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Geographically correlated errors observed from a laser-based short-arc technique

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Abstract. The laser-based short-arc technique has been developed in order to avoid local errors which affect the dynamical orbit computation, such as those due to mismodeling in the geopotential. It is based on a geometric method and consists in fitting short arcs (about 4000 km), issued from a global orbit, with satellite laser ranging tracking measurements from a ground station network. Ninety-two TOPEX/Poseidon (T/P) cycles of laser-based short-arc orbits have then been compared to JGM-2 and JGM-3 T/P orbits computed by the Precise Orbit Determination (POD) teams (Service d'Orbitographie Doris/Centre National d'Etudes Spatiales and Goddard Space Flight Center/NASA) over two areas: (1) the Mediterranean area and (2) a part of the Pacific (including California and Hawaii) called hereafter the U.S. area. Geographically correlated orbit errors in these areas are clearly evidenced: for example, -2.6 cm and $+0.7$ cm for the Mediterranean and U.S. areas, respectively, relative to JGM-3 orbits. However, geographically correlated errors (GCE) which are commonly linked to errors in the gravity model, can also be due to systematic errors in the reference frame and/or to biases in the tracking measurements. The short-arc technique being very sensitive to such error sources, our analysis however demonstrates that the induced geographical systematic effects are at the level of 1–2 cm on the radial orbit component. Results are also compared with those obtained with the GPS-based reduced dynamic technique. The time-dependent part of GCE has also been studied. Over 6 years of T/P data, coherent signals in the radial component of T/P Precise Orbit Ephemeris (POE) are clearly evidenced with a time period of about 6 months. In addition, impact of time varying-error sources coming from the reference frame and the tracking data accuracy has been analyzed, showing a possible linear trend of about 0.5–1 mm/yr in the radial component of T/P POE.

1. Introduction

TOPEX/Poseidon (T/P) carries four independent tracking data systems; satellite laser ranging (SLR), doppler orbitography and radiopositioning integrated by satellite (DORIS), and Global Positioning System (GPS) are the most important in view of precise orbit determination. The performances of these systems have been evaluated several times in the recent years, including global and local error budgets. A dynamic orbit determination methodology is used to compute the precise orbit ephemeris (POE) of T/P from the SLR and DORIS measurements. Thanks to improvements in the gravity and nonconservative force models, radial orbit errors on T/P have been reduced to the 2 to 3 cm level over a 10-day repeat cycle [Nouël et al., 1994; Tapley et al., 1994a]. The force modeling plays obviously a major role in such orbit determination system, but several authors have noted the possible misinterpretation of results by fitting empirical coefficients representing mismodeled forces, more especially as the tracking coverage is not optimal [Marshall et al., 1995a]. That could be not a too important problem for the T/P orbit but for the future, with the objective to reach the 1 cm level for the Jason orbit, it is of great importance to understand the error budget better (orbit/altimetry). As an example, the precision of the SLR sys-

tem, as estimated from the dynamic orbit solutions on T/P, is around 3–4 cm rms in average [Marshall et al., 1995b], although the instrumental noise is generally expected to be at the level of 1–2 cm today [Degnan, 1993]. Thus, except instrumental errors, significant orbit error signals should remain in the SLR residuals. To improve this situation, the determination of a very accurate orbit is necessary and, as a result, its evaluation. The fact that no measure of absolute orbit accuracy exists makes the process of assessing orbit quality difficult at the level of few centimeters. Systematic comparisons at the global and local levels of different ephemeris are necessary and useful but it is not sufficient for assessing the accuracy of orbits used in oceanography.

However, SLR data are known to provide the most accurate and least ambiguous measurement of orbit position. As an example, SLR measurements from high-elevation passes have contributed to estimate the global radial orbit accuracy [Tapley et al., 1994a]. Therefore additional analyses of the laser residuals are very useful to quantify orbit differences, which make the basis for establishing global error budgets, and to provide the necessary link to the absolute orbit error. In this aim, adjusted geometric or kinematic orbits are of great interest because they are much less sensitive to force modeling errors than dynamic orbits. If a good tracking coverage is obtained at least in a local area, an independent evaluation of the dynamical solution can be performed with respect to a geometric solution. It is the case for the SLR system in specific areas, namely, Europe and the United States, where a dense temporal and two-dimensional coverage of this data type permit the use

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of a geometric orbit determination strategy. Presently, thanks to about 3 years of TOPEX/Poseidon SLR data, the analysis of laser tracking residuals and orbit comparisons with independently generated trajectories provide enough information for revealing mean geographically correlated orbit errors, as well as quality control of the SLR system. On the other hand, the time-dependent part of the geographically correlated orbit errors has been studied using the complete series of T/P cycles (from cycle 1 to 217, about 6 years). Indeed, the standards adopted for the precise orbit determination to be performed by CNES and GSFC suggest to investigate potential sources of radial orbit error which vary slowly with time. If we do not account for a low but still possible aliasing between orbit and ocean [see, e.g., Bettadpur and Eanes, 1994], slowly varying sources affecting the radial component of the orbit are connected to geophysical processes such as temporal variations of the gravity field, geocenter motion, or errors in the velocities of tracking stations. This last list is, however, not exhaustive. As a consequence, the question is to know if the T/P POE is affected by such error sources and what is the error budget which is transmitted to the orbit and finally to the mean sea level.

