Modelling Bathymetry by Inverting Satellite Altimetry Data: A Review

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Abstract. With the advent of satellite altimetry it has become possible to determine the gravity field of the oceans on a global scale. This set of data can be used to predict the bathymetry of deep-seafloor features such as seamounts and ridges. During the last two decades, several algorithms which can be used to develop bathymetric predictions from satellite altimeter data have been published. The characteristics and quality of these algorithms are reviewed in this study. Based on this analysis, we suggest some guidelines for processing data towards the production of maps showing predicted bathymetry for economical purposes.

Introduction

Ever since the fifth edition of the GEBCO map was published in 1982, there is a worldwide agreement on the need to renew existing bathymetric maps. It has long been recognized that gravity could be used to model the shape of the seafloor. However, before satellite altimetry came about, the topography of the seafloor was better known than the gravity field in the oceanic environment, and the problem was mostly an academic one. Successive satellites carrying altimeters onboard have provided measurements of the sea surface height that are both accurate and dense and which can be converted into seafloor topography. Haxby *et al.* (1983) have combined Seasat altimetry and continental gravity to produce a very spectacular map of the free-air gravity anomalies in the South-Western Pacific. The algorithms were later used to process the entire Seasat data set and produce the very famous maps of the Gravity Field of the World's Oceans (Haxby, 1985). These maps which revealed quite remarkable details of the gravity field in marine areas where conventional measurements were sparse have brought out, at a very early stage, the enormous potential such data hold for the study of the superficial lithospheric structure.

This study aims to present a review of the successive works upon the detection or modelling of bathymetric features such as isolated volcanoes, volcanic chains or plateaus. Some studies have dealt mostly with the straightforward detection of uncharted submarine features. They are briefly reviewed first. Other studies focused on various ways to predict bathymetry by essentially using satellite data. Because the people who investigated ways to develop the inversion schemes made very different assumptions, it is important to compare these with one anothers and to evaluate their potential use. These papers are more analysed afterwards.

Description of the Physical Problem

Seafloor is the shallowest density interface in the oceanic domain. Depth variations of the seafloor can be considered as height variations of mass elements the density $\Delta\rho$ of which is given by the contrast between rock and sea water densities. These seafloor depth variations disturb the local gravity field. The disturbing potential $T(r)$ due to a given mass element of volume V is:

$$T(r) = G\Delta\rho \int_V \frac{dv}{|r-r'|}. \quad (1)$$

G is the gravitational constant, r is the coordinate vector of location at which the disturbing potential is computed and r' the coordinate vector of the centre of the mass element. The geoid heights are the altitudes of the actual equipotential of the Earth gravity field which best coincide with the mean sea surface relative to the ellipsoidal equipotential of a reference field. Brun's formula relates the geoid heights N to the disturbing potential T:

$$N=\frac{T}{g}, \quad (2)$$

where g is the gravity acceleration at the surface of the

Earth. The signature of a mass anomaly can also be expressed in terms of the derivatives of the disturbing potential. The gravity anomaly Δg is the derivative along the normal direction, and the deflections of the vertical η and ξ are the derivatives on the North and East directions. Laplace's equation links the three derivatives together:

$$\frac{\partial \eta}{\partial x}+\frac{\partial \xi}{\partial y}=-\frac{\partial \Delta g}{\partial z}, \qquad (3)$$

where x, y and z represents a system of local coordinates in which the z axis is vertical and the x axis is pointing North. From Equation (3), data in either form can easily be converted to any another form.

In practice, the computation area in Equation (1) is discretized in elements of surface $\Delta\Omega(r')$ and the geoid heights of the disturbing potential due to depth variations over this area are given by:

$$N(r)=\frac{G}{g}\Delta\rho\sum_{r'}\Delta\Omega(r')\int_{z_b}^{z_t}\frac{dz}{|r-r'|}, \qquad (4)$$

where z_b and z_t are the depth of the bottom and the top of the mass element centered on r', respectively. It should be noted that this equation is not linear in the height of the mass element $z(r')=z_t-z_b$. Either approximations or iterative schemes are necessary to fully recover the $z(r')$ from geoid heights by inverting Equation (4), or from any other type of gravity data. It must also be noted that when they are determined in such a way, the $z(r')$ values are only but integrated heights over the $\Delta\Omega(r')$. This last point is of particular importance in schemes dealing with merging bathymetry heights produced by such a method with shipborn profiles of bathymetry where the depth values have been sampled on discrete areas much smaller than the characteristic size of the $\Delta\Omega(r')$.

