On the use of sea level gauge data for satellite altimetry validation. A review

Niveau de la mer
Marégraphes
Réseau global
Altimetrie
Validation

Sea level
Gauges
Global network
Altimetry
Validation

Christian LE PROVOST

Laboratoire des Écoulements Géophysiques et Industriels, Institut de Mécanique de Grenoble, B.P. 53 X, 38041 Grenoble Cedex, France.

ABSTRACT

The altimetric sea-level data base supplied by the satellite Geosat has permitted numerous studies in the field of ocean science, some of which have addressed, through comparisons with island gauge observations, the question of the quality of the sea level products inferred from the Geosat dataset. The aim of this paper is to provide an overview of these recent studies, illustrating the usefulness of *in situ* sea level gauge measurements for satellite altimetry validation, to present briefly the status of the present worldwide sea level network, and to provide some guidelines on what must be done in the near future to improve this network further. It is shown that some of the discrepancies between altimeter products and tide gauge records are due to insufficient corrections of the altimeter signal (orbit error, tropospheric water vapour, tidal corrections), and that improving these corrections greatly increases agreement with *in situ* observations. It is also demonstrated that, if a maximum misfit of 10 cm is accepted at each sea level gauge location, the two datasets are fully coherent, and that consequently they can be merged to obtain optimized maps of large-scale sea level variability, or of the mean sea level. The major conclusions of this overview are the following: 1) reference to tide gauge measurements is obviously of considerable importance in validating altimeter satellite products; 2) given the accuracy already obtained, and considering the optimal design of the coming Topex/Poseidon mission, it is necessary to improve the *a priori* error bar estimates on tide gauge data, through systematic combination of tide gauge and altimetric data, through regional numerical modelling and through assimilation methods synthesizing the two approaches; 3) the present global sea level gauge network, as developed in WOCE, is on the way to fulfilling the requirements for global validation and improvement of satellite altimetric products; 4) complementary sites, however, still need to be added, mainly at high latitudes: sophisticated methods now exist to allow quantitative investigations of the error reduction in the altimetric products that could result from adding a gauge at a new specific site; 5) given the acknowledged usefulness of tide gauge data, an effort is still needed to ensure the availability of sea level data within short time periods, compatible with the rapid delivery of the altimetric data; 6) in order to guarantee external controls in the use of satellite altimetry to monitor the long-term evolution of the mean sea level at the world scale, tide gauge stations of very high standard have to be linked to the International Earth Reference System (to which the satellite systems also have to be referred), and regularly and carefully surveyed in the long term.

Oceanologica Acta, 1992. **15**, 5, 431-440.

0399-1784/92/05 431 10/$3.00/© Gauthier-Villars

RÉSUMÉ

Sur l'usage de données d'observations marégraphiques du niveau de la mer pour la validation de l'altimétrie satellitaire. Une revue

La base de données altimétriques du niveau de la mer apportée par le satellite Geosat a permis la réalisation d'un grand nombre d'études dans le domaine des sciences de l'océan, et certaines de ces études ont examiné la qualité des produits relatifs au niveau de la mer établis à partir de cette base, au travers de comparaisons avec des observations marégraphiques sur des îles. Le but de cet article est de donner une vue synthéthique de ces récentes études, illustrant l'utilité des mesures marégraphiques du niveau de la mer pour la validation de l'altimétrie satellitaire, de présenter brièvement l'état actuel du réseau mondial d'observation du niveau de la mer, et d'en déduire quelques remarques sur ce qui doit être fait dans les mois à venir pour encore améliorer ce réseau. Il est montré qu'une part des écarts observés entre les produits altimétriques et les enregistrements marégraphiques est due à des insuffisances des corrections du signal altimétrique (erreurs d'orbite, corrections troposphériques, corrections de marées), et que l'amélioration de ces corrections augmente considérablement l'accord avec les observations *in situ*. Il est aussi noté que, si un désaccord maximum de 10 cm est accepté à chaque site marégraphique, les deux bases de données sont totalement cohérentes entre elles, et que, en conséquence, elles peuvent être combinées pour obtenir des produits optimisés (cartes de variabilité à grande échelle du niveau de la mer, niveau moyen). Les conclusions majeures de cette analyse sont les suivantes : 1) la référence à des mesures marégraphiques est à l'évidence d'une importance considérable pour valider les produits altimétriques satellitaires ; 2) compte tenu des précisions déjà atteintes, et considérant l'optimisation de la mission Topex/Poséidon à venir, il est nécessaire d'améliorer les estimations des barres d'erreurs prises à priori sur les mesures marégraphiques, en utilisant des approches combinant les données marégraphiques et altimétriques et des modélisations numériques régionales, à l'aide de méthodes d'assimilations ; 3) le réseau global actuel de stations de mesure du niveau de la mer, tel qu'il est développé dans WOCE, devrait permettre de répondre aux exigences requises pour une validation globale et l'amélioration des produits altimétriques satellitaires ; 4) des sites complémentaires doivent cependant être ajoutés, principalement aux hautes latitudes: des méthodes sophistiquées existent maintenant pour étudier de façon quantitative la réduction d'erreur dans les produits altimétriques qui peut résulter de l'ajout d'un marégraphe dans un nouveau site ; 5) étant donné l'utilité reconnue des données marégraphiques, un effort doit encore être fait pour garantir la disponibilité des données marégraphiques dans des délais compatibles avec la délivrance rapide des données altimétriques ; 6) afin de garantir des contrôles indépendants pour l'utilisation de l'altimétrie satellitaire pour la surveillance de l'évolution à long terme du niveau de la mer à l'échelle globale, des stations marégraphiques d'un très haut standard de qualité doivent être rattachées au Système de Référence Terrestre International (dans lequel les systèmes satellitaires sont eux mêmes repérés), et surveillées régulièrement sur le long terme.

