Reducing Cross-Track Geoid Gradient Errors around TOPEX/Poseidon and jason-1 Nominal Tracks
Application to Calculation of Sea Level Anomalies

J. Dorandeu, M. Ablain, P.Y. Le Traon, CLS Space Oceanography Division

A new method is developed to correct for cross-track geoid gradients in altimeter data. The proposed method is based on direct estimations of geoid variations around nominal tracks and on the knowledge of the ocean signal variability. Apart from measurement errors, ocean variability is demonstrated to be the major source of error in cross-track geoid estimations using altimeter measurements. It largely impacts geoid signal estimation and precision. The method thus uses the outputs of multi-mission ocean signal mapping procedures to improve the estimation of geoid features. A detailed error analysis shows that such a technique reduces the estimation error by a factor of 2. The method is then to 7 years of TOPEX/Poseidon (T/P) data. It provides a gain of about 50% in the cross-track geoid correction when computing Sea Level Anomalies. It also improves the estimation of altimetric mean profiles. From this study, local Mean Sea Surface estimates can be inferred and applied to present and future altimetric missions, since they can be easily updated using more data. New altimetric missions like Jason-1 and Envisat, with the same ground track as former T/P and ERS, make the method even more relevant.

Introduction

Along-track geoid signals are generally taken into account in the collinear analysis interpolation (e.g. Cheney et al., 1983). But Cross-track geoid variations are neglected and translate into errors as large as 10 cm rms in the vicinity of steep geoid features (Brenner et al., 1990). The same authors demonstrated the usefulness of a Mean Sea Surface (MSS) to estimate geoid gradients. But even precise models now available (e.g. Hernandez and Schaeffer, 2000; Wang, 2001) poorly reproduce the shortest geoid wavelengths and thus remain unsatisfactory in regions of high geoid gradients.

This study presents a method for estimating geoid gradients around the T/P and Jason-1 passes, directly based on the data themselves, taking advantage of the very long T/P time series.

Substantial differences and improvements in the estimation method exist relative to the one described in Chambers and Tapley, (1998). Particular attention is paid to error reduction using precise analyses of ocean variability. Knowledge of ocean variability is shown to be crucial to reducing estimation errors. An error analysis is performed at global and local scales. The impact of the method is then investigated in deep geoid variations zones but is also considered in regions of high ocean variability.

Method

A nominal mean profile is built from seven years (1993 – 1999) of T/P data (AVISO, 1996), averaging the real data locations over the whole period. It is along-track sampled, defining reference locations for computing cross-track geoid gradient estimations.
For the whole period, SSH values are computed after data editing (Le Traon et al., 1994) and interpolated using spline functions at the orthogonal projections of the reference points onto the real pass. Figure 1 shows an example of such a SSH distribution..

Figure 1: SSH estimates (cm) at one individual location near the Tonga trench, as a function of the cross-track distance (km)

The method consists in fitting one-degree polynomials to these distributions to obtain an analytical expression of the cross-track geoid gradient for each reference location. A 3-Sigma edition based on a first iteration is used before computing the final adjustment.

Analysis of geoid signals and errors

Identification of major errors in the cross-track geoid gradient estimations

Cross-track geoid gradient estimations performed on T/P ascending passes are plotted on figure 2 (top). It clearly evidences high geoid gradient areas, but also other regions of high ocean variability. In fact, the distance between real and nominal tracks is not random, but evolves slowly. The time sampling of ocean signals can thus translate into an apparent cross-track slope. **This shows that ocean variability makes a large contribution to systematic and random errors** in the cross-track geoid gradient adjustments.

Ocean variability estimation and reduction

In order to precisely estimate the ocean variability, we used SLA maps (MSLA) combining data from the T/P and ERS-2 by optimal analysis (Le Traon et al, 1998, Ducet et al., 2000). In addition, an inverse method was recently developed to estimate long-wavelength errors (orbit errors or high-frequency signals) (Le Traon et al., 1998), (Schaeffer et al., 2002). Both ocean variability and long wavelengths errors are subtracted from SSH values before the geoid slope adjustment.

Analysis of geoid slope signals

Results after applying the above corrections are analyzed on figure 2 (bottom) and figure 3. **The impact of ocean variability is clearly evidenced** and justifies the use of a precise method for reducing the ocean variability before estimating geoid slopes from altimetric measurements.

