GeoForschungsZentrum Potsdam (GFZ)

K. Enninghorst, M. Rentsch

ERS-2 Rapid Products Validation

Validation Report

Division 1: Kinematics and Dynamics of the Earth
German Processing and Archiving Facility (D-PAF)

July 30, 1997

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GFZ/D-PAF
c/o DLR
P.O.Box 1116
D-82230 Oberpfaffenhofen
Germany

Phone: (+49) 8153 28 1435
(+49) 8153 28 1267
Fax: (+49) 8153 28 1207
E-mail: Klaus.Enninghorst@dlr.de
Matthias.Rentsch@dlr.de

1. Scope

This note shortly summarizes the validation activities for the new rapid orbit and altimeter products RPD/ROPR for ERS-2. Besides internal quality measures the products are compared with the operational Preliminary Orbit (PRL) and the Quick-Look Ocean Product Records (QLOPR).

2. Rapid Orbit (RPD) Modeling

The Rapid Orbits are quick estimates of the satellite position and velocity being available every day at noon for the previous day. RPD adjustment is based on quick-look laser ranges, PRARE range and doppler normal point data and improved (Earth and ocean tides, ionospheric model) RA-FD height differences to a mean sea surface model. The altimeter data is heavily downweighted within the process and is only used for backup in case of severe data problems. The output format is identical with the PRL without the block of the state vectors in the inertial reference system. The arc length has been chosen to 4 days, of which two days are covered with observations and the other two are predicted.

The following table briefly describes the models used for the orbit determination. A more detailed description concerning the orbit modeling can be found in the documents "ERS-D-GPM-31200" and "ERS-D-STD-31101".

	Revision 0 (MODID=1)
Earth gravity model	PGM073w (based on GRIM4-S4, deg. 72)
Ocean tides	Schwiderski/PGM073w
Station coordinates	PGM073w
Solar radiation	Multiplier fixed to 1.07
Air drag	CIRA 86
Solar flux	predicted values
Geomagnetic indices	predicted values
Surface forces	Macro-Model
Earth rotation	IERS Bulletin A (predicted)
Nutation	IAU 1980 plus corrections
Earth radiation	albedo and infrared
Earth tides	modified Wahr (Zhu et al., 1991)

The PGM073w Earth gravity model is a derivative of the PGM055 (based on GRIM4-S4 with additional ERS-1 data) by adding ERS-2 PRARE data, GFZ-1 information and by combining this with normals generated from terrestrial and altimetric gravity data provided from NIMA.

The solve-for parameters are:
- six initial orbital elements
- air drag coefficients: one global parameter plus 12 hourly values for the first two days
- 1/rev empirical acceleration cross- and along-track per arc
- time bias per arc, range bias and tropospheric scaling factor for PRARE observations
- range bias for radar altimeter observations

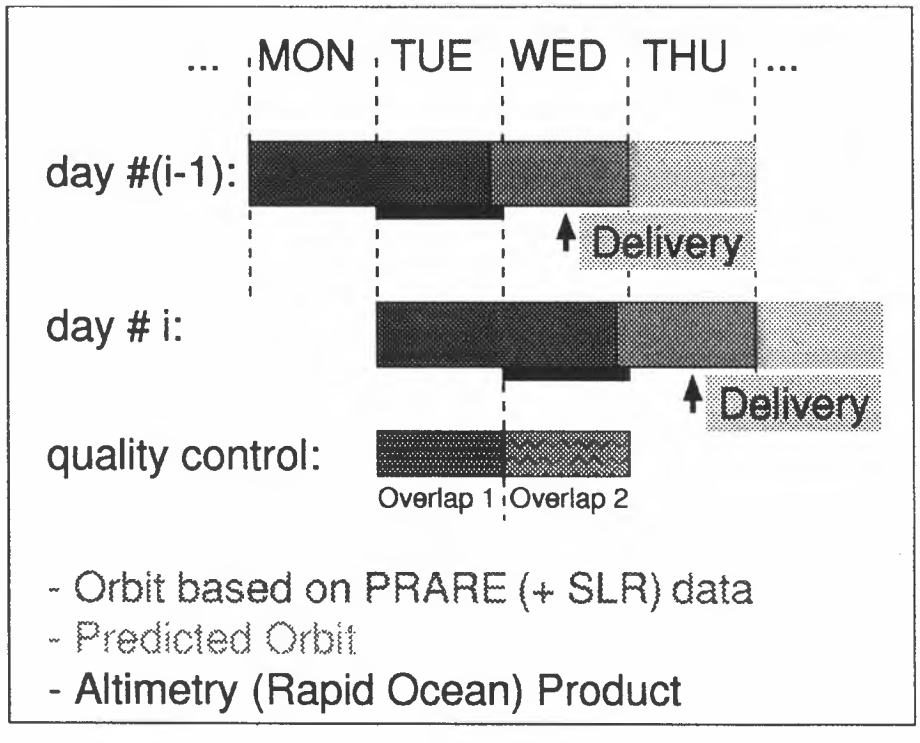

Fig.1: Time Schedule for Rapid Products

3. Internal Measures of the Orbit Quality

The quality of the operational RPDs is routinely analyzed by some internal quality tests:

- A natural measure of the orbit quality is the fit of the used observations to the adjusted orbit. In case of the RPD this means the rms of fit of the SLR, PRARE and RA data.
- Additionally the number of used observations has to be considered.
- Furthermore differences of overlapping orbit segments are an indicator for internal consistencies.

