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Note on the use of an altimeter mean sea surface for mesoscale variability studies

Altimetry
Mean sea surface
Variable oceanic signal
Optimal analysis

Altimétrie
Signal océanique variable
Surface moyenne oceanique
Analyse optimale

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ABSTRACT

This report discusses whether, by the year 1995, altimeter mean surfaces such as those generated by Geosat, ERS-1 [35 days] and Topex-Poseidon will be accurate enough for extracting the variable ocean signal. The mean oceanic signal is estimated from altimetry using an inverse method. Because of the large number of altimeter measurements, the original one-step method is transformed to a two-step method, the iterative inverse method. The space-time distribution of the altimeter data is only needed to calculate the formal error on the altimeter mean surface. Using a year of satellite altimeter measurements, the mean rms errors are 10 cm for Geosat, 8 cm for ERS-1 and 13 cm for Topex-Poseidon. The along-track minima are respectively 8, 7 and 5 cm rms. Errors can be reduced to 4 cm rms minimum to 6 cm rms maximum by combining two years of Geosat and ERS-1 data. These results are preliminary but indicate that the altimeter missions of the 1990s should provide the necessary accuracy.

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RÉSUMÉ

Note sur l'utilisation d'une surface moyenne altimétrique pour des études du signal océanique méso-échelle

L'objectif de cette note est d'établir si, à l'horizon 1995, les surfaces moyennes altimétriques [*e. g.* satellites Geosat, ERS-1 (35 jours), Topex-Poséidon] permettront d'extraire le signal océanique variable avec suffisamment de précision. Le signal océanique moyen est estimé par une méthode d'analyse optimale des mesures altimétriques. Compte tenu du grand nombre de mesures altimétriques, la méthode originale en une étape a été remplacée par une méthode en deux étapes, la méthode inverse itérative. Connaissant seulement la répartition spatio-temporelle des données altimétriques, la méthode permet d'estimer l'erreur formelle associée à la surface moyenne altimétrique restituée. Avec un an de mesures altimétriques, l'erreur moyenne obtenue est de 10 cm rms pour Geosat, 8 cm rms pour ERS-1 et 13 cm rms pour Topex-Poséidon, et des valeurs minimales le long de la trace respectivement de 8, 7 et 5 cm rms. Combiner les données Geosat et ERS-1 permet de réduire ces erreurs. Avec deux années de mesures altimétriques, on obtient une erreur fluctuant entre 4 cm rms minimum et 6 cm rms maximum. Ces résultats sont préliminaires, mais indiquent que la précision que l'on obtiendra devrait être suffisante.

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INTRODUCTION

To access mesoscale variability in altimeter measurements, each measurement must be referenced to a mean ocean level, *i. e.* the geoid height plus the height due to the mean circulation. When a repeat-track satellite measures the sea level over at least two years, its measurements can be averaged along each track to yield the mean ocean height

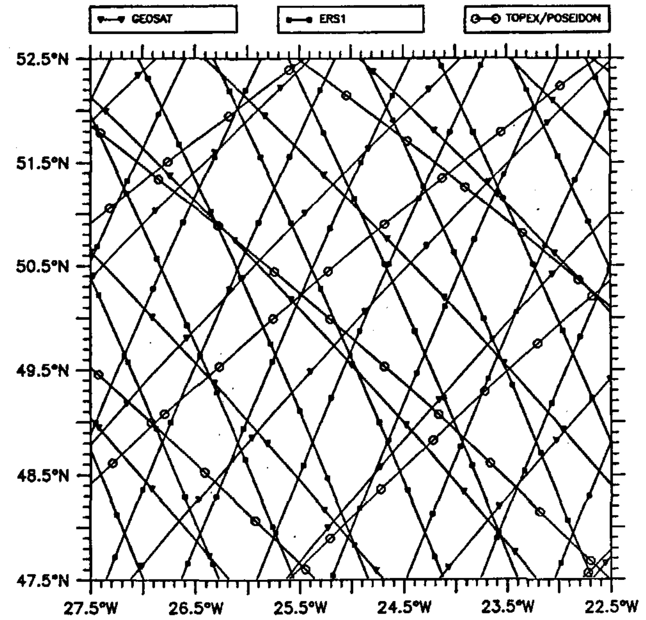


Figure 1

North-East Atlantic ground tracks of repeat-orbit satellites Geosat (17-day repeat period), ERS-1(35-day repeat period) and Topex-Poseidon (10-day repeat period).

Projection au sol en Atlantique Nord-Est de l'orbite des satellites répétitifs Geosat (période de répétitivité de 17 jours), ERS-1 (période de répétitivité de 35 jours) et Topex-Poséidon (période de répétitivité de 10 jours).