Oceanologica Acta, 1992. **15**, 5, 431-440.

INTRODUCTION

Over the past five years, the altimetric sea level measurement data base supplied by the US Navy's geodetic satellite Geosat has given rise to a large number of studies in the field of ocean science (*see* the March and October 1990 issues of the *Journal of Geophysical Research*).Very interesting results have been obtained from these data, although this mission was not designed for this kind of application [indeed the primary available data (Cheney *et al.*, 1987) suffered from considerable deficiencies, linked to the poor precision of the orbit - approximately 3 m for the Exact Repeat Mission phase, ERM, from November 1986 to the end of the mission in 1989], and the absence of an onboard microwave radiometer for atmospheric water vapour corrections of the altimeter). On the one hand, these studies have provided new scientific results in the field of oceanography. On the other hand, they have also permitted progress in the use of altimeter data themselves, leading among other things to more and more sophisticated methods of improving the corrections needed on the altimetric signal before it can be used in oceanographic applications, and increasing our confidence in the power of this kind of data for ocean science.

Several of these studies have addressed the question of the quality of sea level products inferred from the Geosat dataset, through comparisons with island gauges and other *in situ* data : Cheney *et al.* (1989), Tai *et al.* (1989), Miller and Cheney (1990), Wyrtki and Mitchum (1990), and others, have carefully controlled altimetric-derived sea level time series by reference to sea level variations observed *in situ* by tide gauges at individual locations. Others, like Wunsch (1991 *a* and *b*), have used worldwide subsets of available tide gauge measurements to check globally the consistency of large-scale sea surface variability maps that they have built from the Geosat dataset; and have developed methods for incorporating tide gauge data into altimetric estimates in the search for optimized products. These papers provide particularly valuable new insights into the quality of the altimeter data presently available, and on the usefulness of tide gauge datasets for satellite altimeter validation and calibration.

At the same time, in the framework of international programmes like TOGA and WOCE, efforts have been made to set up a sea level gauge network with, among other goals, the objective of complementing satellite altimeter measurements. Lists of sites were established in the implementation plans of these programmes, based partly on selections of gauges known to be working already, but also calling for new stations on sites considered as potentially helpful for the objectives of these programmes: one of the expected outputs of these international programmes is specifically to determine the usefulness of these measurements in monitoring the climate of the ocean, and to provide observations on the long-term sea level rise. To pronounce conclusively on the adequacy of an optimal sea level gauge network for such goals is a difficult exercise. However, the science has progressed recently to the point that quantitative numerical estimates are now possible. The aim of this note is to focus on some recent studies illustrating the usefulness of *in situ* sea level gauge measurements in conjunction with satellite altimetry, and to provide some insights into what must be done in the near future to improve further the worldwide Sea Level Network.

SATELLITE ALTIMETER VALIDATION WITH SEA LEVEL GAUGE DATA

Assessing the quality of the recent sea level satellite products by reference to *in situ* data

As a typical example, let us refer to the paper of Cheney *et al.* (1989), hereafter referred to as CDM89 in which the authors studied the accuracy of Geosat-generated sea level time series in the Tropical Pacific by comparison with *in situ* measurements from fourteen island tide gauges and two thermistor moorings. The comparison is based on monthly mean values over a period of eighteen months (April 1985 to September 1986). Geosat time series were generated from crossover differences in 8 by 1° regions for the sites within 15° of the equator, and 2 by 1° regions for higher altitude sites where spatial scales of variability are smaller. The average agreement is approximately 3.7 cm rms. This result confirms for the Geosat dataset the conclusions of previous work using Seasat altimeter data (Cheney *et al.*, 1983; Fu and Chelton, 1985; Miller *et al.*, 1986): even with considerable orbit errors, satellite altimeter data can supply high quality, long-term datasets for the study of ocean dynamics, with an accuracy comparable to instrument precision (5 cm for Seasat, 3 cm for Geosat).

