ERS Tandem Mission orbits: is 5 cm still a challenge?

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Abstract

The ERS Tandem Mission is particularly interesting for precise orbit determination: a unique occasion of having two altimetric satellites flying the same orbit. While ERS-2 enjoys an abundance of tracking through SLR and PRARE, we can actually use this to improve ERS-1 orbits in a simultaneous orbit determinations. Dual-satellite altimeter crossover height differences are used as a kind of satellite-to-satellite tracking data type, linking the two orbits.

One of the major defects of the official ERS precise orbits by ESA/D-PAF has always been the comparatively large geographically correlated orbit error, resulting from shortcomings in the applied gravity models. Using a straightforward technique we have developed the Delft Gravity Model DGM-E04 an ERS-tailored version of JGM-3, and thus significantly reduced the geographically correlated orbit error, from about 6 to 3 cm. ERS Tandem Mission orbits based on this gravity model are available through WWW and have reached the unprecedented radial orbit error of approximately 5 cm.

Keywords: Orbit determination, ERS, gravity field tailoring

Introduction

The bulky satellites ERS-1 and ERS-2 were never designed for high precision orbit determination (POD) and the loss of the PRARE tracking system left ERS-1 even very poorly equipped for it. Yet, sub-decimetric orbit precision are not of academic interest only. The ERS altimetric system has demonstrated to perform well above expectations and is unique because of its multi-disciplinary character, sampling not only ocean, but also land and ice surfaces, in combination with the suite of instruments on board, providing, *e.g.*, simultaneous measurements of wet tropospheric content and surface temperature. Undoubtedly will ERS always lag behind on the 2-cm orbit precision of the TOPEX/POSEIDON (T/P) altimeter mission, so only when the POD is stretched to its very limits, ERS altimetry will be regarded a reliable source of information. Only then will ERS be able to demonstrate its additive value in ocean research and its unique capabilities in, *e.g.*, monitoring of the ice sheet mass balance.

During the entire ERS-1 mission the Delft Institute for Earth-Oriented Space Research (DEOS) has shown that in the orbit determination significant advances could be made by successive improvement of the modelling of the orbit dynamics (gravity field and surface forces) and inclusion of altimetry as a tracking data type. Starting at radial orbit errors of around 140 cm in 1991, the best available orbits are now believed to be accurate up to about 5 cm [*Scharroo et al.*,, 1993, 1994, 1997] Thus, DEOS was the first to demonstrate and provide sub-decimetric orbits for ERS-1 for almost its entire mission [*Scharroo*, 1996]

In the orbit determination software a capability has been implemented to use altimeter height residuals, altimeter single- and dual-satellite crossovers (XOs), PRARE and SLR tracking simultaneously in the ERS POD. By combining these data types, deficiencies in the SLR tracking network, such as a concentration of laser stations in the Northern Hemisphere, can be overcome. The ERS Tandem Mission is a unique opportunity for satellite orbit determination, having altimetric satellites flying the same orbit. Using dual-satellite altimeter crossovers height differences (XDs) as a kind of satellite-to-satellite tracking can link the orbits of ERS-1 and ERS-2 in a simultaneous orbit determination, so they can both enjoy the advantage of each other's tracking data.

Being able to compute high-precision orbits independent from altimeter measurements is a situation much preferred by the scientific community, preventing aliasing of oceanographic signals in the orbit. It will be demonstrated that ERS-2 SLR/PRARE and SLR/XO based orbits have competitive orbit precision.

Precise orbit determnations

The procedures and models used for the POD are based on the most up-to-date knowledge of gravity and non-conservative force modelling. Two general purpose gravity models, JGM-3 and EGM96 and two tailored gravity models developed at DUT, DGM-E04 and DGM-P01, have been used to describe the gravitational field of the Earth, various combinations of tracking data (SLR, PRARE, single and dual-satellite XOs) are tested, and the parameter estimation (drag coefficients and empirical accelerations) is varied (See Table 1). Details of the modelling are given in [*Scharroo et al.*, 1997] The different orbit solutions are intercompared in order to obtain insight into their respective precision.