Depth variations of crustal density interfaces may relate to depth variations of the seafloor. In the particular case where the variations of the seafloor depth are due to the presence of a submarine volcano, compensation mechanisms rule the shape of the lateral variations of the crustal density interfaces. For clearness, the expressions which follow are given for a single layer crust. Expressions for more complex crustal structures can be found in cited references. Watts (1978) has shown that when loaded by a volcano, the oceanic lithosphere mimics an elastic plate the equivalent thickness (or stiffness) of which increases with the age of the crust. The lithospheric deflection $w(r)$ due to a distributed bathymetric load $\Delta\rho\Delta\Omega(r')b(r')$ is given by (adapted from Tisseau-Moignard, 1979):

$$w(r)=\frac{\Delta\rho}{\pi\Delta\rho'\alpha^2}\sum_{r'}\text{Kei}\left(\sqrt{2}\frac{|r-r'|}{\alpha}\right)\Delta\Omega(r')b(r') \qquad (5)$$

with

$$\alpha=\sqrt[4]{\frac{4D}{g\Delta\rho'}}, \qquad (6)$$

where α is the flexural parameter, Kei is the Kelvin function, D is the plate stiffness, $\Delta\rho'$ is the density contrast between the mantle and the material filling the flexural moat. The plate stiffness is usually expressed in terms of equivalent elastic thickness T_e:

$$D=\frac{ET_e^3}{12(1-\nu^2)}, \qquad (7)$$

where E is Young's modulus and ν is Poisson's ratio. The observed gravity disturbance integrates the signature of the bathymetry and those of the deflected crustal interfaces, which have to be eliminated. In fact, various compensation mechanisms might be invoked (e.g. thermal isostasy, small scale convection...). However, the plate flexure and its limit case of Airy-type crustal thickening are the mechanisms commonly proposed for the compensation of volcanic structures in the reviewed studies and we thus will limit our discussion to these.

Equations (4) and (5) are convolution operations. Thus, most studies dealing with seafloor modelling from gravity data have been conducted in the Fourier domain where the deconvolutions are replaced by function ratios. The Fourier Transform of Equation (4) is, in plane approximation:

$$FT[N(r)]=2\pi\frac{G}{g}\Delta\rho\exp(-|k|z_0)\times\sum_{n=1}^{\infty}\frac{|k|^{n-2}}{n!}FT[z^n(e')] \qquad (8)$$

where r is now the vector formed by coordinates in the x-y plane and k is the modulus of the wave number vector. z_0 is the reference depth of the density interface. $z(r')$ stands for the depth variations of the interface relative to z_0. Details concerning the derivation of the Fourier expansions can be found in Parker (1972). A linear form of Equation (8) is obtained by limiting the series to the first term:

$$FT[N(r)]=2\pi\frac{G}{g}|k|^{-1}\Delta\rho\exp(-|k|z_0)FT[z(r')]. \qquad (9)$$

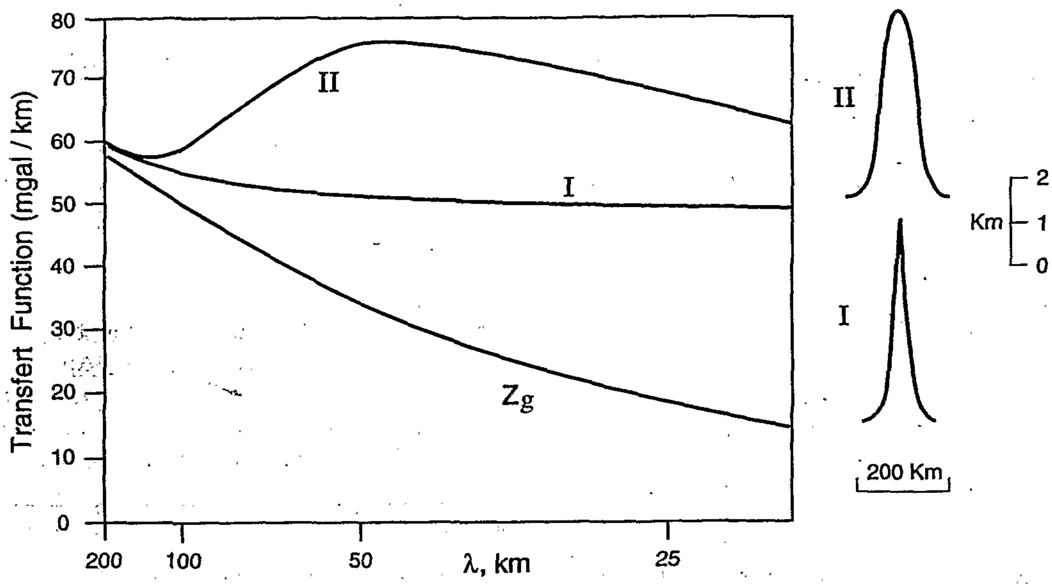

Fig. 1. Full non-linear transfert functions (I and II) versus truncated linear transfert function (Z_g) for uncompensated seamounts, redrawn after Ribe (1982). Curves I and II stand for the gravity to bathymetry ratio for respectively test seamounts I and II, the shape of which is given in the right. Seamount I is $a\exp(-bx)$, seamount II is $a\exp(-bx)\{\cos bx+\sin bx\}$, the value of a being 4 km and that of b being 0.3°. Curve Z_g is given by Equation (11). For wavelengths shorter than 50 km, the Admittance noticeably underestimates the gravity signatures.

