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Jason-1 and TOPEX/POSEIDON Precision Orbit Determination: Status and Plans

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Poster H.1

Abstract

After more than eight years of orbit determination for the TOPEX /POSEIDON (T/P) mission, there are no indications of any degradation in the quality of the NASA POE product. The radial orbit accuracy is estimated to still be at the 2 cm level, with no apparent increase in the altimeter crossover RMS. To maintain a continuous time series into the follow-on mission, the accuracy of the Jason-1 orbits must be at least equivalent to those obtained for TOPEX/POSEIDON (T/P). It should be possible to merge the altimeter products using the orbits for Jason-1 with the long history of data from T/P without introducing any artificial signals, either in terms of mean sea level, or geographic distribution of the systematic errors (which will always be present at some level). This is not an easily attained objective. As demonstrated by the success of the T/P orbit determination activities, external verification and validation of the software system to be used for Jason-1 POD production can help ensure accurate and consistent orbits. In addition, the issues of the models and standards used for Jason-1 orbits must be resolved jointly by the T/P and Jason-1 POD teams, since these choices affect the consistency of the two satellite orbits.

Status of Precision Orbit Determination for TOPEX/POSEIDON

The accuracy of the orbits determined by the NASA Goddard Space Flight Center for inclusion on the Geophysical Data Records (GDRs) is estimated to be near the 2 cm level. While it is difficult to assess this level of orbit error precisely, a number of tests can be applied to help arrive at a reasonable estimate.

1) Covariance analysis of the tuned gravity model, JGM-3 (Tapley *et al*., 1994), predicts that the total radial RMS orbit error induced by commission error is about 9 mm for T/P . By analyzing the contribution of other errors, an estimate of the total orbit error budget can be constructed, as shown in Table 1. For example, analyses have demonstrated that surface force model errors which generate radial orbit errors easily exceeding 1 m, can be reduced below the 2 cm level by the combination of good tracking and appropriate parameterization. The parameterization currently used, *i.e*., the estimation of 8-hour constant and daily once-per-revolution along-track and cross-track accelerations, has been shown to be very effective in reducing the orbit error (see Table 2). This parameterization is feasible because of the significant quantity of precise tracking provided by the DORIS (Nöuel, 1988) system. This same parameterization also reduces the effect of the long-period ocean tide model errors.

2) When high elevation SLR passes are investigated, the RMS of the range biases, which are largely dominated by the radial orbit error relative to the tracking stations, is usually less than 2 cm RMS. The SLR range biases can distinguish the difference between a T/P orbit (of ~ 2 cm accuracy) and a LAGEOS orbit (<1 cm accuracy). The SLR passes in the analysis at CSR were used in the orbit determination and thus would tend to result in a smaller RMS than if they had been excluded. GSFC routinely performs a similar test which does exclude the high elevation passes, providing a more robust test of the radial orbit error. The RMS of those pass biases is usually well under 3 cm, and since this includes the radial orbit error, actual station biases and station coordinate error, an estimate of approximately 2 cm for the radial orbit error appears reasonable. This also demonstrates the value of the SLR tracking as an absolute calibration of the orbit error. As the orbit error is further decreased, it will become increasing difficult to validate the estimates of its true magnitude by other techniques.

3) Comparisons of T/P orbits with independent orbits produced using the "reduced dynamic" technique (Yunck *et al*., 1994) to process the GPS tracking data indicate that the radial differences are less than 2 cm RMS. This is a relative rather than an absolute test, but since the GPS processing relies on a different tracking data type and an orbit determination technique designed to further reduce a portion of the orbit error, the differences can be interpreted as an indicator of the absolute orbit error.

The models upon which the above analysis is based have been used now for several years, yet there is no indication of any degradation in the orbit quality. In Figure 1, the altimeter crossover RMS is plotted for the last 95 cycles. These results are from the CSR verification orbit, but the NASA POE, on average, performs at an identical level. Some editing has been applied to avoid using crossovers in areas of high ocean variability, steep geoid gradients, shallow water (where the tides would be less reliable), as well as outliers beyond the 30 cm level. To avoid the effect of variable ice cover, only data between +/- 50 degrees latitude were used. Not only is there no indication of an increase in the crossover scatter, there is a hint of an improvement, possibly reflecting the switch to the side B of the altimeter. In Figure 2, the fits to the SLR and DORIS tracking are shown, as well as the RMS orbit difference between the POE and the CSR verification orbit. Again, the statistics appear to be steady. There appeared to be a trend in the Z-shifts, but it was discovered that there was a range bias discrepancy at one of the SLR stations. This had been corrected, and the Z-shifts appear to have flattened out.