The following two tables list the ERS-2 results of the above mentioned tests for the period June 30 to July 13, 1997.

Day	RMS of Fit (cm, mm/s)				Number of Obs. (4-day arcs)			
	SLR	PRA	PDO	RA	SLR	PRA	PDO	RA
30-Jun-1997	10.7	8.4	0.51	27.3	208	2225	2038	2784
01-Jul-1997	7.1	7.2	0.49	44.5	193	2178	2169	2660
02-Jul-1997	9.4	8.6	0.56	55.1	246	2099	2197	2689
03-Jul-1997	8.5	9.1	0.57	23.1	241	2480	2461	1360
04-Jul-1997	9.5	7.3	0.49	27.8	333	2410	2377	2671
05-Jul-1997	8.1	8.4	0.49	26.3	114	2807	2814	2319
06-Jul-1997	7.4	8.7	0.50	28.3	131	2889	2796	2362
07-Jul-1997	14.3	10.3	0.61	28.1	197	2731	2712	2765
08-Jul-1997	13.4	9.9	0.56	24.4	339	2776	2658	2779
09-Jul-1997	8.9	7.5	0.46	28.0	321	2703	2620	2676
10-Jul-1997	7.7	7.0	0.46	30.3	297	1690	1773	2833
11-Jul-1997	8.5	6.5	0.43	28.7	445	1831	1941	2777
12-Jul-1997	10.3	8.1	0.54	29.8	353	2572	2688	2593
13-Jul-1997	9.5	9.2	0.56	30.4	251	2740	2805	2626
Mean	9.5	8.3	0.52	30.9	262	2438	2432	2561

The mean residuals of the fit are significantly smaller than the corresponding residuals of the PRL (mean residuals of January to June 1997 are: 12.3 cm SLR, 11.4 cm PRA, 0.74 mm/s PDO). The numbers of observations demonstrate the continous high amount of PRARE data, whereas the number of SLR data varies from day to day.

Although the Radar Altimeter data are heavily downweighted, they fit the computed arc with an almost constant accuracy of approx. 30 cm.

Day	Overlaps: RMS of Differences (cm)		
	radial	cross	along
30-Jun-1997	2.1	8.1	10.0
01-Jul-1997	1.1	8.6	8.3
02-Jul-1997	0.6	2.2	9.5
03-Jul-1997	1.1	4.9	11.1
04-Jul-1997	2.3	3.5	9.5
05-Jul-1997	1.4	5.4	15.3
06-Jul-1997	0.8	5.3	7.4
07-Jul-1997	2.9	4.8	16.4
08-Jul-1997	5.0	8.8	22.5
09-Jul-1997	2.2	4.1	7.7
10-Jul-1997	2.5	6.3	18.0
11-Jul-1997	2.1	15.5	8.5
12-Jul-1997	0.9	3.9	9.5
13-Jul-1997	3.0	2.7	14.4
Mean	2.0	6.0	12.0

The corresponding overlaps of the PRL are 2.7 cm, 19.6 cm, and 10.2 cm resp.

The smaller residuals and the better fit of the overlaps of the RPD with respect to the PRL are a result of the shorter arc lengths, the use of 1/rev empirical cross-track accelerations, and the improved gravity field model.

4. Comparisons of the RPD with the PRL

In order to investigate the absolute quality two external checks are routinely performed:

- Comparison with the Preliminary Orbit (PRL) after approx. 1 week
- Crossover computation in order to estimate the radial accuracy (see chapter 6)

The resulting values for the comparison of the RPD orbit with the PRL orbit are listed in the following table for the period of investigation.

Day	Comparison RPD-PRL: RMS (cm)		
	radial	cross	along
30-Jun-1997	5	14	17
01-Jul-1997	5	17	17
02-Jul-1997	6	12	19
03-Jul-1997	5	10	15
04-Jul-1997	5	11	17
05-Jul-1997	5	12	18
06-Jul-1997	5	17	14
07-Jul-1997	10	17	37
08-Jul-1997	5	12	16
09-Jul-1997	6	15	22
10-Jul-1997	6	19	23
11-Jul-1997	4	11	16
12-Jul-1997	6	10	17
13-Jul-1997	4	10	20
Mean	5.5	13	19

Since the mean deviation of the equipotential surfaces of the two models PGM073w and PGM055 at an altitude of 785 km is approximately 5.5 cm, the observed mean radial orbit RMS difference between PRL (PGM055) and rapid orbit (PGM073w) of 5.5 cm is caused by the difference of these two models.

The deviation of RPD with respect to PRL in cross-track and along-track direction can be explained by a reduced accuracy of the predicted values of solar flux, geomagnetic activity (used in the drag modeling), and pole position.

