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Satellite altimetry from a short-arc orbit technique: Application to the Mediterranean

P. Bonnefond, P. Exertier, P. Schaeffer, S. Bruinsma, and F. Barlier

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Abstract. A short-arc orbit technique was developed, and a very precise and efficient tool for regional orbit determination with a rigorous error budget is proposed for analyzing the TOPEX/POSEIDON (T/P) and ERS 1 missions. The purpose is to be able to determine very accurately, in some conditions, the local orbit, with a very small error in the radial direction, using satellite laser ranging data. A precision at the level of 2 cm is obtained. With this it was possible to cross validate all the different orbit determination techniques as well as the results of the altimeter calibration, showing the great progress made with the TOPEX/POSEIDON mission. After that the T/P mean sea profiles were computed and improved with high accuracy, thanks also to the short-arc orbit technique. As a result, a combined mean sea surface using TOPEX/POSEIDON and ERS 1 data has been computed with crossover difference techniques, the T/P mean sea profiles serving as reference. Fine structures of the mean sea surface have been evidenced. Using this combined mean sea surface, the ERS 1 altimeter calibration was performed over the Mediterranean, again using the short-arc orbit technique. The result is in good agreement with the previous ones (-41.6 ± 7 cm). Finally, the T/P mean sea profiles were computed for different seasons and compared with a yearly averaged mean sea surface. Variations of about 15 cm are evidenced, associated notably with the thermal expansion between fall and winter. The short-arc orbit technique appears to be well suited for monitoring very accurately the temporal variability of the Mediterranean Sea at a subcentimetric level.

1. Introduction

The monitoring of sea level changes yields interesting results from a scientific point of view because numerous oceanographical and geophysical processes have signatures on the sea surface topography. For that purpose, several altimeter missions with instrumental noises of a few centimeters have been carried out recently, and other ones are scheduled in the decade to come. Let us recall that the satellite's absolute location is a fundamental parameter implied in the altimeter measurement, since we are interested in the sea surface positioning with respect to the geoid or to the Earth's center of mass. In order to reach centimeter level accuracy in the sea level determination from space, all these missions require a high accuracy in the satellite orbit determination. For this prospect we have developed a precise, regional orbit computation method for artificial satellites based on a geometrical concept [Bonnefond, 1994]. The motivation behind this study is twofold as follows: first, to establish an accurate short-arc orbit technique which can be applied to several altimeter missions in order to study very accurately the mean sea surface and its variabilities in a given restricted area; and second, to make a contribution to the regional validation and calibration of the TOPEX/POSEIDON (T/P) and ERS 1 products in the Mediterranean. This oceanic area has been under study for a long time [Bernard, 1981; Barlier *et al.*, 1982; Houry, 1989; Houry *et al.*, 1991] and is specific for several reasons. (1) Ocean tides have less amplitude compared with those of great ocean basins, so the mean sea surface is computed more precisely. (2) Global seasonal

variabilities (decimeter level) and a secular variation of the mean sea level exist, but these quantities still have to be determined at the centimeter level or less, if possible. (3) In addition, this area has a dense satellite laser ranging (SLR) network, and it includes two calibration sites, one at Venice for the ERS 1 altimeter and one at Lampedusa island for the POSEIDON altimeter. For all these reasons, we estimate that a short-arc orbit technique is better designed than global dynamical approaches for reaching the required centimeter level with high-performance tracking stations. This is particularly true for the ERS 1 mission.

Therefore the aim of the present work is first to present the principle of the orbit computation method we have developed, with its own characteristics and its precision, through the establishment of an error budget as complete as possible. Moreover, by comparing with other results, we evaluate this precision in the concrete case of the altimeter calibration, where this kind of method for geometric improvement of altimetric satellite orbits is usually used [e.g., Scharoo *et al.*, 1991; Francis *et al.*, 1993]. The short-arc orbit computation technique has actually been applied during the simultaneous calibration experiments of Lampedusa (official site for the POSEIDON altimeter) and Harvest (official site for the TOPEX altimeter, California) and compared with other precise orbit computation sources. The results of all the orbit computations have been used by Ménard *et al.* [1994] and Christensen *et al.* [1994a] to determine the instrumental biases. In return, the quality of their results has permitted us to prove the quality of the short-arc orbit computation with regard to other solutions [Nouël *et al.*, 1994; Tapley *et al.*, 1994; Yunck *et al.*, 1994]. The second purpose of this paper, connected to scientific objectives, is to combine such a short-arc orbit technique with an analysis of the T/P altimeter range measurements (precision of a few centimeters and calibration at the level of 2 cm) in order to provide master mean sea surface profiles in the Mediterranean.

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The objective is to determine a reference grid containing absolute radial position information of high accuracy for (1) properly applying a crossover method between ERS 1 and T/P profiles and (2) studying seasonal sea level changes in the entire Mediterranean area over a period of time of 1 year (about 36 T/P cycles). The objective is then to determine a reference mean sea surface, whose resolution is improved by the European altimeter satellite data (repeat cycle of 35 days), the crossover method serving to merge both data sets (T/P and ERS 1). The other objective consists of quantifying the variability of the Mediterranean mean level from the comparisons between mean sea profiles obtained with T/P subdata sets (e.g., over one season) and an annual solution.

The short-arc orbit determination method being the central part of this work, its characteristics and error budget are presented in section 2. In a schematic way the main feature of our technique consists of a fine and complete a priori analysis of the configuration of the passes in order to have the best radial orbit determination of a satellite along a short arc of the order of 3000-4000 km. As in the work by Sinclair [1989] or Hauck [1988], some criteria have been adopted to optimize the short-arc orbit fit over each pass. In order to have a highly efficient determination method, this examination has been implemented in an automatic process. This permits us to objectively select from all the arcs of trajectory, crossing a given area throughout the considered time period (i.e., the 10-day repeat cycle for T/P), those for which the radial component can be determined with always the same very high accuracy using the SLR tracking data.

Section 3 is focused on the cross-validation of different orbit determination techniques used over Lampedusa and Harvest as well as a comparison between the values of the altimeter biases computed from different sources of precise orbit. Section 4 is dedicated to the regional extension of the method and to the determination of T/P mean sea profiles in the Mediterranean. This extension has been performed using 6 months of T/P data, including available SLR measurements and calibrated altimeter range observations. Through these computations the improvement of the mean sea profiles positioning, thanks to the short-arc corrections, has been quantified, as in the work by Wagner and Melchioni [1989], and the results are presented. Finally, we present in section 5 the main scientific results of our contribution, the determination of the Mediterranean mean sea surface by mixing ERS 1 and T/P altimeter data and the determination of the global seasonal variability over 1 year. These results are particularly important with respect to the objective of obtaining mean sea level determination at the millimeter level.

2. Short-Arc Technique

2.1. Method

Basic concepts. The approach we use for the short-arc orbit determination is to assume that a long-arc orbit is available covering several days (e.g., one repeat cycle) determined from a given global tracking data set (SLR and/or Doppler measurements). We determine corrections to this input orbit for short arcs of the orbit that are typically of 10- to 15-min duration and so of length up to 4000 km. Let us note that the corrected tracks of the satellite are no longer exact solutions of the differential equation system for its motion. Instead of dynamically fitting short arcs, we determine, in fact, kinematic corrections representing the local orbit error. The values of these corrections to be applied to the input orbit are estimated in a least squares procedure from the intensive SLR tracking data that is assumed to be available along the short arcs.

In the context of this paper, short-arc orbit determination is thus defined as a technique to estimate the best trajectory, particularly in the radial direction. Considering the geometric concept behind this method, in order to provide the best radial orbit determination, the essential parameter to be investigated certainly is the configuration of the pass [Sinclair, 1989]. Behind this concept of geometrical configuration, we consider the locations and the number of involved SLR tracking stations, the number and the distribution of SLR range measurements along short arcs, and the nature and the number of orbital parameters that are possible to estimate. The method we have developed can select, from objective criteria, such parameters (described in detail in the next subsection) for guaranteeing the required accuracy on the short-arc orbits. Obviously, such a method absolutely requires the tracking technology to be very accurate in the determination of the radial component of the orbit. Satellite laser ranging is a very precise technology and is known to provide such accuracy at the 1- or 2-cm level (see section 2.2).

Choice of variables to be fitted. According to the quasi-collinearity between the satellite's geocentric vector \mathbf{x} and the direction along which the altimeter range measurement is defined h , the rotating local orbital frame usually used in satellite geodesy has been chosen as a reference frame (Figure 1). Its axes are defined by the radial R , along-track T (in the direction of the satellite velocity), and across-track N directions (see (1)). The use of radial, along-track, and across-track displacements as orbital corrections has advantages over other possibilities such as using osculating elements. This choice allows one to better understand the sensitivity of the SLR measurements with respect to these parameters (R , T , and N) and then to better interpret their cross-correlations in term of the geometrical configuration quality [Sinclair, 1989]. In fact, correlations related to the distribution of SLR measurements along the short arc relative to the time of closest approach as well as the configuration of the ground track relative to the tracking stations are more obvious. They can thus be more simply controlled by adopting in each case a proper set of parameters that is solved for.

$$\begin{aligned}\bar{R} &= \frac{\mathbf{x}}{|\mathbf{x}|} \\ \bar{T} &= \bar{N} \times \bar{R} \\ \bar{N} &= \frac{\mathbf{C}}{|\mathbf{C}|}\end{aligned}\quad (1)$$

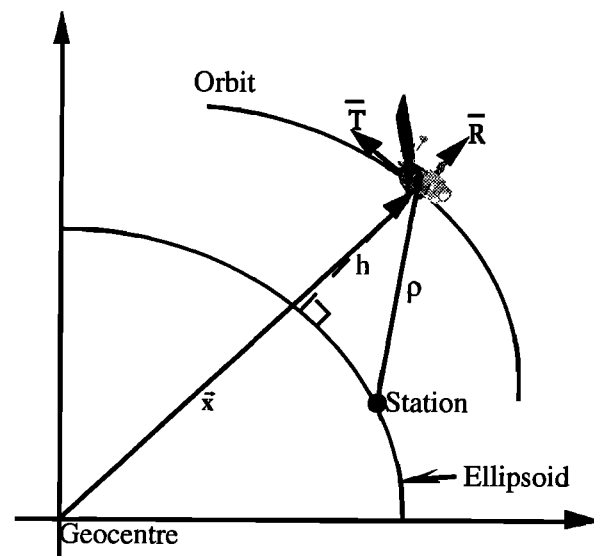


Figure 1. Reference frame of the short-arc orbit technique.

where \mathbf{x} is the geocentric vector (Earth center of mass/satellite), $\dot{\mathbf{x}}$ is the velocity vector of the satellite, and $\mathbf{C} = \mathbf{x} \times \dot{\mathbf{x}}$ is the angular momentum.

Short-arc correction model. The geometrical method uses an input ephemeris (10-day orbits in the case of TOPEX/POSEIDON) from which orbit corrections (in the three directions R , T , and N) are estimated using SLR measurements. Taking into account the short-arc length, it is possible to model these orbit parameters as simple constants or, better, as linear functions of time (see (2)). However, since the precision of the radial component of the T/P input ephemeris will be always better than 10 cm rms at the orbital frequency, the orbit correction on R can already be modeled as a simple bias [Sinclair, 1989]. As a consequence, we will assume in the following that the maximum value of R_1 certainly is too small (about 0.01 cm s^{-1}) to be solved for in our procedure without perturbing the numerical fit. Moreover, neglecting this parameter avoids a high correlation of R_1 and T_0 because each of these parameters causes the range to vary similarly as t/ρ , where t is the time of observation and ρ is the measured station-satellite distance. On the other hand, if the along-track orbit error is not solved for to avoid this correlation, the radial correction (then considered as $R = R_0 + R_1 \cdot t$) would increase from the time of closest approach at the rate of $R_1 = v/h \cdot T_0$, where v is the velocity of the satellite and h is its altitude, both being roughly constant for a circular motion. Let us give a real example. Following our simulations for an along-track orbit error of about 50 cm in the case of TOPEX/POSEIDON, R_1 would have a value of 0.3 cm s^{-1} . As a result, that affects the estimate of the radial component at a higher level than the expected rate term of the radial orbit error itself. Concerning the two other directions (along and across track), the time-dependent parameters T_1 and N_1 allow the achievement of a better orbit error modeling in most cases. Considering our results, the following a priori orbit error model appears to be an optimal compromise in the case of the T/P orbit:

$$\begin{aligned} R &= R_0 \\ T &= T_0 + T_1 \cdot t \\ N &= N_0 + N_1 \cdot t \end{aligned} \quad (2)$$

Criteria for the short-arc parameter selection. Our resolution method is based on both a priori analysis of the geometrical

configuration and a posteriori analysis of the results. The a posteriori analysis accounts for values of the fitted orbit parameters, their expected rms, and the correlation matrix stemming from the least squares fit. The procedure has been implemented in a two-step automatic process.