This linear approximation of the physical problem allows an easy recovery of the topography of an uncompensated interface $b(r)$ from $N(r')$:

$$b(r)=FT^{-1}[Z_N(k)^{-1}FT[N(r')]] \qquad (10)$$

with

$$Z_N(k)=2\pi\frac{G}{g}|k|^{-1}\Delta\rho\exp(-|k|z_0).$$

From gravity anomalies $\Delta g(r')$, $b(r)$ is recovered as:

$$b(r)=FT^{-1}[Z_g(k)^{-1}FT[\Delta g(r')]] \qquad (11)$$

with

$$Z_g(k)=2\pi G\Delta\rho\exp(-|k|z_0).$$

$Z_N(k)$ and $Z_g(k)$ are called the Admittance functions. Needless to say, the Admittance function may noticeably differ from the actual transfert function between bathymetry and gravity (see Figure 1).

For bathymetric structures such as seamounts or ridges, lithospheric compensation must be taken into account. In the Fourier domain, the expression equivalent to Equation (5) is:

$$FT[w(r)]=-\frac{\Delta\rho}{\Delta\rho'}\left[1+\frac{|k|^4D}{g\Delta\rho'}\right]^{-1}FT[b(r')]. \qquad (12)$$

From Equations (11) and (12), a compensated bathymetry can be recovered from gravity anomalies by:

$$b(r)=FT^{-1}[Z_g'(k)^{-1}FT[\Delta g(r')]], \qquad (13)$$

where the modified Admittance function $Z_g'(k)$ is given by:

$$Z_g'(k)=2\pi G\Delta\rho\exp(-|k|z_0)\left[1-\frac{\exp(-|k|t_0}{\left(1+\frac{|k|^4D}{g\Delta\rho'}\right)}\right]. \qquad (14)$$

From Equations (10) and (12), the modified Admittance function $Z_N'(k)$ for geoid height data is given by:

$$Z_N'(k)=2\pi\frac{G}{g}|k|^{-1}\Delta\rho\exp(-|k|z_0)\times\left[1-\frac{\exp(-|k|t_0}{\left(1+\frac{|k|^4D}{g\Delta\rho'}\right)}\right], \qquad (15)$$

where t_0 is the reference depth of the deflected interface below z_0 (t_0 stands for the crustal thickness in the hypothesis of a single-layer oceanic crust). In the space domain, Admittance is replaced by a kernel function the expression of which can be found in Calmant (1994).

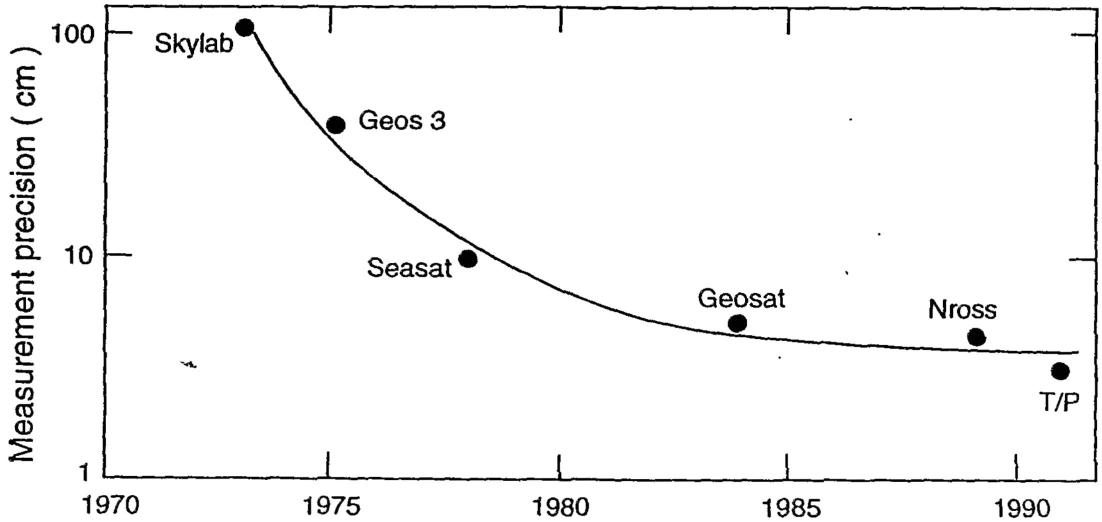

Fig. 2. The evolution of satellite altimetry precision, redrawn after McConathy and Kilgus (1987).

The observed gravitational signature of a structure also may encompass that of sediment layers, the density of which may be neither that of the crustal material nor that of the volcanic load. Indeed, sediments may contribute as a cover of the seafloor and as the material infilling the flexural moats. A sedimentary cover all over a given area of study is of minor importance since it will appear in the gravitational signature as a long wavelength contribution. On the other hand, the gravitational signature of infilling sediments may noticeably merge with that of the studied structure. Yet, for simplification proposes, most studies conducted in the Fourier domain assume that the infilling sediments have same density as the load itself. Indeed, the errors due to this simplification are of the same order than the errors which can be made on the estimate of the density of the load.