Table 1. Estimates of radial orbit error budget for T/P

Error Source	JGM-2 (mm)	JGM-3 (mm)	Goal (mm)
Static gravity	22	9	4
Earth and ocean tides	13	7	4
Temporal gravity [1]	10	10	4
Surface forces [2]	15-20	10-15	5
Data errors [3]	5	5	4
Station location [4]	10	5	4
RSS	~35	~20	~10

1 seasonal and other temporal variations other than tides
2 solar, terrestrial and thermal radiation, atmospheric drag, bias forces
3 data noise, biases, troposphere, cg-offset errors, attitude errors
4 includes station position and velocity errors, geocenter motion

Table 2. Effect of different levels of acceleration parameterization

Case	SLR RMS	Radial RMS
estimate only initial position and velocity	870 cm	115 cm
add 8-hr constant transverse acceleration	80 cm	100 cm
8-hr constant transverse, daily 1/rev transverse	22 cm	3.5 cm
8-hr constant transverse, daily 1/rev transverse and daily 1/rev normal accelerations	< 3 cm	< 3 cm

(all other models identical to current JGM-3 processing)

Figure 1. RMS of altimeter crossovers since Cycle 200

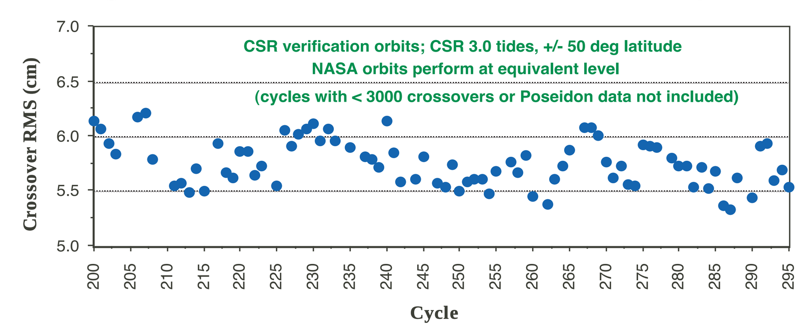
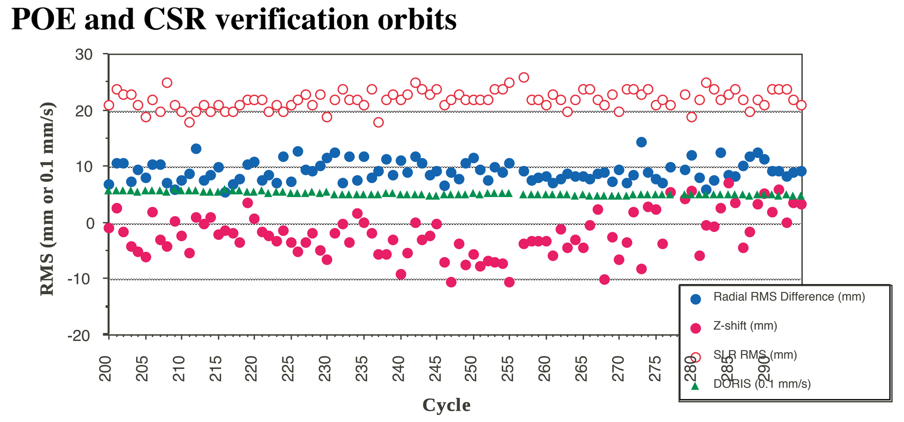


Figure 2. RMS of SLR and DORIS fits since Cycle 200; Mean Z-shift and radial RMS of difference between NASA POE and CSR verification orbits



Jason-1 Orbit Error

The error budget in Table 1 can be expected to apply to Jason-1 as well, presuming that equivalent models and standards are employed. However, some areas can be expected to improve. With 6 years of altimeter data available, we can expect to see better ocean tide models. Efforts at CSR to further improve the static gravity field with 20 cycles of GPS data from T/P provided a modest improvement (few mm reduction in altimeter crossover RMS), nor does the recent EGM-96 gravity model (Lemoine *et al*., 1998) appear to perform significantly better or worse. This may be due in part to the fact that the mean part of the gravity field model is no longer a dominant contributor to the total orbit error. The GPS data from Jason-1, with a more modern receiver capable of tracking more GPS satellites, may provide a more substantial improvement. The Gravity Recovery and Climate Experiment (GRACE) should eventually be able to reduce the contribution of both the static and the seasonal variations of the Earth's gravity field to negligible levels.