(Ménard, 1983). However, in other situations, or if near-real-time studies are conducted, such a method is unsuitable and an external mean sea surface (MSS) is needed (*e. g.* De Mey and Ménard, 1989). If the variable ocean signal, of the order of 10-20 cm, is to be extracted from the altimeter data, the MSS must be accurate to within 2-3 cm. The question is: do altimeter satellites - past or present - provide sufficient accuracy ?

Visual inspection of Geosat, ERS-1 and Topex-Poseidon ground tracks shows how well they cover the oceans. At the mid-latitudes, any half-degree by half-degree ocean box is overflown by at least one satellite (*see* Fig. 1). By 1995, altimeter MSS information will be available within a 40-km radius of any point in the ocean. This report discusses the accuracy.

METHOD

Information on the altimeter signal and its derivatives can be estimated by an optimal analysis known as the inverse formalism (Bretherton *et al.*, 1976; Tarantola and Valette, 1982). Weighting coefficients are established from *a priori* information, namely statistics on the measured ocean signals and measurement errors. The key terms of such a theory are the data and its space-time distribution, the *a priori* and *a posteriori* information. When the method is applied to the estimation of a MSS (Wunsch and Zlotnicki, 1984; Houry and Mazzega, 1990). The matrix equations are:

$$P = Po + C_{PoPo} \,.\, S^{-1} \,.\, (d_o - Po) \qquad (1)$$

$$CPP = C_{PoPo} - C_{PoPo} \,.\, S^{-1} \,.\, C_{PoPo} \qquad (2)$$

$$\text{where } S = C_{dodo} + C_{PoPo} \qquad (3)$$

The definitions are as follows:

d_o = altimeter data (vector)

C_{dodo} = *a priori* data error budget (covariance matrix)

Po = first guess of mean ocean signal

C_{PoPo} = first-guess error (covariance model)
(if there is no first guess, the covariance model represents the signal itself)

S = positive symmetric definite square matrix,
sized according to number of altimeter data values

P = *a posteriori* mean ocean signal

C_{PP} = *a posteriori* error covariance.

The method optimally estimates the mean signal (P) and its error (CPP). CPP is the formal error, stated as a covariance function. Spectral analysis of the error reveals, in terms of wavelengths and accuracy, the proportion of the signal which is recovered from altimetry. Note that to estimate formally the altimeter MSS accuracy (*see* equation 2), all that is required is the first-guess error estimate, the space-time distribution of the altimeter data and the data error budget.

The inverse method is based on a single operation, requiring the resolution of large linear systems sized according to the number of altimeter data values. This calls for a lot of memory space and CPU time. There may also be numerical instabilities. We limited ourselves to 7 000 altimeter values, or one hour of CPU time on the Cray-2. To estimate a mean ocean signal accurately (to within a few centimetres) at all wavelengths, the altimeter data for a given basin would theoretically have to be processed in a single step. Today's computer configurations are still not powerful enough for this. Since the mean ocean signal can be recovered sequentially at different wavelengths (the iterative inverse method: Blanc *et al.*, 1991), we suggest that all wavelengths of the mean ocean signal can be estimated in two steps. First, the long to medium wavelength signatures are estimated over the study area, then the medium to short wavelength undulations over smaller areas measuring a few degrees by a few degrees (*see* Fig. 2).

ALTIMETER DATA ERROR BUDGET

The altimeter space and time distribution were simulated over a one-year period for Geosat, ERS-1 [35 days] and Topex-Poseidon satellite. Each set of data is confined to the data in the study area, which coincided with the AthenA-88 experiment (40°-10°W, 40°-60°N; Boissier and AthenA Group, 1988).

The data error budget, identical for steps 1 and 2, consists of statistical information on altimeter data components. We included four. They are as follows:

Altimeter instrument noise

This is treated as a white noise. Its covariance function D1 is modelled by a 2 cm rms dirac delta (σ_{alt}) depending on the time lag T between any pair of altimeter data points. Geosat altimeter noise is larger (3-4 cm rms) for the one-second average but can be reduced if altimeter data are subsampled. And as the method is not very sensitive to this type of noise (Benveniste, 1989) and for greater convenience, we chose a constant value for both steps, for the three satellite simulations.