Satellite Data

Radar altimeters aboard oceanographic satellites measure the distance from the satellite to the sea surface. Since the path of the orbit is obtained independently, the height of the sea surface over a reference ellipsoid can be determined. In 1975, when Geos-3 was launched, measurement noise and orbit accuracy were not good enough for accurate bathymetric predictions to be performed but the feasibility was demonstrated. Later on, Seasat (1978), Geosat (1986–1989), ERS-1 (1991-) and Topex/Poseidon (1992-) provided both accurate and dense sea surface measurements. The white noise level of today's satellite altimeters is below 5 cm (Richards and LeSchack, 1987) and orbit determinations better than 10 cm are currently achieved on Topex/Poseidon. The evolution of satellite altimetry precision is displayed in Figure 2. Geodetic satellite missions have provided dense coverage tracks of instantaneous heights (Geos-3, Seasat, Geosat, ERS-1), while oceanographic missions with repetitive orbits (Seasat, Geosat, ERS-1, Topex/Poseidon) provide time averaged sea surface heights free of meteo-oceanographic contributions over a limited amount of tracks (see for example Sandwell and McAdoo, 1990).

Detection of Seamounts and Other Bathymetric Features

Lambeck (1981) published one of the first detections of seamounts from satellite altimetry in the Southern Cook Islands using Seasat data. Lambeck and Coleman (1982), in a more detailed study, located seven uncharted seamounts in the same area. Seamount signatures were detected on individual Seasat and Geos-3 tracks.

During the same period, Sailor (1982), Lazarewicz and Schwank (1982) and White *et al.* (1983) developed the implementation of matched filters to automatically detect seamount signatures along Seasat tracks. The purpose of the study was to develop an objective and quick tool to detect and locate uncharted seamounts in the along-track direction.

Dixon and Parke (1983) published maps of a filtered geoid which represent the "first opportunity to investigate synopticaly major bathymetric features in the southern oceans." The shape of the geoid over the EPR was discussed, several previously uncharted seamounts and ridges were detected, and data were used to discuss the morphology of the Eltanin and Udintsev Fracture Zone systems. Sandwell (1984a) constructed images of the sea-surface of the South Pacific by merging along-track derivatives of the vertical from Seasat and Geos-3 data. These maps revealed many new bathymetric features. They confirmed the connection between the Eltanin FZ and Louisville ridge, as first suggested by Dixon and Parke (1983). A list of the location and relative geoid signature intensity of 210 seamounts was provided, from which 72 were uncharted. Individual profiles of along-track deflection of the vertical were also displayed on GEBCO map overlays (Sandwell, 1984b) to allow more detailed studies to be performed.

Detailed studies using Seasat have been performed by several authors on the detection and mapping of fracture zones in order to obtain new constraints for cinematic and regional tectonic models (see, among others, Vogt *et al.*, 1984; Okal and Cazenave, 1985; Shaw, 1987; Royer *et al.*, 1988; Watts *et al.*, 1988). Regional studies of the mechanical behaviour of the lithosphere have lead to the detection of uncharted seamounts signatures (see for example Cazenave and Dominh (1984) on the Louisville Ridge, Freedman and Parsons (1986) on the Musician seamounts). A systematic detection of seamounts along the Louisville Ridge from Seasat tracks was performed by Lonsdale (1988). Data were also used in sismotectonic studies (see for instance Sailor and Okal, 1983) or to assist in hand-contouring conventional bathymetry (Mammerickx, 1992). Geosat Exact Repeat Mission data provided accurate measurements at high Southern latitudes, collected when the ice cover was minimal. These data were used to improve the knowledge of the southern marine gravity field and lead to the detection and interpretation of several new tectonic features (Sandwell and McAdoo, 1988; McAdoo, 1990) and cinematic reconstructions (Royer and Sandwell, 1989; Mayes *et al.*, 1990).

In 1990, the declassification of GEOSAT Geodetic Mission South of 30° S has made available an unequalled dataset of closely spaced tracks which greatly improved the horizontal resolution of geoid determination from satellite altimetry (Sandwell and McAdoo, 1990). This new dataset has in particular been used to follow the geometry of fracture zones (Marks and Stock, 1994) or the morphology of abyssal hills (Macario *et al.*, 1994) in the southern oceans. In 1994–1995, ERS-1 also performed a Geodetic Mission with dense coverage of the sea surface. This dataset should be of similar use North of 30° S than Geosat was in the southern oceans.

Seafloor Topography Modelling

In this section, we will discuss the various techniques used to recover quantitative information on seafloor topography from the processing of satellite altimetry, whether they are merged with other geophysical data or not. Many studies touched upon in the previous section provide information on the bathymetry, i.e. the location of seamounts or fracture zones. Nevertheless, we will presently discuss only those papers which provide some quantitative evaluation of the bathymetry: the bathymetric function itself, or an evaluation of some bathymetric parameters such as the width or the height of the seamounts. The techniques that we will discuss are: the one-dimensional inversion of satellite tracks using linear approximation of the transfer function (Dixon *et al.* 1983; Vogt and Jung, 1991; Jung and Vogt, 1992); the one dimensional adjustment of synthetic and satellite tracks (Baudry *et al.*, 1987); the geometrical analysis of satellite tracks (Craig and Sandwell, 1988), the two dimensional inversion of geoid anomalies (Baudry and Calmant, 1991); and the two dimensional inversion of satellite data and the merging with conventional geophysical measurements (Smith and Sandwell, 1994; Calmant, 1994). The characteristics of the studies discussed in this section are summarized in Table I.

