Quality of the D-PAF ERS Orbits before and after the Inclusion of PRARE Data

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Abstract

The ESA ERS standard products Preliminary and Precise Orbit are operationally generated by GFZ/D-PAF based on ERS tracking data. While for ERS-1 the orbit computation had to rely on satellite laser ranging data combined with radar altimeter data, for ERS-2 additionally the range and doppler measurements from the PRARE system are available and are routinely used along with the laser ranging data since December 1995. The paper summarizes the progress in the ERS orbit determination since the last ERS symposium and reports about the quality of the operational orbit products as resulting from altimeter crossover analysis and other quality tests (internal and external ones), showing an estimated radial orbit accuracy in the order of 7-8 cm. Special emphasis is given to the analysis of the PRARE data for the ERS-2 orbit determination and the influence on the ERS-2 orbit quality is discussed. The presentation is completed by an outlook to the near future (new gravity models etc.).

Keywords: ERS, Orbit Determination, PRARE, D-PAF

Content:

1. Introduction

Since the launch of ERS-1 in July 1991, the ESA standard products "Preliminary and Precise Orbit (PRL, PRC)" are systematically computed at the German Processing and Archiving Facility (D-PAF) within the ERS project. These products are used by other PAFs (D-PAF, F-PAF) for the processing of other ESA standard products (for example quick-look and precision altimeter products) as well as by an increasing number of scientific users.

During the past six years of ERS operations the quality of the orbit products has clearly improved due to modifications in the precise orbit determination (POD) models, mainly the Earth gravity field. But the number of new product revisions had to be kept small in order to minimize the impact of these model changes for the users and also for the POD team, as this always results in a reprocessing of all already delivered PRC products. Up to now only two changes have been made: one in July 1993 (Massmann et.al. 1994) and a second one shortly before the ERS-2 launch in April 1995.

Since then the models for PRL and PRC have been kept fixed, but there has been a modification in the tracking data base. From January 1996 the first operational ERS-2 PRARE (Precise Range and Range Rate Equipment) range and doppler tracking data have been made available (revision 4 data). Due to the microwave frequencies (weather independent) and the good global station distribution this forms an ideal tracking data basis which is independent from the ocean surface. As tests have shown that the orbit quality will not change when replacing the altimeter crossover data by the PRARE measurements, this data substitution has been made for the PRC orbits from mid December 1995 onwards. Based on the experiences from the orbit determination with PRARE, the PRARE preprocessing has been improved throughout 1996, and a new PRARE data set with better measurement corrections (revision 5) has been made available in November 1996. Due to the parametrisation within the orbit determination process there is only a marginal effect on the orbit.

The next chapter describes the now operational PRC orbit products in terms of tracking data, applied geometric and dynamic models as well as the solve-for parameters. In chapter 3 the quality of these orbits is presented with special attention to the introduction of PRARE tracking data. The concluding chapter shows the results of the ERS orbit determination with a recent gravity model and gives an outlook for further improvements.

2. PRC Orbit Products (Revision 2)

On the occasion of the upcoming launch of the ERS-2 satellite an improved model (revision 2) has been introduced for the ERS precision orbit determination. For the PRL this has been done on May 1st, 1995 and due to the limited life time of the product no reprocessing of older products has been performed, while for the PRC the change has been made starting from March 24, 1995, but older products have been reprocessed with this new model in order to have a consistent PRC series. In the following the tracking data, the models (geometric and dynamic) and the solve-for parameters are described for the PRC generation.

2.1 Tracking Data

As the three precision ERS tracking systems are the satellite laser ranging (SLR), the radar altimeter (RA) and PRARE (working on ERS-2 only), the precision orbit determination is based on a combination of them. A general overview about the data used for the PRC generation is presented in Table 1.

	ERS-1	ERS-2
SLR + RA Crossover	27.Jul.91 - 06.Jun.96	28.Apr.95 - 22.Dec.95
SLR	06.Jun.96 - 26.Jul.96	---
SLR + PRARE	---	since 12.Dec.95

Table 1: Periods of ERS tracking data usage for PRC rev.2

Satellite Laser Ranging Data

Throughout the ERS mission the laser data, two-way ground based range measurements, forms the basis of the precision orbit determination. There has been a considerable effort at the stations to improve the quality of the data through hardware and software upgrades. Beginning of 1995 almost all stations delivered high quality normal points as quick-look data making the additional step of the normal point generation from full-rate data obsolete at GFZ/D-PAF. The station distribution has changed only slightly and is depicted in Figure 1 along with the observed passes of one week. There is still the unequal global distribution between Northern and Southern hemisphere with a great cluster of stations in Europe.