$$D1\ (T) = \sigma_{alt}^2 \,.\, \delta(T) \tag{4}$$

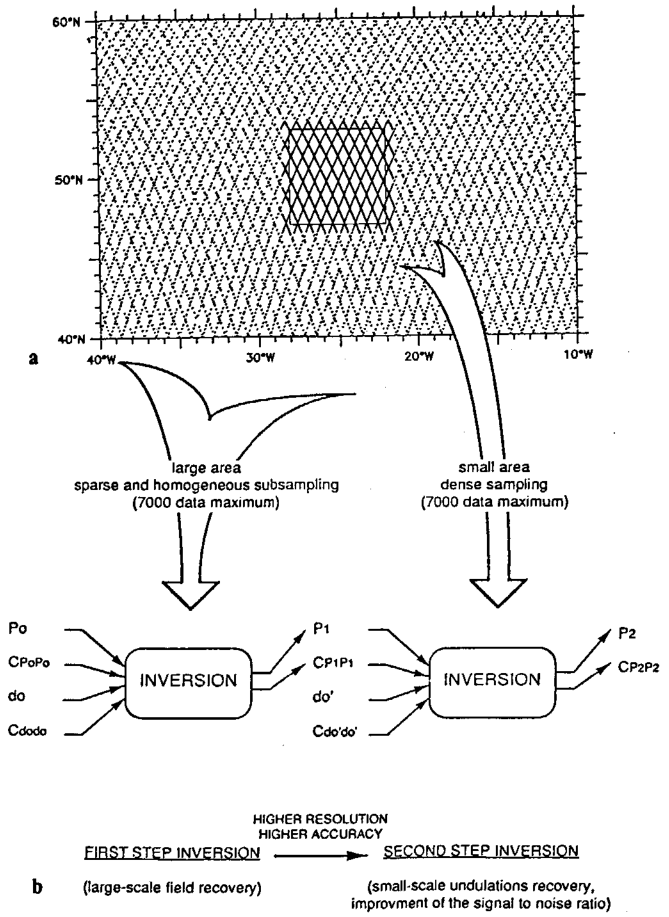


Figure 2

The Iterative Inverse Method. a) the large area is an example of altimeter subsampling in the first step of the inversion. The small inner area is an example of altimeter subsampling in the second step; b) schematic representation of the two-step mapping process used to recover a high-resolution, high-accuracy MSS from altimeter data where: Po = first guess of the mean ocean signal; C_{PoPo} *= first guess error;* d_o *and* $d_{o'}$ *= first step and second step altimeter data;* C_{dodo} *and* $C_{do'do}$ *= first step and second step data error budget; P1 and P2 = first step and second step* a posteriori *mean ocean signal;* C_{P1P1} *and* C_{P2P2} *= first step and second step* a posteriori *error covariance*

La Méthode Inverse Itérative. a) l'échantillonnage altimétrique de la grande zone est un exemple type de sous-échantillonnage des données altimétriques pour la première étape d'inversion. L'échantillonnage altimétrique de la petite zone intérieure est un exemple pour la deuxième étape d'inversion ; b) représentation schématique de la méthode inverse à deux étapes utilisée pour cartographier le signal océanique moyen contenu dans les données altimétriques avec : Po = première estimation du signal océanique moyen ; C_{PoPo} = erreur associée à cette première estimation ; d_o and $d_{o'}$ = données altimétriques, première et deuxième étape ; C_{dodo} and $C_{do'do'}$ = budgets altimétriques d'erreurs, première et deuxième étape ; P1 and P2 = signaux océaniques moyens *a posteriori*, première et deuxième étape ; C_{P1P1} and C_{P2P2} = covariances d'erreur associées, première et deuxième étape.

Radial orbital error

Its frequency spectrum is characterized by a large amount of energy centred on the once-per-orbit revolution frequency ($1/T_{rev}$). Non linearities and non-gravitational (non-conservative) forces acting on the spacecraft complicate this heuristic representation and limit validation of the spectrum to a few revolutions around the earth (Sirkes and Wunsch, 1990). For the purposes of other studies, we computed a Geosat mean sea surface using, first, a simple analytical model of the orbit error covariance, a cosine at one cycle per revolution; and secondly, a more sophisticated model based on the eleven dominant frequencies as calculated by Houry *et al.* (1992). The results proved the 1 cy/rev model to be quite sufficient for our purposes. Another argument for our choice is that the dominant frequencies of the orbit errors are not known for Topex and ERS-1. Therefore, the covariance function D2 is given by a simple empirical model depending on the time lag T, a cosine function whose period is the satellite's period of revolution, exponentially damped over time (Wunsch and Zlotnicki, 1984). The nominal error (σ_{orb}) is 35 cm rms for satellites Geosat and ERS-1, and 15 cm rms for Topex-Poseidon. The period of revolution (T_{rev}) depends on each satellite (~ 100 minutes). The decorrelation time (DT) is set to thirty revolutions, or about two days, but, as the orbital calculation is reinitialized periodically, the correlation is set to zero between two measurements from different calculations, *i. e.* belonging to different orbit integration arcs (Mazzega, 1986). Integration arcs are set to five days (for the Geosat GEM-T2 orbit, ERS-1 and Topex-Poseidon expected orbits).