Dixon *et al.* (1983) published the results of a feasibility study of a bathymetry prediction technique based on the one-dimensional filtering of Seasat tracks. Basically, the algorithm used is the linear approximation of the relationship between the geoid and a given density contrast interface, which is given by Equations (13) and (14). A predictive theoretical filter was applied to Seasat tracks; the authors then discuss the sensitivity of results to various parameters. They concluded that:

- The bathymetry prediction is sensitive to the Moho depth only at long wavelengths.
- The prediction exhibits only moderate sensitivity to the crustal density, mainly at short wavelength (the predicted height of the seamounts varies by approximately $\pm$ 500 m for crustal densities varying from 2.4 to 2.8 g/cm^3.
- The prediction is strongly influenced by the choice of D. Variations of D between 10^{21} to 10^{23} N.m

TABLE I

	Final function obtained	Dimension of the resolved physical problem	Assumption on bathymetry shape	Inversion method	Use of shipborn bathymetry	Accuracy evaluation
Dixon *et al.* (1983)	Along track bathymetry	1D	Infinite in the cross-track direction	Linear filtering (Fourier domain)	No	Empirical from sensitivity to geophysical parameters
Baudry *et al.* (1987)	Seamount off-track location and height	2D reduced to 1D	Isotropic Gaussian seamount	No inversion Direct adjustment on synthetic profiles	No	Empirical from sensitivity to geophysical parameters
Craigh and Sandwell (1988)	Seamount along-track location and width	2D reduced to 1D	Isotropic Gaussian seamounts	No inversion Geometrical analysis of along-track derivatives	No	Empirical
Baudry and Calmant (1991)	2D bathymetry	2D	No	Iterative resolution of the non-linear problem (Fourier space)	No	Analytical
Vogt and Jung (1991) and Jung and Vogt (1992)	Along-track bathymetry	1D	Infinite in the cross-track direction	Linear filtering (Fourier domain)	Adjustment on historical bathymetry	Empirical from external tests
Smith and Sandwell (1994)	2D bathymetry	2D	No	Linear filtering (Fourier domain)	Result is a merging of historical bathymetry ($\lambda > 160$ km) and inverted gravity ($20 < \lambda < 160$ km)	Empirical from external tests
Calmant (1994)	2D bathymetry (least square adjustment)	2D	No	Iterative resolution of the non-linear problem (space domain)	Inverted data set includes satellite altimetry and shipborn gravity / bathymetry	
Baudry and Calmant (this volume)	2D bathymetry	2D	No	Iterative resolution of the non-linear problem (Fourier domain)	Historical bathymetry is used to adjust inverted geoid while iterating	Analytical

caused the bathymetry prediction to vary by as much as 1000 m.

The authors discuss some artefacts and limitations in predicted bathymetry which are due to the high two-dimensionality of the seafloor topography, and the one-dimensional approximation of the technique used to process the data:

- Because the geoid anomaly of a seamount is wider than the topography, the filter can also model seamounts which are in fact located off-track.
- When the satellite tracks pass close to the summit of a seamount, the predicted bathymetry height will be systematically underestimated. This is also a consequence of the one-dimensional approximation, since in order to produce geoid anomalies of identical amplitudes, the height of the modelled one-dimensional ridge running perpendicular to the profile will be less than the height of the actual conical seamount.

Because this 1D linear filtering algorithm has later been used by several investigators, we deem it important to add two comments on the limitations of this technique:

- Firstly, large amplitude topography (and corresponding plate deflection) makes the high-order terms of the full expression of the relationship between geoid and bathymetry (Equation 8 and Figure 1) important relative to the first term. In other words, the amplitude of many seamounts is large enough for non linear response to be significant (Ribe, 1982). Therefore, the greater the amplitude of actual bathymetry, the less accurate the predictive filter will be.
- Secondly, severe problems are to be expected in the results when a predictive filter designed for one-dimensional bathymetry is used to predict bathymetry which is actually two-dimensional. As mentioned by the authors, the implicit assumption of infinite length of the topography perpendicular to the satellite tracks leads to an underestimation of the along-track section of the bathymetric features. Furthermore, for typical wavelengths of the seamount bathymetry (40–150 km), the sensitivity of the predicted bathymetry to the flexural rigidity D is very important in one dimension, and significantly less important in two dimensions (see a detailed analysis in Ribe, 1982). In fact, the inaccuracy of the exact value of D as the major limiting factor on seafloor predictions for small and middle size seamounts is for a large part a consequence of the one-dimensional reduction of the physical problem (see Baudry and Calmant, 1991).