The first step of this process is dedicated to a numerical sensitivity analysis of the values of the partial derivatives of the range station-satellite ρ with respect to the orbit parameters (see (3)). Our interest here is the capability of a given configuration to provide enough information for guaranteeing a high level of accuracy for the orbit, especially on the radial component. Obviously, this depends to a large extent on the shape of the three-dimensional network formed by the tracking stations and the satellite and on the geographical location of the satellite ground track relative to the network. As an example, Figure 2 illustrates the level of information in the three directions R , T , and N that the Lampedusa (Figure 2a) and Helwan (Figure 2b) tracking measurements for calibration pass 222 provide (the Helwan site is far to the east of this pass; see Figure 3). It represents numerical values of the normalized partial derivatives quoted above, computed along this given short arc.

$$\frac{\partial \rho}{\partial R} R + \frac{\partial \rho}{\partial T} T + \frac{\partial \rho}{\partial N} N = \text{laser residual} \quad (3)$$

(observed distance minus computed distance), where R , T , and N are the corrections to be determined (see (2)).

In addition, the satellite topocentric elevation has been plotted because it is also an important parameter to take into account. In this example the radial component of the orbit can be determined by Lampedusa data, while Helwan data contribute primarily to determining the normal component; the along-track component can be determined if the SLR data are homogeneously distributed along the orbital arc. In the general case a set of threshold values of these normalized partial derivatives, corresponding to a minimum level of information, are used for allowing the adjustment of each parameter. Using these criteria (limit values), given in Table 1, along with the a priori orbit error model given above, the method is able to select the set of parameters adapted to each specific case. The parameters are then solved for in a least squares procedure.

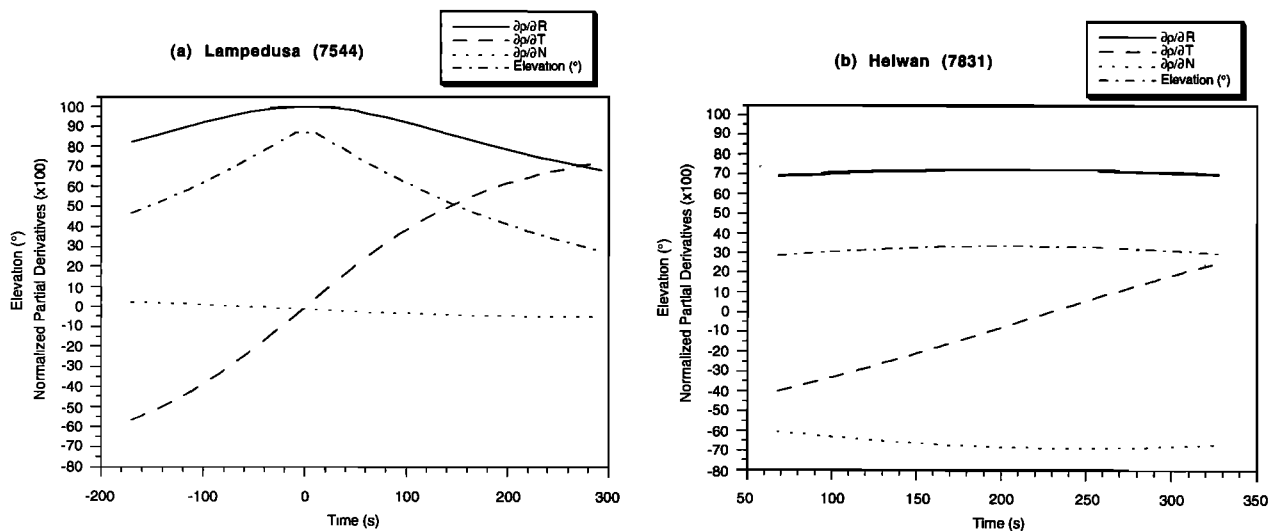


Figure 2. Normalized partial derivatives ($\partial \rho / \partial R$, $\partial \rho / \partial T$, $\partial \rho / \partial N$) for the calibration pass 222 of Lampedusa and for two satellite laser ranging stations, (a) Lampedusa, close to the ground track, and (b) Helwan, far from the ground track.

SATELLITE: TOPEX/Poseidon

GROUND TRACKS FROM 10/03/1993 (23:26) TO 20/03/1993 (08:59)

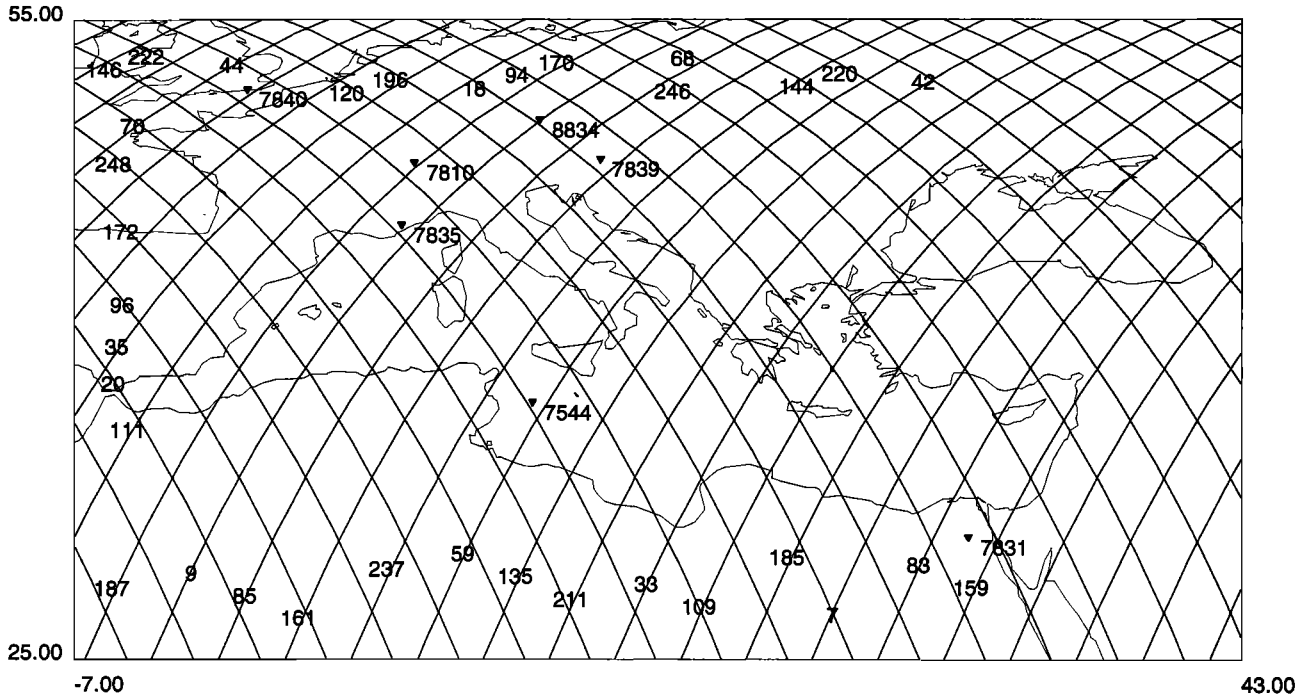


Figure 3. Ground tracks of TOPEX/POSEIDON and distribution of the European SLR stations used for this study (solid triangles). The pass numbers are at the beginning of each track (below for the ascending passes and above for the descending passes).

The second step of the method consists of an analysis of the results of the fit. Indeed, orbital parameters such as T_1 and/or N_1 may have very small values, or high correlations among parameters may appear, these phenomena not being foreseeable at all. Since this can induce numerical problems which degrade the quality of the solution, an iterative process has been developed in order to carefully eliminate at each iteration the adjusted parameters which are associated with poor rms values (stemming from the correlation matrix). This process is iterated until an optimal least squares fit is obtained, the proper determination of the radial component of the orbit being the main goal.

2.2. Error Budget

This section is dedicated to quantifying the a priori errors in the input parameters (models and data) and their effects on the determination of the radial orbit component. These errors can be divided into two parts as follows (Table 2): the “fixed errors” (input orbit, error of orbit corrections model used and geometrical configuration) and the random errors for which the amplitude decreases with the root square of the number of stations involved in the short-arc computation. This error budget does not embrace systematic errors at the regional scale (set of station coordinates,

Table 1. Limit Values for Selecting the Parameters to be Determined

| Number of Stations | Location in Relation to Ground Track | $\partial\rho/\partial R$ | $\partial\rho/\partial T$ | $\partial\rho/\partial N$ | Selected Parameters |
|--------------------|--------------------------------------|---|---------------------------|---|---------------------|
| 1 | under it | at least six values > 0.9 (1.5 minutes) | mean < 0.1 s.d. > 0.3 | | R and/or T |
| at least 2 | one near it | at least six values > 0.86 (1.5 minutes) | mean < 0.1 s.d. > 0.3 | | R and/or T |
| | the other far from it | | | mean of $ \partial\rho/\partial N > 0.5$ | N |
| at least 2 | one on either side of it | at least six values > 0.86 (1.5 minutes) | | opposite sign | $R, T,$ and N |

$R, T,$ and N are the radial, along-track, and across-track directions, respectively, of the orbital frame. The normalized partial derivatives are computed from the station and the satellite positions and velocities at the time of each satellite laser ranging data. For the along-track component a small mean value and a high standard deviation imply that the data are centered and homogeneously distributed around the point of closest approach.

Table 2. Error Budget for the Radial Component and for a Single Station Close to the Ground Track of the Satellite TOPEX/POSEIDON

| Error Sources | Amplitude, cm | RSS of Amplitude*, cm | References |
|--|-----------------|-----------------------|---|
| <i>Errors linked to the Pass</i> | | | |
| Input orbit (1) | $\ll 1^\dagger$ | | this study, <i>Bonnefond</i> [1994] |
| Error model (2) | 1 | 1 | this study, <i>Sinclair</i> [1989] |
| Geometrical configuration (3) | $\ll 1^\dagger$ | | this study |
| <i>Errors Linked to the Station</i> | | | |
| Set of coordinates (4) | | 2 | |
| Errors on the vertical component | 2 | | <i>Boucher et al.</i> [1993] |
| Station eccentricities | $\ll 1^\dagger$ | | <i>Boucher et al.</i> [1993] |
| Solid Earth tides (5) | 1 | 1 | <i>McCarthy</i> [1992] |
| Earth orientation parameters (6) | $\ll 1^\dagger$ | | <i>McCarthy</i> [1992] |
| Normal points (7) | | 1-2 | |
| Calibration | 0.5-1 | | <i>Schwartz</i> [1990] |
| Troposphere | 1 | | <i>Degnan</i> [1993] |
| Signal reflection and RC / CM [‡] (T/P) | 0.5-1 | | <i>Schwartz</i> [1990], <i>Tapley et al.</i> [1994] |

Numbers in parentheses are the error source numbers referred to in text.

*Total root-sum-square is 3 cm.

[†]Value is negligible.

[‡]This refers to the position of the reference center of the laser ring relative to the satellite center of mass.

solid Earth tides, tropospheric correction, etc.); the quantization of their influence is made in section 4 through the orbit comparisons (short arc/global orbit). This study is based only on the random errors at the timescale of a pass (10-15 min) and at the spatial scale of the chosen area.