$$D2\ (T) = \sigma_{orb}^2 \,.\, \cos\ (\,2\,\pi\ T/T_{rev})\,.\, \exp\ (\,-\ T^2/DT^2) \tag{5}$$

Residual geophysical errors

This is a poorly known component. Residual errors of the propagation corrections were evaluated through analyses of tropospheric measurements and model outputs. Its covariance function D3 is described by a cosine function which depends on the spherical distance ψ and on the time lag T between any pair of altimeter data points, exponentially damped in space and time (Benveniste, 1989). The nominal error (σ_{geo}) is taken as 10 cm rms, the cosine period 3200 km (ψ_0) and the spatial and temporal scales (R_{geo} and T_{geo}) 1 700 km and five days.

$$D3\ (\psi,T) = \sigma_{geo}^2 .\cos\ (2\pi\psi/\psi_0)\ .\ \exp\ (-\ \psi/R_{geo})\ .\ \exp\ (-\ T^2/T_{geo}) \tag{6}$$

Variable ocean signal

We represented this signal by the covariance function D4 which depends on the spherical distance ψ and on the time lag T between any pair of altimeter data points. The model is that put forward by Arhan and Colin de Verdière (1985) multiplied by an exponential function in time. The nominal error (σ_{var}) is considered to be homogeneous and of magnitude 10 cm rms. The space and time scales (R_{var}, T_{var}), as estimated from Geosat altimeter measurements in AthenA area (Le Traon, 1991), are set to 30 km and twenty days.

$$D4\ (\psi,T) = \sigma_{var}^2 \ .\ (1 + R + R^2/6 - R^3/6)$$
$$.\ \exp\ (-\ R)\ .\ \exp(-/T/ / T_{var}) \qquad (7)$$

$$\text{with } R = \psi/R_{var} \qquad (8)$$

The complete data error covariance Cdodo is defined as follows:

$$Cd_0d_0\ (\psi, T) = D1\ (T) + D2\ (T) + D3\ (\psi, T) + D4\ (\psi, T) \qquad (9)$$

THE ITERATIVE INVERSE METHOD

Step 1

To restrict the altimeter data to the study area, we have to know *a priori* the long wavelength signatures of the mean ocean signal - a first guess, Po - *i. e.* all wavelengths longer than the area itself. The size of the area must also be compatible with the typical scales of the variability signal and large enough to separate out the orbit error. However, since the orbit error is a function of time over thirty revolutions, the method can perform this separation.

The GRIM4-C2 geoid (Reigber *et al.*, 1991; Balmino *et al.*, 1991: pers. comm.) is a close representation of the long wavelength MSS. It also has a well-documented error spectrum. The signal and its error are calculated from orbit perturbation data generated from many years of laser tracking. They are established in terms of spherical harmonic coefficients expanded up to degree 50 (wavelength of 800 km). The geoid error is neither homogeneously nor isotropically distributed: it depends on the input data.

It is very costly in computer time to implement algorithms which can satisfactorily estimate geoid error covariance between any two geographical points. We decided to be more conservative and use a homogeneous, isotropic covariance, calculated from the diagonal coefficients of the spherical harmonics expansion. The standard deviation is 2.15 m rms. The decorrelation length is of the order of 3 400 km, and that of the residual mean signal relative to this reference geoid of the order of 250 km. To fill out the geoid error spectrum to short wavelengths, we went down to degree 1 000 (wavelength of 40 km) as follows (*see* Fig. 3 *a* and 3 *b*):

- Degree 50 to degree 360 (wavelengths 800 km through 125 km) are represented by the signal spectrum from Ohio State University geoid model (OSU91A, Rapp *et al.*, 1991);
- Degree 361 to degree 1 000 (wavelengths 125 km through 40 km) are established by a polynomial law fitted to repre-