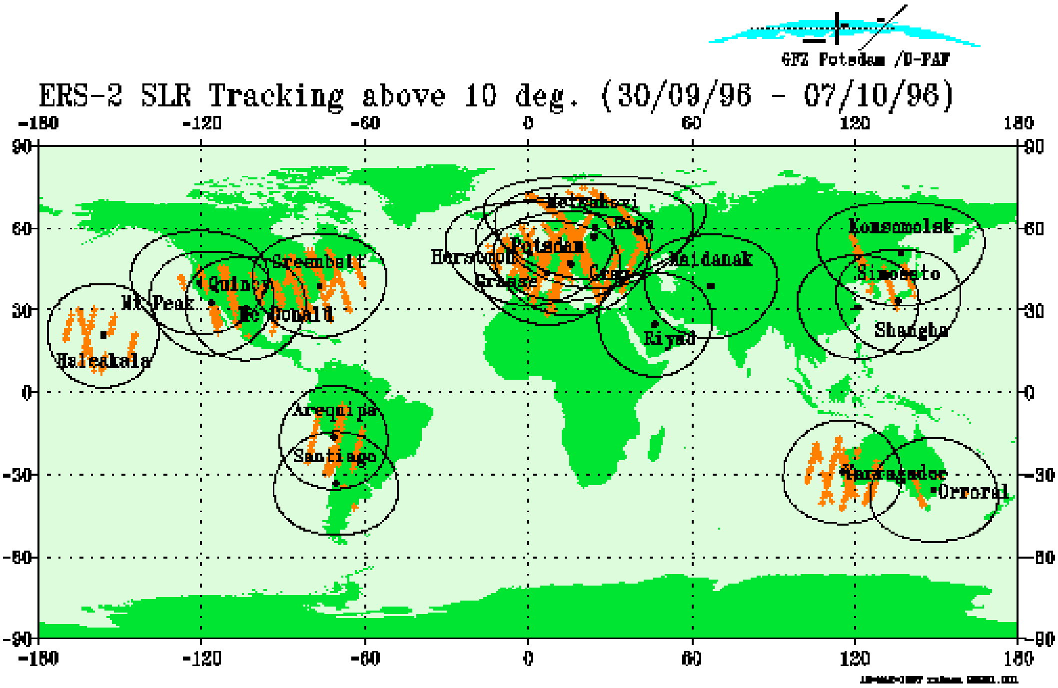

Figure 1: *The ERS SLR tracking network and observations within one week (40/96)*

Radar Altimeter Crossover Data

The radar altimeter data is used in form of crossover height differences, except for short periods between two consecutive manoeuvres, in order to reduce the aliasing effect from the sea surface signal into the orbit. As the locations of the used crossovers are over ocean and as most of the ocean surfaces are on the Southern hemisphere, this data set forms a good complement for the SLR data. For revision 2 the data is based on the precision OPR01 altimeter products from the F-PAF, which have been upgraded to account for some effects, i.e. time bias, USO drift, SPTR range bias (Gruber et.al. 1997b). The available OPR01 products have been generated with the following versions at F-PAF:

3.x (ERS-1: launch till 21-Mar-1995),
5.x (ERS-1: 22-Mar-1995 till 17-Dec-1995; ERS-2: launch till 07-Jan-1996) and
6.x (ERS-1: 18-Dec-1995 till 03-Jun-1996; ERS-2: 08-Jan-1996 till now)

PRARE Range and Doppler Measurements

The space-based PRARE system provides two-way range and doppler measurements and is operational on ERS-2 only. Since January 1996 the system is in its operational phase starting with data of revision number 4. The used data are compressed measurements, so-called normal points, which are computed by the PRARE Master Station at D-PAF. Major improvements in the tropospheric and ionospheric corrections as well as some other small changes resulted in improved PRARE data (revision 5) (Bedrich et.al. 1997), which are distributed since November 1996 and have been used in the orbit determination since then. Figure 2 presents the PRARE tracking network as of March 1997 with the observed passes of one week. This data set also complements the SLR data very well due to its station distribution, especially in the Southern latitudes.