Orbit	SLR	PRARE	Xover	drag	accel
S	2			11	4
P		2		11	4
SP	2	2		11	4
SX2	1 2	2	1 2 1-2	22	24

Table 1. Overview of tracking data and parameter estimation (per satellite and per arc) for the various orbit solutions. 1=ERS-1, 2=ERS-2, accel=empirical accelerations.

Measurements

SLR data are collected from EDC and CDDIS and, if required, converted to 15-second normal points. All ranges are corrected for a distance of 4.3 cm between the effective sphere of reflection and the Laser Retro-Reflector reference point. The data weight combines an overall solution error (5 cm) and system noise.

All ERS altimeter data are retrieved from CERSAT OPRs. Altimetric sea heights are screened and corrected for geophysical and instrument corrections: SPTR range bias jumps and USO clock drift, GFZ/D-PAF precise orbits (based on the PGM055 gravity model), meteorological dry troposphere and ionosphere, Microwave Radiometer wet troposphere, solid earth and pole tides, Grenoble FES95.2.1 ocean tides and loading, 5.5% sea state bias, 100% inverse barometer correction, and OSU MSS95 mean sea surface. Forthwith the 1-Hz relative sea heights are converted to altimeter single- and dual-satellite XDs restricted to a time interval of 17.5 days between ascending and descending passes. The weight of XDs in the POD is based on a model of sea surface variability.

PRARE measurements (Revision 4) from the Mission Execution Network have been retrieved from GFZ and are corrected for the provided atmospheric and instrumental corrections. The data weights are 20 cm and 2 mm/s for PRARE range and range-rate measurements, respectively, for all stations, except Neumayer (80 cm and 8 mm/s), which is located on an Antarctic sheet moving at a pace of about 40 cm/day.

Estimated parameters

Conform DUT practice, the orbital arc length equals 5.5-days, with 2-day overlaps between consecutive arcs. The estimated parameters for the ERS-2-only orbit solutions include a 6-element state vector (position and velocity at epoch), 12-hourly drag coefficients (11 parameters), and one set of empirical forces, consisting of 1-cpr along-track and cross-track accelerations (4 parameters per arc). In case of simultaneous ERS orbit computation, using SLR and single and dual satellite XOs (orbit type SX2 in Table 1) the data coverage becomes so regular we can extend the parameterisation to 6-hourly drag parameters and 22-hourly sets of empirical accelerations for each satellite. For each orbit manoeuvre, one set of constant accelerations in three directions is estimated. Coordinates, range and timing biases are estimated for certain SLR stations. One general timing bias is estimated for the PRARE measurements, and one timing bias for altimeter data from either satellite. Finally, tropospheric scale factors are estimated for each separate pass of PRARE measurements, and one range bias per station per arc.

Gravity model tailoring

The a priori gravity model used in the ERS POD was JGM-3. The perception that much of the orbit error was caused by deficiencies in this gravity model, led to the development of two gravity models tailored to ERS orbit determination.

DGM-E04 is based on ERS-1 and ERS-2 single-mission XOs for the period of April 1992 till August 1995. From these data the geographically anti-correlated radial orbit error was isolated by means of a local averaging of the XDs (See later). Employing Linear Perturbation Theory [*e.g.*, *Rosborough*, 1986] to postulate the part of the radial orbit error implied by deltas to the gravity model coefficients, 1100 of them were adjusted in a least-squares procedure using the JGM-3 covariance matrix as a constraint [*Scharroo et al.*, 1997].

DGM-P01 is based on SLR and PRARE measurements for 1996, adjusting 1244 coefficients of JGM-3. The normal equations were computed by numerical integration of the variational equations with the GEODYN orbit determination program, and were solved using with the JGM-3 covariance matrix as a priori information.

Results

Tracking data residuals

The top part of Table 2 presents the results for 43 orbital arcs of 5.5 days (2 January till 2 June 1996). Listed are the statistics of the SLR range residuals, PRARE range and range-rate residuals, the statistics of the satellite-specific components of the XD residuals (so each single and each dual XO is counted twice). These residuals are a measure for the orbit precision, but should be interpreted with care, since the data that have been used in the POD are likely to underestimate the actual orbit error. Moreover, the SLR and PRARE residuals are a measure of the orbit precision in all three directions, whereas the XDs depend on the radial orbit error only.