However, these statistical estimates are very global, and the above conclusion needs to be considered as an optimistic upper bound. In looking at the detailed statistical comparison of CDM 89, it may be noted that the rms differences range from 1.5 cm to 7.2 cm, for signals of the order of ± 10 cm peak-to-peak, with rms variabilities from 1.7 cm to 8.0 cm. The agreement is indeed better than the average at 9 of the sixteen sites, but it is instructive to examine the reasons for the discrepancies at the poor sites, and endeavour to answer the following question: are the discrepancies between altimetric sea level time series and tide gauge records due to insufficient altimeter corrections or to the inadequate correspondence between the continuous, but local, tide gauge records and the open ocean, but sequential, altimeter measurements ?

Some identified sources of discrepancies between altimetric products and *in situ* observations

The orbit error correction

In their evaluation of the quality of their Geosat products, CDM 89 note that, at half of the locations where they intercompare altimeter time series with nearby tide gauge observations, the altimeter underestimates the signal amplitude by 30 to 40 %. The authors suggest that part of the ocean signal is being removed by the orbit error correction model used (it must be remembered that, for sea level variability studies, it is usual to consider that the dominant radial orbit error has the wavelength of the orbital circumference, about 40,000 km, and can be modelled as a low degree polynomial or sinusoid; the method used then is crossover or colinear difference quadratic adjustment minimization).

This has been confirmed by Cheney *et al.* (1991 *c*), hereafter referred to as CEHW 91, with a second version of the Geosat altimeter geophysical data records just produced by NOAA (Cheney *et al.*, 1991 *a* and *b*). This new release includes a more precise orbit: the new ephemerides computed by Haines *et al.*. (1990) are based on the GEM-T2 geopotential model of Marsh *et al.*. (1990), and the new orbit radial precision is approximately 50 cm. This improvement, by reference to the radial uncertainty of 3-4 m rms for the ephemeris computed by the Naval Astronautics Group (NAG), allows CEHW 91 to model the ephemeris error as a linear trend, over arcs of as much as 10,000 km in length, in contrast with the quadratic model used with the NAG orbits. A test over the Western Pacific Equatorial region confirmed that the linear adjustment, made possible by the more precise T2 orbit, results in less signal attenuation and increases the signal amplitude by about 5 cm peak-to-peak, compared with the quadratic fit.

This example confirms that part of the attenuation in the altimetric sea level variabilities observed by CDM 89 over the tropical Pacific, by reference to tide gauge observations, was due to orbit error correction. Hence the importance of tidal gauge data for validation of satellite altimetric products.

The tropospheric water vapour correction

Typically, this correction ranges from about 35 cm in the tropics to nearly zero at the poles. It was admitted that, in the first release of Geosat GDRs, this correction contained significant uncertainties: it was derived from a global model of the Fleet Numerical Oceanographic Center (FNOC), which was updated at 12 hour intervals, and was known to lack much of the detailed horizontal structure of the real troposphere (Zimbelman and Busalacchi, 1990). In the new release of Geosat GDRs, the second major improvement is on the tropospheric corrections, based on data from other satellites (Tiros Operational Vertical Sounder TOVS, prior to July 1987, and then the Special Sensor Microwave Imager SSMI of the US Department of Defense). CEHW 91 also demonstrated, over the tropical

tions of the satellite orbit. But for future applications to large-scale oceanic phenomena, it will no longer be possible to ignore these inadequacies.

Some very recent papers have illustrated this difficulty, following identification by the authors of unexplained differences between satellite low-frequency sea level variability products and tide gauge observations. Périgaud and Zlotnicki (1992) have pointed out a disagreement between *in situ* observations and Geosat data in their analysis of the low-frequency variability of sea level over the Indian Ocean, polluting the semi-annual and annual signals. They observed that the error was partly attenuated by the classical tilt and bias corrections, but amplified by a sinusoidal one-per-revolution orbit correction. This error has been shown to be due to incorrect elimination of the contribution of the tides to sea level variability: the M2 tidal residual, aliased at 1.15 cycle per year in the Geosat dataset, leads to the appearance in the altimetric signal of a progressive wave, 8° in wavelength, propagating westward at a rate of 3 km per day.

The same kind of difficulty has been identified by Jacobs *et al.* (1991) when addressing the problem of extracting ken, combined with tide gauge and altimeter data assimilation methods, in an attempt to obtain an optimal solution for global ocean tides (*see* for example Le Provost *et al.*, 1987).