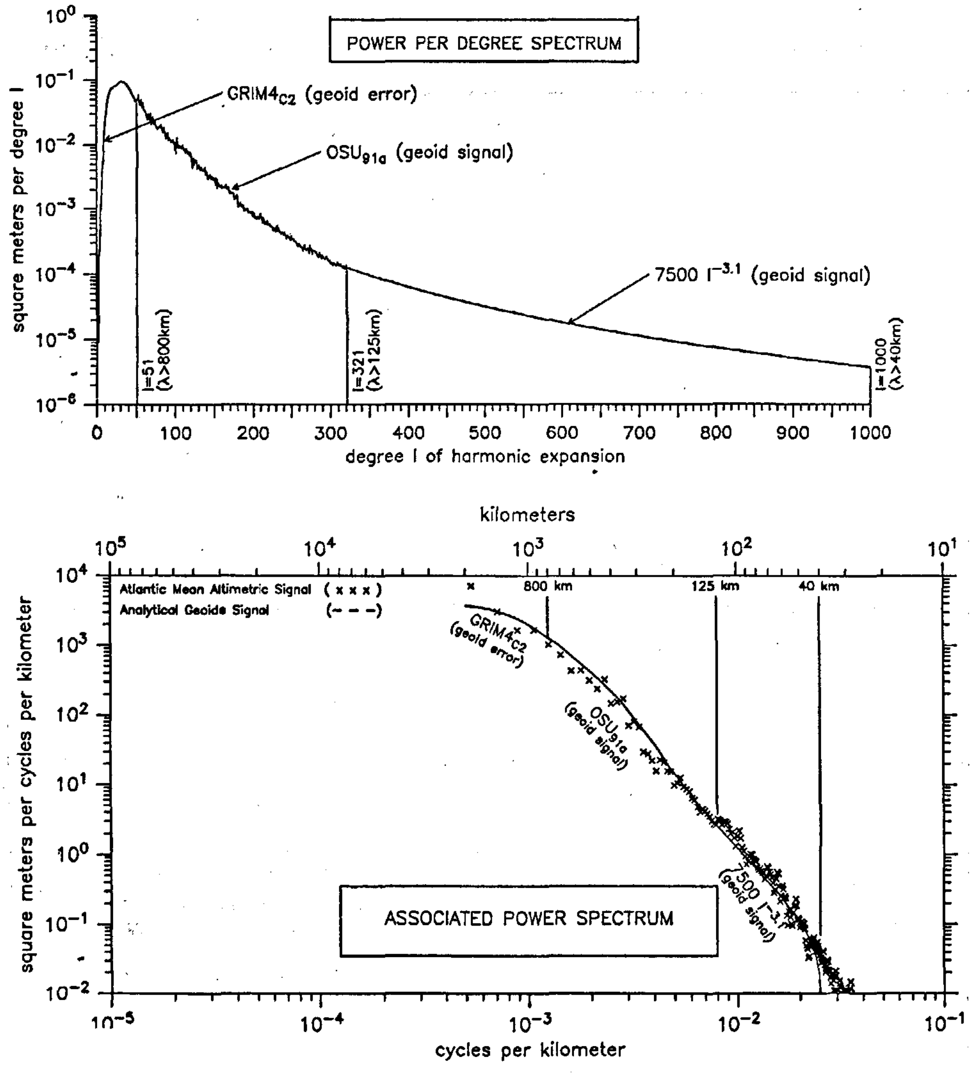


Figure 3

Error on the first guess of the MSS. a) power per degree spectrum as a function of degree l of spherical harmonic expansion (square meters per degree l); b) power spectrum as a function of spatial frequencies (cycles per kilometre).
$l \le 50$ or $\lambda \ge 800$ km = error on GRIM4-C2 geoid
$50 < l \le 320$ or 800 km $> \lambda \ge 125$ km = OSU91-a geoid
$320 < l \le 1\ 000$ or 125 km $> \lambda \ge 40$ km = polynomial law (7500 $l^{-3.1}$)
We overlaid on Figure b *the power spectrum of the mean altimeter profiles computed in Atlantic from one year of Geosat data.*

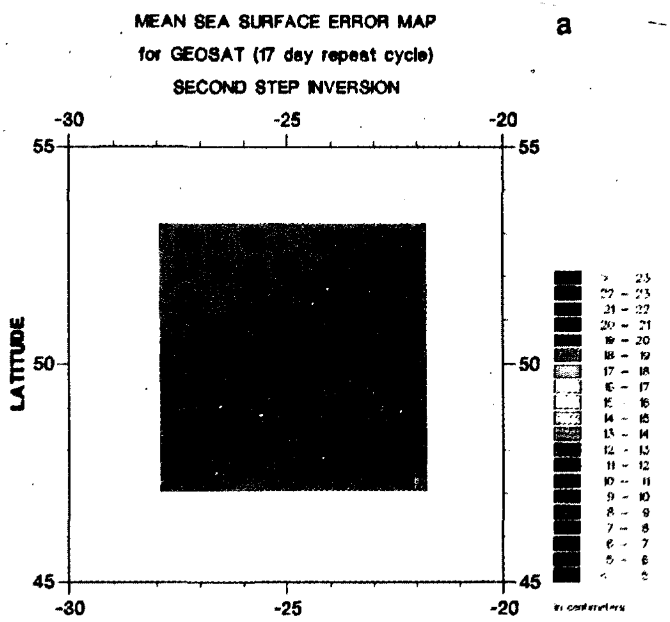
Erreur sur la toute première estimation : *a priori* du signal océanique moyen. a) spectre de puissance par degré en tant que fonction du degré d'expansion en harmonique sphérique l (mètres carrés par degré l) ; b) spectre de puissance en tant que fonction des fréquences spatiales (cycles par kilomètre).
$l \le 50$ ou $\lambda \ge 800$ km = erreur sur le géoide GRIM4-C2 ; $50 < l \le 320$ ou 800 km $> \lambda \ge 125$ km = géoide OSU91-a ; $320 < l \le 1\ 000$ ou 125 km $> \lambda \ge 40$ km = loi polynômiale (7500 $l^{-3.1}$).
Sur la figure *b*, on trouvera aussi le spectre de puissance des profils altimétriques moyens obtenus en Atlantique à partir d'une année de données Geosat.