5. Rapid Ocean Product Records (ROPR)

5.1 Product Definition

ESA distributes fast delivery radar altimeter data (ERS-1/2.ALT.URA) from the ground stations of Kiruna, Maspalomas and Gatineau within three hours after measurement. At D-PAF this data is received, collected and used for further processing (orbit determination, quick-look sea surfaces). Prince Albert data are also transmitted to D-PAF, but with one week delay, hence they are not included in the rapid ocean product records.
The fast delivery altimeter products consist of time-tagged altimeter range, the footprint location, significant wave height, sigma naught and corrections for the dry tropospheric and ionospheric path delay. These corrections are interpolated from standard tables. The dry tropospheric correction is interpolated from look-up tables and the wet tropospheric correction is set to a constant value of -10 cm, thus both corrections are not based on actual meteorological data. Satellite height plus Earth and ocean tides are missing.
For the generation of rapid ocean products, fast delivery altimeter data are upgraded by merging the satellite orbital height, by recomputing the altimeter path delay corrections and by applying the tidal corrections. For this purpose new ionospheric and tidal models are included to the products. The wet tropospheric correction is interpolated from monthly mean models based on ERS-1 radiometer data of a 3-year period.
Some additional corrections to the fast delivery data already were applied at the ground stations. The Doppler sign, which caused errors of ±1.7 cm in range was rectified. The datation offset of +2.45 msec, an improved internal range calibration and a sigma naught decrease of 0.16 dB were applied. For rapid ocean product generation the +83.7 cm distance of the antenna and the centre of gravity is considered. The original fast delivery data already contain a bias value of +40.6 cm which should take into account the relative bias between ERS-1 and ERS-2. Thus no additional bias is applied.
The upgraded fast delivery data then are separated into daily files and operationally transmitted to the D-PAF ftp-server for distribution. The record format is identical with the QLOPR format.

5.2 Compilation of sea surface heights

$$ssh(ROPR) = h_{sat} - (h_{alt} + c_{COG} + c_{ot} + c_{tl} + c_{set} + c_{wet} + c_{dry} + c_{ion})$$

h_{sat}: Interpolated satellite height from D-PAF rapid orbit (ERS-2.ORB.RPD) above WGS84 reference ellipsoid
h_{alt}: Uncorrected altimeter range from fast-delivery data (ERS-2.ALT.URA)
c_{COG}: Distance between the antenna and the centre of gravity (+83.7 cm)
c_{ot}: Ocean tide from FES95.2.1 (Le Provost et al., 1996)
c_{tl}: Tidal loading based on FES95.2.1 (Andersen & Ray, 1996)
c_{set}: Solid Earth tide (Schwiderski, 1980)
c_{dry}: Dry tropospheric correction according to original correction in the fast-delivery data
c_{wet}: Wet tropospheric correction retrieved from a wet tropospheric model, which was exclusively implemented for the rapid ocean product record generation. The model is

based on ERS-1 radiometer data of a 3-year time period. The model considers day/night and monthly variations of the wet troposphere. Quality tests have shown an accuracy of the wet tropospheric model of better than ±3 cm. In case of absence of the model correction the original constant correction from the fast-delivery data is taken and marked by a flag.

c_{ion}: Ionospheric correction from IRI95 model (Bilitza, 1996)

The quality of the rapid ocean product records is given primarily by the standard deviation of the fast delivery altimeter measurements coming from the LRDPF (Low Rate Data Processing Facility). Moreover the quality depends on the orbit accuracy and the accuracy of the models used to compute the altimeter path delay and the tidal corrections. This is defined in the record status flag at the end of each record. This record flag together with the standard deviation of altimeter range is an indicator for the quality of each record.

6. ROPR Crossover Statistics

The following table shows the statistics of SSH crossover differences between ascending and descending tracks. Sea surface heights were computed as described above (see chapter 5.2). Both crossover events are located within the same day, thus the maximum time difference is always less than 24 hours. A 3-sigma criterion was applied in order to reject outliers. For the investigation period not more than 1 outlier per day was detected.

Day	Mean (cm)	RMS (cm)	No. Crossover
30-Jun-1997	2.1	12.1	42
01-Jul-1997	3.6	7.6	29
02-Jul-1997	1.9	11.5	49
03-Jul-1997	-0.8	10.3	43
04-Jul-1997	-3.7	13.6	24
05-Jul-1997	7.5	11.8	22
06-Jul-1997	-0.1	10.6	44
07-Jul-1997	7.3	13.2	42
08-Jul-1997	0.8	14.6	36
09-Jul-1997	3.3	9.2	44
10-Jul-1997	4.7	12.0	41
11-Jul-1997	2.9	13.8	44
12-Jul-1997	4.1	12.8	50
13-Jul-1997	4.3	9.9	42
Mean	2.7	11.6	39

7. Comparison of ROPR with QLOPR

For this purpose crossover statistics were generated for QLOPR for the same period as for the ROPR (chapter 7.2). Furthermore ROPR and QLOPR altimeter tracks were investigated by means of collinear track analysis (see chapter 7.3), and by performing gradient tests for both data sets with respect to a long-period sea surface height model based on ERS-2 OPR02 altimeter data (see chapter 7.4).