The first source of fixed errors comes from the input ephemeris. From different sources of input ephemeris (provided by the Service d'Orbitographie Doppler orbitography and radiopositioning integrated by satellite (DORIS) (SOD) of Centre National d'Etudes Spatiales (CNES) mainly; see section 2.3) which were classified in the same class of precision, the capability of the geometrical fit to converge to the same solution has been measured, the radial orbit error being considered as a bias in all cases. The results indicate that convergence is provided by the method at the centimeter level (source 1 in Table 2). An example is presented in section 4.1 in the case of T/P, when using both the preliminary precise orbits and the precise orbits as input ephemeris (SOD/CNES). The second type of error is due to the adopted error model in which the radial component is approximated as a simple bias. As explained in section 2.1, the radial error of the input ephemeris may have a local drift with a theoretical value of $R_1=0.01 \text{ cm s}^{-1}$; but for T/P orbits the comparison of various input ephemeris solutions clearly shows this drift to be less than 0.005 cm s^{-1} . Considering the short-arc length above the Mediterranean area (around 10 min), the error in the geometrical solution due to this contribution is about 1 cm rms (error source 2 in Table 2), with a maximum value of 3 cm above Europe or North Africa, which is outside the considered area. The third type of error due to a poor geometrical configuration can be neglected (source 3 in Table 2) because only those passes which allow a good decorrelation of the fitted parameters R , T , and N and guarantee the required precision on the radial component are selected.

Regarding the errors for which the amplitudes decrease with the root square of the number of participating stations, we are concerned primarily with the computation of the instantaneous coordinates of the tracking stations. The station coordinate errors come from the following three sources: the a priori error of the set of mean coordinates, the solid Earth tide model, and the Earth orientation parameters. The largest of these is the a priori error of

the set of mean coordinates used. Indeed, in the case of a geometrical orbit computation there is a quasi-direct transfer of this last error (in the station altitude, especially) on the determination of the radial component of the orbit. This problem is most severe when there is a single tracking station close to the satellite ground track. For the set of mean coordinates we have used (SSC(DUT)93L05, solution of Delft University of Technology (DUT) submitted to International Earth Rotation Service (IERS) [*Noomen et al.*, 1993]) the error is estimated to be about 2 cm rms on the vertical component [*Boucher et al.*, 1993] (source 4 in Table 2); let us note that it corresponds to random errors at the scale of the area and does not embrace geocentric reference frame errors. The reasons for this choice are explained in section 2.3. The part of the error coming from mismodeling of the solid Earth tides model (IERS Standards) is at the centimeter level (source 5 in Table 2) and can be considered constant during the pass (10-15 min). In that case, also, there is a quasi-direct transfer of the error on the radial component determination, but this is not a systematic effect and varies from one pass to another. The last error source linked to the computation of the instantaneous position of the tracking stations is due to the Earth orientation parameters (IERS Standards). However, the error transfer on the radial component of the orbit remains much less than 1 cm (source 6 in Table 2), the coordinate error corresponding to horizontal displacements of the station position.

The last important component of the error budget concerns the SLR data quality. The use of normal points (provided by Goddard Space Flight Center (GSFC)) allows one to reduce the noise of the measurements without loss of information. It also allows one to homogenize the number of measurements per station, hence avoiding large differences of weighting in the least squares fit. The precision of the normal points is of the order of 2 cm (source 7 in Table 2), and they are generally calibrated to better than 1 cm [*Degnan*, 1993]. We may point out that the data provided by the SLR stations in the area of Harvest have a better precision (~ 1 cm) than those provided by the stations in the Mediterranean area (~ 2 cm). This has been corroborated by applying our method over both the Harvest and Lampedusa calibration sites.

In summary, the maximum error in the geometrical determination of the radial component of the orbit should not exceed 3 cm rms. This is an estimate for a computation using a single station close to the satellite ground track. The selected geometrical configurations correspond to passes observed by a minimum of two stations, suggesting the precision of the short-arc technique described in this paper is at the level of 2 cm. This estimate corresponds to the expected precision of this method; quantization of the accuracy is addressed in section 3.

2.3. Data Used

All the numerical computations have been done on the Cyber 992 and 2000 computers (CNES computer center) with the CALTIM software we have developed. The data used are from the first year of the TOPEX/POSEIDON mission.

The input orbits used were provided by SOD/CNES and computed with the ZOOM software. They correspond to the precise orbits using (1) DORIS data only (preliminary precise orbits during the validation phase) and (2) both SLR and DORIS data (precise orbits during the operational phase, given in the geophysical data records (GDR) Archiving, Validation, and Interpretation of Satellite data in Oceanography (AVISO) CD-ROM) [Nouël *et al.*, 1994]. Other orbits, like National Aeronautics and Space Administration (NASA) precise orbit ephemeris (POE) [Tapley *et al.*, 1994] and Global Positioning System (GPS)-based reduced dynamic orbits [Yunck *et al.*, 1994], were also used, principally for making several orbit comparisons during the calibration experiments at Lampedusa and Harvest.

The SLR normal points were provided by GSFC, while the altimetric data were provided by AVISO on the GDR CD-ROMs. The Earth orientation parameters correspond to version B of the IERS bulletin and the solid Earth tides model correspond to the IERS Standards [McCarthy, 1992]. The set of coordinates used for the SLR stations was determined by the Delft University of Technology (SSC(DUT)93L05) [Noomen *et al.*, 1993]. This station coordinate set was used in the International Terrestrial Reference Frame (ITRF) 92 solution [Boucher *et al.*, 1993]. The main reason for this choice is the use in the solution of the SLR data provided by the Lampedusa station (7544) during the calibration campaign (September to December 1992). It induces an improvement in the precision of the coordinates of this tracking station which appear to be an important point for the orbit computation of the calibration passes. Moreover, this set of coordinates has been adopted for the calibration experiment at Lampedusa [Ménard *et al.*, 1994].

3. Cross-Validation of Different Orbit Determination Methods

In section 2.2 the internal error budget of the short-arc technique has been made from relatively simple assumptions. The purpose of this section is to present, in the case of T/P, external controls based on a cross-validation of results obtained from various orbit determination methods. In particular, we use the GPS-based reduced dynamic orbits computed at Jet Propulsion Laboratory (JPL) and the various long-arc orbits computed at CNES and NASA. In order to better understand the influence of a given orbit determination method on the computation of the sea level, two kinds of control have been realized. The first control is based on differences in the estimated satellite heights above the T/P ellipsoid, and the second, on various altimeter bias determinations that have been obtained over the Lampedusa and Harvest sites.

Table 3. Satellite Height Differences at the Time of Closest Approach Determined From Three Types of Orbits for Lampedusa and Harvest Sites

| | Mean, cm | Standard Deviation, cm | Standard Error, cm | Number of Values in Common |
|--------------|----------|------------------------|--------------------|----------------------------|
| CERGA - JPL | 0.0 | 3.0 | 0.8 | 16 |
| CERGA - NASA | 0.2 | 2.7 | 0.6 | 22 |
| CERGA - CNES | 0.4 | 2.5 | 0.5 | 22 |

Values given were taken above the TOPEX/POSEIDON ellipsoid. Centre de Recherches en Géodynamique et Astronomie (CERGA) are the short-arc orbits. JPL refers to the Global Positioning System (GPS)-based reduced dynamic orbits of Jet Propulsion Laboratory. NASA and Centre National d'Etudes Spatiales (CNES) are precise orbits (NASA and CNES orbits are the same as the AVISO geophysical data records).

The satellite heights above the reference ellipsoid computed from several orbit determination methods have been compared over the calibration sites (passes 222 and 43). The number of differences corresponding to the number of short arcs that have been possible to determine geometrically is not very high. However, we can say there is a strong consistency and very few systematics between the various methods, the main part of these orbit differences being in the range of ± 2 cm (75%) and the mean values of the differences being near zero. Table 3, corresponding to Figures 4 and 5, summarizes these results. In consideration of our 2-cm estimate of the error for the short-arc technique (section 2.2) and the values of the standard deviations given in Table 3, the orbit error attributable to the other orbit computations (CNES, JPL, and NASA) appears to be at the same level (~ 2 cm for this sample). When considering a wider geographical area (the overall Mediterranean area), we will see in the following that the radial orbit corrections computed by the short-arc technique from the input ephemeris provided by CNES can lead to values a little bit higher than 2 cm rms.

We consider as a second external control, a comparison of different altimeter bias determinations. Our goal is to estimate the impact of the orbit computation method on these determinations; thus the POSEIDON and TOPEX altimeter biases given herein are computed using a common set of sea level values and altimetric corrections. These values were supplied by Christensen *et al.*

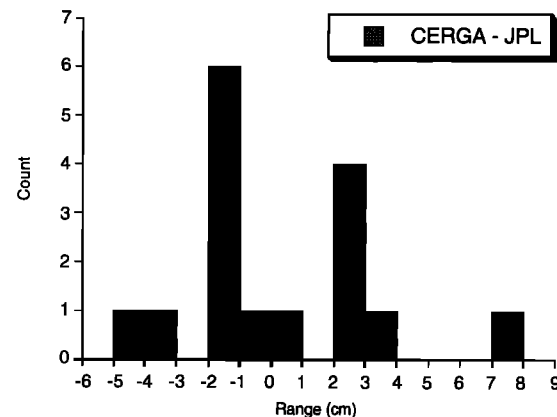


Figure 4. Histogram of the satellite height differences (above the TOPEX/POSEIDON ellipsoid) at the time of closest approach determined from the short-arc orbits (CERGA) and the Global Positioning System (GPS)-based reduced dynamic orbits (Jet Propulsion Laboratory (JPL)).

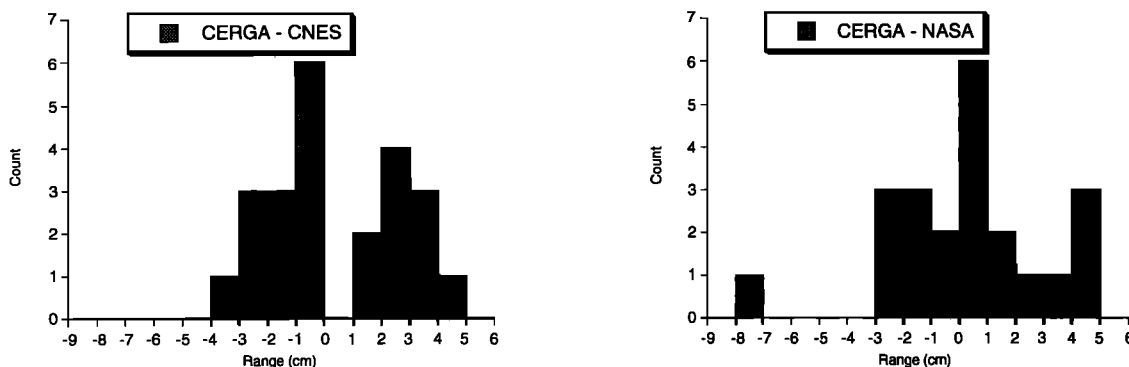


Figure 5. Histograms of the satellite height differences (above the TOPEX/POSEIDON ellipsoid) at the time of closest approach determined from the (left) short-arc orbits (CERGA) minus Centre National d’Etudes Spatiales (CNES) precise orbits, and (right) short-arc orbits (CERGA) minus NASA precise orbits (the NASA and CNES orbits are the same as the AVISO geophysical data records).

[1994a] and *Ménard et al.* [1994], and details concerning their derivations can be found in the papers dedicated to the calibration experiments. The results in Tables 4 to 7 concern the data from the two verification sites (Lampedusa and Harvest). For a given TOPEX altimeter (NASA, ALT) or POSEIDON altimeter (CNES, SSALT) they have been gathered together in order to improve the statistical sample, the two calibration experiments being of equivalent precision; let us note that the scatter is the same, but longer time series ensures Harvest will yield more precise determination (this experiment is still going on). In the case of Lampedusa, owing to various problems (notably weather) and a too short calibration period (September to December 1992) the SSALT altimeter bias does not have the same statistical significance as the one of the ALT altimeter bias (calibration period, September 1992 to September 1993).

First of all, it is really remarkable that these different bias determinations are often equivalent at the subcentimeter level. Moreover, they are in very good agreement (at the centimeter level) with the values provided by the calibration experiments themselves, -14.8 cm (± 2.6) for the TOPEX bias and +1.0 cm (± 2.4) for the POSEIDON bias [*Christensen et al.*, 1994a; *Ménard et al.*, 1994], compared with the values deduced from Tables 4 to 7, -14.0 cm and +0.8 cm, respectively (relative bias between the altimeters, 14.8 cm, compared with 15.5 cm ± 1 cm determined by *Le Traon et al.* [1994]). Their standard deviation is of the order of 3.5 cm when computed from all the data. However, this dispersion is probably symptomatic of the expected error on the instantaneous altimeter bias determination, which represents the lack of knowledge in not only the orbit determination, but also the in situ measurements and the altimeter range observations. Assuming the orbit error is at the level of

2 cm rms (see above), the error originating from the in situ data, altimeter measurements, and associated corrections is at the level of 3 cm rms. This is consistent with the estimate made by *Ménard et al.* [1994]. As a result, the expected error on the mean of those bias determinations (the instrument biases themselves assuming they can be treated as constants), which is generally defined as the standard error, is of the order of 2 cm for POSEIDON and 1 cm for TOPEX (Tables 4 to 7).