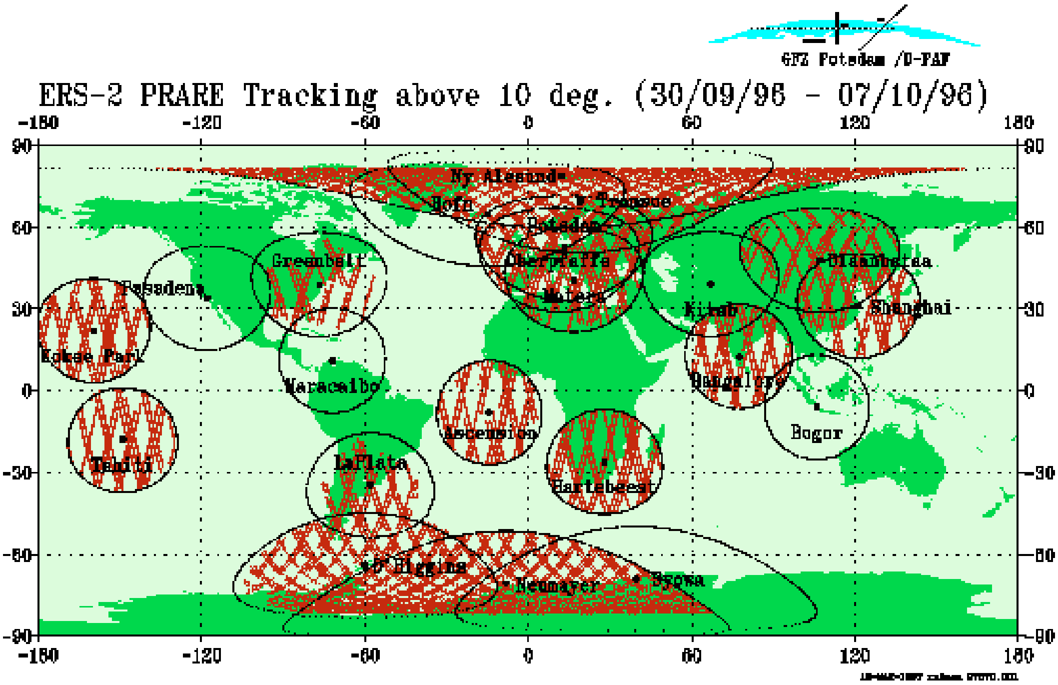

Figure 2: *The ERS PRARE tracking network and observations within one week (40/96)*

2.2 Models

The models and constants adopted for the ERS precision orbit determination are described in detail in the ERS Standards (Zhu et.al. 1996), which follow the IERS Standards to a large extent. A summary can be found in Table 2 to 4.

In general the *reference system* has been kept constant throughout the mission and there has been no change for revision 2 (see Table 2). One major difference to other reference systems is the use of the zero mean pole. This results in two large rotations. From a 7 parameter Helmert transformation the following parameters are estimated for the transformation from the D-PAF(PGM055) system into ITRF94 (Zhu et.al. 1996):

Translations: 0.4 cm/0.3 cm/2.9 cm,
Scale: 0.38 10^{-8} ,
Rotations: 286.14 mas/44.54 mas/-0.91 mas.

CIS	mean equator and equinox of J2000.0
Precession	IAU 1976
Nutation	IAU 1980 plus Zhu 1990 correction
Earth rotation	ERP(BIH)87C02, IERS Bulletin B (transformed to zero mean pole)
CTS: Z-axis	ERP(DGFII)87L03: zero mean pole 1/1980 - 10/1986
CTS: X-axis	SSC(DGFII)87L03 (epoch 1984.0)
Time evolution	no global-net-rotation
Origin	Earth's centre of mass
Table 2: Reference System	

The *dynamical model* parameters are listed in Table 3. Changes to the revision 1 model are:

new satellite-only gravity model PGM055 (see also Gruber et.al. 1997a)
improved ocean tide model as estimated along with PGM055
modeling of 1/rev empirical accelerations in normal direction
higher resolution of 1/rev along-track empirical accelerations

Earth: constants	R=6378136 m; 1/f=298.25781 (inverse flattening of reference ellipsoid); mean angular velocity of Earth= 0.7292115 /10^4 rad/s; GM = 398600.440 km^3/s^2 ; C_{00}=0.999999995
Earth: Gravity model	PGM055 (=EGM2-2S) satellite-only gravity model (epoch 1984.0) complete up to degree/order 60, resonances up to 69; C_{21}, S_{21} modelled with respect to zero mean pole (effect of pole tide not considered)
Solid tides	Modified solid tides (permanent tide not removed)
Ocean tides	improved spher. harm. model from Schwiderski 1deg x 1 deg grid, 11 tides plus Sa, deg./order: max. 19/4, 76 coeff. improved
Third bodies	Sun , Moon and 5 planets as point masses, DE200/LE200 ephemerides
Relativity	none
Atmospheric drag	CIRA 1986, daily flux, 3-hourly geomagnetic indices
Solar radiation	solar constant 4.5605 10^{-6} Nm^{-2} at 1 AU, exp. regular. function
Earth	albedo and infrared

radiation	
Emp. accelerations	in along-track and cross-track directions
Surface Sat.model	ERS macro model consisting of 8 pieces, rotating solar panel: variable area/mass
Table 3: Dynamical model	

The parameters of the *geometrical model* referring to tracking station positions and observation related models, quantities and corrections are summarized in Table 4. The changes to revision 1 are: updated station coordinates, PRARE related corrections.The PRARE coordinates are the result of a combined solution of PRARE range and doppler data from 11 weeks (rev.4). The range- and doppler-only solutions differ by 3-5 cm only.