In using a short-arc orbit technique to analyze the orbit error [Bonfond *et al.*, 1995], we have to take into account systematic errors arising from the terrestrial reference frame realization and the tracking data. Actually, both are potential error sources in the geometric approach which are also geographically correlated, inducing differences between the "observed" and "true" part of the so-called geographically correlated orbit errors. Thus influences of station coordinates, as a time-dependent reference frame, and tracking data accuracy have been also investigated. At a timescale of about 6 months, it is clear that both POEs (GSFC and CNES) have time-dependent geographically correlated errors with a standard deviation of 6–8 mm whatever the area, Europe or the United States. Although the long-term instrumental instability of the SLR systems has been estimated at the level of 4–8 mm thanks to the tracking on LAGEOS satellite, the short-arc orbit technique using quasi-simultaneous SLR tracking data from several stations cannot be affected at that level. On the other hand, possible secular effects to be identified by our method at the level of 1 mm/year and less in the radial component of the T/P orbit are not obvious even if all available T/P cycles and SLR data are presently included. Nevertheless, this suggests that POD standards have to be completed in order to decrease radial orbit errors that are slowly variable with time.

Concerning the Earth orientation parameters, their precision is estimated to be below 1 milliseconds of arc (mas) (3 cm on the Earth) [International Earth Rotation Service (IERS), 1996]: thus the potential effects on the radial orbit component have been estimated to be below the millimeter level and will be neglected in this study.

It will be shown that results are in good agreement with those obtained with other methods [Haines *et al.*, 1995], but also with global gravity field error analysis [Exertier and Bonfond, 1997]. When applied systematically on the T/P CNES and NASA POEs, since the beginning of the T/P mission, this study provides also a detailed description of the differences between SLR data over the Europe and the United States areas.

The global framework as well as the methodology are presented in section 2. Section 3 will be focused on the presentation of the orbit comparisons and the validation of our results.

Finally, a detailed discussion on results is presented in section 4.

2. Methodology and Framework

The laser-based short-arc technique has been described in detail by Bonfond *et al.* [1995]. In this section, we will only recall its basic concepts and will describe the various parameters and data used (geographical areas, input orbits, SLR data, and set of station coordinates).

2.1. Basic Concepts

The approach we use for the short-arc orbit determination strategy 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 (in practice, essentially SLR and DORIS data). We determine corrections to this dynamic orbit for short arcs that are typically of 10 to 15 min duration and so of length up to about 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 local orbit errors as well as station coordinate errors or systematic errors in the tracking data. 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 are assumed to be available along the short arcs. Moreover, criteria on the geometrical configuration, between the tracking network and the passes, have been determined and selected in order to guarantee a short-arc radial precision better than 2 cm. This implies that some passes can never be corrected, decreasing as a consequence the number of possible determinations over a given area by a factor of 3 to 4 generally [Bonfond *et al.*, 1995].

2.2. Studied Areas

The short-arc technique has been applied over two areas. One is located in Europe and roughly centered to the Mediterranean ($+15^\circ < \varphi < +60^\circ$ and $-25^\circ < \lambda < +72^\circ$). The other, called hereafter the U.S. area, contains California and a part of the Pacific Ocean ($0^\circ < \varphi < +50^\circ$ and $-180^\circ < \lambda < -80^\circ$). The main reason for choosing such areas is largely due to the geographical configuration of the permanent SLR tracking network. In addition, the spatial characteristics of the T/P radial orbit error, as assessed through orbit comparisons or perturbation analyses, exhibit long wavelength patterns over the two areas (Plate 1). Their amplitude can be assessed independently by our analysis. As an example, the mean values of the radial orbit differences only generated by gravity modeling differences (JGM-2 minus JGM-3) over the Mediterranean and U.S. areas are expected to be at the level of +1.7 cm and -1.7 cm, respectively [Exertier and Bonfond, 1997].

2.3. Dynamic Orbits

When orbit differences are investigated at few centimeters level, as for T/P, the discrepancies in the nature of the solution, especially across dynamic, reduced-dynamic, or kinematic/geometric techniques, have to be assessed. In this study,

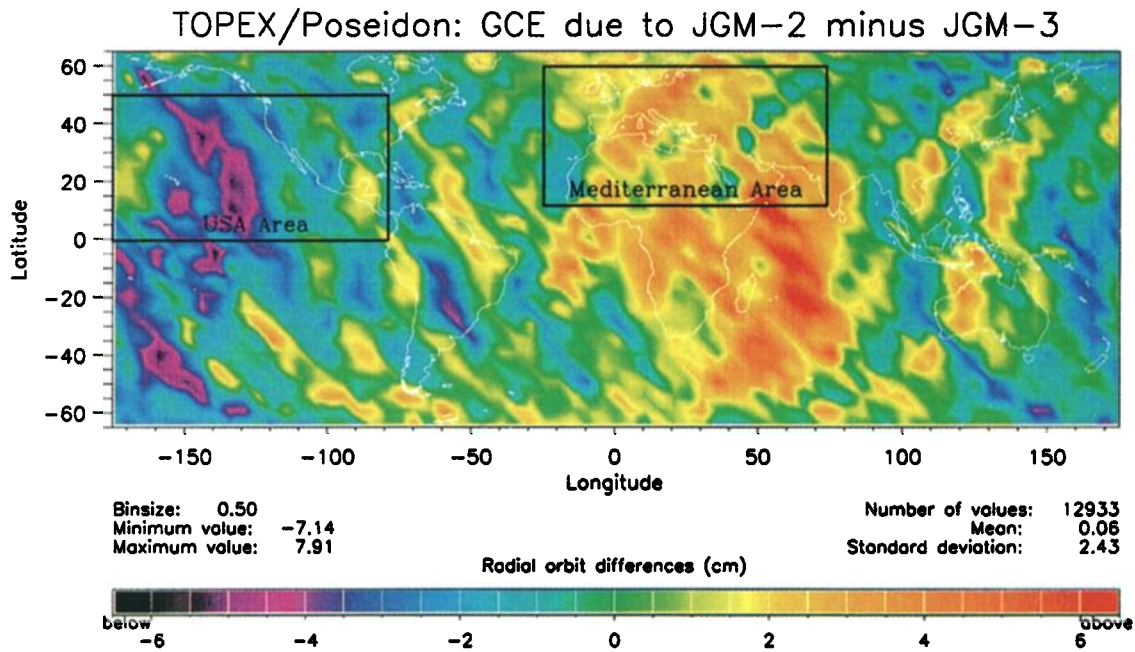


Plate 1. Map of the geographically correlated orbit errors deduced from JGM-2 and JGM-3 coefficient differences [from Exertier and Bonnefond, 1997].