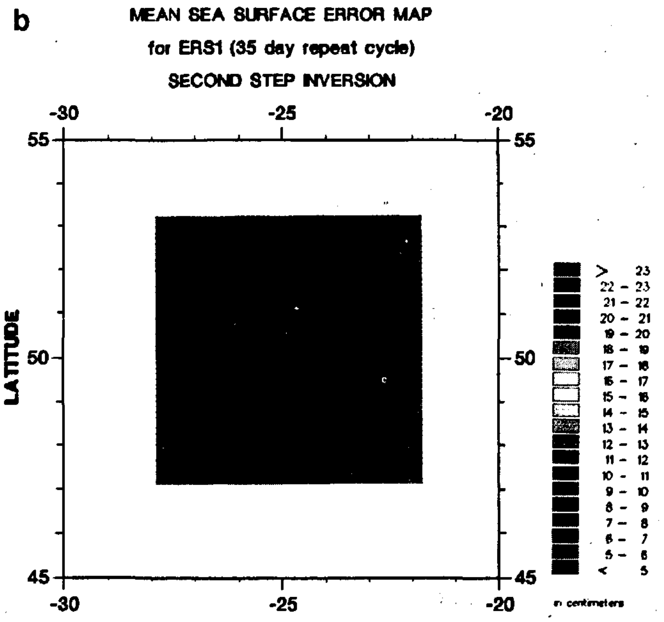
sent the spectral energy content of Geosat mean altimeter tracks in the North Atlantic.

The error due to omitting the geoid signal at very short wavelengths (below 40 km, degree 1 001 to infinity) is lower than 2 cm rms. However, it should be recalled that this is a global value, and is meaningless in fracture zones and ridges as the geoid varies strongly over short distances.

The geoid signal contains no dynamic topography information. For the *a priori* mean signal to be a true MSS, the dynamic topography spectrum must be overlaid on the geoid spectrum. It is deduced from the Levitus climatological atlas (Levitus, 1982).

The long and medium wavelength field of the mean ocean signal is extensively observed and measured by satellite altimetry. Therefore, for the first step of inversion, the altimetry data were sparsely and homogeneously sub-sampled in the study area. Ten measurements per square degree (or one point in fifty for a year of altimeter mission) are sufficient for the inverse formalism to map the long and medium wavelength signatures of the MSS (> 300 - 400 km), separating it from the long wavelength error signals (*e. g.* orbit error signal). For satellites with relatively short repeat periods, our sub-sampling rate excludes some of the cycles. The apparent repeat period is 30-35 days. However, the apparent cross-track distance is as defined by the satellite orbital configuration [1.5°, 0.7° and 2.8° for Geosat, ERS-1 (35 days) and Topex-Poseidon].





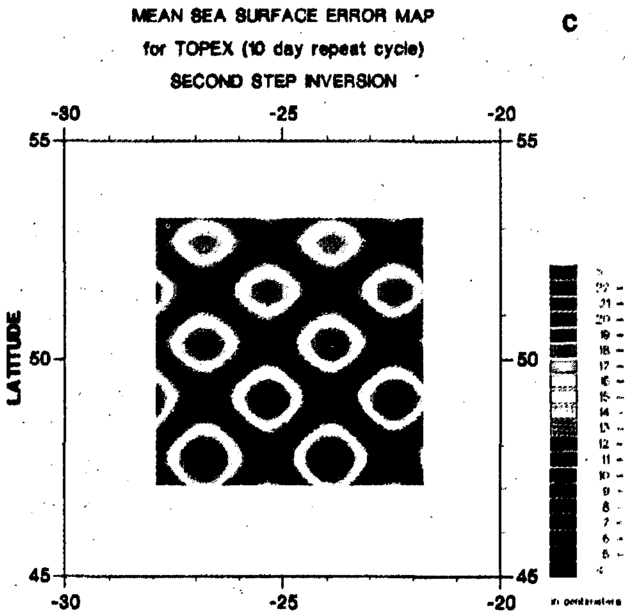


Figure 4

Error maps on altimeter mean sea surface (standard deviations). Unit is cm rms and contour intervals are 1 centimetre with gridding of 0.25°. a) Geosat rms error; b) ERS-1 rms error; c) Topex-Poseidon rms error .