Station positions: laser	SSC(DPAF)PGM055
Station positions: PRARE	D-PAF Rev.4 solution
Station horizontal velocities	SSC(DPAF)PGM055, AMO-2, Nuvel-1
Site displacem.: Earth tides	modified Wahr
Site displacem.: ocean loading	based on Schwiderski ocean tide model (Scherneck approach)
Site displacem.: Pole tide	IERS 1989
Troposph. refraction: laser	Marini and Murray
Troposph. refraction: PRARE	Davis
Ionosph. refraction: PRARE	Rev.4: first order correction obtained from the difference of two frequency measurements; Rev.5: derived from difference of range and doppler measurements (DRVID)
Range bias	PRARE range: correction per station per arc
Relativity	laser: range effect
Laser array correction	varying from 3.8 to 4.5 cm (elevation dependent)
Table 4: Geometrical model	

2.3 Solve-for Parameter and Weighting

Within the least squares orbit adjustment process a number of parameters are solved-for in the 5-7d arcs, which are listed in Table 5 assuming normal conditions. It has to be mentioned that some parameters are estimated only in case of systematically corrupted data (SLR range and time bias), upcoming new stations, manoeuvre events or the use of altimeter ranges (seldom between manoeuvres, if other tracking data can not give a reasonable solution). As the 1/rev cross-track accelerations are strongly correlated with the solar radiation factor, the latter one has been fixed to one. With respect to the PRARE specific parameters the following has to be mentioned:

A global *time bias* is routinely solved-for in order to monitor systematic differences which appear as a time bias. The resulting values are generally under 20 microseconds. This is slightly higher than the accuracy of the PRARE clock model used for the time synchronisation, which is usually in the order of better than 2 microseconds.
From tests within the commissioning phase it has been seen that a station dependent *range bias* exists, which has to be monitored.
As not all PRARE stations are equipped with a meteorological station, in the PRARE data either global mean conditions are given (rev.4) or interpolated monthly mean values from ECMWF data along the track are included (rev.5). In order to account for errors in these data, *tropospheric scaling parameters* per pass are estimated. These parameters are modelled as one common effect from range and doppler data, because hardware and the environmental measurements are identical for both observation types. In general the estimated values are varying up to 15% (rev.4) /5% (rev.5) from unity (perfect modelling). There also exists a high correlation between the PRARE range bias and a tropospheric factor calculated from range data only.
The PRARE station at *Neumayer* (Antartica) is located on the shelf-ice, which is moving about 40 cm/d. In order to account for this motion, the coordinates at epoch are kept fixed and the *horizontal rates* are solved-for per arc (This gives identical results with the approach fixing the rate and solving for coordinates per arc). The computed movements since February 1996 are showing a continous displacement of meanwhile 160 m in North-West direction.

Parameter	**Obs.type**	**Frequency:** once per ..
Orbital elements (6)	all	arc
Drag coefficients	all	6 h
1/rev empirical acc.: along- /cross-track	all	day
manoeuvre accelerations	all	manoeuvre
Range bias	SLR	station or pass (occasionally)
Range bias	PRARE range	station
Range bias	Altimeter	arc
Time bias	SLR	station or pass (occasionally)
Time bias	Crossover	arc
Time bias	PRARE	arc
Station coordinates	all	arc (new stations only)
Station velocity	PRARE	arc (Neumayer only)
Tropospheric scaling factor	PRARE	station
Table 5: PRC solve-for parameter		

The following weights have been assigned to the different tracking data types: SLR versus Crossover has been weighted equally with 10 cm. In case of laser and PRARE range and doppler data the weighting has been SLR 6 cm, PRARE range 12 cm and PRARE doppler 1 mm/s.

3. Quality Assessment

In the following chapter the quality of the PRC orbits as described before will be discussed with special emphasis on the change from crossover to PRARE data.

3.1 PRC based on SLR and Crossover

A first quality check is the inspection of the root mean square (rms) of fit of the used observations to the computed orbit. Typical values for the PRC arcs are 6-8 cm for the laser rms and 9-11 cm for the crossover rms, indicating a radial accuracy in the order of 7-8 cm (rms). Figure 3 geographically displays the crossover height differences based on PRC orbits for a 35d period (June 19 to July 24, 1995). The figure shows some systematics resulting from the gravity modelling, while regional effects are close to coasts etc. where problems with the ocean tide model used in the altimeter data processing are known.