These results show the very high consistency between the various orbit determination methods. They confirm the very good agreement between the precise orbits computed by NASA and CNES, which has also been shown through steady comparisons since the beginning of the T/P mission (2-3 cm rms) (Comptes rendus d’exploitation, *Orbite Précise TOPEX/POSEIDON* (every 4 T/P cycles), SOD/CNES, unpublished reports, 1992 to 1994). Considering it is, in fact, legitimate to speak in terms of accuracy and not only in terms of precision, given the geometrical character of the short-arc technique, the external aspect of these evaluations leads us to conclude that the accuracy of our method is of the order of 2 cm. This is an important point and has encouraged us to apply our method in future altimeter bias calibration experiments such as the one for ERS 2 (F. Barlier and P. Exertier, a proposal for the Mediterranean Sea: application of the mean surface topography for oceanographic and geophysical studies, response to the ERS announcement of opportunity, European Space Agency (ESA), 1994).

It is also important to note that the accuracy of the short-arc technique combined with an averaging process should provide a determination of the mean sea level, with respect to a regional network, with at least a centimetric precision (and probably better). These ideas and the estimation of the accuracy on the mean sea level determination are developed in the next section.

Table 4. TOPEX Bias Determined From the Short-Arc Orbits and the GPS-Based Reduced Dynamic Orbits

| Orbit | TOPEX Bias, cm | Standard Deviation, cm | Standard Error, cm | Number of Values in Common |
|-------|----------------|------------------------|--------------------|----------------------------|
| CERGA | -13.1 | 3.3 | 1.0 | 11 |
| JPL | -14.1 | 2.2 | 0.7 | 11 |

CERGA are the short-arc orbits. JPL are the GPS-based reduced dynamic orbits. All values come from the Harvest site [*Christensen et al.*, 1994a].

Table 5. POSEIDON Bias Determined From the Short-Arc Orbits and the GPS-Based Reduced Dynamic Orbits

| Orbit | POSEIDON Bias, cm | Standard Deviation, cm | Standard Error, cm | Number of Values in Common |
|-------|-------------------|------------------------|--------------------|----------------------------|
| CERGA | 0.4 | 4.8 | 2.1 | 5 |
| JPL | 2.4 | 2.1 | 1.0 | 5 |

Two determinations are from the Lampedusa site, three from the Harvest site [*Ménard et al.*, 1994].

Table 6. TOPEX Bias Determined From the Short-Arc Orbits and the NASA and CNES Precise Orbits

| Orbit | TOPEX Bias, cm | Standard Deviation, cm | Standard Error, cm | Number of Values in Common |
|-------|----------------|------------------------|--------------------|----------------------------|
| CERGA | -14.2 | 4.1 | 1.0 | 16 |
| NASA | -14.4 | 3.2 | 0.8 | 16 |
| CNES | -14.1 | 3.1 | 0.8 | 16 |

All values come from the Harvest site [Christensen *et al.*, 1994a].

Table 7. POSEIDON Bias Determined From the Short-Arc Orbits and the NASA and CNES Precise Orbits

| Orbit | POSEIDON Bias, cm | Standard Deviation, cm | Standard Error, cm | Number of Values in Common |
|-------|-------------------|------------------------|--------------------|----------------------------|
| CERGA | -0.3 | 4.6 | 1.9 | 6 |
| NASA | 0.7 | 5.7 | 2.3 | 6 |
| CNES | 0.8 | 5.2 | 2.1 | 6 |

Two determinations are from the Lampedusa site, four from the Harvest site [Ménard *et al.*, 1994].

4. Regional Validation of T/P Products

The aim of this section is to present the analysis of the Mediterranean based on the first 18 cycles of T/P data. Using the short-arc technique as a precise orbit determination method, we compute reference mean sea profiles using the calibrated altimeter range measurements. We note that the geometrical fit is not possible for all the orbital arcs crossing this area during the first 6 months of the mission (September 1992 to March 1993), due either to insufficient SLR coverage or inadequate geometrical configurations (see criteria in section 2). Thus we have to average instantaneous sea height profiles derived from both short-arc and long-arc solutions.

We present first the short-arc orbit determinations based on available European SLR range measurements during this period of time and computed from the input ephemeris provided by CNES. Next, the altimetric data processing, i.e., the mean sea profile determination method, is explained. Finally, the improvement of the mean sea profile positioning attributable to the use of the short-arc technique is quantified.

4.1. Short-Arc Orbit Corrections

In order to better understand the effects of the use of the short-arc technique on the T/P orbit, the following two kinds of input ephemeris have been used: the preliminary precise orbits and the precise orbits, all of them being computed by the SOD group at CNES (see section 2.3).

As explained previously, the short-arc computation depends on the number of SLR stations involved, the number of SLR data, and their distribution along the track. Figure 6 illustrates the very high correlation (80%) between the number of SLR data (Figure 6a) and the number of short arcs adjusted for each cycle (Figure 6b).

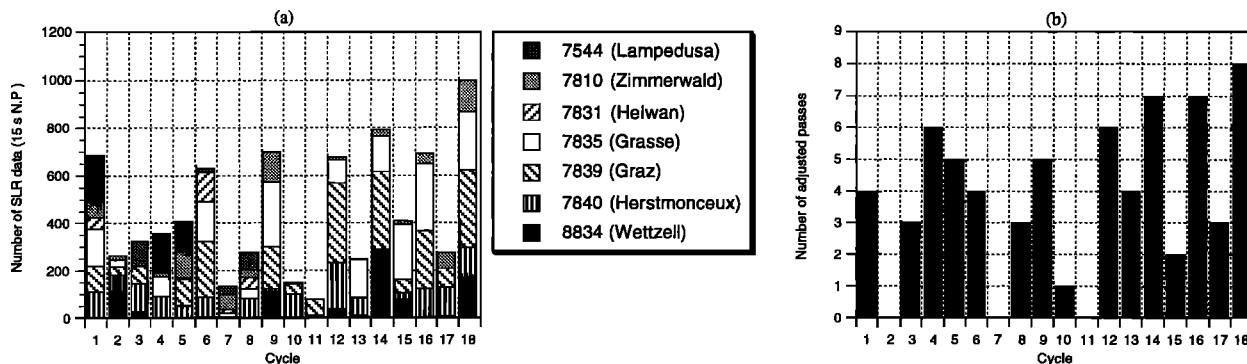


Figure 6. (a) Number of SLR data (15-s normal points) per cycle and per SLR station of the European network (only the stations used for the short-arc computation). (b) Number of passes corrected by the short-arc technique (for the radial component) per cycle.

Figure 7 shows for each pass the number of short arcs that have been selected based on our criteria that define optimal configuration (i.e., a configuration that will likely yield an orbit with a precision of 2 cm in the radial direction). These 60 short arcs represent only 18% of all the short arcs that would be available if there were constant and uniform SLR coverage over the Mediterranean Sea. This small fraction of the total possible passes is due to the SLR coverage over Europe during the winter of 1992/1993 mainly and also to our selection method requiring well-defined configurations to guarantee high precision of the orbit.

The values of the short-arc corrections computed by our technique from the two kinds of input ephemeris (preliminary precise orbits and precise orbits, described in section 2.3) are shown in Figure 8 and in the associated Table 8. The lower standard deviation of the short-arc orbit corrections to the precise orbits (versus the preliminary precise orbits) (Table 8, from 7.0 to 4.8 cm) is an important point to be emphasized. In an independent manner, it shows the improvement which has been gained by the SOD/CNES group in the determination process of the TOPEX/POSEIDON orbit, due notably to the use of SLR data and also the Joint Gravity Model JGM-2 and empirical forces [Nouël *et al.*, 1994]. The amplitudes of the corrections determined by the short-arc technique are much smaller when the precise orbits are used as input orbits; the main part of these corrections is ± 5 cm (72%), which changes to ± 8 cm (with the same percentage) with the use of the preliminary precise orbits.

The two short-arc orbit solutions obtained are equivalent at the centimeter level; they have been compared in the radial direction, and results show a mean of 0.1 cm and a standard deviation of 0.7 cm. This gives us confidence in the method for the use of the short-arc technique in cases of less accurate a priori orbits such as those of ERS 1; this is illustrated in section 5.1.

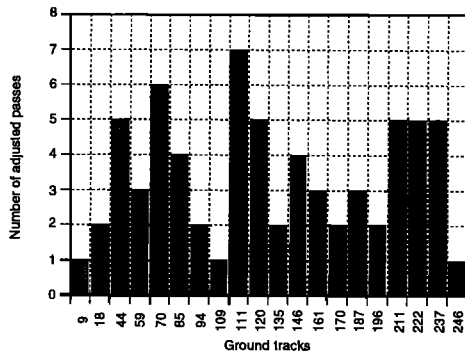


Figure 7. Number of adjusted passes per ground tracks.

The mean values of the short-arc orbit corrections are subcentimetric (Table 8) for the two kinds of input orbit used. This is fine in the sense of a very high homogeneity of reference systems used. The small differences (~0.4 cm) are probably due to the fact that the set of coordinates used by the CNES (SSC(CSR)93L02, solution of Center for Space Research (CSR), University of Texas, submitted to IERS) [Tapley et al., 1994] is different than ours. The impact of these differences, linked mainly to the vertical station component, is estimated at 0.6 cm (SSC(DUT)93L05 minus SSC(CSR)93L02). A part of these differences can also come from geographically correlated errors; their amplitude is here partly compensated by differences linked to the set of coordinates (0.6 cm). Indeed, the part of geographically correlated errors (GCE) estimated from differences presented in Table 8 (-0.4 cm) is 1 cm by using the following formula:

$$\text{differences}_{\text{GCE}} = -(\text{differences}_{\text{orbit}} - \text{differences}_{\text{set of coordinates}}) = -[(-0.4) - (+0.6)]$$

the negative sign serving to return to differences “dynamic-geometric”.

This estimation corresponds well to the geographically correlated errors estimated by Nerem et al. [1994] (1.5 cm) and observed by Christensen et al. [1994b] (~2 cm) for the Mediterranean area; the positive sign corresponds well to differences observed between dynamic orbits (NASA POE) and GPS-based reduced dynamic orbits (JPL) presented by Bertiger et al. [1994]. The different value found by Bertiger (~4 cm) may be partly attributed to a systematic difference (“Z bias” along the terrestrial rotation axis) between dynamic orbits (NASA POE and

GPS-based reduced dynamic orbit (JPL)); the origin of this phenomenon is under investigation.

Finally, the statistics of laser residuals by station are presented in Table 9. It shows well the factor of improvement, thanks to orbit corrections by the short-arc technique. The global standard deviation of 3.4 cm before adjustment (precise orbits, SOD/CNES) is in good agreement with results presented by Nouël et al. [1994]. The global standard deviation after adjustment (short-arc orbits) is 2.1 cm and corresponds well to the uncertainty on the normal points used (see section 2.2). This is, of course, an internal estimator of the quality of short-arc orbit fits. We will see thereafter external estimators of orbit improvement through the impact of the short-arc technique on the mean sea profile determinations.

4.2. Mean Sea Profiles Computation

The mean sea profile computation consists of averaging over a given period of time (cycles 1 to 18 here) the sea heights determined by subtracting the corrected altimeter range measurements computed from the satellite altitudes. For this purpose, the instrumental corrections (ionospheric delay, wet and dry troposphere, electromagnetic bias, atmospheric pressure effects, etc.) have been applied from the T/P merged geophysical data records (GDR-M) [Archiving, Validation, and Interpretation of Satellite data in Oceanography (AVISO), 1992] (Table 10), while the geophysical and oceanographical corrections have been computed using available models in our software (solid Earth tides, IERS Standards [McCarthy, 1992]; ocean tides, Vincent and Canceill [1993]). These corrections have been computed in order to have the same solid Earth tides as those used for the SLR stations coordinates and because of a finer grid for the ocean tide model (0.125° versus 1° in GDRs). Also, recent estimates of the calibration values for the ALT and SSALT altimeter biases have been applied (-15 and +1 cm, respectively [Christensen et al., 1994a; Ménard et al., 1994]). The inverted barometer correction has been applied [AVISO, 1992] following the recommendations of Larnicol et al. [this issue].