Cartes d'erreur (déviations standard) sur le signal altimétrique moyen. L'unité est le centimètre rms. L'incrément entre les courbes de niveau est d'un centimètre. Le pas de grille est de 0,25°. a) erreur rms Geosat ; b) erreur rms ERS-1 ; c) erreur rms Topex-Poséidon.

Table 1

A posteriori *errors (standard deviations) for Geosat, ERS-1 and Topex-Poseidon: minimum, maximum and mean values.*

Erreurs *a posteriori* (déviations standard) pour Geosat, ERS-1 et Topex-Poseidon : valeurs minimum, maximum et moyenne.

SATELLITE	*A POSTERIORI* ERRORS minimum	 maximum	 mean
Geosat (17-day repeat period)	7.6 cm rms	13.3 cm rms	9.9 cm rms
ERS-1 (35-day repeat period)	6.6 cm rms	**9.9 cm rms**	**7.9 cm rms**
Topex (10-day repeat period)	**4.6 cm rms**	22.2 cm rms	13.4 cm rms

Step 2

The second step repeats the inversion process (*see* Fig. 2), taking the *a posteriori* estimations from the first step (the mean sea signal and its formal error) as *a priori* information.

The first step *a posteriori* error is expressed as a tabulated covariance which contains information on estimated wavelengths and their accuracy and information on missing wavelengths and their spectral content. We computed several covariance functions, with different origins (on a track or between tracks) and different directions (zonal or meridional). The span of the covariance function is 10°, the tabulation step 0.1°. Covariances are averaged to give the *a priori* covariance for the second step.

The study area is split into sub-areas, sized according to the wavelengths missing in the mean signal (< 300-400 km). We set it at 6° x 6°. Over these small areas, the dense altimeter data sub-sampling (one point in four) increases the signal-to-noise ratio relative to step 1 and should enhance resolution of the mean ocean signal.

The second step refines the accuracy of the long and medium wavelength signatures in the mean signal, and maps small wavelength undulations (from 40 km to 300-400 km).

RESULTS

A posteriori errors (standard deviations) of the iterative inverse method ($C_{P_2P_2}$) are mapped for Geosat, ERS-1 [35 days] and Topex-Poseidon cases on Figure 4, *a*, *b* and *c* respectively and summarized in Table 1. It is clear that the *a posteriori* errors are coherent with the altimeter data distribution, with an error minimum under-tracks and maximum in between (corresponding to altimeter data gaps). The typical diamond patterns formed by the ground tracks appear clearly on Figures 4 *a* and 4 *c*. The error at the centre of the patterns reduces with latitude where the tracks get closer, while the along-track error remains homogeneous. It is not easy to subsample the altimeter data really homogeneously. Non-homogeneities in the data set induce some local minima in the error maps (*see* Fig. 4 *b* and 4 *c*). They correspond to a concentration of altimeter data. Topex-Poseidon with its short repeat period, its long cross-track distance and its low orbit error, induces the smallest

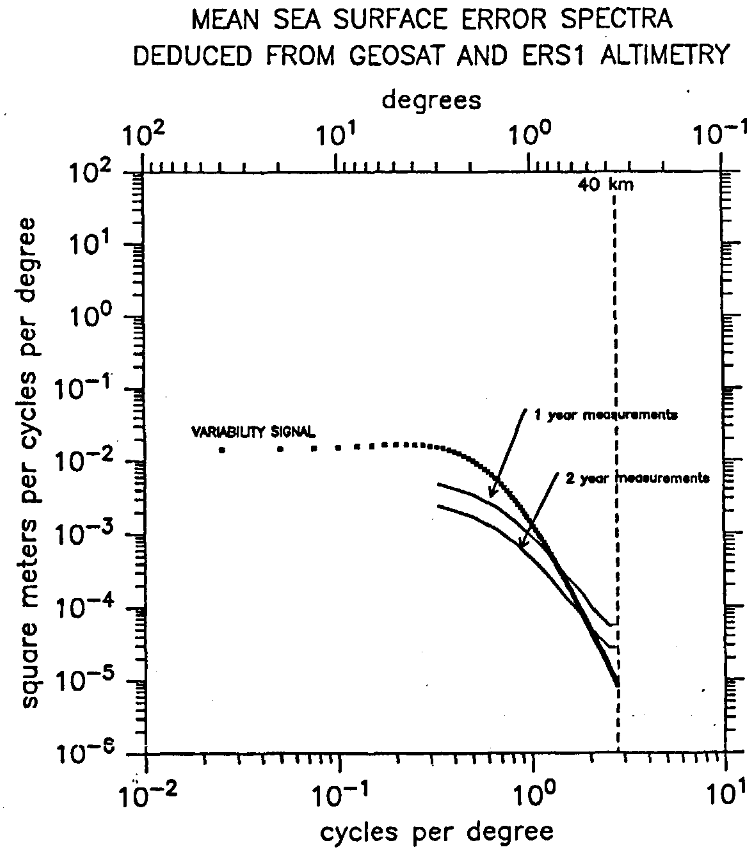


Figure 5

A posteriori *power error spectra for combined Geosat and ERS-1 mean sea surfaces, using one or two years of altimeter measurements per satellite. We overlaid the variable ocean signal spectrum as defined in the inverse method. Wavelengths are in spherical degrees.*