orbit differences refer to the short-arc orbit solutions we have determined for cycles 1 to 92, that is, from September 1992 to March 1995. Dynamic orbits consist in the nominal T/P Precise Orbit Ephemeris (POE). The first POEs were based on the JGM-2 gravity model [Nerem et al., 1994] but, after December 1994, it was decided to use the JGM-3 model and then to recompute all the orbits [Tapley et al., 1994b]. Owing to this change of configuration, JGM-2 POE were not available routinely from GSFC after cycle 92. Nevertheless, 92 10-day cycles are largely sufficient in order to reveal the geographically correlated orbit errors from orbit differences [Christensen et al., 1994; Exertier and Bonnefond, 1997]. As an example, a computation based on about twice T/P cycles (JGM-3 GSFC) show that results do not change at the millimeter level. In addition, since these POEs have been provided by both Goddard Space Flight Center (GSFC) and Centre National d'Etudes Spatiales (CNES) groups, they will be used and called in the following JGM-2/GSFC, JGM-2/CNES, JGM-3/GSFC, and JGM-3/CNES [Tapley et al., 1994a; Nouël et al., 1994].

Table 1. Statistics on the Orbit Differences With Short-Arcs (SA), using SSC(CSR)95L01 set of coordinates, in the Mediterranean Area

	Mean, cm	s.d.,* cm	E_{sa} ,* cm	Difference,* cm
JGM-3 GSFC [†] - SA	-3.2	±4.3	±0.7	
JGM-2 GSFC [†] - SA	-0.8	±5.4	±0.8	+2.4
JGM-3 CNES [†] - SA	-2.5	±4.1	±0.6	
JGM-2 CNES [†] - SA	-1.0	±5.6	±0.8	+1.5

*Here, s.d., standard deviation of the orbit differences; E_{sa} , mean rms of the SA orbit corrections; Difference, JGM-2 minus JGM-3 orbits.
[†]Kindly provided by CNES/SOD Team (cycle 1 to 92).

2.4. SLR Data

Fifteen second normal points (NP), determined routinely at GSFC for the T/P POE, have been used including the nominal calibration already applied by the SLR stations. Because of the limited SLR coverage during the time period of interest (cycles 1 to 92), it has been possible to adjust only a limited number of short arcs. There are 6 and 11 passes per cycle in average which have been corrected by the short-arc technique for the Mediterranean and U.S. areas, respectively. This represents about 35% and 54% of the selected passes, for which the geometrical criteria have been reached, showing differences in the tracking capabilities of the two areas. Differences in the instrumental precision are also evidenced; this will be discussed in section 4.

2.5. SLR Set of Coordinates

We have used the SSC(CSR)95L01 (from Center of Space Research, Texas) and SSC(DUT)93L05 (from Delft University of Technology, Netherlands) set of coordinates which have

Table 2. Statistics on the Orbit Differences With Short-Arcs (SA), Using SSC(CSR)95L01 Set of Coordinates, in the U.S. Area

	Mean, cm	s.d.,* cm	E_{sa} ,* cm	Difference,* cm
JGM-3 GSFC [†] - SA	-0.3	±4.0	±0.3	
JGM-2 GSFC [†] - SA	-1.5	±4.5	±0.4	-1.2
JGM-3 CNES [†] - SA	+0.3	±3.7	±0.3	
JGM-2 CNES [†] - SA	-1.4	±4.7	±0.4	-1.7

*Here, s.d., standard deviation of the orbit differences; E_{sa} , mean rms of the SA orbit corrections; Difference, JGM-2 minus JGM-3 orbits.
[†]Kindly provided by CNES/SOD Team (cycle 1 to 92).

Table 3. Statistics on the Orbit Differences Between JGM-2/3 Orbits and GPS-Based Reduced Dynamic Orbits, in the Mediterranean Area

	Mean, cm	Difference,* cm
JGM-3 GSFC [†] - GPS [‡]	+1.3	
JGM-2 GSFC [†] - GPS [‡]	+3.2	+1.9

*Difference, JGM-2 minus JGM-3

[†]Kindly provided by CNES/SOD Team.

[‡]Results are from *Haines et al.* [1995] (only available from cycles 17 to 50), kindly provided by B.J. Haines (JPL).

Table 4. Statistics on the Orbit Differences Between JGM-2/3 Orbits and GPS-Based Reduced Dynamic Orbits, in the U.S. area

	Mean, cm	Difference,* cm
JGM-3 GSFC [†] - GPS [‡]	+0.8	
JGM-2 GSFC [†] - GPS [‡]	-0.9	-1.7

*Difference, JGM-2 minus JGM-3.

[†]Kindly provided by CNES/SOD Team.

[‡]Results are from *Haines et al.* [1995] (only available from cycles 17 to 50), kindly provided by B.J. Haines (JPL).

participated in the ITRF 94 and ITRF 92 global solutions [Boucher *et al.*, 1995], respectively. Pure SLR solutions have been preferred instead of ITRF ones in order to be more homogeneous with the laser-based short-arc technique, and also because they were commonly used in orbit computations. When using ITRF 94 solutions (instead of SSC(CSR)95L01), differences in the radial orbit component are at the 1-3 mm level because it is true that both solutions are very close. Let us note, however, an important difference in the definition of the CSR and DUT terrestrial reference frames. The DUT coordinate set used a vertical component in the estimation of the station coordinate velocities. We have used this last solution instead of SSC(CSR)93L01 (also part of ITRF 92) in order to assess the impact of the discrepancies, in the reference frame definition, into the short-arc orbit solutions; this point will be discussed further in section 4.

