.8° E), have large amplitude negative anomalies about the spreading axis reflecting a major (~2 km) rift valley.

While the correlation between along-track gravity anomaly and seafloor topography is generally high, it is nonunique. For instance, two identical seamounts which formed on lithosphere of different age can have gravity amplitudes which differ by a factor of 2 or more (Watts and Ribe, 1984). This nonunique relationship reflects the degree and mode of isostatic compensation. Although the amplitude relationship is nonunique they still have the same phase. Except in areas of thick sedimentary cover, a prominent gravity anomaly signal is always associated with seafloor topography. The type of topographic feature can usually be determined from the morphology of the gravity profile. Many previously uncharted features can be found by comparing both ascending and descending overlays with the GEBCO series.

Acknowledgements

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References


Sheet 02, Descending, 40 mgal/deg
Sheet 11, Ascending, 40 mgal/deg
Sheet 13, Descending, 40 mgal/deg
Sheet 15, Ascending, 40 mgal/deg
Sheet 15, Descending, 40 mgal/deg
Sheet 16, Ascending, 40 mgal/deg map
Sheet 16, Descending, 40 mgal/deg
Order Form

Full size (25" by 50") GEBCO overlays or digital profile data (6250 BPI tape) can be obtained from:

Geological Data Center, 0223
Scripps Institution of Oceanography
La Jolla, CA
92093-0223

(619) 534-2752
Internet: ssmith@ucsd.edu
Fax: (619) 534-5306

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