These examples of inaccuracy in the corrections applied by scientists when using Geosat data contribute in the same way a partial answer to the question stated above: some of the discrepancies between the altimeter products and the tide gauge records are actually due to insufficient correction of the altimeter signal; and improving these corrections greatly increases the agreement with *in situ* observations. Such a conclusion is an illustration of the importance of the availability of good tide gauge observations to validate altimeter measurements.

These improvements are of course dependent on the location and the space and time scales of the studied phenomena. The tropospheric errors are maximum in the tropics, and nearly zero at the poles. In the tropics, the large-scale and low-frequency characteristics of the sea level variations permit the calculation, with little loss of information, of space and time scale averages which are not adequate for the smaller-scale and higher-frequency oceanic processes of the mid and high latitudes. In contrast with what has been observed by CEHW 91 for the Equatorial Pacific, for mesoscale studies, it makes little difference whether a quadratic or linear trend over long arcs is used to reduce orbit errors; and for global scale studies, none of these methods, based on the removal of a best-fitting line or sinusoid to comparatively short data segments (no longer than an orbit period), is adapted for orbit error removal. For the tidal corrections, it was noted that their inadequacies had no dramatic consequences for the use of satellite altimetry in mesoscale ocean process studies; this observation is not entirely valid, and a nice counter-example has been given by Thomas and Woodworth (1990). They have shown that, in the area of the Iceland-Faroes Front, the large values of sea surface height variability observed in the Geosat data, de-tided with the standard Schwiderski GDRs tidal prediction, are considerably reduced when a regional model developed by Flather (1981) is used. Actually, all these examples and counter-examples illustrate the complexity of the problem and the importance of careful and mutual validation of both kinds of measurements - satellite altimetry and sea level gauge measurements - for ocean science studies.

ASSIMILATION OF SEA LEVEL GAUGE DATA IN SATELLITE ALTIMETER PRODUCTS

Global large-scale sea surface variability

Altimetry, from its beginning in the seventies, has held out the only real promise of an instrument capable of measuring one element of the ocean circulation at the global scale and on a continuous basis. However, little has been learned so far on the subject because of the gap between instrument system capabilities and the precision required to detect these oceanic signals. The Topex/Poseidon mission has been designed to reach this goal. In anticipation of this mission, Wunsch (1991 *a* and *b*) has recently used the Geosat dataset to explore the handling of this kind of data in investigations of the ocean dynamics on large space and time scales. One element of this study which is relevant to our present concerns is the extensive use of tide gauge measurements for validation and assimilation purposes.

By correcting Geosat altimetric data for a set of line frequencies, in order to reduce the orbit error, and then by averaging in space and time, Wunsch has been able to produce a set of global maps of sea surface variability over time intervals ranging from three months to two years.

In a first stage, altimetry alone was used to produce a set of maps for the globe on the basis of orbit-corrected and detided data divided into groups of approximately three days' duration, each group being treated as contemporaneous and expanded into spherical harmonics to degree and order 18. After subtracting a mean sea surface deduced from the time average of these spherical harmonics, estimates of large-scale low-frequency sea surface variability were produced. These individual time series of sea surface maps being extremely noisy, both spatially and temporally, spatial smoothing was applied by dropping all harmonics degrees and order beyond 10, and time smoothing introduced by averaging the harmonic coefficients over three-month periods. The result of this long process is a set of maps derived purely from altimetric data. And, despite the crudeness of the Geosat data, comparisons with more conventional products, like the monthly maps of the Pacific sea level variations produced by the TOGA Sea Level Center of the University of Hawaii (Wyrtki *et al.*, 1988), reveal a fair degree of qualitative agreement.

In a second stage, Wunsch combined the altimetric data with a subset of the worldwide network of tidal gauge measurements, through a form of recursive least-squares.The subset of tide gauges included 34 gauges with continuous records over the first two years of the Geosat ERM period, and 55 with fragmentary records, mainly from open-ocean islands, but with some coastal stations. The filtered records were critically examined for values which appeared to reflect locally anomalous conditions: these values were then down-weighted in the fitting procedure. A simple white noise of 10 cm was assigned to each tide gauge, representing harbour effects, mesoscale eddies, instrument errors, *etc.* New maps incorporating the gauge data into the previous altimetric estimates were thus produced. As before when using the altimeter data alone, the new deviation surfaces remained very noisy, so that similar smoothings were applied. The output of this whole procedure was a second set of three-month average sea level variability maps. And the major result was that this new set did not greatly differ from the purely altimetric set. The numerical values of these two sets are of course different, with more information in the combined data maps, and, as expected, error estimates reduced for the latter maps in the areas of the tide gauge positions. But the purely altimetric maps closely resemble the combined sets, qualitatively and quantitatively, thus providing confidence in the overall results, especially in areas where no tide gauges are available (the Indian and the Southern Oceans).