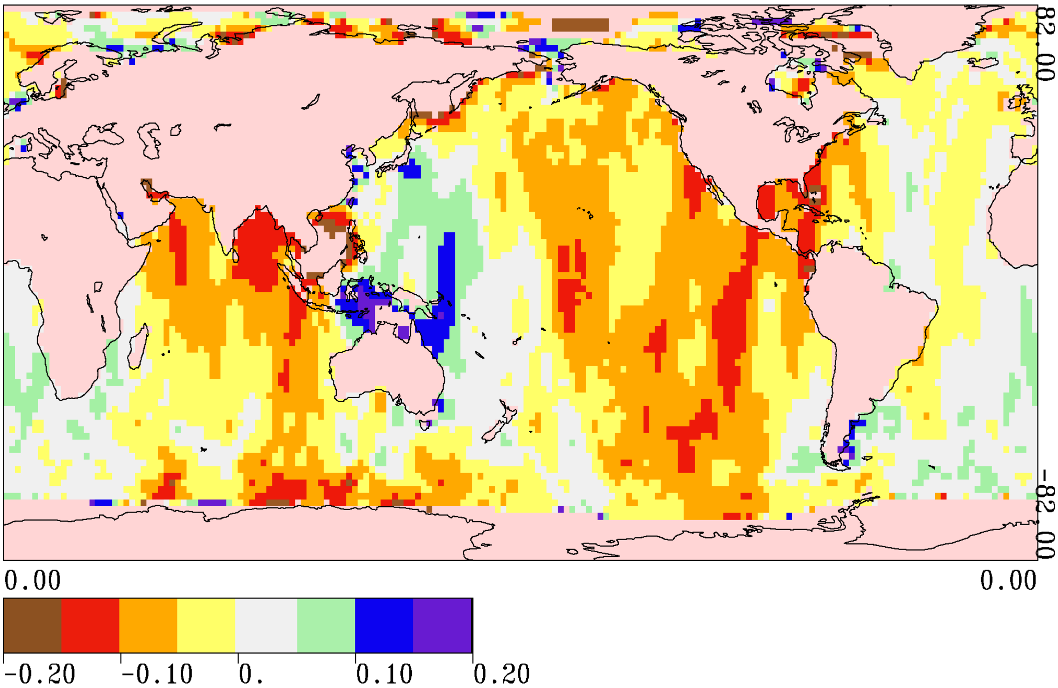

Figure 3: ERS-1 Crossover differences based on PRC (SLR+Xover) (June 19 to July 24, 1995)

Figure 4 compiles monthly crossover statistics (all possible crossovers within one month). The mean of the crossover differences, which is an indicator for systematic differences between ascending and descending arcs, is in most cases close to zero. Large mean values are visible for the periods where OPR data of revision 5 have been used. The rms is around 14 cm with some spikes. Clearly visible is the higher rms in case that OPR01 data of version 5 have been used and the crossover statistic uses OPR02 data version 6. For the peak in January 1996 we do not have an explanation yet. The last values in the curve, where version 6 OPR data has been consistently used, seem to indicate the higher quality of the OPR version 6.