3. Orbit Comparisons

Tables 1 and 2 summarize differences in the T/P radial orbit component between dynamic and geometric orbits. Given the geometric criteria adopted for the short-arc (SA) technique and the SLR data coverage available during the studied period, the number of passes it has been possible to fit is 556 and 1027 for the Mediterranean and U.S. areas, respectively. First of all, an assessment of the gravity modeling differences between JGM-2 and JGM-3 is made through the comparison of {JGM-2 minus SA} and {JGM-3 minus SA} differences. The aim is to show that our sampling of passes, which has a limited coverage in space and time, is able to provide confidence in the quality and consistency of the short-arc orbits, and then the absolute

orbit error. From Tables 1 and 2, the differences of standard deviation (s.d.) show that the orbit improvement, in terms of radial orbit component, between JGM-2 and JGM-3 POEs is at least at the level of 1 cm, as it is confirmed also by *Marshall et al.* [1995b] and *Haines et al.* [1995]. Moreover, the statistics show that 80% of radial orbit differences are within ± 5 cm when using the JGM-3 POE instead of 68% with the JGM-2 POE.

Concerning the GSFC and CNES solutions, there is a very good consistency (1-2 cm) already evaluated by comparisons made routinely by both POD teams. From another point of view, JGM-3/GSFC and JGM-3/CNES orbits differ in average by a small but significant mean value of -0.6 cm (Tables 1 and 2). However, let us note that the JGM-3/CNES solution is not purely dynamic. It uses a DORIS-based reduced-dynamic technique (ELFE solution [Barotto *et al.*, 1996]) permitting certainly to reduce a part of the geographically correlated orbit errors and thus explaining this temporally invariant orbit difference. However, we will see that such orbit differences are lesser than other investigated error sources and thus can be averaged in the following.

Computing averaged radial orbit differences over the Mediterranean and U.S. areas between the JGM-2 and JGM-3 POEs is a second step for checking the qualitative and quantitative aspects of our sampling of passes. It gives around +2.0 cm and -1.5 cm for the two quoted areas, respectively, which is in good agreement with values of the geographically correlated differences predicted by *Exertier and Bonnefond* [1997] (+1.7 cm and -1.7 cm) and results found by *Haines et al.* [1995] (+1.9 cm and -1.7 cm, see Tables 3 and 4). Figures 1 and 2 summarize these orbit comparisons very well by plotting

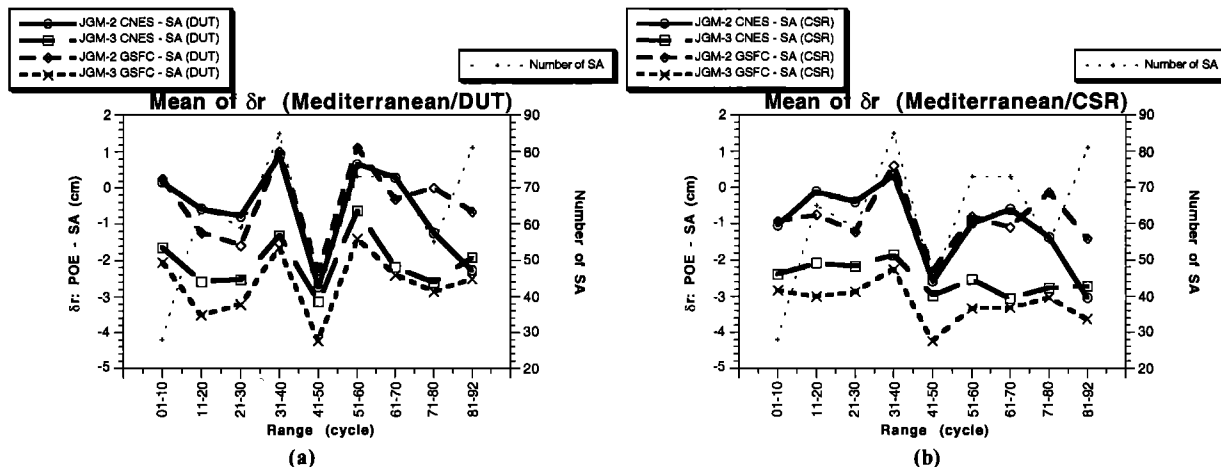


Figure 1. Radial orbit differences (POE minus SA) averaged every 10 T/P repeat cycles in the Mediterranean area. (a) Corresponds to the short-arc solution using SSC(DUT)93L01 and (b) corresponds to the short-arc solution using SSC(CSR)95L01.

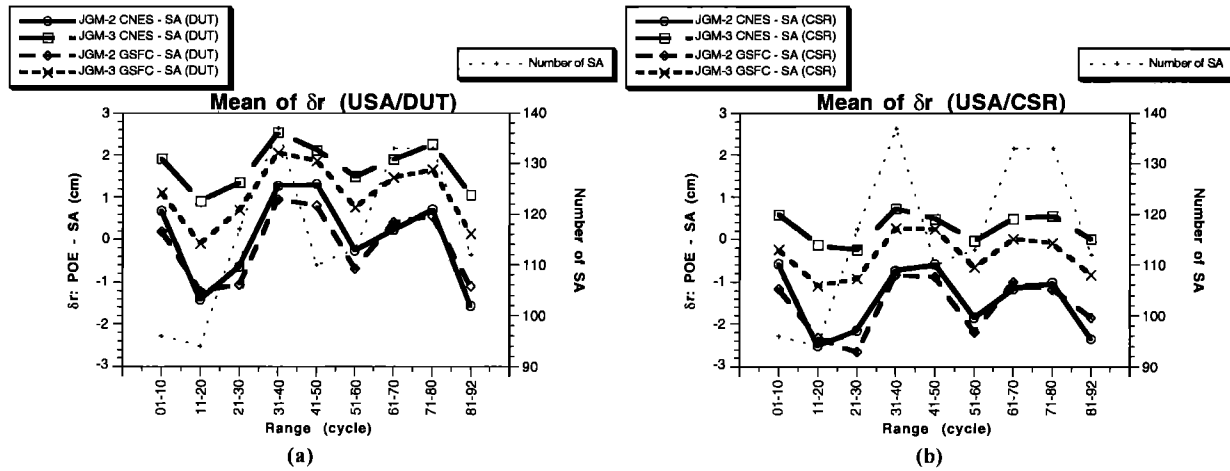


Figure 2. Radial orbit differences (POE minus SA) averaged every 10 T/P repeat cycles in the U.S. area. (a) Corresponds to the short-arc solution using SSC(DUT)93L01 and (b) corresponds to the short-arc solution using SSC(CSR)95L01.