.	.		JGM-3		EGM96		DGM-P01			DGM-E04	
.	Number	S	SP	SX2	SX2	S	P	SP	SX2	SP	SX2
Tracking data residuals ERS-1 (all arcs)											
SLR (cm)	45280			5.62	5.54				4.07		4.96
XDs (cm)	83208			9.80	9.34				8.65		8.33
Tracking data residuals ERS-2 (all arcs)											
SLR (cm)	45580	8.62	9.25	5.41	5.48	6.45		6.68	3.84	8.68	4.74
PRARE-range (cm)	194557		11.22				8.53	8.86		9.24	
-Doppler (mm/s)	187061		0.70				0.57	0.59		0.61	
XDs (cm)	79559			9.13	8.70				7.87		7.49
Orbital overlaps ERS-1 (manoeuvre-free arcs)											
along-track (cm)	35			11.3	10.0				7.2		8.0
cross-track (cm)	35			13.7	18.5				10.7		14.0
radial (cm)	35			1.80	1.49				1.05		1.28
Orbital overlaps ERS-2 (manoeuvre-free arcs)											
along-track (cm)	35	49.0	13.3	11.3	11.1	30.2	229	10.4	7.8	12.8	9.6
cross-track (cm)	35	10.0	7.1	13.7	18.6	8.1	8.2	6.5	10.3	7.2	17.1
radial (cm)	35	6.41	3.08	1.80	1.59	3.16	3.11	2.52	1.13	3.13	1.37
Crossover height differences ERS-1											
Timing bias (ms)				-1.2	-1.4				-1.4		-1.5
XDs ERS-1 (cm)	162981			10.2	9.7				8.9		8.4
XDs ERS1-T/P (cm)	208402			8.5	7.9				7.2		7.2
Crossover height differences ERS-2											
Timing bias (ms)		-1.0	-1.0	-1.0	-1.2	-1.2	-1.2	-1.2	-1.2	-1.3	-1.3
XDs ERS-2 (cm)	143277	11.5	11.0	9.9	9.5	9.2	9.2	9.1	8.6	9.6	8.3

XDs ERS2-T/P (cm)	195737	9.3	9.0	8.4	7.9	7.5	7.3	7.3	7.2	7.9	7.2

Table 2. Results of the orbit determination of 43 orbital arcs (2 January till 2 June 1996). Rms XDs given in the bottom part of the table are from a data set spanning the entire period with a maximum time interval of 17.5 days for ERS crossovers and 5.0 days for ERS-T/P crossovers. To all XDs the listed timing bias is subtracted and data are screened using a 3.5-sigma filter.

Orbital overlaps

Another measure of the internal consistency of the orbits can be obtained by differencing the 2-day overlaps of two consecutive orbital arcs. Since gravity induced orbit errors cancel on overlaps, their statistics are most indicative of non-conservative force model errors. In Table 2 we can see that by increasing the number of solve-for parameters in the SX2 solutions we absorb much of these errors and significantly reduce the overlap differences in radial and along-track direction, even more than is achieved by increasing the number of observations (compare S, P, SP, and SX2 solutions). PRARE tracking helps to tie down the cross-track.

The smallest overlap differences and the smallest SLR and PRARE residuals are found for the DGM-P01 orbit solutions, which is a direct result of the fact that this model was tailored to these observation types. It performs much better than the JGM-3 model from which it was developed and even significantly better than the recent EGM96 model.

Crossover height differences

The most independent indicator for the radial orbit error are ERS XDs that span beyond the limits of the orbital arcs (Bottom of Table 2). Comparing the various SLR/PRARE (SP) orbit solutions, DGM-P01 gives the lowest rms XDs, while for the SLR/XO (SX2) orbits it is DGM-E04. This controversy indicates that the two tailored models have not reached the ultimate state of general applicability, but still apply best to the data types to which they were originally tailored.

Figure 1 shows the dramatic reduction of the ERS XDs from the D-PAF to the DGM-E04 orbits. In order to make a fair comparison with T/P we restricted the ERS XDs to latitudes up to 66 degrees and extended T/P XOs to 17.5-day intervals. The rms XD of 8.0 cm for T/P is but a few millimetres lower than the 8.3 cm obtained for ERS, using the DGM-E04 orbits.