The method we have developed consists of averaging the instantaneous sea surface heights and their associated geographical coordinates within a spatial window of 0.047° wide in latitude (~5 km). In this way, the size of the window corresponds to the mean spacing of the 1 s⁻¹ altimetric data computed for each profile. From the temporal point of view each “altimetric normal point” has been computed with at least 60% of all possible data in

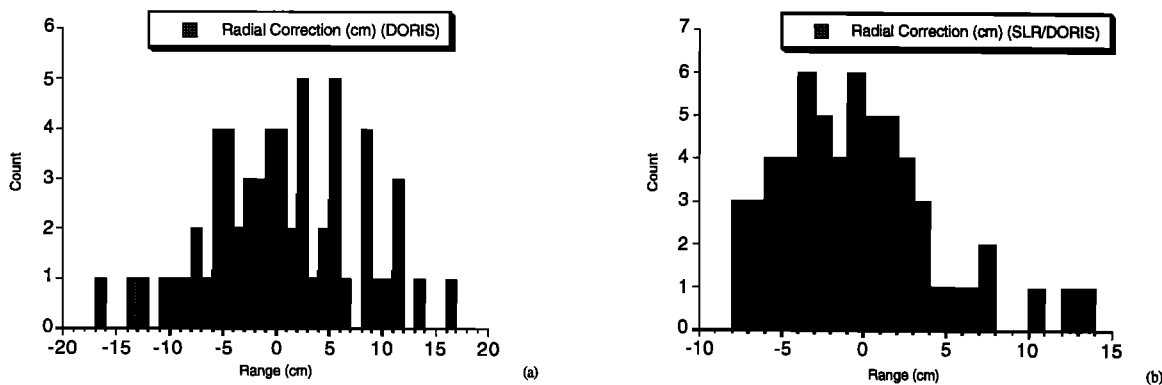


Figure 8. Histograms of the radial corrections computed by the short-arc technique using (a) preliminary precise orbits with Doppler orbitography and radiopositioning integrated by satellite (DORIS) data and (b) precise orbits with SLR/DORIS data, as input orbits, both provided by Service d’Orbitographie DORIS (SOD)/CNES.

Table 8. Radial Corrections Computed by the Short-Arc Technique Using Preliminary Precise Orbits and Precise Orbits

| Input Orbits* | Mean, cm | Standard Deviation, cm | Standard Error, cm | Number of Values in Common |
|---|----------|------------------------|--------------------|----------------------------|
| Preliminary precise orbits [†] | 0.4 | 7.0 | 0.9 | 60 |
| Precise orbits [‡] | -0.4 | 4.8 | 0.6 | 60 |

*Provided by Service d'Orbitographie DORIS (SOD) of CNES.

[†]Doppler orbitography and radiopositioning integrated by satellite (DORIS) data were used.

[‡]Satellite laser ranging (SLR) and DORIS data were used.

order to ensure a high homogeneity along a given mean sea profile. Each normal point is independent, minimizing unwanted smoothing along the profile. In order to avoid the effect of discontinuities from the lack of data along instantaneous profiles, the averaging is performed in two iterations. After computing a first mean sea profile, it is possible to deduce from this reference the mean differences with each instantaneous profile. In the second iteration these quantities are used to shift the corresponding instantaneous profiles; then, the averaging process is reiterated to define the final reference mean sea profile.

The main challenge in this averaging process is to avoid systematic effects in the vertical positioning of reference mean sea profiles. As an example of such a difficulty, the residual radial orbit error may not always be perfectly averaged. An internal check of these potential errors can be made by examining the crossover differences between the T/P mean sea profiles computed in the Mediterranean area (Figure 9 and Table 11). It can be seen that the mean value of these differences is very small and that their standard deviation (3.1 cm) represents mainly a residual random part after the averaging process. Indeed, the crossover differences between instantaneous sea profiles have a standard deviation of about 12 cm (AVISO, unpublished reports, 1993), and at least 12 cycles have been used to determine our mean sea profiles. As a consequence, assuming a random Gaussian distribution, there should be a factor of reduction of about $\sqrt{12}$ (~3.5) between the instantaneous crossover differences and the mean ones. This is in good agreement with our results.

4.3. Impact of the Short-Arc Corrections on the Absolute Position of the Mean Sea Profiles

Because of the limited SLR coverage over the Mediterranean area during the time period of interest (cycles 1 to 18), it has been possible to adjust only a limited number of short arcs. For a given

mean sea profile it is possible to know if one or several of its instantaneous sea profiles have been computed from the short-arc technique. The goal of this section is to clearly identify the final impact of the short-arc technique on the determination of the mean sea profiles in the case of T/P. For this purpose, the crossover differences corresponding to ascending and descending mean sea profiles which contain adjusted short arcs have been selected. Figure 10 and Table 11 show the statistics on these differences depending on whether the short-arc technique is applied or not.

The decrease of the crossover differences can reach 1 cm (passes 85 and 146), and there is a general reduction of their dispersion. The small number of short-arc corrections (~18%) necessarily leads to a small improvement of the dispersion ($1.4 \text{ cm} = \sqrt{2.5^2 - 2.2^2}$). It is also important to point out that the mean value of the differences is reduced from 0.5 cm to zero. The use of short-arc corrections computed with the method described in this paper is thus able to slightly improve the absolute position of the mean sea profiles. This result is particularly important for the mean sea level monitoring at a few millimeter level. Though the improvement is small in the case of T/P, it can still be important for studying oceanographical and geophysical effects with T/P data, particularly in the Mediterranean Sea, where the secular variation of the mean sea level is 1 or 2 mm yr⁻¹.

5. Regional Analysis of Altimetric Data

5.1. The Mediterranean Mean Sea Surface

Here we see how it is possible to combine ERS 1 altimetric data with those of TOPEX/POSEIDON, thus guaranteeing a great accuracy on the combined mean surface. This allows one to take advantage of the great spatial resolution of ERS 1 (~75 km, Figure 11) and the high precision of the TOPEX/POSEIDON orbit. This increase in the resolution allows the determination of fine geophysical structures. We will also see the use of the combined mean sea surface to calibrate the ERS 1 altimeter.

ERS 1 data. Precise orbit determinations of the ERS 1 satellite that are realized by different groups using dynamic methods (Delft University of Technology and CNES, notably) show that the precision on the radial component is of the order of 20 cm [Scharroo *et al.*, 1992]. It is therefore important to reduce orbit errors so as to best profit from the ERS 1 altimetric measurements, whose precision, of the order of 2-3 cm [Francis, 1992], is entirely comparable to that of TOPEX/POSEIDON. This precision concerns, of course, the noise of the ERS 1 altimeter; indeed, deduced sea heights have a far more important noise linked both to orbit errors and to uncertainties on measurement corrections

Table 9. Statistics of Laser Residuals (Normal Points) for Cycles 1 to 17 of TOPEX/POSEIDON

| Station | Precise Orbits* | | Short-Arc Orbits | | Number of Adjustments |
|--------------------|-----------------|------------------------|------------------|------------------------|-----------------------|
| | Mean, cm | Standard Deviation, cm | Mean, cm | Standard Deviation, cm | |
| 7544, Lampedusa | -0.6 | 4.2 | -0.2 | 2.4 | 18 |
| 7810, Zimmerwald | 2.7 | 4.0 | -0.5 | 3.0 | 16 |
| 7831, Helwan | -9.4 | 3.6 | -0.1 | 2.1 | 8 |
| 7835, Grasse | -0.5 | 3.4 | -0.2 | 1.8 | 18 |
| 7839, Gratz | 1.6 | 3.0 | -0.1 | 1.5 | 19 |
| 7840, Herstmonceux | 2.9 | 2.7 | 0.9 | 2.1 | 27 |
| 8834, Wettzell | 4.1 | 3.1 | 1.5 | 2.4 | 5 |
| Total | 0.7 | 3.4 | 0.1 | 2.1 | |

*Data are from SOD/CNES.

Table 10. Corrections Applied to the Altimetric Measurements of TOPEX and POSEIDON

| Corrections | TOPEX | POSEIDON |
|----------------------|------------------------------|------------------------------|
| Ionospheric | TOPEX correction | DORIS correction |
| Dry troposphere | <i>Saastamoinen</i> [1972]* | <i>Saastamoinen</i> [1972]* |
| Wet Troposphere | TOPEX microwave radiometer | TOPEX microwave radiometer |
| Electromagnetic bias | <i>Fu and Glazman</i> [1991] | <i>Fu and Glazman</i> [1991] |

*Pressure was determined from the model of the European Centre for Medium-Range Weather Forecasts.

(electromagnetic bias, notably). However, the use of the short-arc technique is made difficult by the weak quantity of SLR data; passes of the ERS 1 satellite, due to its low altitude (800 km), have a very short duration (less than 10 min). The quantity of adjustment of the radial component on a 35-day cycle is generally very weak (less than 1%) and does not allow one to constrain sufficiently the mean profile determination in order for it to serve as a reference in a crossover adjustment.

Mixing TOPEX/POSEIDON and ERS 1 mean sea profiles. For the first time, mean profiles of ERS 1 have been determined by using the process described in section 4. The period used (cycles 5 to 9 of ERS 1) corresponds to the first 6 months of the TOPEX/POSEIDON mission (cycles 1 to 18). It is, first of all, important to note that the number of cycles used for ERS 1 is very small and that the standard deviation from mean points is therefore higher than in the case of TOPEX/POSEIDON, even after the reduction process of the instantaneous profile dispersion. Here this standard deviation is of the order of 10 cm (mean standard deviation from mean points), compared with 6 cm obtained for TOPEX/POSEIDON.

The level of coherence for the ERS 1 mean profile is 29 cm and is estimated by the standard deviation of sea height differences at crossover points (Table 12). This important value, in comparison to that obtained for the TOPEX/POSEIDON mean sea surface (3.1 cm for the same period of time), shows well the weak impact of the averaging on variable phenomena (mainly the orbit errors) when too small a number of cycles is used.

Concerning the positioning of the ERS 1 mean profiles with respect to these of TOPEX/POSEIDON, the standard deviation of the sea height differences at crossover points is 24 cm (Table 12). Figure 12 illustrates these differences before adjustment in the form of histograms. Figure 12 shows well the large spectrum of these differences, both for TOPEX/POSEIDON - ERS 1 differences (Figure 12a) and ERS 1 - ERS 1 differences (Figure 12b).

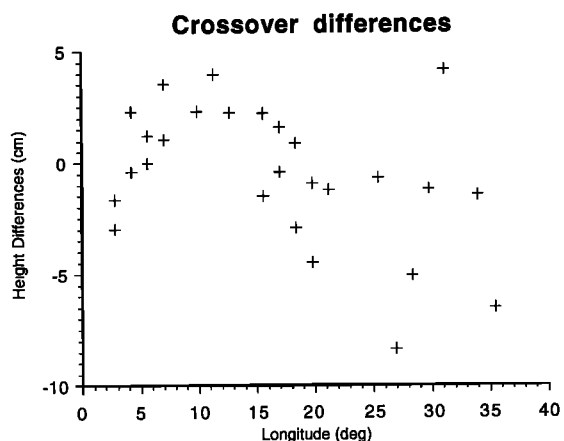


Figure 9. Graph of the crossover differences between the mean sea profiles of the Mediterranean Sea using the TOPEX/POSEIDON altimeter data from cycles 1 to 18.

The average of differences at crossover points between TOPEX/POSEIDON and ERS 1 is -78 cm (Table 12) and reflects the difference of positioning of the two surfaces. This value comes from the following two effects: (1) the bias of the ERS 1 altimeter has not been corrected (~-40 cm), and (2) altitudes of the satellite read on OPR02 tapes were referenced (for cycles 5 to 8) to a different ellipsoid than that used for the TOPEX/POSEIDON surface (GRS80). This difference of ellipsoid, whose semimajor axes differ by -60 cm and their flattening by -9.10^{-9} , generates an average difference of the order of -40 cm on mean height of mean profiles.