7.1 Compilation of QLOPR sea surface heights

The computation of sea surface heights from QLOPR differs from sea surface height processing based on ROPR concerning the orbit information and several range corrections. In the following the sea surface height computation for QLOPR is briefly summerized, a detailed description is given by (Gruber et al., 1997).

$$ssh(QLOPR) = h_{sat} - (h_{alt} + c_{USO} + c_{SPTR} + c_{COG} + c_{ot} + c_{tl} + c_{set} + c_{wet} + c_{dry} + c_{ion})$$

h_{sat}: Interpolated satellite height from D-PAF prelimenary orbit (ERS-2.ORB.PRL) above WGS84 reference ellipsoid

h_{alt}: Uncorrected altimeter range from fast-delivery data (ERS-2.ALT.URA)

c_{USO}: Range correction due to the drift of the ultra stable oscillator (USO drift). For the investigation period a value of +12 mm was applied.

c_{SPTR}: Range correction due to an internal timing error. The error can be quantified from the single pulse target response (SPTR) internal calibration data. For the investigation period values of -37 mm (30-Jun-97 to 03-Jul-97), -18 mm (04-Jul-97 to 12-Jul-97) and -17 mm (13-Jul-97) were applied.

c_{COG}: Distance between the antenna and the centre of gravity (+83.7 cm)

c_{ot}: Ocean tide from FES95.2.1 (Le Provost et al., 1996)

c_{tl}: Tidal loading based on FES95.2.1 (Andersen & Ray, 1996)

c_{set}: Solid Earth tide (Schwiderski, 1980)

c_{dry}: Dry tropospheric correction (Saastomoinen, 1972) using ECMWF meteorological data (provided by UK-PAF). In case of absence of the actual meteorological data the original correction from the fast-delivery data is taken.

c_{wet}: Wet tropospheric correction (Tapley et al., 1984) using ECMWF meteorological data (ibid.) . In case of absence of the actual meteorological data the original correction from the fast-delivery data is taken.

c_{ion}: Ionospheric correction from IRI95 model (Bilitza, 1996)

7.2 QLOPR Crossover Statistics

The table shows the statistics of SSH crossover differences,which were computed in the same way as described above (chapter 6).

Day	Mean (cm)	RMS (cm)	No. Crossover
30-Jun-1997	0.2	13.3	50
01-Jul-1997	3.8	11.0	38
02-Jul-1997	6.1	14.2	56
03-Jul-1997	2.2	12.3	52
04-Jul-1997	-4.4	12.2	35
05-Jul-1997	6.1	16.0	28
06-Jul-1997	-0.4	8.6	50
07-Jul-1997	-3.5	9.7	54
08-Jul-1997	4.7	16.9	46
09-Jul-1997	2.9	10.3	53
10-Jul-1997	3.5	10.5	55
11-Jul-1997	2.2	13.4	52
12-Jul-1997	-0.3	12.3	60
13-Jul-1997	2.2	8.2	49
Mean	1.7	11.9	48

The first remarkable divergence to the crossover statistics of the ROPR is the higher number of crossovers. The reason for this is the missing fast-delivery data from Prince Albert ground station in the ROPR. Moreover, it has to be noted that many crossovers are located in ice-covered areas. In open ocean areas the crossovers are grouped on latitude bands, thus the crossover differences are representative for comparison studies only, but not suitable for further investigations.

7.3 Collinear Analysis between ROPR and QLOPR

Collinear tracks between ROPR and QLOPR were compared by subtrackting QLOPR sea surface heights from ROPR sea surface heights. The statistics were generated for each day of the investigation period in order to compare the results with the statistics of the crossover differences. In order to distinguish between the influences of orbit and corrected range two additional statistics were generated. The radial orbit difference was computed from ROPR interpolated satellite height minus QLOPR interpolated satellite height. It should be noted that these differences were calculated at single altimeter points, which is not comparable to the differences given in the table before (see chapter 4), in which the differences are made at normal points with a 30 seconds time spacing. Additional, the statistics of ROPR corrected ranges minus QLOPR corrected ranges were also listed. This means in detail:

$$ssh(ROPR) - ssh(QLOPR) = h_{sat}(ROPR) - h_{alt\_c}(ROPR) - h_{sat}(QLOPR) + h_{alt\_c}(QLOPR)$$

$$= \{h_{sat}(ROPR) - h_{sat}(QLOPR)\} - \{h_{alt\_c}(ROPR) - h_{alt\_c}(QLOPR)\}$$

Day	ssh difference		radial orbit differ.		RA range differ.	
	Mean (cm)	RMS (cm)	Mean (cm)	RMS (cm)	Mean (cm)	RMS (cm)
30-Jun-1997	3.4	7.8	0.0	4.9	-3.4	6.0
01-Jul-1997	3.4	7.6	0.1	6.6	-3.3	7.6
02-Jul-1997	2.8	9.1	-0.4	7.8	-3.1	7.1
03-Jul-1997	3.6	7.8	0.2	5.7	-3.3	5.4
04-Jul-1997	4.8	6.9	-0.1	4.8	-4.9	5.4
05-Jul-1997	4.6	7.6	-0.3	5.3	-4.9	5.1
06-Jul-1997	5.8	8.3	1.4	9.0	-4.4	8.4
07-Jul-1997	6.3	12.0	1.4	13.3	-4.9	8.3
08-Jul-1997	5.5	8.2	0.2	5.5	-5.3	6.0
09-Jul-1997	5.4	9.1	0.3	6.5	-5.2	6.3
10-Jul-1997	8.2	12.3	0.2	5.3	-8.0	10.4
11-Jul-1997	6.1	8.2	0.6	5.0	-5.5	6.5
12-Jul-1997	4.7	8.3	-0.2	6.5	-4.9	5.6
13-Jul-1997	6.1	7.4	0.6	5.1	-5.5	5.3
Mean	4.9	8.9	0.1	6.7	-4.8	6.8