every 10 T/P cycles mean orbit differences between the four dynamic orbits used and the SA solution. Signals are strongly correlated with the number of short arcs used to compute the mean values along the time. Another important characteristic of these plots is the clear separation between the two classes of dynamic orbits, JGM-2 and JGM-3.

4. Discussion

This section is dedicated to the analysis of results. It will be focused on the various error sources: SLR data precision/accuracy, set of coordinates, and orbit error. To this aim, Figures 1 and 2 are also very useful for assessing the various error sources. Their impact on the geographically correlated orbit errors determination will be addressed also.

4.1. SLR Data Precision and Accuracy

In Table 5, the standard deviations of the SLR normal points residuals to the short-arc orbits clearly show a better precision of the U.S. tracking data (1 cm) compared to those acquired in Europe (2 cm). This factor 2 is thus present in the formal errors (E_{SA}) of the geometric corrections derived from the SA technique (Tables 1 and 2), showing the precision of this method is mainly limited by the SLR data precision. Concerning the mean values of laser residuals per station, they are also more homogeneous for the U.S tracking sites than for the European ones, whatever the nature, dynamic or geometric, of the orbit from which laser residuals are computed. Actually, the discrepancies in the SLR residuals between the United States and Europe seem to be due to the disparity of SLR measurement biases observed in Europe as well as a probable

Table 5. Statistics of Laser Residuals (Normal Points) for Cycles 1 to 92 of TOPEX/Poseidon (Using SSC(CSR)95L01)

Station	JGM-3 Precise Orbits*		Short-Arc Orbits		Number of NP
	Mean, cm	Standard Deviation, cm	Mean, cm	Standard Deviation, cm	
7810, Zimmerwald	3.0	3.2	-0.6	2.9	2173
7811, Borowiec	2.8	2.6	0.5	2.3	746
7831, Helwan	-1.4	2.3	0.5	2.1	1060
7835, Grasse	6.4	2.6	1.0	1.9	4966
7839, Gratz	-1.4	1.7	-1.6	1.3	4063
7840, Herstmonceux	2.7	2.0	-0.4	1.9	5326
8834, Wettzell	6.1	2.4	1.5	2.3	3083
Total†	+3.1	2.3	0.0	2.0	21417
7080, McDonald	0.6	1.9	0.1	1.1	10670
7105, Washington	1.9	1.0	-0.1	0.6	875
7109, Quincy	-0.0	1.3	0.2	1.2	6226
7110, Monument Peak	-0.9	2.8	-0.2	1.2	15234
7122, Mazatlan	0.2	1.4	-0.1	1.7	544
7210, Maui	-0.3	5.0	0.0	1.0	9208
Total†	-0.2	2.8	0.0	1.1	42757

*Data are from GSFC/NASA

†Average weighted by the number of NP.

lower precision of the station coordinates in this area. Table 6, kindly provided by UT/CSR (Austin, Texas), shows these measurement biases; their values have been averaged because for some stations the bias, mostly due to errors on the instrumental calibration, was not constant over the studied period. This fact would have to be investigated. This implies that the short-arc orbit solutions are probably more biased, by SLR data, in the Mediterranean area (mean bias of +1.3 cm) than in the U.S. area (mean bias of -0.5 cm) in average. This implies also that the induced orbit biases are presently more or less time-dependent. During the period from September 1992 to March 1995, the possible temporal change of the SLR data biases at least for one or two European sites is a realistic scenario to explain the small linear trend, not negligible for oceanographers, which is evidenced in the plot of mean orbit differences between dynamic and SA orbits over the Mediterranean area (Figure 1b). Its value is of -1.2 cm over the 92 T/P cycles, whereas the value over the U.S. area is found to be negligible. On a qualitative point of view, these results show that the SLR data accuracy is at least as important as their precision and becomes an actual difficulty in view of the 1 cm challenge, in radial orbit precision.

4.2. Impact of Station Coordinates

Differences in the definition of the terrestrial reference frame exhibit time-invariant characteristics in the error budget of the SA orbit technique. For example, mean values of the radial orbit differences computed between dynamic and geometric SA orbits contain also the signature due to the choice of the station coordinate set. Here the SSC(CSR)95L01 set has been chosen first, but the short-arc orbit solutions have been determined also from the SSC(DUT)93L05 set. The comparison shows a mean difference in the radial component of the orbit at the centimeter level which depends essentially on the considered area: +0.6 cm and +1.5 cm for the Mediterranean and U.S. areas, respectively (DUT minus CSR solutions). However,

Table 6. Biases of the SLR Stations (mean values for the studied period, Cycles 1 to 92)

Station	Bias, ° cm
7810, Zimmerwald	+3.5
7811, Borowiec	+1.0
7831, Helwan	+0.0
7835, Grasse	+5.0
7839, Gratz	-5.0
7840, Herstmonceux	+0.0
8834, Wetzell	+4.7
Total†	+1.3
7080, McDonald	+0.4
7105, Washington	+0.0
7109, Quincy	+0.0
7110, Monument Peak	+0.5
7122, Mazatlan	-2.0
7210, Maui	-3.7
Total†	-0.5

*Results are from UT/CSR (Austin, Texas).