The more robust GPS data should also support a higher level of parameterization of the surface forces (such as the 'reduced dynamics' technique), so that the contribution from this error source may be substantially reduced. The contribution from the geocenter motion is still not well determined, but perhaps accurate observations of the seasonal variations may be eventually be possible. Finally, the determination of the SLR, DORIS and GPS station positions and velocities has steadily improved, and the new ITRF solutions are bringing these various reference systems into a common frame. This is an essential element in the requirement to maintain consistency over the span of the T/P and Jason-1 missions. Changing the models from the current T/P standards, however, will likely require a reprocessing of the T/P orbits to preserve this consistency.

Whether all these improvements are sufficient to approach the 1 cm orbit accuracy level remains to be seen. Consequently, a reprocessing of T/P should perhaps be delayed until after a year or two of Jason-1 data has been analyzed. At that time, substantial improvement in many of the models should be available. If we are too quick to adopt new models, other than those that cannot be avoided (such as an updated reference system), it may be necessary to reprocess both T/P and Jason-1 more than once. When the time series of Jason-1 altimeter data starts to become long, it will then be important that the differences between the two missions be eliminated through reprocessing. This is one of the issues that remains to be resolved in the POD preparation plans.

Contribution of Tracking Data Types for TOPEX/POSEIDON

It is interesting to examine how each data type contributes to the overall orbit accuracy. Since the GPS receiver on T/P was primarily designed for demonstration of the GPS tracking technique (Melbourne *et al*., 1994), the nominal orbit for T/P is based on SLR and DORIS tracking. (For Jason-1, it will be some combination of all three data types.) Examination of the increase in the variance of the altimeter crossover residuals for orbits based on subsets of the tracking data indicates that the dominant contribution to the orbit accuracy is the large number of well distributed DORIS stations providing near continuous coverage of the orbit. In Figure 2, we can see that the orbit error increases slightly when the SLR data is not used but increases significantly when the DORIS data is not used.

On the other hand, the SLR data has important contributions as well. In addition to reducing the overall orbit error, it provides an important constraint on the orbit centering along the Earth's polar axis (the Z-axis). In Figure 3, the orbits with SLR tracking appear to be more stable about the Z-axis, with the variations generally under 5 mm. It is assumed that the orbit with the complete SLR and DORIS networks should be the best centered in Z, an assumption that seems reasonable based on the geocenter analyses of the LAGEOS satellites (Chen *et al*., 1998). The orbits based entirely on GPS data appear to be the least well centered, with variations exceeding 2 cm. This has been seen in orbits determined with GPS tracking using the standard dynamical method at CSR and the 'reduced dynamics' method at JPL. This suggests that the SLR data can be expected to play an important role in the centering of the Jason-1 orbit. With a new SLR tracking station in South Africa (Hartebeesthoek), the hemispherical coverage will be significantly improved, as well as provide an even better centering of the orbit along the Z direction.

Figure 2. T/P radial orbit error as a function of tracking data used

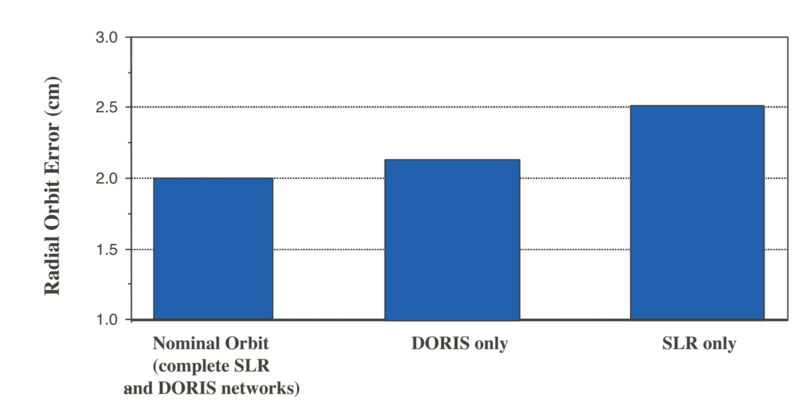
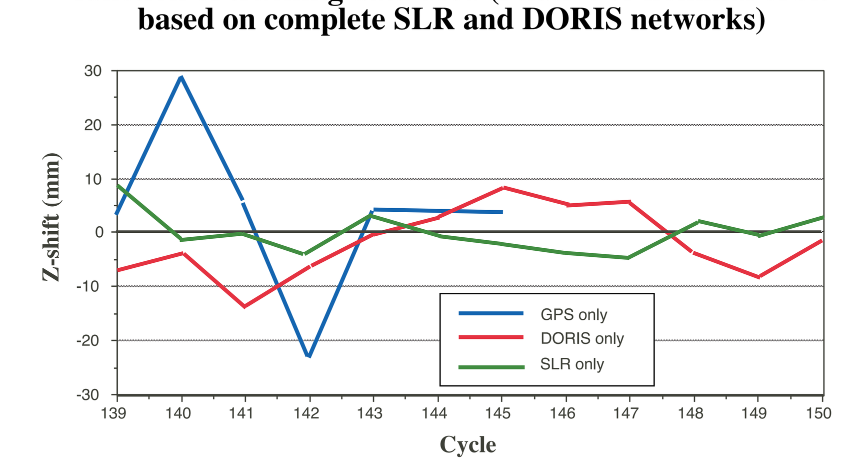