Line color	Satellite	Orbit
Green	ERS-1/2	D-PAF/PGM055
Brown	ERS-1/2	DUT/JGM-3
Blue	ERS-1/2	DUT/EGM96
Magenta	ERS-1/2	DUT/DGM-P01
Red	ERS-1/2	DUT/DGM-E04
Grey	T/P	NASA/JGM-3
Click image to get a full-size version.		

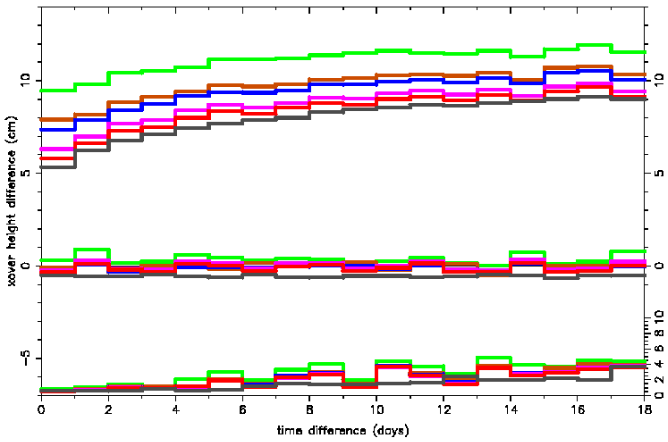


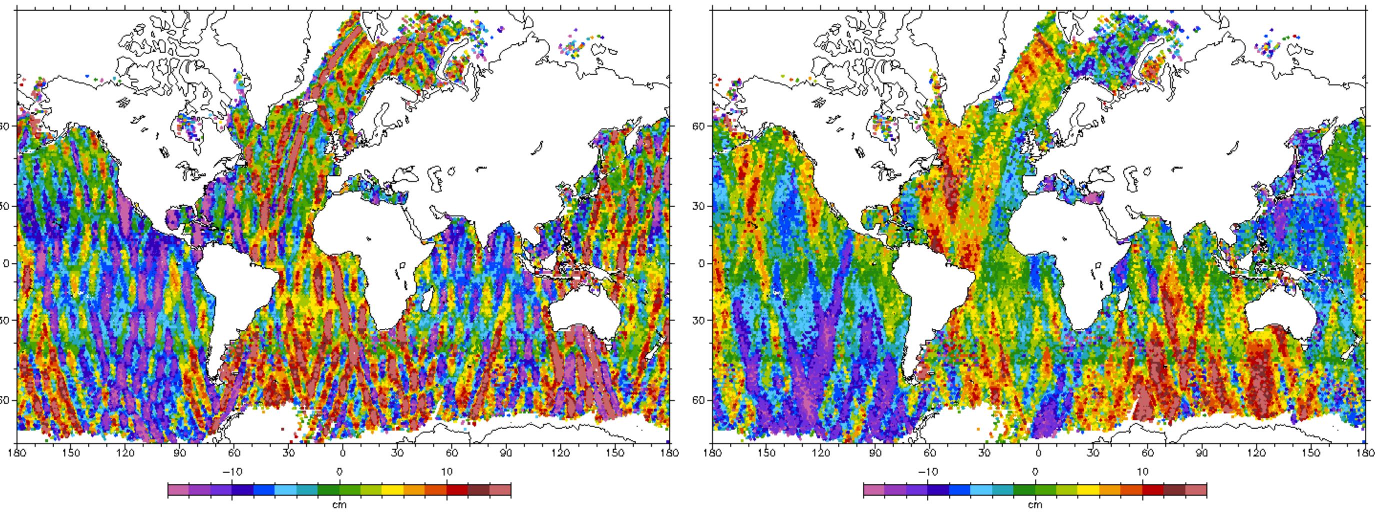
Figure 1. Rms and mean XD (asc-des) as a function of time interval. Different coloured lines relate to ERS simultaneous (SX2) orbit solutions. The grey lines are for T/P. Period: January-May 1996.