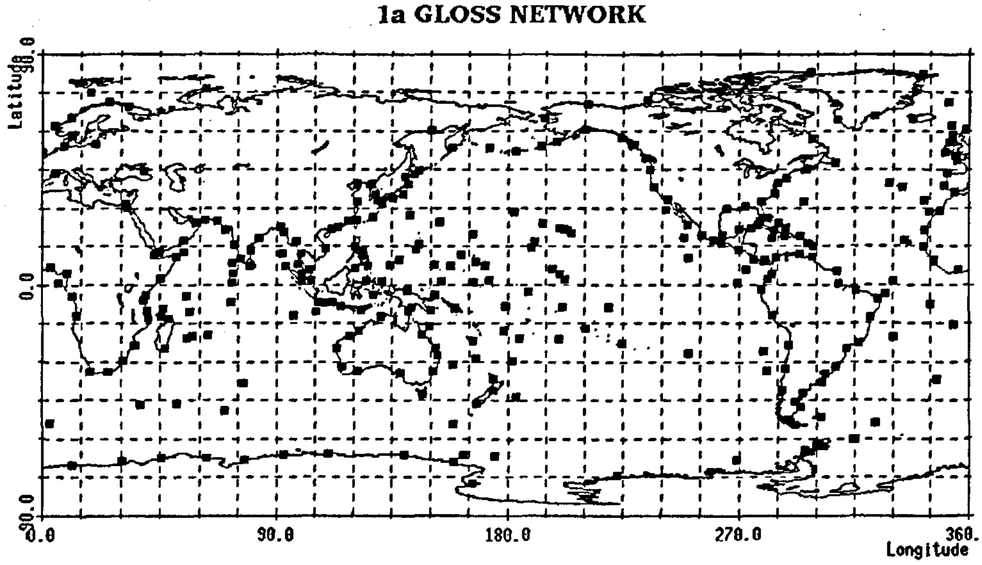
Several conclusions relevant to our present concerns emerge from these results.

a) Wunsch's findings demonstrate that there is no inconsistency between altimetric and tide gauge datasets, despite the crudeness of the Geosat altimetric system. With a few exceptions, the misfits are within the estimated errors (10 cm rms). Only one record is off by 20 cm or more, at Saipan, where no specific explanation can be found, except that this site is located in an area of very complex geography. This is coherent with the results, mentioned earlier, of the individual intercomparisons made over the tropical Pacific by Cheney and others.

b) Given the low values of the rms discrepancies observed, it seems reasonable now to think of more optimistic error bars for the tide gauges. Surely, as already noted by Wunsch, with better altimetric datasets, it will be necessary to reduce the estimated error on the tidal gauges, and to seek centimetre rather than decimetre errors. However, this will need carefull analysis of the error budget at the individual gauges. One major question to address is the extent to which a particular tide gauge responds dominantly to motions on the scales being mapped. With Topex/Poseidon, it should be possible to compute the global scale variability of the ocean over much shorter averaging periods (ten days or less), and to carry wavenumber filter cut-off to much shorter spatial scales than has been done by Wunsch. A subject of future research should then be to understand the range of frequencies/wavenumbers where coastal dynamics produces space/time scales different from the open ocean circulation.This could be addressed possibly through the systematic combination of tide gauge and improved altimetric datasets, through regional numerical modelling near specific tide gauge sites, and through assimilation procedures synthesizing these two approaches.

c) For this kind of global variability mapping exercise, it appears that one is dealing with a statistical calibration problem, where no particular gauge is of special importance. If several Pacific gauges were arbitrarily chosen and taken out of the above computations, almost nothing would change (confirmed by Wunsch, pers. comm.). What would be more useful would be to have gauges in all parts of the oceans, so as to have a more or less uniform distribution.