Baudry *et al.* (1987) put forward a method to determine the approximate size and off-track location of seamounts based on an analysis of parallel satellite altimeter tracks. A set of synthetic altimetric tracks was constructed from independent variations of the following parameters: the height of seamounts (the shape of which is supposed to be Gaussian), the cross-track distance between seamounts and satellite tracks, and the flexural rigidity of the lithosphere. By looking for the best rms adjustment between this set of synthetic profiles and at least two satellite tracks passing in the vicinity of a seamount, the authors showed that some realistic values of both height and off-track distance of the seamounts could be determined. If the assumed tectonic setting of seamounts is correct (on-ridge or off-ridge seamounts), the accuracy in seamount cross-track positioning is about 15 km. Since the synthetic altimetric tracks are extracted from two-dimensional synthetic geoid anomalies, the sensitivity of the signal to the flexural rigidity parameter is reduced compared with one-dimensional modelling. Apart from the assumption made on the on-ridge or off-ridge seamount tectonic setting, the main limitation of this method is the additional assumption of a Gaussian shape for the topography of seamounts.

Craig and Sandwell (1988) used the deflection of the vertical (along-track derivative of the geoid height) to determine the characteristic width of seamounts. This work further developed preliminary results obtained by Groeger (1981a, b). The announced results are (i) the width of seamounts can be directly deduced from the peak to trough distance along the profiles of vertical deflection; (ii) a single satellite track may be sufficient provided that it passes over the seamount but not necessarily over the summit; (iii) the flexural parameter can theoretically be deduced from the zero crossings in the signatures although noise in the data prevents an accurate determination. In fact, most of these results flow from the mathematical properties of the analytical function (an isotropic Gaussian curve) primarily assumed for the shape of seamounts. As noted by the authors, the conditions needed for this method to be satisfactorily applied are rarely fulfilled altogether. This method nevertheless provides realistic first approximations of the width and tectonic setting of seamounts of Gaussian shape.

Baudry and Calmant (1991) published the first work which attempted to make seamount bathymetry predictions with (i) no linear approximation; and (ii) two-dimensional modelling. Geoid anomalies on 2D grids centered over the seamounts were first computed using a collocation algorithm (Moritz, 1978) which allowed the actual accuracy of altimetric measurements from various satellites to be taken into account. It was thus possible to produce both geoid anomaly and associated accuracy. This anomaly was then inverted using an iterative algorithm in order to apply the fully developed function of Equation (8). The Admittance hypothesis provided the initial solution for the bathymetry which was iteratively refined by taking the higher degree terms into account. The function describing the uncertainty relating to the geoid anomaly was used to compute a function of the uncertainty relating to the predicted bathymetry which was due to the noise and spatial distribution of the processed satellite altimeter data. Uncertainties in predicted bathymetry due to density and lithospheric flexural rigidity were only locally estimated. One major result of this work was to show that, for intermediate size seamounts, the high uncertainty relating to the lithospheric flexural uncertainty does not produce bathymetry uncertainties as important as those suggested by the previous one-dimensional analyses (see above). The method described in this paper allows detailed seamount bathymetry modelling to be performed. On the other hand, since it requires detailed handling and processing of the data, the processing of very large areas requires a large amount of work. With this algorithm it is not possible to process bathymetric shipborn data together with altimetric measurements. Baudry and Calmant (this volume) have presented an improved version of this algorithm where shipborn data and a crustal structure model were used to constrain the solution of the inversion during iteration.

Vogt and Jung (1991) and Jung and Vogt (1992) performed bathymetric predictions along GEOSAT ERM tracks in the South Atlantic Ocean at locations where corresponding suborbital shipboard gravity and bathymetry profiles were available. Basically, the algorithm used was the one used by Dixon *et al.* (1983), i.e. a linear filtering of geoid profiles (Equation (10)) performed in one dimension. The terms of the filter were set to zero for wavelength shorter than 20 km using a cosine function. A powerful solution, used by the authors to improve the predicted bathymetry at intermediate and long wavelengths, was to adjust this predicted bathymetry to some "archival bathymetry" provided by ship-tracks. This was effected by replacing the slope of a section of predicted bathymetry between two neighbouring points in the archival bathymetry data, with the slope defined by the measured depth at these two points. In these papers, the authors did not use archival bathymetry, but simulated archival bathymetry obtained by re-sampling the subsatellite shipborne bathymetry.

In a first test, Jung and Vogt used simulated historical bathymetry with small sampling intervals (32 to 45 km). These bathymetric data strongly constrained the predicted bathymetry, not only at long wavelength, but at short wavelengths as well. Not surprisingly, the predicted bathymetry adjusted at these points showed a much greater similitude with ship bathymetry than unadjusted predicted bathymetry did.

A second test was performed by adjusting bathymetry predicted from shipboard gravity to simulated historical bathymetry. Mean sampling intervals of simulated historical bathymetry varied from 117 km to 7 km. Based on these tests, the authors concluded that bathymetric predictions based on a combination of shipborne gravity and archival bathymetry was superior to those based on archival bathymetry data alone, provided that the average data interval of archival bathymetry exceeded 10 km. In other words, they showed that shipborne gravity provided bathymetric information at wavelengths greater than 20 km, which is the shortest wavelength that can be produced by a 10 km sampling interval signal. This 20 km wavelength limit for a significant output signal was to be expected, since the terms of the admittance function had been set at zero for wavelengths shorter than 20 km. The authors indicated that this filtering technique was best suited to situations where altimeter tracks cross strongly lineated topography at right angles, and that better predictions could be made if the problem was solved in two dimensions.