The crossover adjustment of ERS 1 and T/P (fixed) mean sea profiles has been realized in two steps. First, only crossover points between ERS 1 mean profiles and those of TOPEX/POSEIDON have been used. Crossover points of the ERS 1 surface then play the role of external control to the adjustment process. The standard deviation of sea height differences (ERS 1 - ERS 1) is then 8 cm (Table 12) and shows the factor of improving the positioning of the ERS 1 profiles. The use of the TOPEX/POSEIDON mean profiles as a reference in the crossover adjustment of ERS 1 mean profiles allows one therefore to increase the level of coherence of the ERS 1 mean sea surface by at least a factor of 3.

In the second step the all sea height differences at crossover points (TOPEX/POSEIDON - ERS 1 and ERS 1 - ERS 1) have been minimized by also fixing the TOPEX/POSEIDON mean profiles. Results presented in Table 12 show that the global coherence level of the combined surface (TOPEX/POSEIDON and ERS 1) is of the order of 5.5 cm (averaged standard deviation). Figure 13 illustrates sea height differences at crossover points after adjustment in the form of histograms. The spectrum of these differences is narrow (80% values between ± 5 cm) and shows well the factor of improvement due to the process of minimization (to compare with Figure 12). Only some values (less than 10%) have an amplitude greater than 10 cm. Reasons for obtaining such values are under investigation; it is probably due to too small a number of equations in the crossover adjustment for some mean profiles, notably in the Straits of Gibraltar and the Adriatic (weak dimension areas).

Table 11. Statistics on the Crossover Differences in the Mean Sea Profiles of the Mediterranean Sea

| | Mean, cm | Standard Deviation, cm | Standard Error, cm | Number of Values |
|-------------------------|----------|------------------------|--------------------|------------------|
| Crossover differences* | -0.5 | 3.1 | 0.6 | 27 |
| Without SA [†] | 0.5 | 2.5 | 0.7 | 11 [‡] |
| With SA [†] | 0.0 | 2.2 | 0.7 | 11 [‡] |

SA refers to short-arc technique corrections.

*Profiles were obtained using T/P altimeter data from cycles 1-18.

[†]Not all the crossovers are involved because only some passes could be corrected by the short-arc technique.

[‡]Values indicate the number in common.

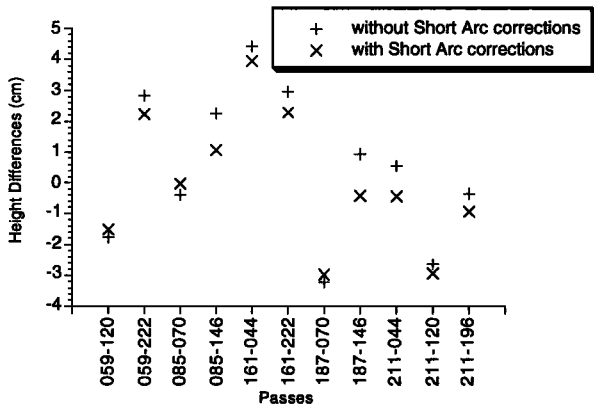


Figure 10. Graph of the crossover differences for common crossover points between mean sea profiles computed with or without short-arc corrections. Only passes which have been corrected by the short-arc technique are shown.

The combined mean surface obtained from altimetric data of the TOPEX/POSEIDON and ERS 1 satellites (September 1992 to March 1993) has therefore an internal coherence level of the order of 5.5 cm. Mean profiles of TOPEX/POSEIDON having been fixed in the process of adjustment, the global positioning of this mean surface benefits from the level of accuracy of the TOPEX/POSEIDON mean sea surface that is of the order of 1 cm.

The combined mean sea surface (TOPEX/POSEIDON and ERS 1) is presented in Figure 14. The increase of the level of detail, owing to the great resolution of the ERS 1 altimetric data, is very sensitive, notably in the western basin and the Straits of Gibraltar (Figure 15). This level of detail allows one to reveal the complexity of the mean surface and therefore probably of the geoid and the bathymetry in some areas. This enables one to determine fine geophysical structures that were not possible to observe using TOPEX/POSEIDON only.

On using the combined mean sea surface to calibrate the ERS 1 altimeter. We have seen previously that the weak quantity of SLR data did not allow one to obtain sufficient orbit corrections to constrain the ERS 1 mean sea profile determination. However, some ERS 1 passes have been corrected by the short-arc technique, and this subsection is devoted to the impact of these corrections on the analysis of the ERS 1 altimetric measurements.

Input orbits used for this analysis have been determined with the GINS software of the Groupe de Recherches de Géodésie Spatiale (GRGS), Toulouse. Radial orbit correction values are presented in Table 13. The amplitude of corrections can reach the meter level, showing the ERS 1 input orbit precision, at least for this sample.

In order to study the impact of these orbit corrections on the analysis of altimetric measurements, mean differences δh of sea heights with respect to the combined mean sea surface have been calculated. The mean differences (Table 13) have been determined before and after the application of radial orbit corrections. These mean differences are representative of the ERS 1 altimeter bias, and their dispersion reflects the effect of the variability of the mean sea surface and the orbit errors. The utilization of orbit corrections allows one to reduce the effect of orbit errors on the precision of the short-arc technique (~2 cm) and leads to an improvement factor of 2 (from 50.8 to 21.5 cm). Nevertheless, the obtained dispersion remains greater than that expected. Indeed, considering the variability expected in the Mediterranean (~10 cm), the error on the mean profile positioning (~5 cm), the residual orbit error (~2 cm), and the error on the sea heights determination (~8 cm, noise measurement and corrections, P.-Y. Le Traon, personal communication, 1995), the quadratic sum of these errors is of the order of 14 cm. This difference between the expected uncertainty and the found dispersion can be due to the weak studied sample that emphasizes the effect of the variability in the Mediterranean. Indeed, the two determinations most distant in time (pass 110 of cycle 6 and pass 353 of cycle 9) correspond to the maximum and minimum of the variability of the mean sea

TOPEX/Poseidon & ERS-1 Mean Sea Profiles

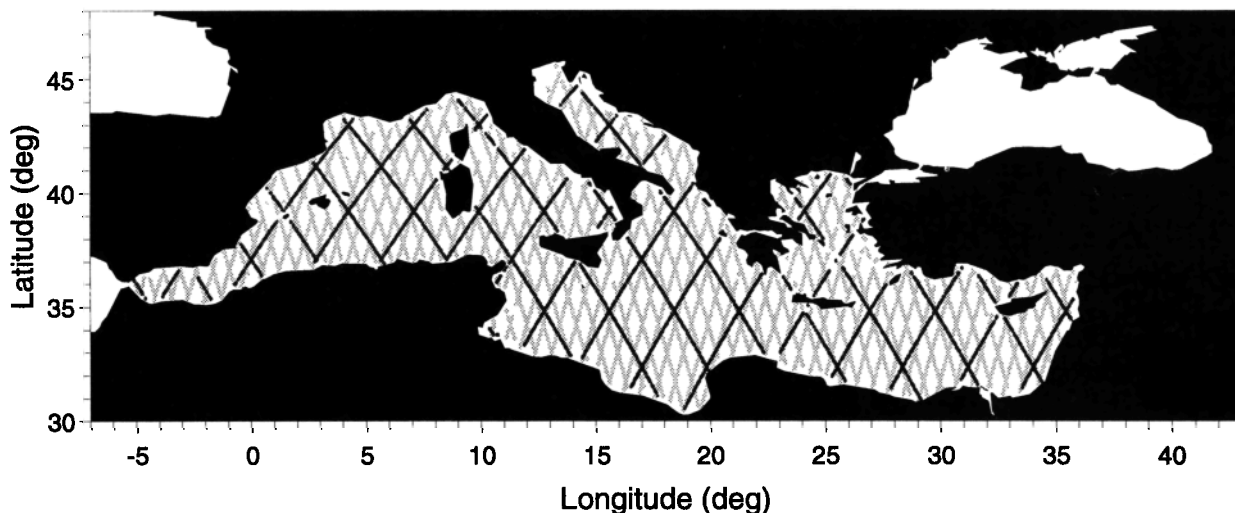


Figure 11. Altimetric profiles of TOPEX/POSEIDON (solid lines) and ERS 1 (shaded lines) in the Mediterranean.

Table 12. Statistics of Sea Height Differences at Crossover Points Between Mean Profiles of TOPEX/POSEIDON and ERS 1 Before and After the Process of Difference Minimization at Crossover Points

| | Before Adjustment | | After Adjustment Using T/P - ERS 1 Crossover Points | | After Adjustment Using T/P - ERS 1 and ERS 1 - ERS 1 Crossover Points | | Number of Crossover Points |
|---------------|-------------------|---------------------------|--|---------------------------|---|---------------------------|-------------------------------|
| | Mean, cm | Standard Deviation, cm | Mean, cm | Standard Deviation, cm | Mean, cm | Standard Deviation, cm | |
| T/P - ERS 1 | -78. | 24. | 0. | 5. | 0. | 6. | 219 |
| ERS 1 - ERS 1 | 0. | 29. | -1. | 8. | 0. | 5. | 218 |

Adjustment involves minimizing the crossover differences between T/P and ERS 1 or by minimizing globally the crossover differences between T/P and ERS 1 and between ERS 1 and ERS 1.

level observed with TOPEX/POSEIDON, respectively (see Figure 16 and section 5.2, cycles 3 and 15). These two determinations correspond to the minimum and maximum of differences, respectively (the residual on the altimetric measurement is the inverse of the residual on the sea height). The elimination of these two values decreases the dispersion by 8 cm and leads to a value close to the one expected (13.3/21.5 cm). It changes the mean by little (-40.3/-41.6 cm), which shows the stability of the solution. Concerning the values before orbit corrections, the dispersion is a little changed (48.8/50.8 cm), while the average value varies by 6 cm (-33.4/-39.0 cm). Orbit corrections allow one therefore to stabilize the average value, and the important dispersion is surely linked to the variability in the Mediterranean that, weak on the average over a year (~10 cm), can reach more than 60 cm for the instantaneous profiles.

The total mean (-41.6 ±7 cm) is very close to the value of the ERS 1 altimeter bias (-41.5 ±5.2 cm) [Francis, 1992]. The standard error on the altimeter bias determination by this method is of the order of 7 cm (i.e., the standard deviation / \sqrt{n} , where n is the number of values). This error is particularly weak, although the effect of the variability on the sea heights has been averaged, while it is measured by tide gauge data in the case of in situ calibrations. Moreover, this is obtained with solely nine values, which allows one to hope the precision will be greater if this study were extended to a greater period of time. This result allows one, furthermore, to show the quality of the absolute positioning of the combined mean sea surface obtained from TOPEX/POSEIDON and ERS 1 altimetric data.

5.2. Variability of the Mediterranean Mean Sea Level

The determination of the mean sea surface variabilities requires the determination of mean sea surfaces of different temporal resolutions, corresponding to timescales of phenomena to study. Moreover, these surfaces have to be of comparable precision, notably concerning their positioning, allowing comparisons between surfaces that will reflect only the temporal variations of the mean sea level. The precision of the different surfaces (obtained from altimetric measurements of TOPEX/POSEIDON), methods allowing one to compare them, and, finally, the quantification of the seasonal evolution of the mean sea level of the Mediterranean are the topics of this section.

Mean sea surface precision. The process of mean sea profile determination of the considered periods (3 and 6 months, and 1 year) and the method of adjustment using crossover points have been described previously (section 4). The reference mean sea profiles that have been improved by the short-arc technique are fixed in the crossover adjustment. We will present the results in detail here as well as the precision of the positioning of each surface constituted by the corresponding mean sea profiles. Table 14 presents statistics on sea height differences at the crossover points of mean sea profiles before and after their adjustment by the crossover adjustment.