Finally, Table 2 also lists XDs between ERS and T/P (time intervals restricted to 5.0 days). When we compare the SX2 solutions computed with different gravity models, the two DGM models fit equally well to T/P data (7.2 cm rms), significantly better than with JGM-3 from which these models were tailored (8.4 cm rms). This is somewhat remarkable as T/P data were not involved in the tailoring process. Also, this tackles the widely distributed legend that combining altimeter data from different satellites requires orbits to be determined with the same gravity model. This argument is an obvious misperception for orbits so entirely different in altitude and inclination as ERS and T/P.

Gravity induced radial orbit error

(a) PGM055: Rms = 7.77 cm

(b) JGM-3: Rms = 6.14 cm



(c) DGM-P01: Rms = 4.50 cm

(d) DGM-E04: Rms = 3.03 cm

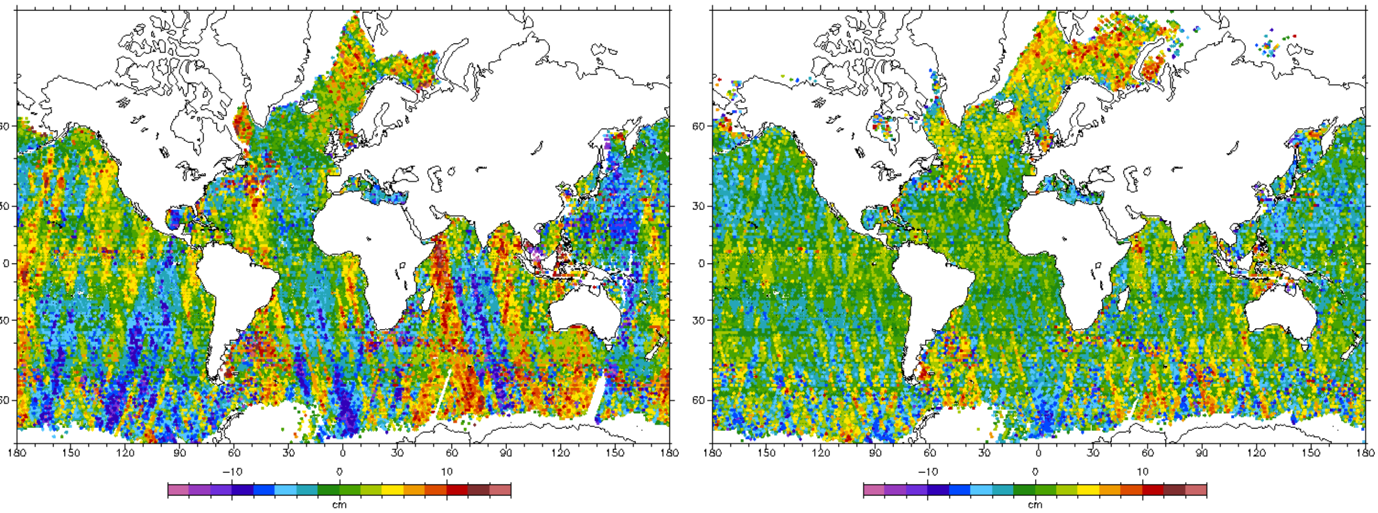


Figure 2. Averages of ERS-1 and ERS-2 single-mission XDs for the Tandem Mission. The various graphs pertain to different ERS orbit solutions: D-PAF PGM055 orbits (a) and DUT JGM-3 (b), DGM-P01 (c) and DGM-E04 (d). In each case the best fitting apparent altimeter time tag bias is applied.

The gravity induced radial orbit error can be decomposed into a geographically correlated and anti-correlated part. In single-satellite XDs the correlated part cancels, but the anti-correlated part is observed at double efficiency. In order to separate the gravity included radial orbit error from the non-conservative (*i.e.*, time variant) orbit errors, the local average (and variance) of the ERS-1 and ERS-2 XDs in each XO location are computed. In Figure 2 the average XDs based on the D-PAF orbits, and three of the SX2 orbit solutions (JGM-3, DGM-P01, and -E04) are intercompared and clearly depicts the comparatively large gravity induced radial orbit errors in the D-PAF orbit (3.9 cm). The cross-track gradient in these orbit errors could easily lead to unrealistic oceanographic results. It comes to no surprise that of the two tailored gravity models -E04, being tailored with XDs, shows the smallest anti-correlated radial orbit error (1.5 cm). The local variance of the XDs in Figure 3 is virtually free of any sign of orbit error and reflects meso-scale variability in the western boundary currents.

