VALIDATING PREDICTED BATHYMETRY: AN APPROACH USING TWO-DIMENSIONAL COHERENCE BETWEEN GRAVITY AND MULTIBEAM BATHYMETRY

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ABSTRACT

Global ocean depth models rely on satellite altimetry to fill the gaps between sparse ship surveys. Altimetric gravity anomalies are converted to depths by spectral projection techniques that exploit the correlation between gravity and depth variations and are calibrated to fit in situ data. When Smith and Sandwell [1,2] developed this technique there were insufficient in situ data to permit the empirical development of the spectral projection filter. Therefore a simple Wiener optimization theory was used, employing educated guesses about the expected signals in bathymetry and signal-to-noise ratios in altimetric gravity. This approach minimizes the mean square error in altimetrically estimated bathymetry. We compiled 25 recent multibeam surveys to test the filter design by computing radially symmetric coherence between multibeam depths and altimetric gravity in the 20-160 km waveband. We find the spectral projection filter does an excellent job of capturing the waveband where altimetry and bathymetry may be correlated.

1. INTRODUCTION

In situ ocean depth measurements made by ships carrying echosounders cover only a few percent of the global ocean. Global models of ocean depth rely on satellite altimetry to fill the gaps. Altimeter data are processed to yield sea surface gravity anomaly maps [3]. The gravity maps are then converted to depth maps by spectral projection techniques exploiting the correlation between gravity variations and depth variations, and calibrated to fit the available in situ data [1,2].

When this altimetric bathymetry technique was developed [1,2] the available in situ data were insufficient to permit empirical development of a spectral projection filter. Therefore a simple Wiener optimization theory was used, employing educated guesses about the expected signals in bathymetry and signal-to-noise ratios in altimetric gravity, both as functions of wavenumber. If correct, this approach should minimize the mean square error in altimetrically estimated bathymetry.

It is now possible to test the performance of the Smith and Sandwell filter design directly, as there are now some areas of ocean floor that are sufficiently covered by detailed multibeam acoustic bathymetry surveys. We compiled acoustic bathymetry and co-registered altimetric gravity data in 25 map areas (Fig. 1) covering various tectonic regimes throughout the world's oceans. The size of each mapped area is large enough to permit estimation of two-dimensional cross-spectral coherency between altimetry and bathymetry over the range of spatial wavenumbers used by Smith and Sandwell (~20 to 160 km wavelength).

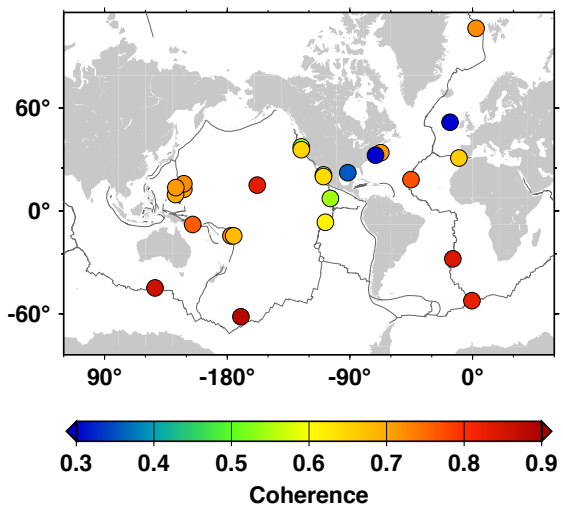

Figure 1. Twenty-five areas examined in this study. Colors indicate mean coherence over the 20-160 km waveband

2. DATA

We compiled 25 multibeam grids that met these requirements: (1) survey coverage mostly exceeding 160 km on each side, (2) surveys having relatively complete map coverage with few gaps between swaths, (3) small (< 1000 m) grid spacing, and (4) sampling a variety of geologic settings in the world's oceans. We downloaded multibeam grids from the National Geophysical Data Center, the University of New Hampshire, Lamont-Doherty Earth Observatory,

Table 1. Coherence results.

Region name	Setting	Longitude	Latitude	Mean coherence	Data cutoff	Filter cutoff
AAD	S	127.0	-49.0	0.8597	18.48	17.71
Atlantic	SM	-67.25	39.25	0.7118	19.23	17.42
Atlantic	SH	-71.25	37.75	0.1193	142.31	16.88
Bouvet TJ	S	-0.5	-54.75	0.8259	15.84	14.96
Clipperton FZ	FZ	-104.25	9.25	0.5434	26.18	16.20
Fram	S	2.5	79.0	0.7229	19.87	16.06
Gorda	S	-125.75	41.63	0.5482	24.47	14.79
Gorda	FZ	-125.75	41.63	0.6493	21.59	15.41
Gulf of California	LT	-109.45	25.0	0.5902	23.68	12.89
Gulf of California	LT	-109.45	25.0	0.6425	15.30	13.04
Gulf of Mexico	SH	-91.5	27.0	0.3559	51.97	12.97
Hawaii	SM	-157.93	18.7	0.8327	20.19	18.79
Ireland	SH	-16.5	54.37	0.2416	—	13.94
Kane FZ	S	-45.25	22.5	0.7700	17.02	16.82
Lau Basin	B	-176.2	-17.85	0.7265	17.04	14.14
Lau Basin	B	-176.2	-17.85	0.6794	20.75	14.66
Mid-Atlantic	S	-14.5	-33.13	0.8433	17.61	16.07
Mariana Trench	T	148.2	15.75	0.7025	21.16	19.82
Mariana Trench	T	148.2	19.5	0.7227	20.84	19.00
Mariana Trench	T	142.0	12.0	0.6980	19.68	18.00
Mariana Trough	B	142.3	16.8	0.7130	18.17	17.39
Pacific-Antarctic	F	-170.0	-61.0	0.8854	16.50	17.52
Spain	SH	-10.0	36.25	0.6589	23.50	17.55
Wilkes FZ	FZ	-108.0	-8.25	0.6136	18.90	16.39
Woodlark Basin	S	154.6	-9.87	0.7625	17.69	16.24