1a GLOSS NETWORK



1b WOCE NETWORK

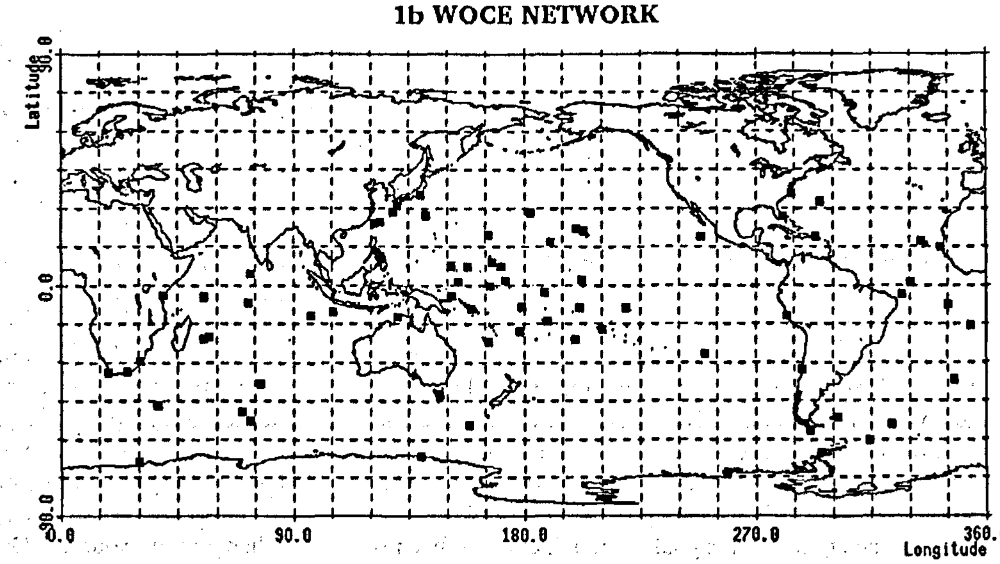


Figure 1

a) GLOSS; and b) WOCE sea level sites designed in their implementation plans.

Sites de mesure du niveau de la mer prévus dans le plan de mise en oeuvre des programmes GLOSS (a) et WOCE (b).

Given the present distribution of the WOCE implemented sea level network, these conclusions lead to a strong recommendation for giving prioritiy to establishing more gauges in some of the more empty parts of the world ocean, such as the Southern Ocean.

d) This first effort at global ocean variability mapping, combining altimeter and tide gauge data, demonstrates that it is now becoming possible to obtain quantitative estimates of the impact of a given sea level station on the quality of these optimized products, and thus to provide a numerical estimate of the error reduction which would result from the addition of a new station.

Global mean sea surface

Joint inversion methods for gravity, orbit error and oceanographic mean topography recently applied to Seasat or Geosat data have lead to interesting improvements in the accuracy of these different components, especially for the geoid estimate (Denker and Rapp, 1990; Marsh *et al.*, 1990; Nerem *et al.*, 1990). However, these inversions were applied only to altimetric systems.

The combination of altimetric data with tide gauge measurements has been applied recently to the Mediterrannean Sea by Houry and Mazzega (1991) for Seasat data, and by Houry and Vincent (1991) for Geosat. One interesting outcome of these studies is the demonstration of the limited effects of tide gauge data in improving the orbit error, within this inverse approach. The inverse method, which consists in defining, among other *a priori* covariances, the space-time correlations of the orbit error, whatever the amplitude of this error, make it possible to eliminate from the mean sea surface the incidence of the orbit error in a consistent way. Consequently, the use of tide gauge data, necessarily linked to the same absolute reference system as the satellite ephemeris, only improves accuracy by a few centimetres, and the better the satellite orbit the more the improvement is limited to the vicinity of the tide gauge location. This demonstrates the need for very high quality tide gauge data, not only in terms of instrumental precision as noted before, but also in terms of the precision of the