Some statements can be concluded from the table above. The mean values of the radial orbit differences vary slightly around 0, only at the interchange between July 6 and July 7 higher variations appear, maybe due to a track containing corrupt PRARE or laser information. The mean values of the ssh differences are in general caused by the mean values of the range differences. In this context first a 16 mm jump from July 3 to July 4 is visible, which is caused by the SPTR correction (see chapter 7.1). With the assumption that all path delay and tidal corrections are equal for ROPR and QLOPR, the corrected ranges of the investigation period from ROPR should be larger than the QLOPR ranges due to USO drift and SPTR range correction. This is, however, not convenient for the wet and dry tropospheric correction, which introduce a bias of -6 to -8 cm to the corrected altimeter ranges. This means that a bias between ROPR and QLOPR is caused by the USO drift and SPTR range correction, which are only applied for QLOPR, and by the tropospheric corrections. This statement, however, has to be seen independently from an assumption concerning a bias to an absolute reference.

7.4 Gradient tests

Gradients tests of ROPR and QLOPR were performed for the entire investigation period with respect to a 1.5-year sea surface model (SSH_L96319) which is based on ERS-2 OPR02 altimeter data. The table displays the statistics of 3 seperate analysis: Case A shows the RMS differences of computed along-track sea surface heights from ROPR and QLOPR minus the interpolated sea surface heights from the model. The next test (case B) reveals the RMS of the gradients of the computed along-track sea surface heights. At least, for case C the gradients of the differences between the computed along-track sea surface heights and the interpolated model sea surface heights were calculated and a statistic analysis was performed. A small RMS in case C represents a good agreement between the along-track sea surface heights and the model.

	ROPR		QLOPR	
	Mean	RMS	Mean	RMS
case A [cm]	10.5	40.9	4.9	37.9
case B [cm/km]	0.0	2.47	0.0	2.45
case C [cm/km]	0.0	1.64	0.0	1.63

Case A shows that the SSH differences with respect to the long-period sea surface model have higher variations for ROPR than for QLOPR. The higher mean value results from the shorter corrected range for ROPR (see chapter 7.3). Case B exibits a slightly higher variation for ROPR, maybe one reason for this is the higher noise due to missing corrections like actual meterological corrections, USO drift and SPTR range correction. Case C shows that the along-track sea surface heights from ROPR are on the same level of agreement as the QLOPR along-track sea surface heights with respect to the model sea surface heigths.

8. Conclusion

For the investigation period from June 30 to July 13, 1997 several quality tests were performed concerning the orbit determination and the altimetry. Internal and external checks concerning the orbit determination revealed a good and stable quality of RPD orbit, which is comparable to the quality of PRL orbit. Although the altimeter tracks from Prince Albert ground station are missing in the ROPR, the quality is slighly worse by a few cm than QLOPR, which has been demonstrated by the RMS differences at crossover points and the gradient tests. The tropospheric corrections of ROPR ranges are based on look-up tables and model assumptions only, also missing are the USO drift and SPTR range correction. Thus, a bias of approx. 5 cm and slighly higher noise are included in the ROPR altimeter ranges, which was pointed out by collinear analysis. Better coverage of ROPR data can be obtained if altimeter data from Prince Albert ground station will be available within 3 hours after acquisition, as well as the data from the other 3 ground stations.

9. References

9.1 Applicable Documents

ERS-D-GPM-31200; The German PAF for ERS; *Altimeter and Orbit Global Products Manual*; issue July 14, 1997.

ERS-D-STD-31101; The German PAF for ERS; *ERS Standards used at D-PAF*; issue September 1996.

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Le Provost C., Lyard F., Molines J.M., Genco M.L., Rabilloud F. (1996); *A hydrodynamic ocean tide model improved by assimilating a satellite altimeter derived data set*; in press at Journal of Geophysical Research.

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Tapley B.D., Lundberg J.B., and Born G.H. (1982); *The Seasat Altimeter Wet Tropospheric Range Correction revised*; Marine Geodesy 8, 221-248.

Zhu, S.Y., Reigber, Ch., and Massmann F.-H. (1991); *Some Improvements of the Solid Earth Tide Model*; Manuscripta Geodaetica 16, 215-220.

Abbreviations

CIO	Conventional International Origin
CIRA	COSPAR International Reference Atmosphere
CIS	Conventional Inertial System
CTS	Conventional Terrestrial System
D-PAF	German Processing and Archiving Facility for ERS
DMA	Defence Mapping Agency
ECMWF	European Centre for Medium-Range Weather Forcasting
ERS	European Remote Sensing Satellite
ESA	European Space Agency
FES	Grenoble Finite Element Solution
GFZ	GeoForschungsZentrum Potsdam
GPS	Global Positioning System
GRGS	Groupe de Recherche de Geodesie Spatiale
IAU	International Astronomical Union
IERS	International Earth Rotation Service
IRI95	International Reference Ionosphere 1995
ITRF	International Terrestrial Reference System
JPL	Jet Propulsion Laboratory
LRDPF	Low-Rate Data Processing Facility
NIMA	National Imagery Mapping Agency
QLOPR	Quick-Look Ocean Product Record
PDO	PRARE Doppler
PGM	Potsdam Gravity Model
PRA	PRARE Range
PRARE	Precise Range and Range Rate Equipment
PRL	Preliminary Orbit
RA	Radar Altimeter
RA-FD	Radar Altimeter Fast-Delivery Data
RPD	Rapid Orbit
ROPR	Rapid Ocean Product Record
SLR	Satellite Laser Ranging
SPTR	Single Path Target Response
USO	Ultra Stable Oscillator
UTC	Universal Time Coordinated
WGS	World Geodetic System