AAD=Australian Antarctic Discordance, B=basin, FZ=fracture zone, LT=leaky transform, S=spreading ridge, SH=continental shelf, SM=seamount, T=trench, TJ=triple junction. Mean coherence is over the 20-160 km waveband. Cutoff is wavelength, in km, at which coherence crosses 0.5

Geoscience Australia, and the University of Hawaii. The regions covered by the multibeam grids are tabulated in Table 1. Corresponding altimetric gravity data are from Sandwell and Smith [3; version 18.1].

3. COHERENCE ANALYSIS

The cross-spectral coherence between a pair of inputs is the square of the linear correlation coefficient as a function of wavelength, indicating how much of the variance in one input can be correlated with the other input through a linear filtering operation. Coherence near 1 indicates nearly perfect linear correlation, while coherence near 0 indicates the absence of any significant linear relationship. A coherence of 0.5 can be interpreted as a signal-to-noise ratio of 1:1 in one input if the other input can be assumed to be noise-free [4; Eq. 6.39]. In the context of bathymetric prediction, the portion of gravity that is correlated with seafloor topography is considered to be the "signal," and bathymetry is considered to be noise-free because modern multibeam measurements are accurate to a few tenths of a percent of depth [5].

The altimetric gravity and multibeam grids were prepared for coherence analysis as described in [6]. Coherence estimation requires averaging of spectral estimates [4]. We obtain one estimated coherence function for each map area, by azimuthally averaging the spectra. We convert the two-dimensional wavenumbers from Cartesian to polar coordinates, and then average around all polar angles. This results in coherence as a function of wavelength, where wavelength is in any and all directions, weighted equally. This approach is justified because the gravitational field of a point mass is radially symmetric. Therefore, if the topography of the seafloor is of uniform density, the associated gravity anomaly field is related to the topography through a radially symmetric operator.

4. RESULTS

The Kane Fracture zone area demonstrates our process. The bathymetry (Fig. 2a) has an axial trough and fine-scale abyssal hill topography crossed by a fracture zone and propagating rift, giving rise to gravity anomalies at both short and long wavelengths (Fig. 2b). The cross-spectral coherence of these two grids is shown in Fig. 3.

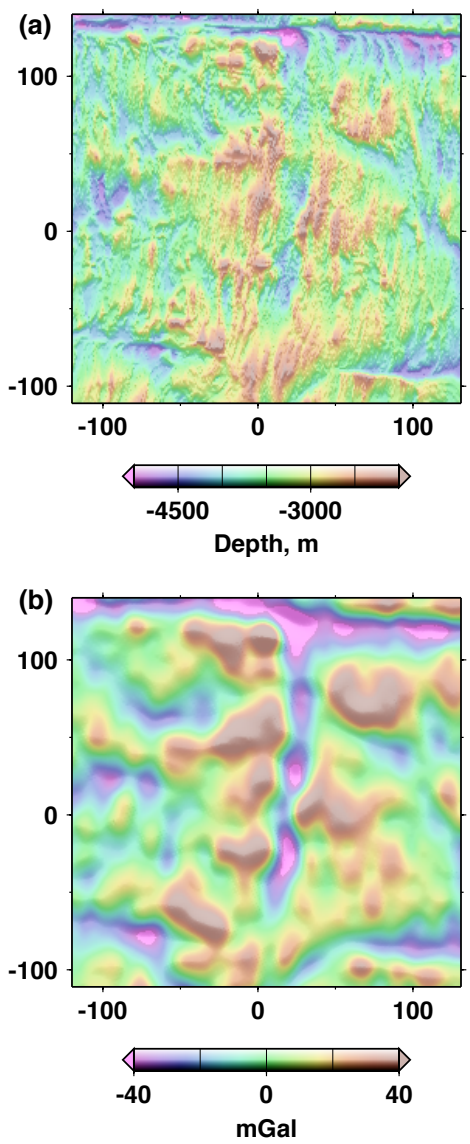

Figure 2. Subset of grids of (a) regional multibeam bathymetry and (b) altimetric gravity over the Kane Fracture zone, for input into 2-D coherence analysis

The results show coherence > 0.5 for wavelengths greater than ~17 km. The coherence also appears to decrease at wavelengths greater than 100 km, a result expected due to isostatic compensation, though not reliably estimated because there are few coherence points at longer wavelengths.