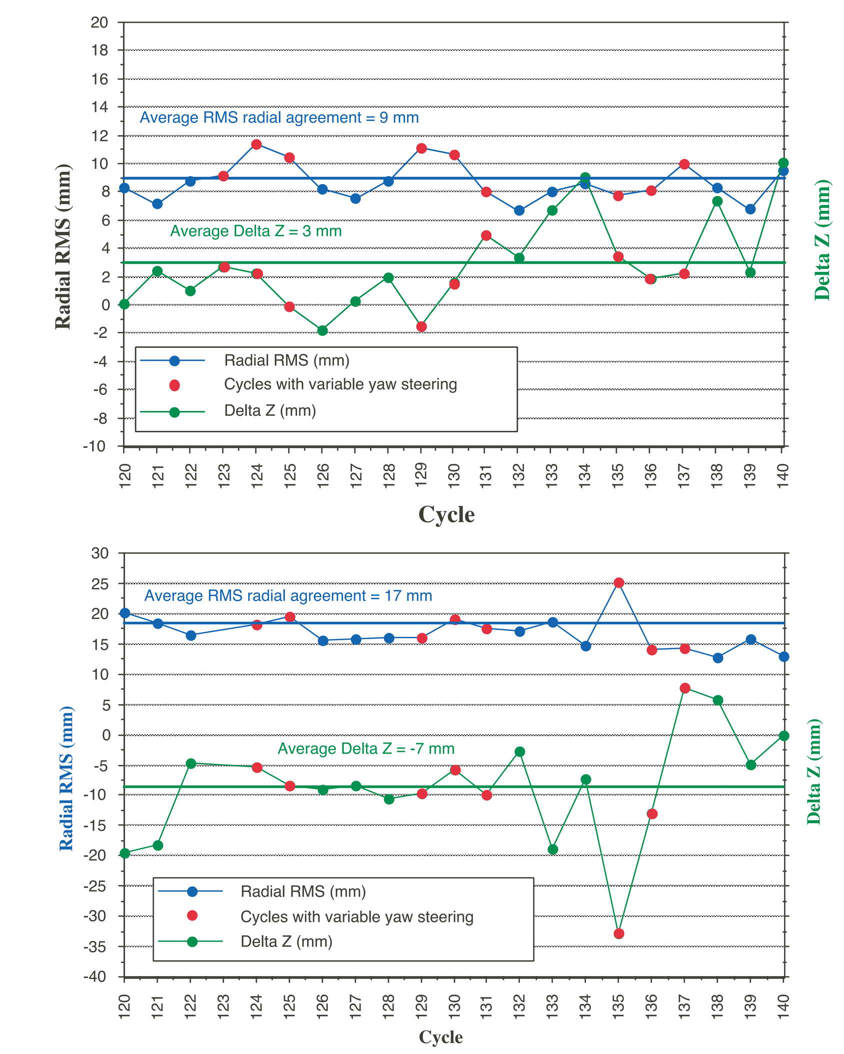
Figure 3. Variation in orbit centering in the Z direction as a function of tracking data used (relative to nominal orbit based on complete SLR and DORIS networks)



POD Comparisons

Because of an intense verification effort between GSFC and CSR, the Precision Orbit Ephemerides tend to agree very well with the verification orbits at CSR. The agreement with the CNES orbits is not as good, as shown in Figure 4 . It is recognized, however, that the CNES models used were not intended to agree with the GSFC models to the same degree of fidelity as the CSR models. The CNES models originate from different groups and have not been optimized for use together, resulting in a significant increase in the altimeter crossover residuals. In addition to a Z shift of 7 mm during this particular period, there is also an 8 mm mean radial bias between the CSR and CNES orbits, while the radial bias between CSR and GSFC is less than 1 mm. This bias is not critical since it would be removed during cross-calibration between the altimeters, but it would tend to confuse the orbit comparisons, and it indicates one or more model discrepancies. Based on recent comparisons, it is believed that the sources of the radial bias are understood. An essential part of the POD verification activity will be to adopt and validate a common set of models and standards which produce equivalent results from all POD systems involved.