†Average weighted by the number of NP (see Table 5)

when considering the complete period of time of 92 cycles (2.5 years), the orbit signature due to the temporal evolution of station altitudes predicted by the DUT reference frame is not negligible. A radial effect of about +0.4 cm/yr on the short-arc orbits is clearly evidenced by orbit comparisons made between SA computed from the DUT and CSR reference frames in the Mediterranean area (Figure 1). Actually, for the short-arc solutions based on DUT (Figure 1a), this last effect is fully compensated by the effect due to the evolution of SLR biases quoted above which has the same amplitude but with an opposite sign. This investigation proves that the short-arc orbit technique is extremely sensitive to the definition of the terrestrial reference frame. Moreover, it seems that the vertical motions of the reference frame, determined in the DUT model, are extremely correlated to any temporal change of the SLR data biases in Europe which occurred these last years.

In a purely theoretical sense, the ITRF solutions would be less biased than purely SLR solutions, being the results of several techniques including information provided by collocation sites. However today, taking into account different analysis of orbit errors on T/P, the better accuracy that would be provided by a given solution is not so clear at the centimeter level. Thus, the solution we propose below concerning the terrestrial reference frame is no more than the average solution obtained using CSR or DUT frame.

4.3. Time-Independent Geographically Correlated Orbit Errors (GCE)

Assuming the GCE is only due to mismodeling of the gravity field, the mean orbit differences between dynamic (CNES or GSFC POEs) and geometric (laser-based SA or GPS-based reduced-dynamic) solutions are able to represent such errors at least theoretically. By averaging all the orbit differences obtained from both JGM-3 POEs (GSFC and CNES) with respect to the SA orbits generated with the two sets of coordinates (CSR and DUT), the mean GCE is found to be of -2.6 cm and +0.7 cm for the Mediterranean and U.S. areas, respectively. This permits to reduce the influence of the station coordinates, quantified in previous paragraph, in the “observed” GCE. It is particularly important because independent solutions (CSR or DUT) can be affected by local shifts in the stations coordinates. In the Mediterranean area, the mean GCE for JGM-3 (-2.6 cm) compared to those obtained from JGM-2 (-0.6 cm) is relatively high. As no other estimators seem to show that JGM-3 is worse in this area and because the large positive pattern (Plate 1) seems to be removed thanks to improvements included in JGM-3 [Haines *et al.*, 1995], we propose an explanation thanks to comparisons with GPS results in the following paragraph.

4.4. Time-dependent geographically correlated Orbit Errors

As previously mentioned in section 2 (*Dynamic Orbits*), The constant part of the GCE can be estimated very precisely over a short period of time (few T/P cycles). On the other hand, the time-dependent part of the GCE, which can be due to mismodeling in the gravity field (notably the temporal variations due to displacement of atmospheric and/or oceanic masses) or errors in the reference frame (e.g., vertical velocities of SLR stations, atmospheric and oceanic loading), needs to be analyzed

over long time series. We are now able to study such phenomenon using 6 years of T/P short-arc orbit corrections (cycles 1 to 217), and we propose to add very recent results to our analysis due to a long time between the first version of this paper and the present one. Actually, we have shifted to ITRF 96 set of coordinates to study the time variations of radial short-arc orbit corrections. The reasons of this choice are two-fold: (1) ITRF 96 seems to be more accurate for station coordinates and velocities, and (2) this solution includes vertical velocities. Let us note, however, that using ITRF 96, the time-independent part of GCE in the U.S. area is identical to this listed in Table 2 (differences below 1 mm), while in the Mediterranean area differences from Table 1 are at the level of 7 mm. In addition to ITRF 96, we have reduced the number of SLR stations in Europe to keep only those of long-term stability in term of precision/accuracy (7810, 7831, 7835, 7839, 7840, see Table 5): that is 2-4 mm according to International Laser Ranging Service (ILRS) analysis based on Lageos [Husson, 1998].

As a result of the long term analysis of the time-dependent part of GCE, Figure 3 and 4 show fluctuations in the radial orbit corrections. The level is of 0.7 cm rms for both Mediterranean and U.S. areas, with peak to peak variations of 2 cm at a timescale of about 20 cycles (near 6 months). However, these “semi-annual” fluctuations do not appear to be periodic (below 3 mm with no clear peak in the periodogram). It is thus

difficult to clearly identify which phenomenon affects the radial orbit precision at that period. However, it is clear that the observed signals are coherent in both CNES and GSFC input orbits: the correlation coefficient is greater than 84% and the standard deviation is about 4 mm for both Mediterranean and U.S. areas (see Figure 3 and 4, respectively). In the near future, our efforts will be focused on the identification of the origin of these signals. Among different methods to analyze such a signal, a semi analytical one will be used as by Bettadpur and Eanes [1994], but with atmospheric mass redistribution as a source of gravity change and mismodeling.

Now we want to focus on possible “secular trends” which could affect the T/P precise orbits. From the smoothed values of radial short-arc orbit corrections, we have determined linear trends for both CNES and GSFC JGM-3 POEs in the Mediterranean and U.S. areas (Table 7). In order to estimate the impact of the reference frame, especially in the vertical component, short-arc orbit computations have been realized using both ITRF 96 and ITRF 94 solutions. First of all, one should note the very high consistency of results in the U.S. area whatever the input orbits and/or the reference frame used. Second, the relatively large value which is found (2.8 mm/yr) is not only due to a possible linear trend in the radial orbit component of the POEs. In fact, errors in the vertical velocities of SLR stations and/or time-dependent errors in the SLR measurements can affect the short-arc orbit computations. The impact of time-