We computed mean coherence in the 20–160 km waveband to get a single value to characterize each area. Bathymetry and downward-continued gravity data may show a linear correlation in this waveband. Table 1 lists the mean coherence results for all the study areas, as well as their tectonic settings. We find that the mean coherence varies with geologic setting (Fig. 1, Table 1). Seamounts and slow-spreading ridges have high (> 0.7) mean coherence, other ridges and trenches have intermediate (0.5 - 0.7) coherence, and continental shelves have lower (< 0.5) values [6].

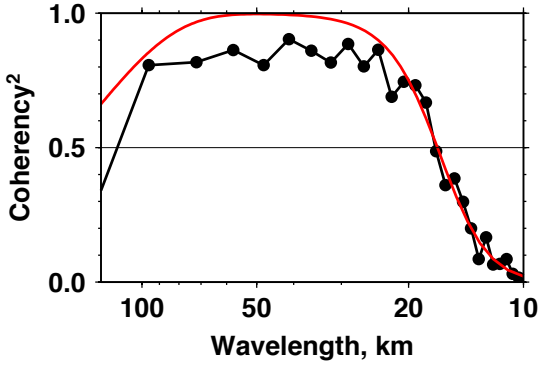

Figure 3. 2-D coherence (black line) between the grids shown in Fig. 2. Red curve is filter used by [1] to select gravity for bathymetric prediction

5. DISCUSSION AND CONCLUSIONS

Smith and Sandwell [1] devised a simple bathymetric estimation method that has two steps: (1) a spectral projection operator that transforms sea surface gravity anomalies into anomalies that may be tested for correlation with seafloor topography; and (2) a test for correlation, which yields a scaling factor that converts milliGals of projected gravity into meters of estimated topography. Our results are used to examine aspects of both steps.

The spectral projection operator is a linear and radially symmetric filter having two components: a downward continuation operator and a band-pass filter, designed to select a range of length scales over which one may seek to correlate spectrally projected gravity with sea floor topography. Because short wavelengths grow exponentially with downward continuation, the short-wavelength cutoff of the filter is crucial. If the cutoff is too large, not enough gravity signal will be passed, underestimating and over-smoothing the estimated topography. If it is too short, exponentially amplified noise will obscure the true details of the estimated topography.

Because there were insufficient available data to determine the short-wavelength cutoff empirically, Smith and Sandwell [1] shaped the band-pass filter using the signal-to-noise ratio in Geosat altimetry [7], making it a simple function of the local mean depth. The red curve in Fig. 3 shows the filter shape, using the mean depth of the Kane Fracture zone area, compared to our coherence results. The filter is correctly selecting coherent "signal" and rejecting "noise" in this area. The filter has a maximum value of 1, whereas our coherence

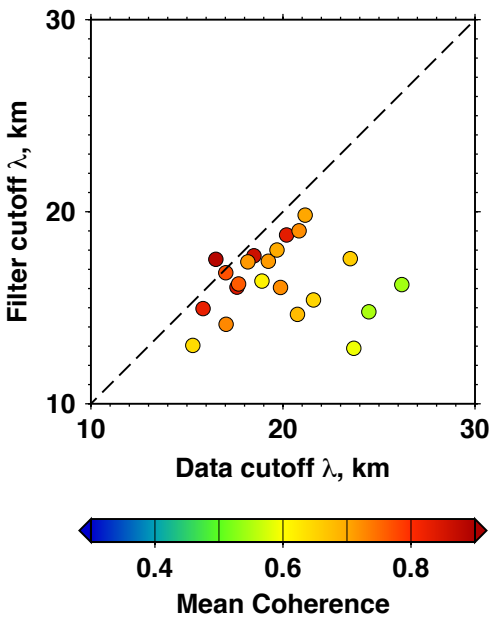

Figure 4. Mean coherence (colored circles) of regions listed in Table 1 plotted against the "cutoff" wavelength at which coherence crosses 0.5 from data, and from the spectral projection filter. Dashed line represents 1:1 ratio between cutoff wavelengths

maximum is somewhat less, suggesting that not all the gravity anomaly should be used to predict depth. This is dealt with in the second step of their method, where the scale factor effectively reduces the amplitude of the prediction as needed.

To compare our results to their filter in all areas, we computed the wavelength at which our coherence estimates cross 0.5 (the data cutoff), and plotted them against the filter cutoff wavelength (shown in Fig. 4 and listed in Table 1). Areas of high mean coherence tend to have cutoff wavelengths that are shorter, and nearer the cutoff of their filter. In areas where mean coherence is low, the cutoff wavelength is also longer. These areas are down-weighted in the second step of the bathymetric estimation process. The spectral projection filter is doing a good job of passing the waveband of potentially high coherence and rejecting the wavelengths where gravity cannot predict bathymetry.

6. REFERENCES

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