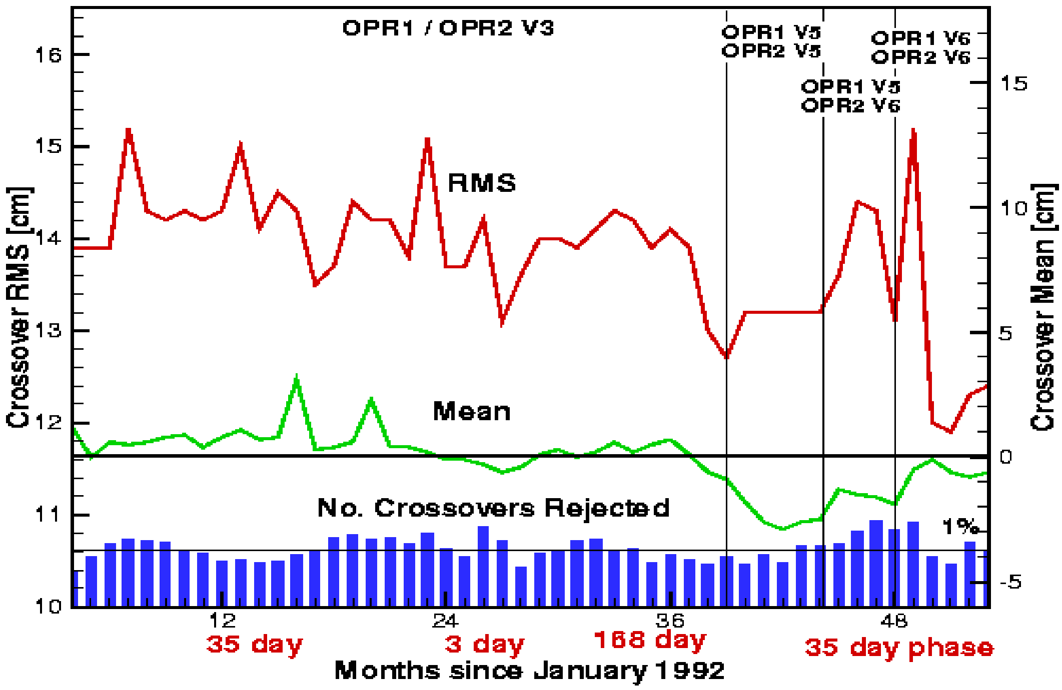

***Figure 4:** ERS-1 monthly crossover statistics (since 1992)*

A stronger quality test is the comparison with orbits computed independently, for example orbits computed by Scharroo (DEOS/DUT) on the basis of the NASA gravity model JGM3 or orbits from Shum et.al. (CSR/UTEX) on the basis of the CSR gravity model TEG3. It has to be mentioned that both models are combined models using terrestrial data (gravimetry, altimetry). These external orbits use almost the same tracking data, but include also other modeling differences, so that the comparison give a summary of all modeling discrepancies. In Figure 5 the orbit differences are plotted in radial and cross-track direction for the individual PRC subarcs. It has to be kept in mind that the period of the external orbits is different from ours. In general one can see that the orbits show an agreement of about 8 cm (rms) radially, 20 cm in cross-track and 30 cm in along-track direction (see also Shum et.al. 1997). An indirect comparison for the radial component can be performed by using the crossover differences generated from independently computed orbits: for example the comparison of our orbits versus the DUT JGM3 ones (see fig.5 in Gruber et.al.1997a) shows in general a good agreement with some differences in the mean values (ours being closer to zero).

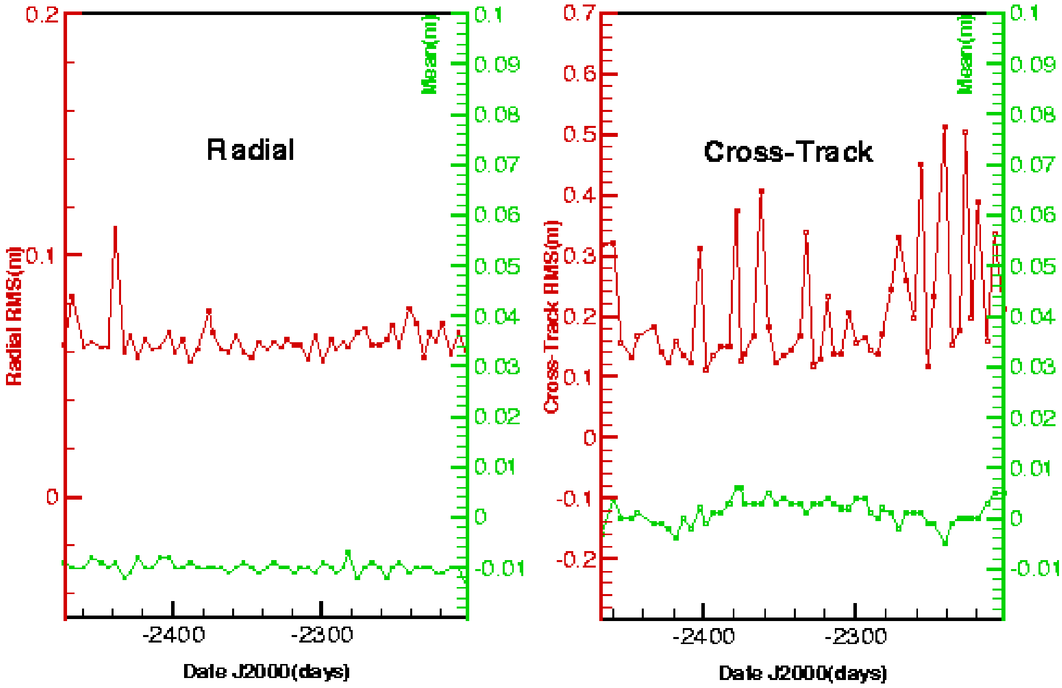

Figure 5: *Comparison of PRC with CSR/UTEX orbit (radial and cross-track component)*

3.2 PRC based on SLR and PRARE

The ERS-2 orbits computed with SLR and PRARE range and doppler data show orbitals fits in the order of 7-10 cm for laser and PRARE range and 0.6-0.7 mm/s for PRARE doppler data. In case of solving the tropospheric parameters for PRARE range and doppler separately, the doppler rms decreases to 0.4-0.5 mm/s. A clearer indication for the radial accuracy is again derived from the monthly crossover statistic of the available OPR02 data (see Figure 6). Again the mean of the crossover differences is close to zero and the rms curve shows a similiar behaviour as the one plotted in Figure 6 with a peak in January 1996, which here could be explained by an ERS-2 platform anomaly followed by a lack of tracking data for some days.