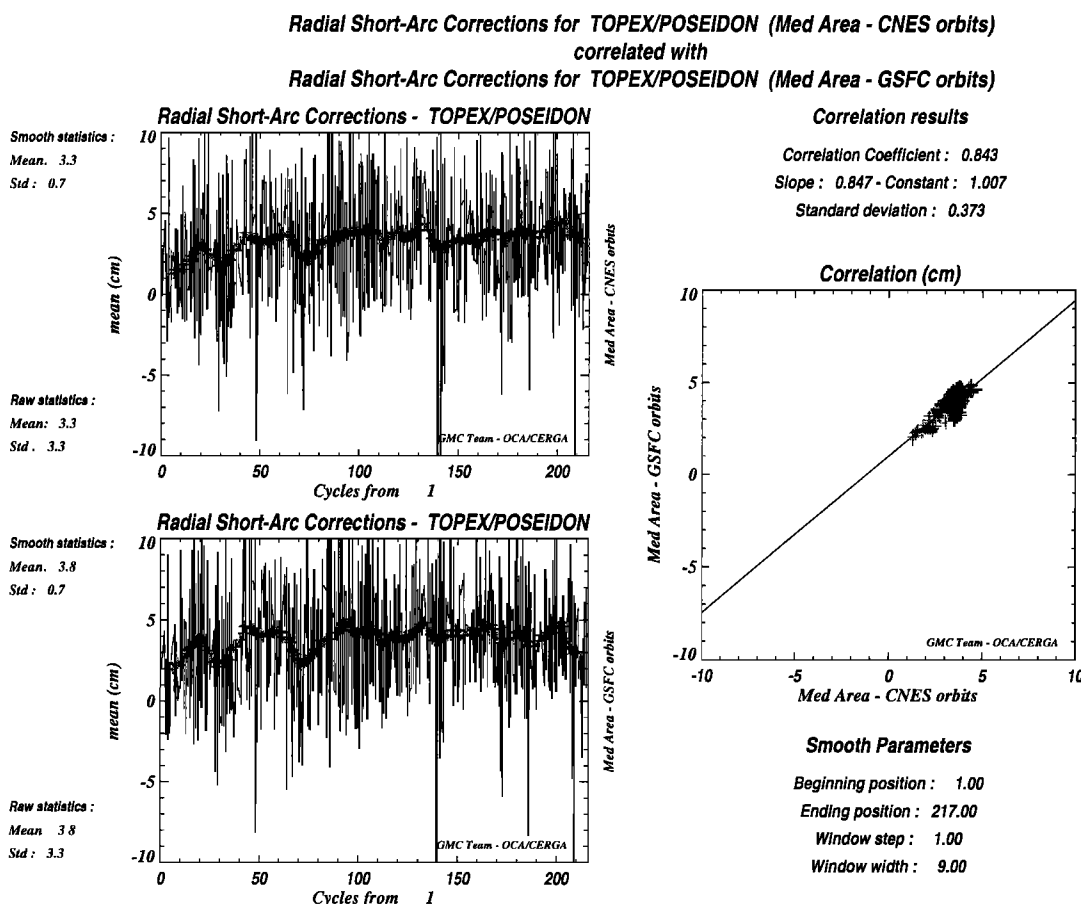


Figure 3. Time evolution of radial short-arc orbit corrections in the Mediterranean area from T/P cycle 1 to 217. This figure also shows the correlation between the smoothed radial orbit corrections computed from both JGM-3 POEs (CNES, left/top and GSFC, left/bottom). Crosses correspond to the smoothed radial orbit corrections determined from a boxcar average using a window width of nine T/P cycles (about 3 months).