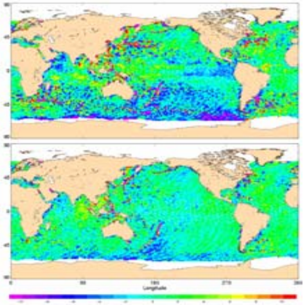

Figure 2: cross-track geoid gradient (cm/km) without removal of ocean variability (top) and after removal of ocean variability (bottom).

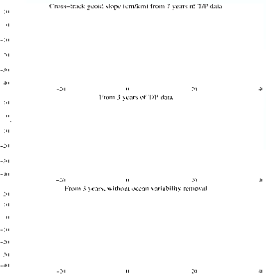

Figure 3: cross-track geoid gradient (cm/km) along T/P track 223 depending on the time series length and on the use of the ocean variability estimation.

Error analysis

The least-square adjustment error is analyzed at global scale (figure 4) and for a selected track (figure 5) in different cases. **After removal of SLA variability the error estimates are globally reduced by a factor of two**, but the error decreases more particularly in high variability zones and in areas of steep geoid features. Given the complex spectrum of ocean variability, a precise SLA variability estimation method is thus needed before geoid signal adjustments.
An additional **improvement of 10%** in terms of error reduction is provided **by reducing long-wavelength errors**. It seems particularly significant at high latitudes where high-frequency signals and long-wavelength errors are larger.

Higher error remain in high ocean variability areas due to mesoscale signals not fully resolved by the mapping procedure. At high latitudes, formal adjustment errors increase as cross-track distances relative to the mean profile decrease.

The impact of the time series length is analyzed on figures 4, 5, and 6. **With seven years of data, the global error estimate is 50% of that obtained with only two years**. The error trend of figure also suggests that only weak improvements can be expected by more than seven years of data.

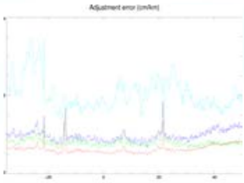

Figure 5: Adjustment error (cm/km) along T/P pass 223:
Light blue curve: 3 years of data, no ocean variability removal
Dark blue curve: 3 years of data, after ocean variability removal
Red curve: 7 years of data, after ocean variability removal
Green curve: 7 years of data, after ocean variability and long wavelength errors removal.

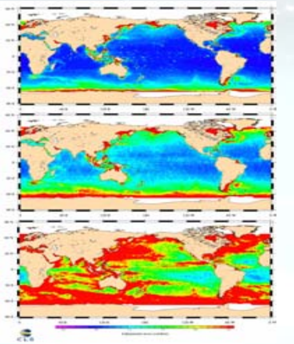

Figure 4: geoid gradient adjustment error (cm/km) estimated over 3 years without removal of ocean variability (bottom), over 3 years after removal of ocean variability (middle), over 7 years after removal of ocean variability (top).

Figure 6: Adjustment error (cm/km) along T/P pass 223 after ocean variability removal, as a function of the amount (years) of T/P data used.

Using geoid slope corrections in SLA calculation

In the repeat-track analysis, SSH observations are interpolated at the reference mean track locations. Geoid slopes are taken into account and used as a SSH correction. The quality of the geoid cross-track correction derived from our method can thus be evaluated and compared to the correction derived from a global MSS.
Figure 7 maps the gain in percentage of SLA variance achieved by using the cross-track geoid gradients. The mean gain in variance is about 1% (i.e. 1 cm^2 of variance), but can be considerably larger in regions of steep geoid features. Analysis of track 223 shows improvements of about 100 cm^2 in these areas (figure 8). The adjustment error is not significantly higher in high ocean variability areas, showing the efficiency of the ocean variability estimation method.

The improvement of our direct method relative to a global MSS has been analyzed on figure 9. The gain in SLA variance is about 8 cm^2 in areas of strong geoid variations. **At global scale, our proposed geoid slope estimation method improves the cross-track correction by about 50% relative to the correction based on a global MSS**.

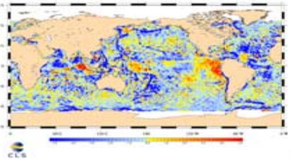

Figure 7: Gain in percentage of T/P SLA variance when using the cross-track geoid correction during the interpolation.