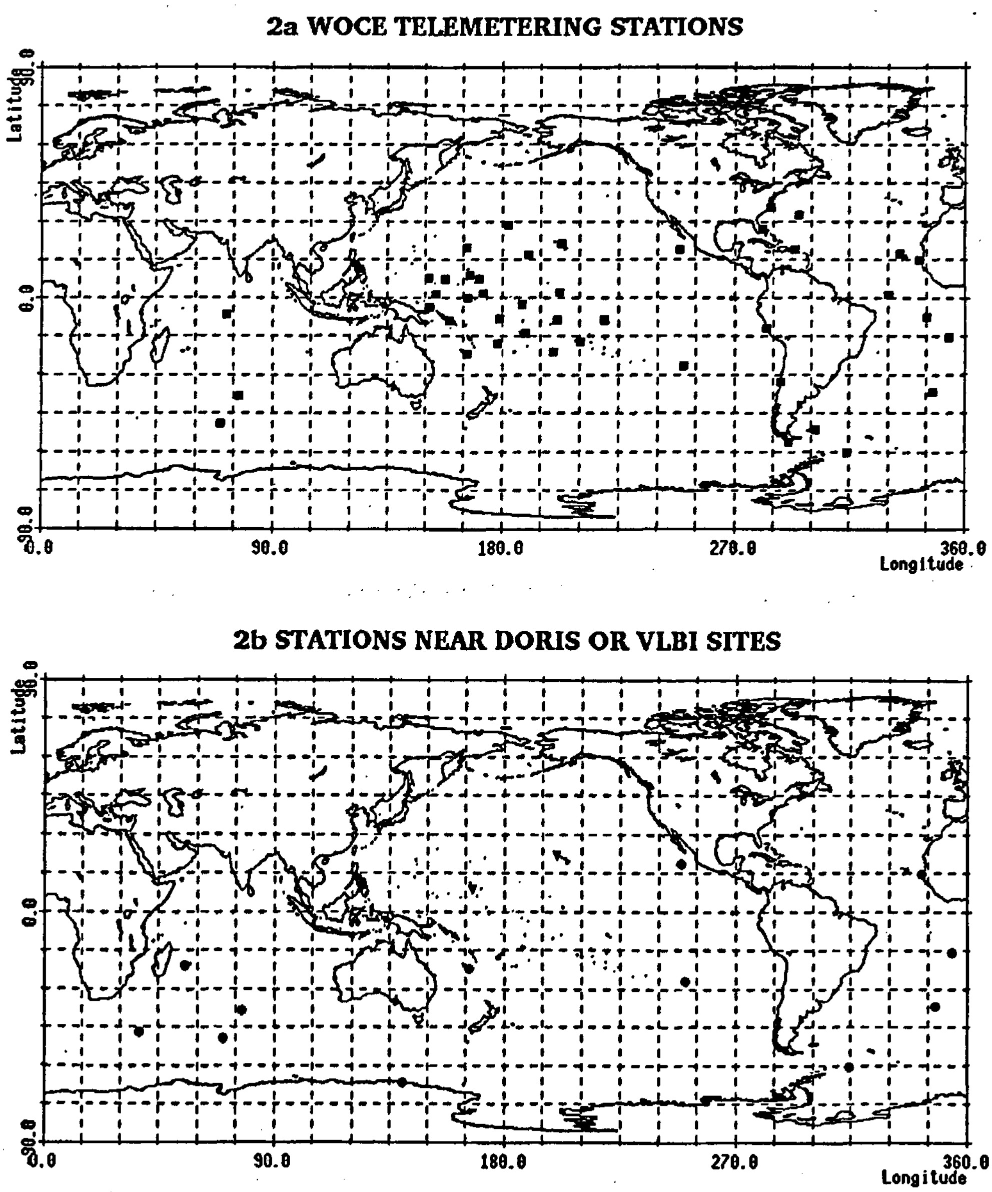


Figure 2

a) WOCE sea level stations planned with real time Data Transmission; b) WOCE sea level stations: with nearby DORIS stations (o); with nearby VLBI stations (v). DORIS: Doppler Orbit and Radio Positioning Integration by Satellite; VLBI : Very Long Baseline Inferometry.

a) stations WOCE de mesure du niveau de la mer prévues avec transmission de données en temps réel ; b) stations WOCE de mesure du niveau de la mer avec dans leur voisinage une station DORIS (o) ou VLBI (v). DORIS : Doppler Orbitographie et Positionnement Intégrée par Satellite ; VLBI : Interférométrie à très grande base.

geographical location and altitude of the station, within an absolute reference frame - the same as for the satellite systems (*i. e.* IERS) -, including continuous monitoring of the associated benchmarks. As noted above for the hydrodynamic environmental conditions of tide gauges used in the study of sea level variability, the need arises here, in regard to the mean sea level, for a detailed analysis of the geodetic characteristics of the area of each tide gauge site. These requirements are especially relevant to long-term monitoring of the sea level, and to the use of the tide gauge network as a necessary external control for the application of satellite altimetry in this context. Such a high quality sea level gauge network will ensure that there is no long term drift of the captor corrections, and will help to guarantee the quality of the links between different altimetric missions.

THE STATUS OF THE WORLDWIDE SEA LEVEL NETWORKS

Since 1986, a coherent global sea level network has been progressively set up under the coordination, at the international level, of the Intergovernmental Oceanographic Commission [IOC (*cf.* UNESCO Report, *in* GLOSS Implementation Plan, 1990)]. This Global Sea Level Observing System is known as GLOSS: Global Level Of Sea Surface.The objective is to establish an operational global network of permanent sea level stations reporting monthly mean averages to the Permanent Service for Mean Sea Level (PSMSL). This system is intended to serve many purposes, including international and regional research programmes as well as practical applications at the national level. The aim is to cover the entire spectrum in time and space of sea level variability, from the short-lived tsunami to changes related to long term sea level rise and tectonic processes. The implementation plan proposed a network of some 300 sea level gauges (*cf.* Fig. 1 *a*). Many of these gauges were already operating, but required upgrading in terms of levelling, accuracy, telemetry (possibly), and systematic procedures for data transmission to the PSMSL. About 100 sites were new, many on islands, and are in the process of being implemented, but in a few cases, especially in polar regions, implementation still poses formidable problems. At present, about 200 gauges of the GLOSS network are operational.