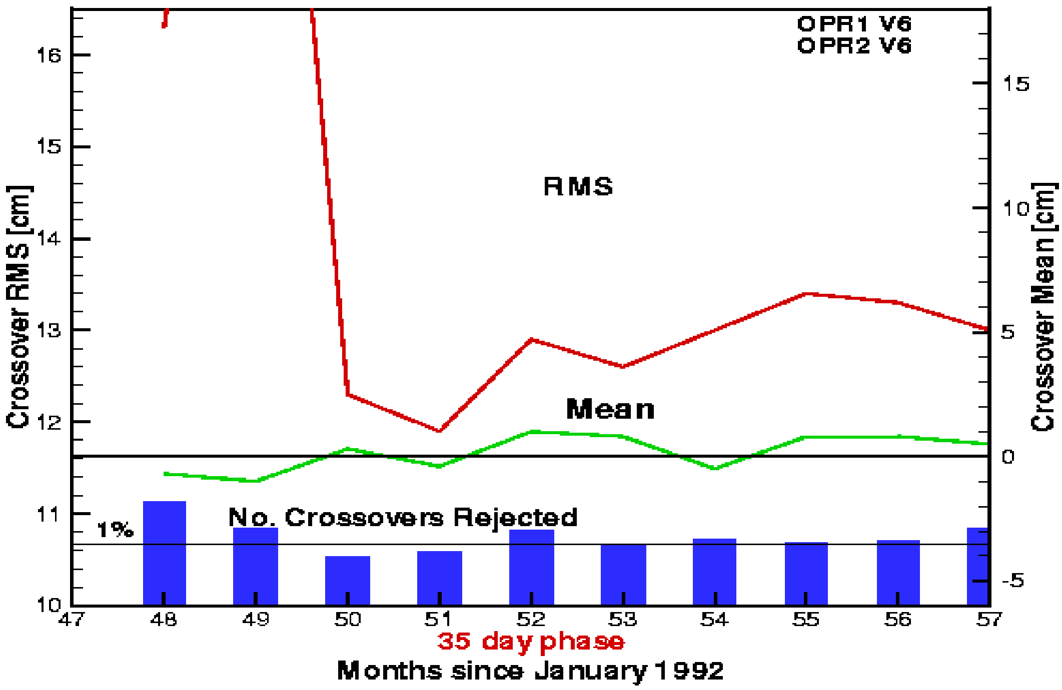

Figure 6: *ERS-2 monthly crossover statistics (since 1996)*

The effect of exchanging the radar altimeter crossover data by the PRARE data in the orbit determination can be seen either from direct comparisons of the computed orbits or by comparing the resulting crossover height differences. The first approach has already been described for all tracking data combinations (Massmann et.al. 1997) showing radial rms differences of smaller than 3 cm. The SLR and crossover orbit versus the SLR plus PRARE orbit gave rms differences of 2.1 cm (radial), 3.3 cm (cross-track) and 14.3 cm (along-track).The result of the second approach is displayed in Figure 7 for a period with moderate PRARE tracking (10 stations). The differences are small (below 2 cm) with a few exceptions and concentrating around Australia, which can easily be explained by the lack of PRARE data in that area.

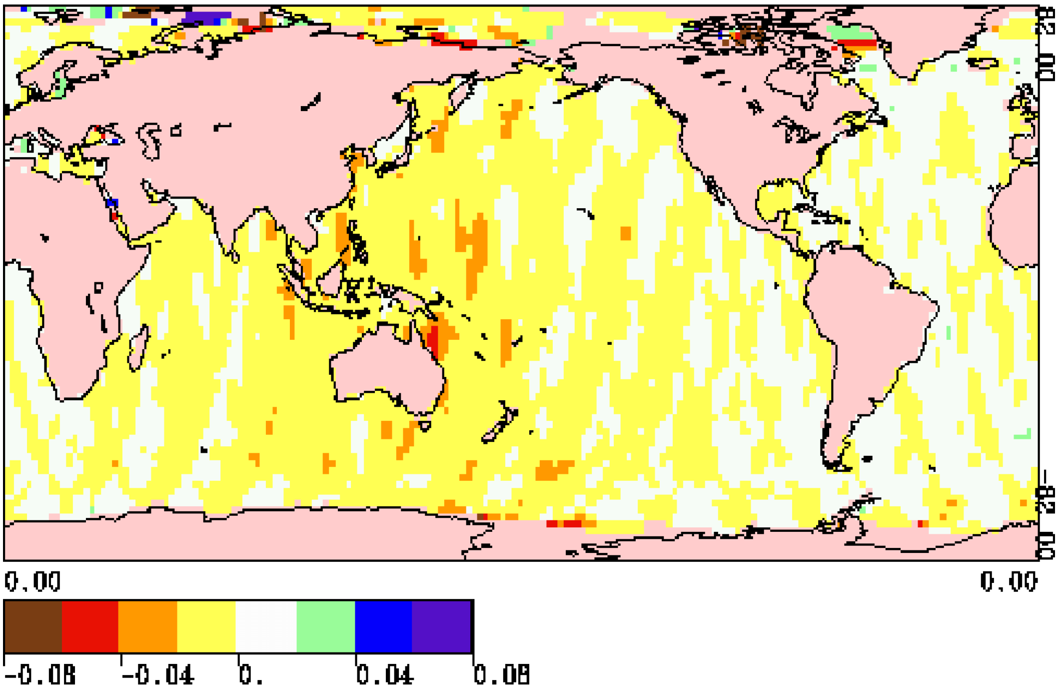

Figure 7: *Crossover difference between orbits with PRARE vs. crossover (March 27 to May 1, 1996)*