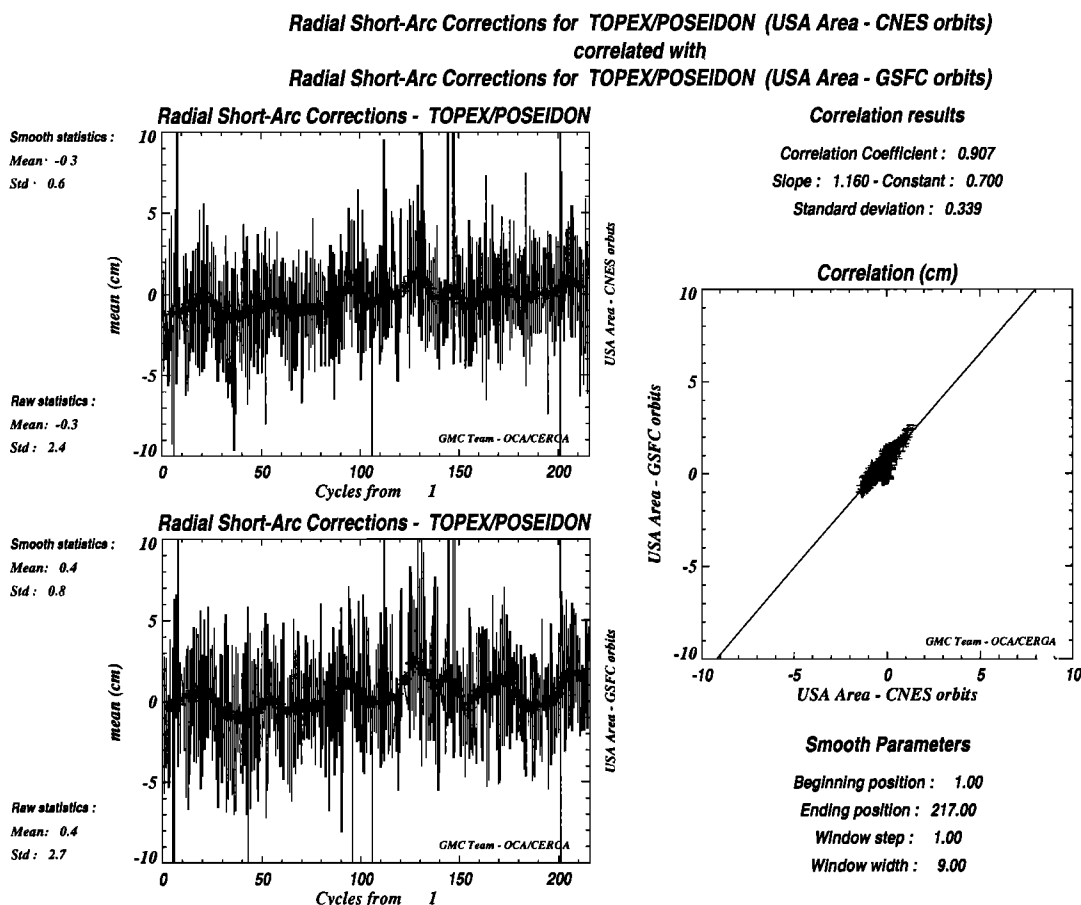


Figure 4. Time evolution of radial short-arc orbit corrections in the U.S. area from T/P cycle 1 to 217. This figure also shows the correlation between the smoothed radial orbit corrections computed from both JGM-3 POEs (CNES, left/top and GSFC, left/bottom). Crosses correspond to the smoothed radial orbit corrections determined from a boxcar average using a window width of nine T/P cycles (about 3 months).

dependent errors in SLR measurements is difficult to determine, but from a long-term stability analysis made on the Lageos satellites, range biases of our chosen SLR stations are known to have a stability better than 8mm. Thus the induced linear trends are probably below 1 mm/yr. Results are more inhomogeneous for the Mediterranean area than for the U.S. one. They clearly identify the impact of the reference frame, in particular the European network: ITRF 96 vertical velocities imply that the radial short-arc orbit corrections have a linear trend of 1.2 mm/yr higher than that which is found when using ITRF 94. In addition, differences between CNES and GSFC orbits exist in this area at the level of ~1.1 mm/yr; we have no clear explanation of this surprising phenomenon. Because all parameters are identical for both computations and because it appears using either ITRF 96 or ITRF 94, it seems to be really due to differences in the input orbits. In conclusion, if we assume that the time-dependent error sources which affect the shot-arc orbit computations are at the level of 1-1.5 mm/yr, a linear trend of 0.5-1. mm/yr could exist in the radial orbit component of TOPEX/Poseidon POEs. The method is able to detect signals at that level, but present values have to be investigated more clearly.

4.5. Comparisons With GPS Results

First, we have to point out that results obtained in the U.S. area agree very well with those presented in Table 4 from Haines et al. [1995]: +0.7 cm (JGM-3 - SA) compared to +0.8 cm (JGM-3 - GPS), and -0.7 cm (JGM-2 - SA) compared to -0.9 cm (JGM-2 - GPS). It proves that the GPS reduced-dynamic and SLR short-arc methods, being both less sensitive to

Table 7. Linear Trends of Radial Short-Arc Orbit Corrections

Input Orbits / Reference Frame	Mediterranean area	U.S. area
JGM-3 GSFC / ITRF 96	1.7	2.7
JGM-3 CNES / ITRF 96	2.8	2.8
JGM-3 GSFC / ITRF 94	0.5	2.8
JGM-3 CNES / ITRF 94	1.6	2.8

Units are in mm/yr. Formal errors for linear trend determinations are at the level of 0.1-0.2 mm/yr.

gravity field modeling errors, are able to reveal the geographically correlated error at the same level. In the Mediterranean area, the difference between the absolute GCE obtained from the laser-based SA (-2.6 cm) and the GPS-based reduced-dynamic (+1.3 cm) techniques is +3.9 cm. As previously said, one part of this difference could be explained by the effect of the SLR biases of European tracking stations on the SA orbit solutions, but only at the level of about 1.5 cm. The other part, that is 2.5 cm, could be interpreted as a local difference in the adopted station coordinate solutions in the SLR and GPS computations [see also Marshall *et al.*, [1995b]. As previously mentioned, using ITRF solutions leads to millimeter differences. It really seems to be due to "errors" in some stations coordinates induced by poor SLR data quality in the past. This last point needs further investigations. As an example, Grasse coordinates (7835) exhibit a difference of 2.4 cm in the altitude between ITRF 94 and ITRF 96.

5. Conclusion

This analysis of SLR residuals has permitted to quantify, with an independent method, the orbit improvements made in the T/P POEs routinely computed at CNES and GSFC. Indeed, the short-arc technique parameters remain the same during our 6 year analysis permitting to reveal any change in these orbits. For example, the use of input orbits based on JGM-3 and JGM-2 has permitted to quantify the improvement link to the gravity field: as shown in orbit comparisons, the standard deviation of radial orbit corrections is reduced by 1 cm when using JGM-3 (Tables 1 and 2).

Mean geographically correlated orbit errors for T/P have been determined in the Mediterranean and U.S. areas. However, their "absolute" amplitudes are corrupted by the precision/accuracy of the terrestrial reference frame, and the SLR data accuracy. Our analysis demonstrates that the induced geographical systematic effects are at the same level of amplitude (~1-2 cm). As a consequence, without SLR tracking system improvements in the near future at least in the Mediterranean area, it could be really difficult to decorrelate all these error sources.

The time-dependent part of the GCE has also been studied over 6 years of T/P data. Results show coherent signals for both JGM-3 POEs (CNES and GSFC) at the level of 2 cm (peak to peak). They indicate also a possible linear trend of 0.5-1. mm/yr in the TOPEX/Poseidon POEs. However, the origins of such signals being presently not very clear, further investigations are recommended.

Finally, disparities between the Europe and U.S. areas, in terms of instrumental precision (United States better by a factor 2) and accuracy, and station coordinates have been demonstrated. It is particularly important for regional orbit determination processes, such as the laser-based short-arc technique we have used. This technique has a great capability to detect problems in both SLR data and station coordinates, and demonstrates their strong correlation and their impact in the orbit determination process. Indeed, it can also affect the global orbit determination or, at least, reduce the homogeneity of the solution. This is a very important point for the future and notably for the altimeter calibration of Jason and EnviSat.

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