In 1985, the Scientific Plan for the World Climate Research Programme (WCRP) attached particular emphasis to a Sea Level Observing System. The associated oceanographic components of this programme (TOGA and WOCE) offer a particularly stimulating context for upgrading part of the existing sea level network, and implementing new sites as in the GLOSS plans. The TOGA programme priorities were for stations located in the near equatorial regions. The WOCE priorities are for a relatively thin global network of about seventy stations uniformly distributed over the world ocean, with particular emphasis on major straits and passages. For these programmes, hourly or even more frequent observations are required, and these datasets need to be carefully controlled for quality and made available to the scientific community in a timely fashion compatible with the distribution of other datasets like satellite altimetry.

Figure 1 *b* shows the 73 sites currently considered as WOCE sites. Of these, by January 1992, 7 are not yet operational and 27 have not transmitted any data to the WOCE approved Data Assembly Centers (DACs). For this network to obtain a uniform global coverage, in order to meet the requirements noted above, complementary sites are still needed at high latitudes: in the Southern Ocean, the North Pacific and the North Atlantic. Also, as stated earlier, it is necessary to give particular priority to improvements in the data processing and distribution system in order to make sea level gauge data available within a short time period, hopefully two months, in the near future. Figure 2 *a* shows the 43 stations of the WOCE network which are expected to be telemetering their observations during the WOCE period. Currently, many of these telemetering gauges are found in the Pacific Ocean, having been established as part of the TOGA sea level effort in conjunction with the Pacific Tsunami Warning System. Other sites are benefiting from the National Oceanic and Atmospheric Administration (NOAA) programme for upgrading the US national sea level gauge network and its Climatic and Global Change Program. Sites from the Southern Atlantic and the Southern Indian Ocean are being equipped by the United Kingdom and France. On Figure 2 *b*, we have also plotted the 15 stations which are near VLBI (Very Long Baseline Inferometry) or DORIS (Doppler Orbit and Radio Positioning Integration by Satellite) sites, which will be of considerable use in ensuring absolute levelling by reference to a global geodetic reference system [*i. e.* the conventional terrestrial reference frame established by the International Earth Rotation Service (IERS)].

CONCLUSIONS

The major conclusions to be drawn from this overview of the input and availability of tide gauge data for the validation of satellite altimetric measurements may be summarized as follows:

- Recent studies using Geosat altimeter measurements show that this dataset is consistent with tide gauge data, within the 10 cm rms limit *a priori* taken as a (pessimistic) first guess, and this despite the crudeness of the Geosat system.

- Reference to the tide gauge measurements is obviously of considerable importance for validation of the altimeter satellite products. Different improvements in the altimeter corrections recently produced in the literature all illustrate that most of the discrepancies currently observed between altimeter products and tide gauge time series are linked to unsatisfactory corrections within the altimetric system, thus increasing the importance of the availability of valuable *in situ* sea level gauge measurements.

- Given the level of accuracy already obtained, and considering the optimal design of the coming Topex/Poseidon mission, it is necessary to improve the *a priori* error bar estimates on the tide gauge data. Each individual site, in order to be useful for optimization or validation of altimeter satellite products for oceanic studies, needs to be carefully characterized in terms of error budget and representativeness of surrounding oceanic processes. This could possibly be addressed through systematic combination of tide gauge and improved altimetric data, through regional numerical modelling and through assimilation methods synthesizing the two approaches.

- Sophisticated methods now exist to permit quantitative investigations to obtain numerical estimates of the error reduction in altimetric products that could result by adding a gauge at a new specific site. The clear zero order criterium on the optimal distribution of tide gauges for improving satellite altimetric datasets is a uniform coverage of sites representative of the scales being studied.

- Given the acknowledged usefulness of tide gauge data, an effort needs to be made to upgrade the data processing and transmission system to enable it to provide the scientific community with sea level data within a short time period, say two months.

- In order to guarantee external controls for the use of satellite altimetry in monitoring the long-term evolution of the mean sea level at the world scale, tide gauge stations of very high standard have to be linked to the International Earth Reference System (to which the satellite systems have also to be referred), and regularly and carefully surveyed in the long term. The number and location of such high-standard stations cannot yet be clearly defined on a scientific basis: this is one of the issues of the TOGA and WOCE programmes. However, tools now exist to investigate the problem. Considering the extent of the constraints resulting from the need for highest quality geodetic links and benchmarks monitoring, such investigations are worth considering.

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