At the end of 1996 the improved PRARE data (rev.5) became available. In order to investigate the influence of this change orbits have been computed using PRARE rev.4 data and others based on rev.5 data. The difference between the crossover height differences is geographically plotted in Figure 8. Again, the differences are small (less 1 cm) and in accordance with the marginally smaller crossover rms for the revision 5 orbits.

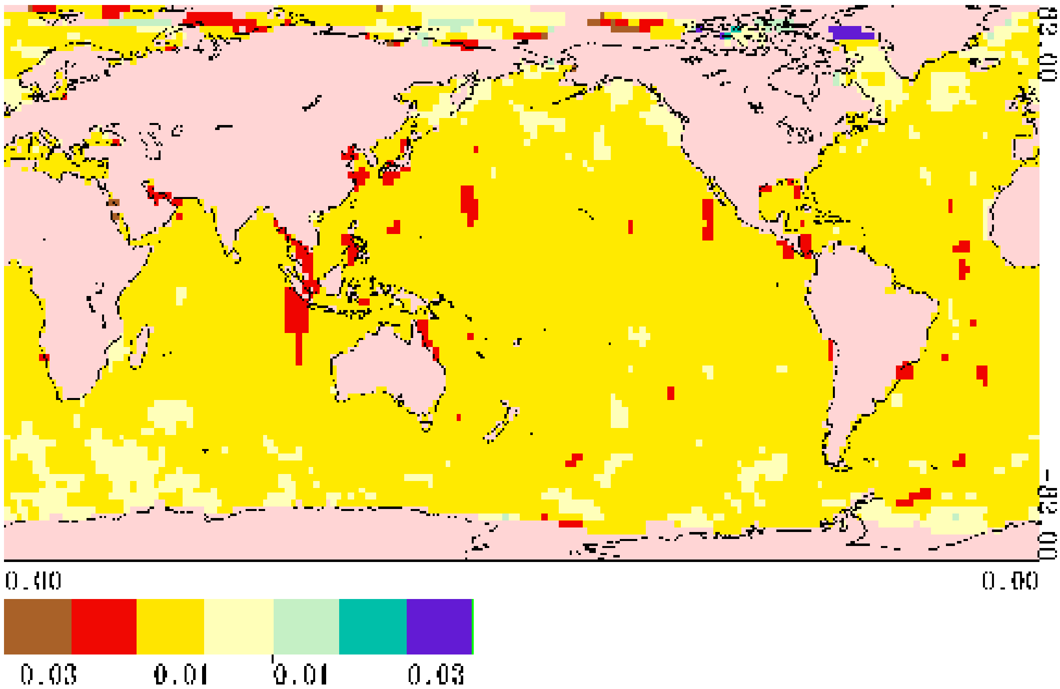

Figure 8: *Crossover difference between orbits with PRARE rev.4 and 5 (March 27 to May 1, 1996)*

It also should be mentioned that the large amount of PRARE data which is acquired independently from weather stabilises the orbit, which can be seen in the overlapping parts of the orbit. The overlaps are smaller, especially in cross- and along-track directions.

4. Conclusions and Outlook

The operational PRC orbits for ERS-1/2 are computed with the socalled revision 2 model, which has been introduced in spring 1995. The basis of this model is the PGM055 satellite-only gravity model which has been the most recent one at that time. The quality of the orbit products is in the order of 7 cm (radial rms) and 20 cm respectively 30 cm for the cross- and along-track directions. The use of PRARE data in the orbit computation did not result in significant smaller radial accuracies, as the gravity model uncertainties are dominating the solution. The major improvements in the ERS orbit determination in the past have been resulting from newer global gravity models and to a smaller extent from the use of other tracking data. As shown on the basis of the operational POD model, the inclusion of PRARE data in the processing results only in small changes of the computed orbit.

Efforts have been undertaken at GFZ/D-PAF to further update the gravity model by inclusion of PRARE data from ERS-2 and GFZ-1 satellite data (380 km altitude). The resulting model shows a small improvement of a few mm in the crossover rms, while a combination of the satellite-only model with new terrestrial data leads to a reduction of the crossover rms by about 1 cm (see also Gruber et.al.1997a).

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