Spectres de l'erreur *a posteriori* associée à la surface moyenne altimétrique combinée Geosat-ERS-1, et obtenue avec une ou deux années de mesures altimétriques par satellite. Nous y avons surimposé le spectre du signal océanique variable tel qu'il est défini dans le formalisme inverse. Les longueurs d'onde sont en degrés sphériques. Le spectre est limité sur les basses fréquences par la longueur des profils de covariance, et sur les hautes fréquences par le pas de tabulation des covariances.

Table 2

A posteriori *errors (standard deviations) on combined Geosat-ERS-1 mean sea surface using one or two years of altimeter measurements per satellite: minimum, maximum and mean values.*

Erreurs (déviations standard) sur la surface moyenne altimétrique combinée Geosat et ERS-1, obtenue avec une ou deux années de mesures altimétriques par satellite : valeurs minimum, maximum et moyenne.

	Minimum	Maximum	Mean
1 year	5 cm rms	8 cm rms	6 cm rms
2 years	**4 cm rms**	**6 cm rms**	**4.5 cm rms**

minimum error, 5 cm rms, and the largest maximum error, 22 cm rms. ERS-1 with its long repeat period and its short cross-track distance induces the smallest maximum error, 10 cm rms, and the smallest mean error, 8 cm rms. Geosat is an intermediate case between Topex-Poseidon and ERS-1 results. Note that along-track error is comparable to the error obtained assuming decorrelation of errors after one cycle, e^2 being equal to σ^2/N with $\sigma^2 = \sigma_{alt}^2 + \sigma_{orb}^2 + \sigma_{var}^2 + \sigma_{geo}^2$ and N the number of cycle. This error amounts to 8 cm rms for one year of Geosat.

Assuming that Geosat and ERS-1 errors are decorrelated, estimations of the two altimeter MSSs could be simply combined. Since the satellites, instruments and measurement periods are all different, this is a reasonable assumption. The combined Geosat-ERS-1 MSS accuracy deduced from one year of altimeter measurements is better than 8 cm rms, decreasing to a minimum of 5 cm rms. The mean error is 6 cm rms. If we consider two years of altimeter measurements for both satellites and assuming decorrelation of errors after one year, these errors are reduced by a factor of $(1/2)^{1/2}$ (*see* Tab. 2).

The error spectrum is shown in Figure 5. The error energy level is weaker than for the signal of interest, the variable signal. The difference is even more noticeable with two years of measurements. This implies that it is feasible to extract the variable ocean signal using such an MSS. Note also that the repeat track analysis, which is the most commonly used method to extract the variable oceanic signal, can induce relatively large errors (Le Traon, 1992). These errors must be taken into account when comparing the two extraction methods.

CONCLUSION

The mean ocean signal and its error covariance can be deduced from altimetry using an optimal analysis. They are estimated sequentially for different wavelengths. However, their estimation depends on *a priori* information, namely the statistical description of the signal of interest and the other signals measured by satellite altimetry, which must be both comprehensive and realistic.

Combining Geosat and ERS-1 [35 days] data reduces error spectral energy levels by roughly an order of magnitude relative to the mesoscale ocean signal spectral energy level. Clearly, Topex-Poseidon satellite data will improve the MSS estimation and refine its accuracy. This applies even more to ERS-1, with its very small cross-track distance and 176-day repeat orbit. However, merging the altimeter data is not an easy task, and further study is needed. A few items have already been defined to improve the MSS estimation from altimetry. Defining the altimeter budget amounts to listing all its components and realistically describing the statistical behavior of each. The non-homogeneous, non-isotropic nature of the errors must therefore be considered. Currently, the transition from one step to another assumes, however, that there is no correlation between steps. The *a priori* error on the mean signal for the current step uses the mean *a posteriori* error covariance from the previous step. It is important now to consider the non-homogeneous, non-isotropic nature of the error for the following step. Another important point is that the *a posteriori* errors depend on the first guess, which is identical for the three satellites. One way to circumvent the combination problem is to merge the different altimeter data sets upstream of the method. This may call for more than two iterations so that all the altimeter data can be used or until sufficient resolution and accuracy are obtained.

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