GeoForschungsZentrum Potsdam (GFZ)

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GFZ/D-PAF
c/o DLR
P.O.Box 1116
D-82230 Oberpfaffenhofen
Germany

Phone: (+49) 8153 28 1435
(+49) 8153 28 1267
Fax: (+49) 8153 28 1207
E-mail: Klaus.Enninghorst@dlr.de
Matthias.Rentsch@dlr.de

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Geomagnetic indices	predicted values
Surface forces	Macro-Model
Earth rotation	IERS Bulletin A (predicted)
Nutation	IAU 1980 plus corrections
Earth radiation	albedo and infrared
Earth tides	modified Wahr (Zhu et al., 1991)

The PGM073w Earth gravity model is a derivative of the PGM055 (based on GRIM4-S4 with additional ERS-1 data) by adding ERS-2 PRARE data, GFZ-1 information and by combining this with normals generated from terrestrial and altimetric gravity data provided from NIMA.

The solve-for parameters are:
- six initial orbital elements
- air drag coefficients: one global parameter plus 12 hourly values for the first two days
- 1/rev empirical acceleration cross- and along-track per arc
- time bias per arc, range bias and tropospheric scaling factor for PRARE observations
- range bias for radar altimeter observations

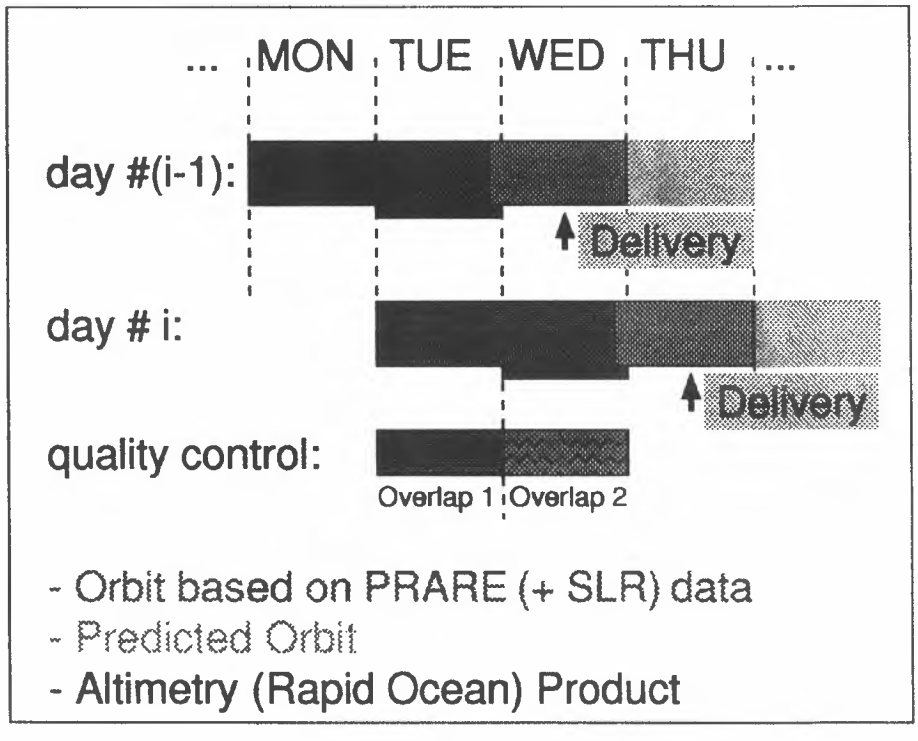

Fig.1: Time Schedule for Rapid Products

3. Internal Measures of the Orbit Quality

The quality of the operational RPDs is routinely analyzed by some internal quality tests:

- A natural measure of the orbit quality is the fit of the used observations to the adjusted orbit. In case of the RPD this means the rms of fit of the SLR, PRARE and RA data.
- Additionally the number of used observations has to be considered.
- Furthermore differences of overlapping orbit segments are an indicator for internal consistencies.

The following two tables list the ERS-2 results of the above mentioned tests for the period June 30 to July 13, 1997.

Day	RMS of Fit (cm, mm/s)				Number of Obs. (4-day arcs)			
	SLR	PRA	PDO	RA	SLR	PRA	PDO	RA
30-Jun-1997	10.7	8.4	0.51	27.3	208	2225	2038	2784
01-Jul-1997	7.1	7.2	0.49	44.5	193	2178	2169	2660
02-Jul-1997	9.4	8.6	0.56	55.1	246	2099	2197	2689
03-Jul-1997	8.5	9.1	0.57	23.1	241	2480	2461	1360
04-Jul-1997	9.5	7.3	0.49	27.8	333	2410	2377	2671
05-Jul-1997	8.1	8.4	0.49	26.3	114	2807	2814	2319
06-Jul-1997	7.4	8.7	0.50	28.3	131	2889	2796	2362
07-Jul-1997	14.3	10.3	0.61	28.1	197	2731	2712	2765
08-Jul-1997	13.4	9.9	0.56	24.4	339	2776	2658	2779
09-Jul-1997	8.9	7.5	0.46	28.0	321	2703	2620	2676
10-Jul-1997	7.7	7.0	0.46	30.3	297	1690	1773	2833
11-Jul-1997	8.5	6.5	0.43	28.7	445	1831	1941	2777
12-Jul-1997	10.3	8.1	0.54	29.8	353	2572	2688	2593
13-Jul-1997	9.5	9.2	0.56	30.4	251	2740	2805	2626
Mean	9.5	8.3	0.52	30.9	262	2438	2432	2561