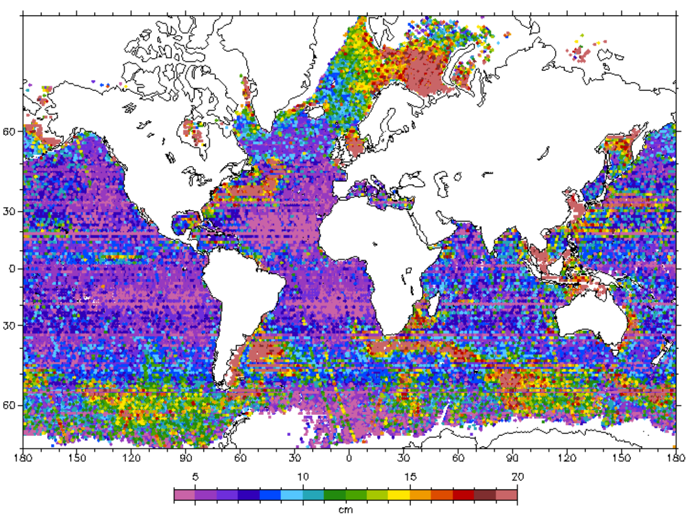


Figure 3. Local variance of ERS-1 and ERS-2 single-mission XDs for the Tandem Mission, based on DGM-E04 orbits.

Assuming T/P sea surface heights to be an error-less reference, we can isolate the geographically correlated orbit error by local averaging of ERS-T/P dual satellite XDs (Figure 4). The D-PAF orbits again show orbit errors with sharp gradients, while the DUT orbit solutions appear to be mainly hampered by coordinate shifts along the Z- or X-axis. Even though DGM-P01 and -E04 differ in this respect, the tailoring has still reduced the correlated orbit error from 4.7 to about 3 cm.