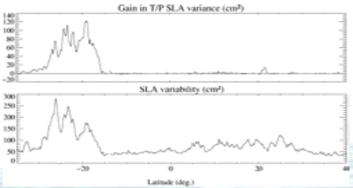

Figure 8: Gain in T/P SLA variance (cm^2) along T/P track 223, when using the cross-track geoid correction during the interpolation.

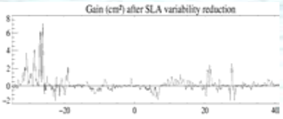

Figure 9: Gain in T/P SLA variance (cm^2), when using our cross-track geoid correction rather than a global MSS estimation.

Impact on mean profiles

The cross-track geoid correction impact can also be estimated by the intrinsic quality of mean profiles derived from the collinear method. Indeed, the geoid slope correction is applied during the interpolation. The variance of mean profile crossover differences should be zero in an ideal case. The crossover variance is reduced from 3.03 cm^2 to 2.75 cm^2 when using our proposed method rather than a global MSS in the mean profile calculation.

Using geoid slope estimations to build a local Mean Sea Surface

For any altimeter measurement point, a Local Mean Sea Surface Height (LMSSH) can be interpolated using the mean profile and the geoid slope estimates derived from our method.

SLAs relative to this Local MSS are compared to those derived from the use of the CLS_SHOM98.2 global MSS over a three-year period (figure 10). For every T/P cycle, **the SLA variance is reduced using of the local MSS**. Over the whole three-year period, the mean gain in variance is higher than 2 cm^2, that is, about 1.8%.

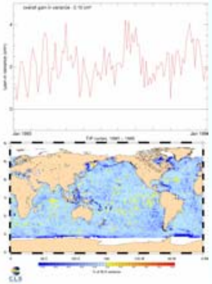

Figure 10: Gain in T/P SLA variance when computed relative to the local along-track MSS derived from the proposed method rather than to the global MSS (CLS-SHOM98.2)

Acknowledgements
This work was supported by

Geoid slopes estimations derived from this study are available at :
ftp://ftp.cls.fr/pub/oceano/calval/ctgg

References

AVISO, 1996: Archiving, Validation, and Interpretation of Satellite Oceanographic Data, AVISO Handbook for merged TOPEX/POSEIDON products. 3° ed. AVI-NT-02-101-CN, 201 pp. CNES Toulouse, France.

Brenner, A. C., C. J. Koblinsky, and B. D. Beckley, 1990: A preliminary estimate of geoid-induced variations in repeat orbit satellite altimetric observations. *J. Geophys. Res.*, **95,** 3033-3040.

Chambers, D. P. and B. D. Tapley, 1998: Reduction of Geoid Gradient Error in Ocean Variability from Satellite Altimetry. *Mar. Geod.*, **21,** 25-39.

Cheney, R. E., J. G. Marsh, and B. D. Beckley, 1983: Global mesoscale variability from collinear tracks of Seasat altimeter data. *J. Geophys. Res.*, **88,** 4343.

Ducet, N., P.-Y. Le Traon, and G. Reverdin, 2000: Global high resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1 and -2. *J. Geophys. Res.*, **105,** 19477-19498.

Hernandez, F. and P. Schaeffer, 2000: Altimetric Mean Sea Surfaces and Gravity Anomaly maps inter-comparisons AVI-NT-011-5242-CLS, 48 pp. CLS Ramonville St Agne.

Le Traon, P.-Y., F. Nadal, and N. Ducet, 1998: An improved mapping method of multisatellite altimeter data. *J. Atmos. Oceanic Technol.*, **15,** 522-534.

Le Traon, P.-Y., J. Stum, J. Dorandeu, P. Gaspar, and P. Vincent, 1994: Global statistical analysis of TOPEX and POSEIDON data. *J. Geophys. Res.*, **99,** 24619-24631.

Schaeffer, P., C. Boone, and P.-Y. Le Traon, 2002: Empirical Correction of Long-Wavelength Bias in Altimeter Data Using An Optimal Analysis Method. Manuscript to be submitted to *J. Atmos. Oceanic Technol.*

Wang, Y. M., 2001: GSFC00 mean sea surface, gravity anomaly, and vertical gravity gradient from satellite altimeter data. *J. Geophys. Res.*, **106,** 31075-31083.

Jason-1 SWT meeting, Biarritz, June 2002