Figure 4. RMS radial orbit agreement for ten-day arcs CSR vs GSFC (top) and CSR vs CNES (bottom)



Effect of Reference System on Orbits and Determination of Mean Sea Level

With the long time series of sea level that T/P and Jason-1 will provide, an area of recent concern has been the influence of the reference system used for POD. To understand the manner in which the choice of reference system affects the orbit, and consequently sea level, a series of experiments were conducted. The results, summarized in Table 3, indicate that the orbit is unaffected by small reference system errors or changes that result in a miscentering in the equatorial plane (the X and Y axes). The parameters typically estimated for most orbit determination methods are unable to accommodate a miscentering or other motion of the reference system in these directions because the Earth rotates in inertial space once per day. (This would likely not be true for very short arcs or if a large number of subarc acceleration parameters per day were estimated.) It is clear, however, that the orbit responds quite strongly, almost one for one, with a reference system motion in Z.

As a consequence, if the reference system happened to have a drift in Z of 10 mm/y, due to a systematic error in the station velocities for example, the orbit would follow that drift at about the same level. If this drift in Z is mapped into the global mean sea level, we find that because the Earth is largely covered by ocean, only ten percent of the signal, or 1 mm/y, shows up. However, the hemispherical signal is considerably larger, with 4–5 mm/y showing up in the North and South hemispheres.

Note that the difference between the nominal system used for the GSFC and CSR orbits (based on the CSR95L01 and CSR95D02 station solutions) and the ITRF97 reference system results in a drift of approximately 2 mm/y in Z. This reflects the lumped effect of the different station velocities between the two systems. As seen above, this would be 0.2 mm/y error in the global mean sea level observation, and an antisymmetric drift of 0.8–1.0 mm/y in the two hemispheres. The velocities for the DORIS stations in CSR95D02 were based only on 3 years of DORIS data, and thus are not sufficiently accurate to be used indefinitely. Consequently, a new reference system is required.

Because the ITRF reference system attempts to combine the SLR, DORIS and GPS networks into a common reference system, it is a reasonable choice. The 2 cm Z-shift and 2 mm/yr Z-drift in ITRF97 made that reference system unacceptable for the NASA POE production, but the indications are that this will be largely removed in the ITRF2000 solution. In this latest solution, the origin of the reference will be determined entirely by the weighted combination of the SLR station solutions, which appear to be fairly consistent with each other and with the CSR solution. It is likely that ITRF2000 can be adopted by both NASA and CNES for the remainder of the T/P mission and into the Jason-1 mission, with no significant effect on the existing mean sea level time series.

Table 3. Effect of reference system changes on T/P orbit

Case 1: 30 mm random errors in every station coordinate
Case 2: systematic 10 mm/year error for every station
Case 3: reduce all station velocities to zero
Case 4: switch from nominal SLR/DORIS coordinates to ITRF97

	Case	1	2	3	4
T/P orbit	X	0	0	0	0
effect	Y	0	0	0	0
(mm/yr)	Z	2	9	12	2
RMS radial orbit difference (mm)		9	28	52	9

(comparison is with nominal orbit over 5 years)

Conclusions

The orbit accuracy for the T/P orbits appears to be steady at the 2 cm RMS level. This is encouraging for Jason-1, since it implies that the models are likely to continue to perform well into the transition phase between the two missions. The quality of the orbits being produced for T/P demonstrates the value of the verification and validation activities directed toward the T/P POD system. A similar effort is planned for Jason-1 to ensure that the orbits are equally accurate and consistent. During prelaunch preparation as well as after launch, a careful assessment and validation effort is essential to assure that the Jason-1 POD system will perform as required, and this investigation is intended to support that activity.

If the models for Jason-1 are modified or improved, T/P may require a complete reprocessing to maintain consistency. In particular, it has been shown that the reference frame choices can significantly affect the determination of sea level from the altimeter data. Since it is unlikely that a set of station coordinates determined at this time can span the entire life of the combined T/P and Jason-1 missions, a method to switch to updated reference systems without introducing discontinuities or trends into the orbits is essential. These are the kinds of issues which must be resolved jointly between the T/P and Jason-1 POD teams.

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