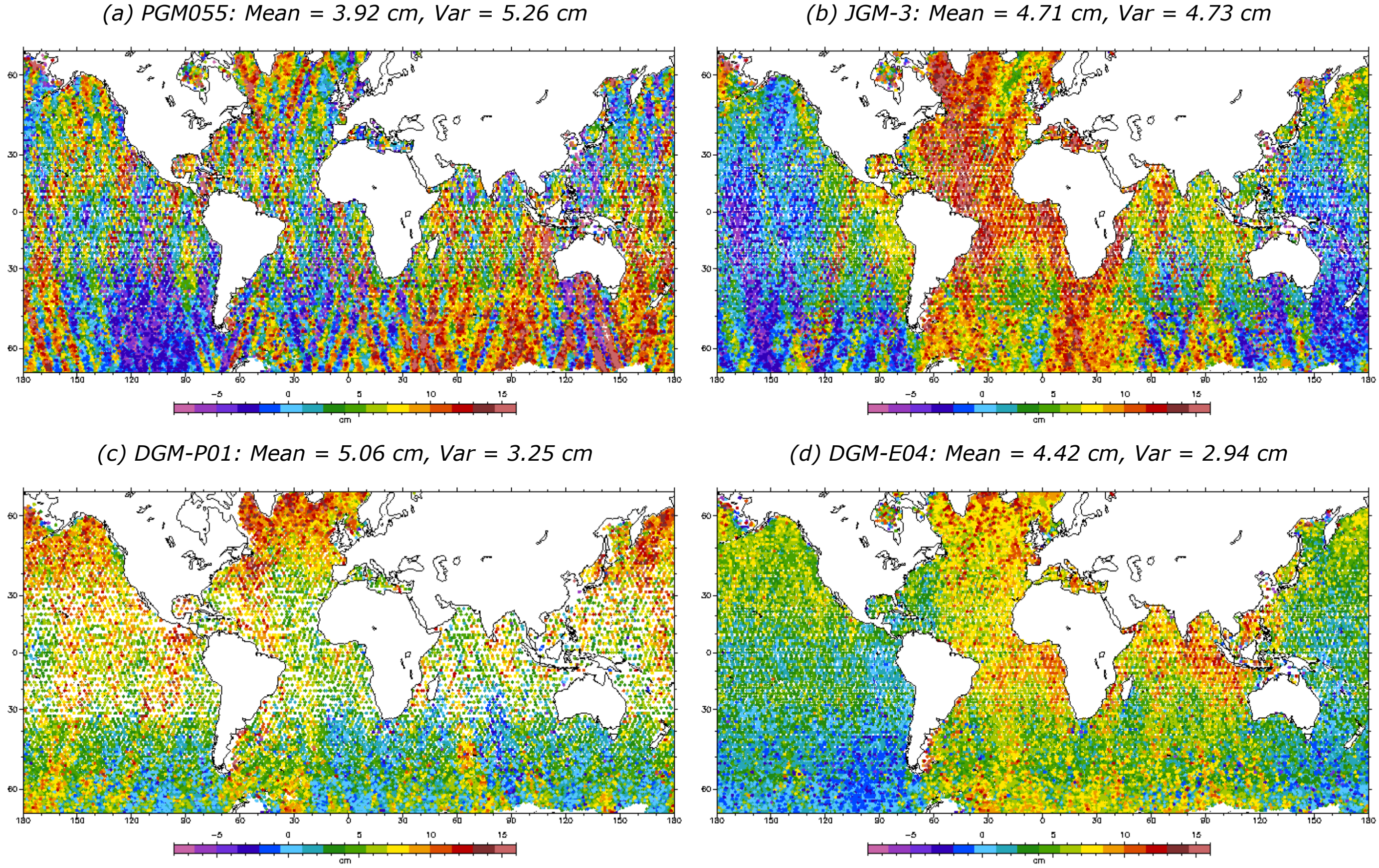


Figure 4. Locally averaged ERS-T/P crossover height differences for the ERS Tandem Mission. The graphs pertain to different orbit solutions for ERS: D-PAF PGM055 (a) and DUT JGM-33 (b), DGM-P01 (c) and DGM-E04 (d). In each case the best fitting apparent altimeter time tag biases for ERS-1 and ERS-2 is applied. (Click images to get a full-size version.)

Orbit differences

Table 3 lists rms radial orbit differences between some of the orbit solutions discussed in this paper. The choice of tracking data, either SLR/PRARE (SP) or SLR/XO (SX2), appears to have less influence on the computed orbit than the choice of gravity model (compare red with blue and green numbers). Also the two tailored models, though independently developed, are closer together than either is to their parent JGM-3 (compare green with blue numbers). For these models the radial orbit differences are generally around 3-4 cm.

.		JGM-3		DGM-P01		-E04
.		SP	SX2	SP	SX2	SP
JGM-3	SX2	3.77				
DGM-P01	SP	5.61	5.28			
DGM-P01	SX2	6.04	4.94	2.19		
DGM-E04	SP	4.41	5.47	4.01	4.54	
DGM-E04	SX2	5.50	4.32	3.60	2.90	3.53

Table 3. Cross orbit comparisons for 2 January till 2 June 1996. Rms of radial orbit differences (cm) for manoeuvre-free orbit arcs.

Discussion and conclusions

All analyses indicate that radial orbit errors for ERS have come down to about 5 cm. We have left the times behind that this could only be achieved by non-dynamic orbit improvement using T/P as a reference, with its associated risks of dissolving oceanic features [*e.g.*, *Smith and Visser*, 1995, *Le Traon et al.*, 1994]. These unprecedented precisions are the result of tailoring the gravity model and enriching the SLR tracking with crossovers or PRARE. We have demonstrated that orbits based on SLR/XO or SLR/PRARE are quite similar in precision and match even closer. However, a detailed analysis of the differences at various temporal and spatial scales is required in order to assess whether concerns about the use of XO data in orbit determination are justified.

The two ERS tailored gravity models are close in the sense that they appear to provide orbits with similar precision, but clearly have very different characteristics in the handling of tracking data. Where the one provides superior fits of SLR and PRARE, the other dwells much better on XO data, providing the best orbits in radial direction. The next step is to combine both assets into one model, equally suitable for ENVISAT.

More issues have not been discussed: remaining deficiencies in the non-conservative force modelling, the effect of the solve-for parameters, tidal gravity. Clearly, at 5 centimetres the challenge only *starts*.

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