The first remark concerns the factor of improvement of the standard deviation of the crossover differences; this factor is, in general, all the more large when the number of used cycles is small (seasonal surfaces). This corresponds mainly to the fact that the orbit errors are much better averaged when more cycles are

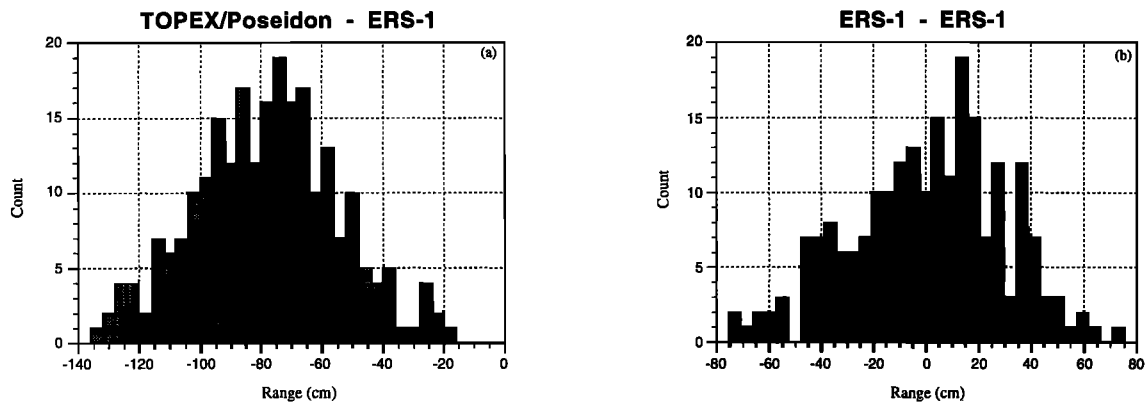


Figure 12. Histograms of sea height differences at crossover points before adjustment (a) between mean profiles of TOPEX/POSEIDON and ERS 1, and (b) of ERS 1 mean profiles.

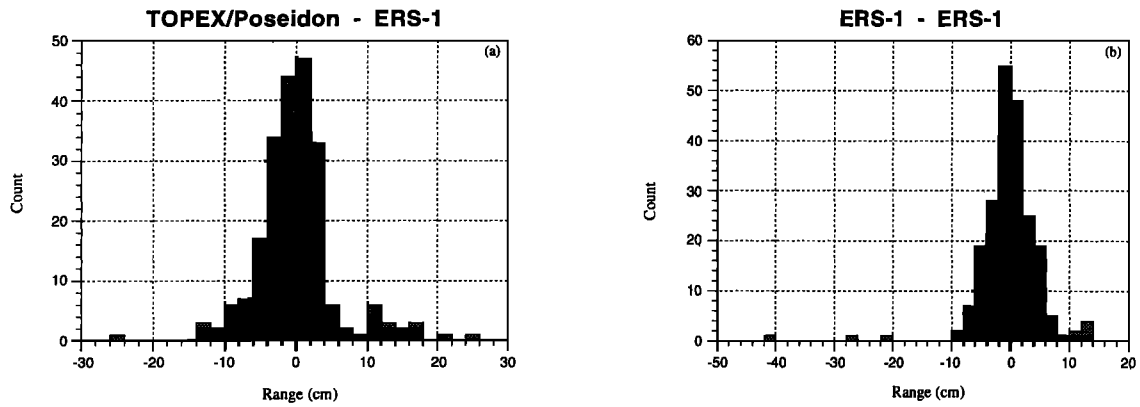


Figure 13. Histograms of sea height differences at crossover points after adjustment (a) between mean profiles of TOPEX/POSEIDON and ERS 1, and (b) of ERS 1 mean profiles.

used (annual surface). In cases where the number of cycles is small, it is therefore all the more important to use a crossover adjustment.

The impact of the adjustment process is, of course, less important as soon as the number of cycles is sufficient (~18 cycles), but it allows one to guarantee a constant precision. Besides, we can notice the difference in the value of the standard deviation (~1 cm) between the two semiannual surfaces before adjustment (3.1 cm for cycles 1-18 and 2.2 cm for cycles 19-36), while the period of time and the number of reference mean profiles are equivalent. This corresponds to the fact that the variability of the mean sea surface between autumn and winter is more important than between spring and summer. The amplitude of this phenomenon will be quantified when comparing the surfaces. Concerning the annual surface, the weak improvement comes, on the one hand, from the large number of used cycles and, on the other hand, from the important number of reference mean profiles (22, 73% of the profiles in Mediterranean), thus strongly constraining the standard deviation to remain constant. Moreover, we

notice that the standard deviation value after adjustment is nearly constant (~2 cm), whatever the period considered; the reference mean profiles being fixed, this value reflects the constant and intrinsic precision of these mean profiles. Let us recall that the reference mean profiles have been improved by the short-arc orbit corrections, and thus these results show the factor of improvement obtained, thanks to our technique.

It is also important to note that the mean of crossover differences has also been reduced, attributable to the adjustment process. This improvement can reach 1 cm in the case of seasonal surfaces and allows one therefore to reduce the possible systematics between descending and ascending profiles coming, for example, from an insufficient averaging of orbit errors.

The process of mean sea profile adjustment allows one therefore to obtain a constant precision, whatever period of time is used. This is an important point for the comparison of these surfaces in order to determine the time variations of the mean sea surface.

Mean sea surface comparisons. The comparison of the dif-

TOPEX/POSEIDON & ERS-1 Mean Sea Surface above GRS80 (m)

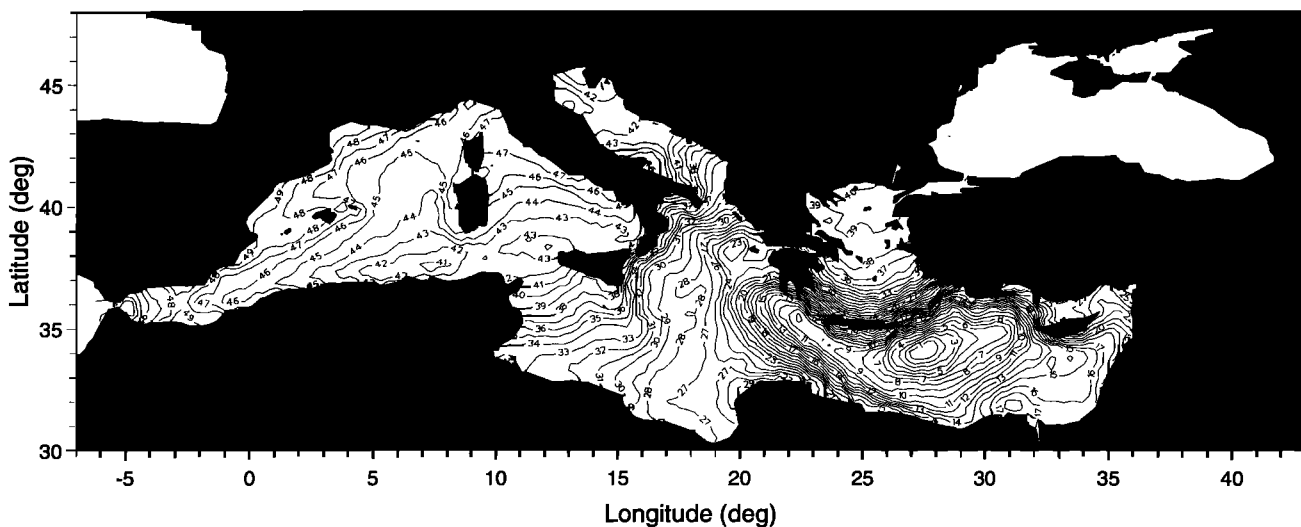


Figure 14. Mean sea surface of the Mediterranean obtained from altimetric data of TOPEX/POSEIDON and ERS 1 (September 1992 to March 1993). Mean heights are given in meters above the ellipsoid GRS80.

**TOPEX/Poseidon & ERS 1
Mean Sea Surface in the Eastern Mediterranean Basin**

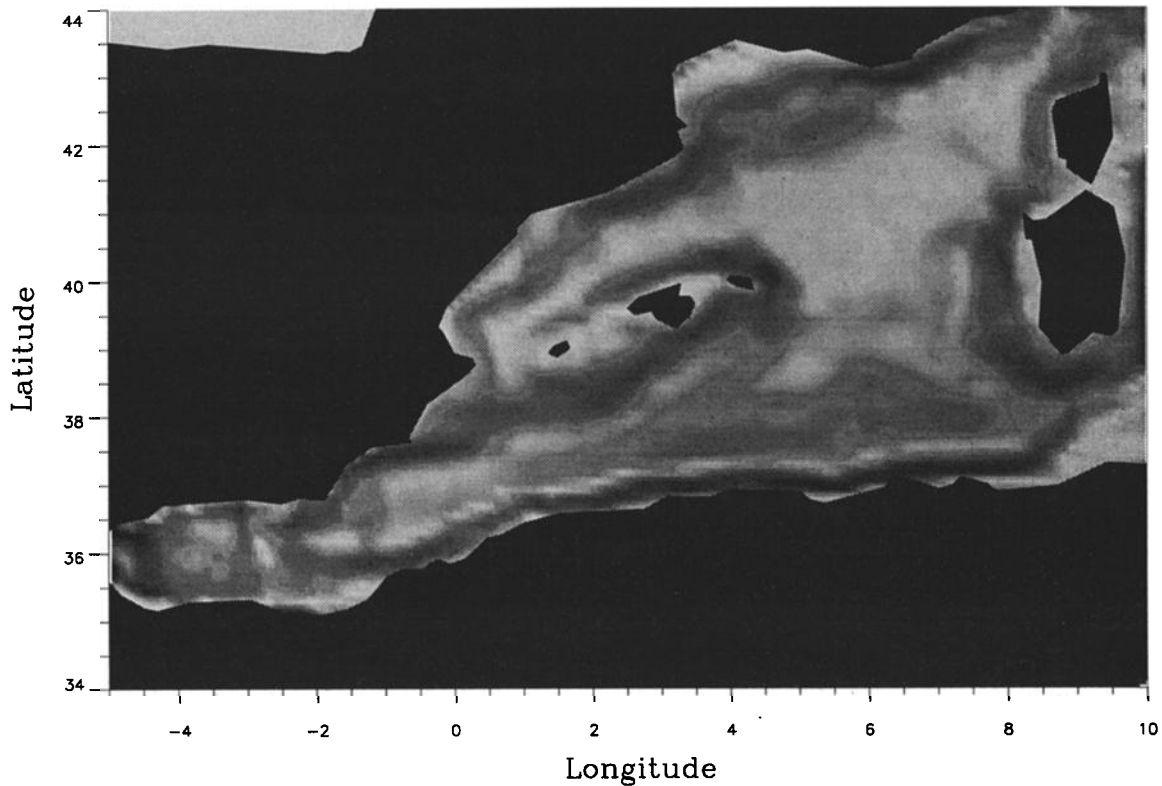


Figure 15. Shaded surface of the combined mean sea surface (TOPEX/POSEIDON and ERS 1) in the western basin (the light source is at the top left corner).

ferent mean sea surfaces (seasonal, semiannual, and annual) necessitates comparison of mean sea heights on a totality of common geographical positions (for example, mean points constituting mean profiles). However, the evolution of the ascending node of the TOPEX/POSEIDON orbit generates a shift in longitude between the satellite ground tracks for the same geographical pass. This shift is constrained to the interval of ± 1 km, thanks to maneuvers undertaken regularly on the satellite. This guarantees that the altimetric repetitive measurements of TOPEX/

POSEIDON (cycle by cycle) are effectuated from geographical locations whose differences in distance are inferior to the dimension of the altimetric radar spot (~ 5 km). Differences of sea height linked to the position of the measurement are therefore minimized but not negligible [Rapp and Yi, 1994], notably in areas where the gradient of the geoid is important.

This phenomenon generates also a shift in longitude for the mean profiles computed for a considered period (Table 15). This shift has a weak amplitude but can generate mean sea height differences that will be all the more important when the gradient (in longitude) of the mean sea surface is strong. These differences will be, of course, less important on mean heights than on instantaneous heights for an equal shift in longitude.

In the eastern Mediterranean basin the gradient is one of the most important of the world mean sea surface. To quantify the effect of the shift in longitude of the mean profiles, the maximal gradient in longitude of the mean sea surface has been determined (near Crete); it is of the order of 4 cm km^{-1} and generates therefore a difference close to 2 cm in the comparison of the sea heights (in this area) between the mean profile of cycles 1 to 9 and the mean profile determined over 1 year. However, the areas in which the influence of the mean profile position can reach similar magnitude represent less than 10% of the total surface of the Mediterranean; the effect of the shift in longitude on comparisons of the Mediterranean mean sea level remains therefore subcentimetric.