The mean residuals of the fit are significantly smaller than the corresponding residuals of the PRL (mean residuals of January to June 1997 are: 12.3 cm SLR, 11.4 cm PRA, 0.74 mm/s PDO). The numbers of observations demonstrate the continous high amount of PRARE data, whereas the number of SLR data varies from day to day.

Although the Radar Altimeter data are heavily downweighted, they fit the computed arc with an almost constant accuracy of approx. 30 cm.

Day	Overlaps: RMS of Differences (cm)		
	radial	cross	along
30-Jun-1997	2.1	8.1	10.0
01-Jul-1997	1.1	8.6	8.3
02-Jul-1997	0.6	2.2	9.5
03-Jul-1997	1.1	4.9	11.1
04-Jul-1997	2.3	3.5	9.5
05-Jul-1997	1.4	5.4	15.3
06-Jul-1997	0.8	5.3	7.4
07-Jul-1997	2.9	4.8	16.4
08-Jul-1997	5.0	8.8	22.5
09-Jul-1997	2.2	4.1	7.7
10-Jul-1997	2.5	6.3	18.0
11-Jul-1997	2.1	15.5	8.5
12-Jul-1997	0.9	3.9	9.5
13-Jul-1997	3.0	2.7	14.4
Mean	2.0	6.0	12.0

The corresponding overlaps of the PRL are 2.7 cm, 19.6 cm, and 10.2 cm resp.

The smaller residuals and the better fit of the overlaps of the RPD with respect to the PRL are a result of the shorter arc lengths, the use of 1/rev empirical cross-track accelerations, and the improved gravity field model.

4. Comparisons of the RPD with the PRL

In order to investigate the absolute quality two external checks are routinely performed:

- Comparison with the Preliminary Orbit (PRL) after approx. 1 week
- Crossover computation in order to estimate the radial accuracy (see chapter 6)

The resulting values for the comparison of the RPD orbit with the PRL orbit are listed in the following table for the period of investigation.

Day	Comparison RPD-PRL: RMS (cm)		
	radial	cross	along
30-Jun-1997	5	14	17
01-Jul-1997	5	17	17
02-Jul-1997	6	12	19
03-Jul-1997	5	10	15
04-Jul-1997	5	11	17
05-Jul-1997	5	12	18
06-Jul-1997	5	17	14
07-Jul-1997	10	17	37
08-Jul-1997	5	12	16
09-Jul-1997	6	15	22
10-Jul-1997	6	19	23
11-Jul-1997	4	11	16
12-Jul-1997	6	10	17
13-Jul-1997	4	10	20
Mean	5.5	13	19

Since the mean deviation of the equipotential surfaces of the two models PGM073w and PGM055 at an altitude of 785 km is approximately 5.5 cm, the observed mean radial orbit RMS difference between PRL (PGM055) and rapid orbit (PGM073w) of 5.5 cm is caused by the difference of these two models.

The deviation of RPD with respect to PRL in cross-track and along-track direction can be explained by a reduced accuracy of the predicted values of solar flux, geomagnetic activity (used in the drag modeling), and pole position.

5. Rapid Ocean Product Records (ROPR)

5.1 Product Definition

ESA distributes fast delivery radar altimeter data (ERS-1/2.ALT.URA) from the ground stations of Kiruna, Maspalomas and Gatineau within three hours after measurement. At D-PAF this data is received, collected and used for further processing (orbit determination, quick-look sea surfaces). Prince Albert data are also transmitted to D-PAF, but with one week delay, hence they are not included in the rapid ocean product records.
The fast delivery altimeter products consist of time-tagged altimeter range, the footprint location, significant wave height, sigma naught and corrections for the dry tropospheric and ionospheric path delay. These corrections are interpolated from standard tables. The dry tropospheric correction is interpolated from look-up tables and the wet tropospheric correction is set to a constant value of -10 cm, thus both corrections are not based on actual meteorological data. Satellite height plus Earth and ocean tides are missing.
For the generation of rapid ocean products, fast delivery altimeter data are upgraded by merging the satellite orbital height, by recomputing the altimeter path delay corrections and by applying the tidal corrections. For this purpose new ionospheric and tidal models are included to the products. The wet tropospheric correction is interpolated from monthly mean models based on ERS-1 radiometer data of a 3-year period.
Some additional corrections to the fast delivery data already were applied at the ground stations. The Doppler sign, which caused errors of ±1.7 cm in range was rectified. The datation offset of +2.45 msec, an improved internal range calibration and a sigma naught decrease of 0.16 dB were applied. For rapid ocean product generation the +83.7 cm distance of the antenna and the centre of gravity is considered. The original fast delivery data already contain a bias value of +40.6 cm which should take into account the relative bias between ERS-1 and ERS-2. Thus no additional bias is applied.
The upgraded fast delivery data then are separated into daily files and operationally transmitted to the D-PAF ftp-server for distribution. The record format is identical with the QLOPR format.