Smith and Sandwell (1994) basically used the same linear relationship between gravity and bathymetry in the Fourier space (Equation (11)). The data set used was the gravity grid computed by Sandwell and Smith (1992) using Seasat, Geosat-GM and preliminary ERS-1 (35 day ERM mission) data. The data processing was performed using an actual 2D expression of Equation (11). The main steps of the data processing were as follow:

- Filtering was operated in two steps. The first step involved in band-pass filtering the gravity data set and computing a downward continuation of the filtered gravity:

$$G(k) = G_0(k)\,W(k)\exp(2\pi kd), \tag{16}$$

where d is the mean water depth and where the band-pass filter $W(k)$ has been designed according to Wiener's optimization theory and an empirical determination of the noise-to-signal ratio. In particular, this filter smoothed out the gravity spectrum in all the wavebands where the plate deflection might have a significant input. According to the hypothesis of linear relationship between bathymetry and gravity of the Admittance theory, $G(k)$ can be converted into bathymetry by simply multiplying it by a numerical constant $S=(2\pi G\rho)^{-1}$. Instead of using this theoretical value of S, authors determined experimental values of S over areas having a 135 km radius. S was computed using linear regressions of downward continued gravity $G(x)$ and band pass filtered bathymetry over each area. This allowed S to take into account the value of ρ as well as the actual correlation between gravity and bathymetry in the computation area. Experimental values of S were bounded between 0 and $(2\pi G\rho)^{-1}$. Very low values for S were obtained in sedimentary basins where the gravity signal was dominated by buried basement topography instead of by the shape of the seafloor as before. This process allowed to recover the bathymetric variations from the band-pass filtered gravity.

- Global bathymetric grid $d(x)$ was constructed using low pass filtered shipborn bathymetry in order to obtain regional long wavelength bathymetric depths.
- These two bathymetric functions were merged to recover the all-components bathymetry $b_p(x)$ over the global map:

$$b_p(x) = d(x) + S(x)g(x). \tag{17}$$

This process was directed toward the processing of a large amount of data. It allowed the production of a global bathymetric map but according to the authors, the main limitation of this scheme was that the short wavelengths of the bathymetry were not recovered. This is due in the first place to the linear approximation of the Admittance theory and secondly, the low pass filtering of the gravity data set when computing the downward continuation. Another critical point is that, when it existed, the short wavelength bathymetry originating from ship cruises had been removed when effecting $d(x)$ and had not been re-introduced in $b_p(x)$, the final bathymetry. Thus, in areas where the ship coverage was good, short wavelength bathymetric information was actually available but has disappeared from the final bathymetry.

Validation has been achieved by comparing the predicted bathymetry with a ship bathymetric track across the Pacific-Antarctic Rise which was not incorporated in the computation of the prediction. When very long wavelengths ($\lambda > 2000$ km) are removed along the track, the mean amplitude of the filtered bathymetry is of the order of 500 m which is in fact a favorable case in regard to the linear computing scheme. Comparison between shipborn and predicted bathymetry shows that 80% of the discrepancies are within 240 m. Visual inspection of both profiles shows that these discrepancies are mostly at short wavelengths. Therefore these 240 m of resolution should be compared to the 500 m amplitude of the signal and generalization of this resolution to areas of high amplitude signal should be made with caution.

As a matter of fact, the produced bathymetry $b_p(x)$ contains information which came, for wavelengths greater than 160 km, from shipborn bathymetry, and for wavelengths between 20 and 160 km, from the satellite altimetry alone. Therefore the map which was produced is of major interest in areas where shipborn data are lacking. As suggested by the authors, it can be helpful for planning of oceanographic cruises since it can reveal new features, and for checking the reliability of older charts.

This map should be used with caution since artifacts are present in the resulting bathymetry. An example of these artifacts is the axial valley of the South Tasman Ridge (South East Australia). It appears on the map although it is has become an inactive spreading center with a buried axial valley, not visible on shipborn data (GEBCO map). This kind of artifact is probably a product of the regional evaluation of the correlation coefficients, thus encompassing features which may be adjacent within each computation cell which in turn may present very different correlations with the gravity field. This example of artifact shows the limits of such a statistical approach to the variable physical model which relates gravity signatures and bathymetric features.