Another method of comparing surfaces consists of computing mean height differences at crossover points of mean profiles orig-

Table 13. Radial Orbit Correction Values and Mean Sea Height Differences δh Before and After Applying the Short-Arc Technique

| ERS 1 Cycle | Pass | Radial Orbit Correction, cm | δh before, cm | δh after, cm |
|-------------|------|-----------------------------|-----------------------|----------------------|
| 6 | 110 | -27.7 | -110.2 | -82.1 |
| 7 | 67 | 90.1 | 48.1 | -42.2 |
| 7 | 153 | 37.8 | -12.4 | -50.3 |
| 7 | 196 | -35.1 | -95.1 | -60.8 |
| 8 | 10 | -71.8 | -89.4 | -18.5 |
| 9 | 196 | 14.5 | -26.3 | -40.8 |
| 9 | 332 | -3.2 | -39.5 | -36.3 |
| 9 | 339 | 13.9 | -19.5 | -33.4 |
| 9 | 353 | 3.3 | -7.0 | -10.3 |

The mean of δh before applying the short-arc technique is -39.0, standard deviation is 50.8; the same values after applying the short-arc technique are -41.6 and 21.5.

Table 14. Statistics on Sea Height Differences at the Crossover Points of Mean Sea Profiles Before and After Adjustment for Seasonal, Semiannual, and Annual Surfaces Obtained From TOPEX/POSEIDON Altimetric Data

| Period | Cycles | Before Adjustment | | | After Adjustment | | | Number of Reference Mean Profiles | Number of Crossover Points |
|----------|--------|-------------------|------------------------|--------------------|------------------|------------------------|--------------------|-----------------------------------|----------------------------|
| | | Mean, cm | Standard Deviation, cm | Standard Error, cm | Mean, cm | Standard Deviation, cm | Standard Error, cm | | |
| Fall | 1-9 | -1.0 | 3.3 | 0.8 | 0.0 | 1.5 | 0.3 | 7 | 20 |
| Winter | 10-18 | -0.7 | 3.5 | 0.7 | 0.0 | 1.3 | 0.3 | 9 | 24 |
| Spring | 19-27 | 0.1 | 3.7 | 0.7 | -0.2 | 1.5 | 0.3 | 9 | 27 |
| Summer | 28-36 | 1.1 | 3.1 | 0.6 | 0.0 | 2.2 | 0.4 | 15 | 24 |
| 6 months | 1-18 | -0.5 | 3.1 | 0.6 | 0.0 | 1.9 | 0.4 | 16 | 27 |
| 6 months | 19-36 | 0.3 | 2.2 | 0.4 | 0.4 | 2.1 | 0.4 | 19 | 28 |
| 1 year | 1-36 | 0.0 | 2.3 | 0.4 | 0.2 | 2.1 | 0.4 | 22 | 28 |

Period is September 1992 to September 1993. Adjustment refers to the process of minimization of the mean sea height differences at crossover points.

inating from each surface (ascending profiles from one minus descending profiles from the other and vice versa). This allows one to eliminate the problem of shift in longitude of the mean profiles, since the differences are determined for common geographical positions. On the other hand, the sampling of these differences is weaker (~30 points) than when the mean profiles are directly compared (~3000 points).

Results of comparisons undertaken by the two described methods are presented in Table 16. The agreement at the millimetric level between results shows well the weak influence of the effect of the shift in longitude, especially when one is interested in the average of differences of the entire Mediterranean. These results show also that the sampling from crossover points of TOPEX/POSEIDON is sufficient to represent the global seasonal evolution of the mean sea surface in the Mediterranean. On the other hand, the comparison of sea heights along the mean profiles of different natures (seasonal, semiannuals, or annuals) is necessary to emphasize the seasonal variability of a local viewpoint (for example, differences between the western basin and the eastern basin).

Analysis of the seasonal signal. The seasonal variability of the mean sea surface in the Mediterranean can provoke mean sea level differences reaching more than 15 cm (peak to peak, between autumn and winter). The quantification of these effects has been obtained with a subcentimetric precision, owing to positioning of the different mean sea surfaces of high quality. On the other hand, the study of variable phenomena on a timescale inferior to a season (nine cycles) is difficult to realize with an equal precision. Indeed, the averaging of the different errors (mainly orbit errors) will be less.

However, we want to present qualitatively the evolution of the mean sea level of the Mediterranean surface, cycle by cycle (10 days); the effect of the shift in longitude will be this time more important but will probably not exceed 4-5 cm, given the ampli-

Table 15. Average Shift in Longitude of the Mean Sea Profiles

| Period | Cycles | Average Shift in Longitude, m |
|----------|--------|-------------------------------|
| Fall | 1-9 | 431 |
| Winter | 10-18 | 24 |
| Spring | 19-27 | -350 |
| Summer | 28-36 | -76 |
| 6 months | 1-18 | 215 |
| 6 months | 19-36 | -215 |

Period is September 1992 to September 1993.

tude of this shift. To that end, mean differences of instantaneous profiles (by cycle) relative to mean profiles of the annual surface have been determined and are presented in Figure 16, with seasonal differences (Table 16) represented by crosses. Figure 16 highlights the general form of the evolution of the Mediterranean mean sea level for the considered period.

The signal and the amplitude of the evolution of the mean sea level in Mediterranean seem to be in good agreement with the thermal expansion effect of the sea. This phenomenon is all the more important, since the Mediterranean is a semienclosed basin which forces the water to dilate, mainly in the vertical direction.

The observed maximum difference (Figure 16) is in fall and is probably due to the summer warming of the upper layer. Indeed, the thermal content of the layer 0-100 m is at the maximum in October and November, while the temperature of the surface has already decreased. Just to give an order of magnitude, the estimate of the amplitude of this effect can be made from the formula $dV/V=b dT$, where b is the coefficient of dilation, which is equal to approximately $2.5 \cdot 10^{-4} \text{ } ^\circ\text{C}^{-1}$ for salinity and temperature values found in the western basin (V and T represent the volume and the temperature, respectively). By making the approximation $dV/V=dH/H$ (closed basin), where H represents the thickness of the considered water layer, the variation of the height of water would be 12 cm for a temperature difference of 10°C (for $H=50$ m) (J.P. Béthoux, personal communication, 1994).

The effect of the water expansion due to the temperature is certainly not the only cause for the seasonal evolution of the mean sea level of the Mediterranean, but its influence seems to be

Table 16. Mean Sea Height Differences Between Seasonal and Semiannual Surfaces and the Annual Surface

| Period | Cycles | Mean Sea Height Differences | |
|----------|--------|-----------------------------|-------------------------|
| | | Along the Mean Profiles, cm | At Crossover Points, cm |
| Fall | 1-9 | 9.0 | 9.4 |
| Winter | 10-18 | -7.2 | -7.3 |
| Spring | 19-27 | -5.2 | -5.3 |
| Summer | 28-36 | 0.9 | 0.8 |
| 6 months | 1-18 | 1.2 | 1.3 |
| 6 months | 19-36 | -1.4 | -1.4 |

Period is September 1992 to September 1993. These differences have been obtained, on the one hand, by comparing mean profiles corresponding to common geographical passes and, on the other hand, by using mean sea height differences at crossover points.

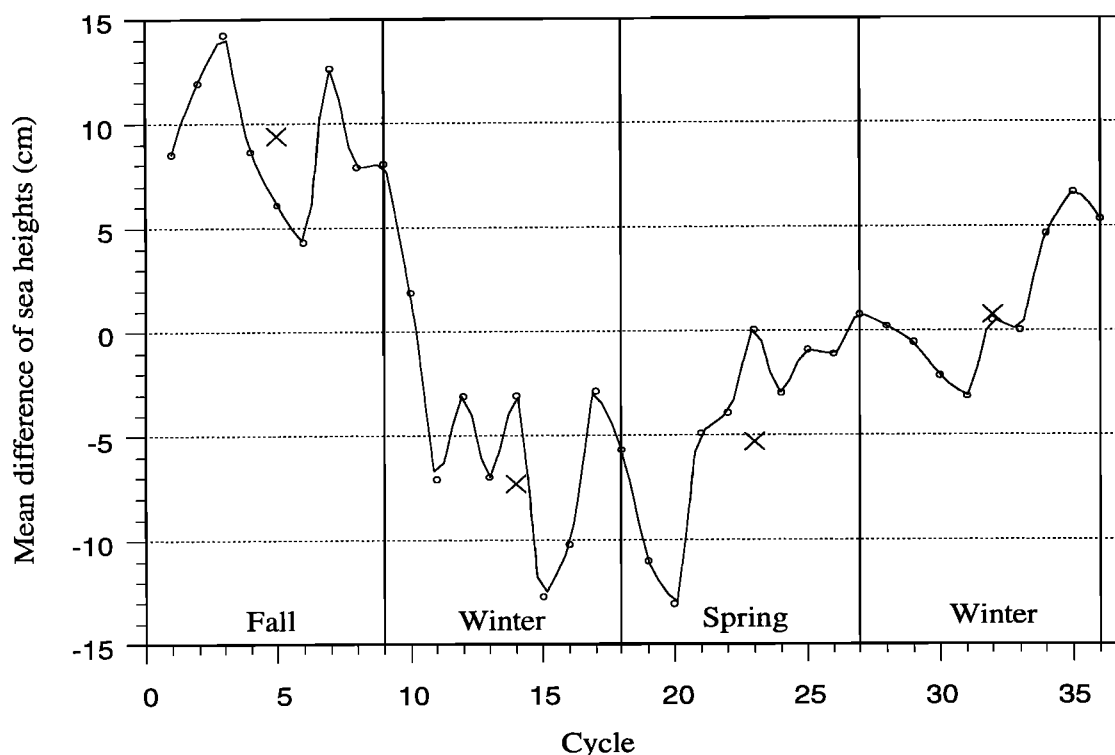


Figure 16. Mean differences by cycle (circles) of sea heights stemming from instantaneous profiles as compared with the annual mean sea surface (cycles 1-36). Crosses represent the mean of sea height differences at crossover points of seasonal surface as compared with the annual surface (cycles 1-36).

preponderant [Larnicol *et al.*, this issue]. A more thorough analysis of these seasonal variations, notably by comparison to temperature curves of the Mediterranean, will be attempted in the future in collaboration with oceanographers.

6. Conclusions

A precise orbit determination method has been developed with a short-arc technique, yielding a precision of 2 cm in the radial position according to the error budget. External comparisons have also been performed, confirming this result and allowing a positive cross-validation of the different orbit determination techniques. Concerning TOPEX/POSEIDON, an important result is that these techniques are now at the same level of precision (~ 2 cm) in an area such as the Mediterranean, and no very significant systematism has been found. However, a difference of 1 cm has been detected with the dynamical precise orbit based on DORIS and SLR data. It can be interpreted in terms of geographically correlated errors, in agreement with results obtained by other authors, but it is small.

The role of laser data in the CNES precise orbits based on DORIS and laser data is clearly evidenced. The fit of SLR data in the Mediterranean is also significantly improved with the short-arc technique (Table 9). Finally, the orbit determination by short-arc technique allows the calibration of the TOPEX and POSEIDON altimeters and gives an excellent cross validation of different methods. The following values are found: for TOPEX, -14 cm (± 1 cm); for POSEIDON, 0.8 cm (± 2 cm), with relative bias between the two altimeters of 14.8 cm.

The mean sea profile computation has been carried out with TOPEX/POSEIDON data which are then improved with the short-arc technique. This improvement is small due to a limited number of short arcs. However, it is satisfactory, in that the mean

value of crossover differences becomes zero with a standard deviation of 2.2 cm (Table 11). Subsequently, a combined mean sea surface of TOPEX/POSEIDON and ERS 1 data has been computed by using crossover difference techniques. The spatial resolution is significantly improved (~ 75 km), allowing the determination of fine structures with a precision of 5.5 cm (Table 12). From this result and the use of the short-arc technique, the ERS 1 altimeter calibration has been performed in the Mediterranean with a result in agreement with previous ones (-41.6 cm ± 7 cm).

Finally, the mean surface can be computed for different periods of time and different seasons. The improvement obtained with the short-arc technique is particularly clear for the seasonal mean sea surfaces (Table 14). A maximum difference of about 15 cm is found between fall (1992) and winter (1993). The thermal expansion effect certainly plays an important role.

In conclusion, the short-arc technique applied in the Mediterranean yields not only a very good cross-validation of different techniques and methods, but also very precise results on the variability of the sea surface, particularly when short intervals of time are considered. In the future this technique will be of interest, specifically when a very precise orbit is difficult to compute in a global sense.

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