Calmant (1994) analysed the importance of all parameters involved in the problem in order to determine the accuracy that may be expected on a bathymetric map obtained by inversion of altimetric heights, and the associated uncertainties. The analysis encompassed the type of the data from which a given bathymetry is obtained, their coverage and their accuracy, the effect of the linear approximation in the inversion scheme, and the part played by the assumed values for the geophysical parameters such as elastic thickness of the lithosphere and volcano density. The inversion was performed in the space domain. Conversely to inversions currently performed in the Fourier domain, inversion in the space domain allows the joint inversion of data of different kinds such as altimetric heights and shipborne gravity and/or bathymetric profiles whereas others deal separately with altimetric and bathymetric information. This method furthermore allowed to take into account the different accuracies of the successive altimeters. To do so, the bathymetric solution was achieved as a least square solution. Finally, it provided an estimate of the uncertainty alongside any bathymetric value. These uncertainties accounted for those produced by the data set (coverage, type of data, relative accuracy of the different datasets used), any a-priori knowledge of the bathymetry to be restored and the use of non-exact values for the geophysical parameters. The study was performed by comparing results of inversion with a reference set comprising the bathymetry of a synthetic seamount (2 km high, anisotropic Gaussian shape) and its geoid and gravity signatures. Results were that (i) the linear hypothesis generates very large errors (up to 800 m on the submittal height, i.e. 40%), even for such a smooth structure (low energy in short wavelengths); (ii) errors vary from 50 to 120 m (rms) for altimetric data uncertainty from 5 to 10 cm; (iii) a wrong estimate of the elastic plate thickness and volcano density generates errors up to 170 m (rms) and 500 m (maximum error). Lastly, the influence of the interpolator used to generate a 2D bathymetry from a set of scattered data was studied. In this scheme, the interpolator also took into account the covariance function of the errors on an a-priori bathymetric solution. It was shown that an interpolator which alters the spectral contents of the studied bathymetric feature may also generate large errors in the bathymetric result (up to 800 m errors are evidenced) and that it also bears on the confidence one can have in this result. The conclusion of this work is that by properly taking into account all sources of errors it is possible to restore a bathymetry with limited errors, and that realistic estimates of probable errors are both possible and necessary since they may present large variations over small areas.

Discussion

All these studies show that it is realistic to try to map the bathymetry from altimetry datasets despite the very negative prognosis of Watts and Ribe (1984): "... These considerations indicate that it may not be possible to use satellite altimeter data to predict bathymetry in the oceans with any degree of reliability". Some of the quoted papers have been followed by field tests. Keating *et al.* (1984) reported the results of four field tests conducted on targets pointed out by detection studies based on matched filters. The field tests were unsuccessful and led to believe that seamount detection from altimetry was "less reliable than most investigators had thought" (in Keating *et al.*, 1984). They reflected in fact that the matched filters were much too sensitive to erroneous data to be used in processing individual tracks of Seasat measurements. Other published series of field tests have been conducted in 1986 and 1987. They took place in the South West Pacific during Seabeam and SeaMARK II surveys (Baudry and Diament, 1987; Baudry *et al.*, 1988; Hill and Baudry, 1992). All these tests were successful, i.e. all predicted seamounts were found within 15 km of the predicted location. These field tests showed that bathymetric predictions based on the joint processing of several satellite tracks were reliable.

Bathymetric maps generated by inverting gravity data have limited applications in fundamental geophysics. They cannot be used to constrain the mechanisms of lithospheric compensation any further since the latter are necessarily postulated in the inversion schemes; the resolution of these maps is too low to be used in detailed structural analysis in the same way as shipborn data. In fact, these maps are of interest in marine science fields other than geophysics, such as physical oceanography (Roden, 1987) or marine biology (Boelhert and Genin, 1987), and for economic activities such as submarine navigation (Vogt and Jung, 1991), fishery resources (Uchida and Tagami, 1984; Seki and Tagami, 1986; Sasaki, 1986; Fonteneau, 1991; Baudry, 1994a) and mineral resources (Keating, 1989; De Carlo, 1991; Pichocki and Hoffert, 1987; Halbach *et al.*, 1983) to name but a few. To that end, detailed surveys have been performed in areas of the South Pacific and Indian oceans which were poorly mapped by conventional bathymetry. The objective of these surveys was to provide as exhaustive as possible bathymetric information on the size and location of seamounts from both satellite altimetry and shipboard bathymetry (Baudry 1994b).

The present analysis leads us to the following conclusions:

- It is not warranted to use algorithms which alter the quality of the produced bathymetry, particularly insofar as the mapping of short-wavelength bathymetry is concerned. For this reason, linear simplification of the transfer function and 1D processing of the data should be avoided.
- Various methods integrate the use of archival bathymetry, from adjustment of the predicted bathymetry onto the archival one to an integration of the archival bathymetry into the dataset to be inverted. Shipborn bathymetry and gravity-derived bathymetry are complementary because in many places of the southern ocean shipborn bathymetry is very sparsely and irregularly distributed. Archival bathymetry contains, where it exists, information up to wavelengths much shorter than altimetry can recover. Therefore, actual bathymetry will have to be introduced or re-introduced at all wavelengths in the final bathymetric maps.
- The introduction of a statistical approach to tune a model at the regional level in order to enable a global processing of the altimeter data set may generate artifacts in the produced bathymetry. The opposite method, which involves a separate modelling

of individual features, should better take into account the variable geophysical relationship between gravity and bathymetry. It should be possible to produce better global maps this way.

- Since the method is ultimately unable to provide bathymetric depths with as high an accuracy as modern shipborn equipments do, and since the physical relationship between the data and the seafloor heights cannot be precisely determined, since some of its parameters are always estimated values, it is of the utmost importance that the uncertainty at any location within gravity-derived bathymetric maps be provided. It has shown that uncertainty maps which can take into account most of the sources of errors in the prediction scheme could be satisfactorily generated. This information should accompany the publication of any bathymetric map.

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