5.2 Compilation of sea surface heights

$$ssh(ROPR) = h_{sat} - (h_{alt} + c_{COG} + c_{ot} + c_{tl} + c_{set} + c_{wet} + c_{dry} + c_{ion})$$

h_{sat}: Interpolated satellite height from D-PAF rapid orbit (ERS-2.ORB.RPD) above WGS84 reference ellipsoid
h_{alt}: Uncorrected altimeter range from fast-delivery data (ERS-2.ALT.URA)
c_{COG}: Distance between the antenna and the centre of gravity (+83.7 cm)
c_{ot}: Ocean tide from FES95.2.1 (Le Provost et al., 1996)
c_{tl}: Tidal loading based on FES95.2.1 (Andersen & Ray, 1996)
c_{set}: Solid Earth tide (Schwiderski, 1980)
c_{dry}: Dry tropospheric correction according to original correction in the fast-delivery data
c_{wet}: Wet tropospheric correction retrieved from a wet tropospheric model, which was exclusively implemented for the rapid ocean product record generation. The model is

based on ERS-1 radiometer data of a 3-year time period. The model considers day/night and monthly variations of the wet troposphere. Quality tests have shown an accuracy of the wet tropospheric model of better than ±3 cm. In case of absence of the model correction the original constant correction from the fast-delivery data is taken and marked by a flag.

c_{ion}: Ionospheric correction from IRI95 model (Bilitza, 1996)

The quality of the rapid ocean product records is given primarily by the standard deviation of the fast delivery altimeter measurements coming from the LRDPF (Low Rate Data Processing Facility). Moreover the quality depends on the orbit accuracy and the accuracy of the models used to compute the altimeter path delay and the tidal corrections. This is defined in the record status flag at the end of each record. This record flag together with the standard deviation of altimeter range is an indicator for the quality of each record.

6. ROPR Crossover Statistics

The following table shows the statistics of SSH crossover differences between ascending and descending tracks. Sea surface heights were computed as described above (see chapter 5.2). Both crossover events are located within the same day, thus the maximum time difference is always less than 24 hours. A 3-sigma criterion was applied in order to reject outliers. For the investigation period not more than 1 outlier per day was detected.

Day	Mean (cm)	RMS (cm)	No. Crossover
30-Jun-1997	2.1	12.1	42
01-Jul-1997	3.6	7.6	29
02-Jul-1997	1.9	11.5	49
03-Jul-1997	-0.8	10.3	43
04-Jul-1997	-3.7	13.6	24
05-Jul-1997	7.5	11.8	22
06-Jul-1997	-0.1	10.6	44
07-Jul-1997	7.3	13.2	42
08-Jul-1997	0.8	14.6	36
09-Jul-1997	3.3	9.2	44
10-Jul-1997	4.7	12.0	41
11-Jul-1997	2.9	13.8	44
12-Jul-1997	4.1	12.8	50
13-Jul-1997	4.3	9.9	42
Mean	2.7	11.6	39

7. Comparison of ROPR with QLOPR

For this purpose crossover statistics were generated for QLOPR for the same period as for the ROPR (chapter 7.2). Furthermore ROPR and QLOPR altimeter tracks were investigated by means of collinear track analysis (see chapter 7.3), and by performing gradient tests for both data sets with respect to a long-period sea surface height model based on ERS-2 OPR02 altimeter data (see chapter 7.4).

7.1 Compilation of QLOPR sea surface heights

The computation of sea surface heights from QLOPR differs from sea surface height processing based on ROPR concerning the orbit information and several range corrections. In the following the sea surface height computation for QLOPR is briefly summerized, a detailed description is given by (Gruber et al., 1997).

$$ssh(QLOPR) = h_{sat} - (h_{alt} + c_{USO} + c_{SPTR} + c_{COG} + c_{ot} + c_{tl} + c_{set} + c_{wet} + c_{dry} + c_{ion})$$

h_{sat}: Interpolated satellite height from D-PAF prelimenary orbit (ERS-2.ORB.PRL) above WGS84 reference ellipsoid

h_{alt}: Uncorrected altimeter range from fast-delivery data (ERS-2.ALT.URA)

c_{USO}: Range correction due to the drift of the ultra stable oscillator (USO drift). For the investigation period a value of +12 mm was applied.

c_{SPTR}: Range correction due to an internal timing error. The error can be quantified from the single pulse target response (SPTR) internal calibration data. For the investigation period values of -37 mm (30-Jun-97 to 03-Jul-97), -18 mm (04-Jul-97 to 12-Jul-97) and -17 mm (13-Jul-97) were applied.

c_{COG}: Distance between the antenna and the centre of gravity (+83.7 cm)

c_{ot}: Ocean tide from FES95.2.1 (Le Provost et al., 1996)

c_{tl}: Tidal loading based on FES95.2.1 (Andersen & Ray, 1996)

c_{set}: Solid Earth tide (Schwiderski, 1980)

c_{dry}: Dry tropospheric correction (Saastomoinen, 1972) using ECMWF meteorological data (provided by UK-PAF). In case of absence of the actual meteorological data the original correction from the fast-delivery data is taken.

c_{wet}: Wet tropospheric correction (Tapley et al., 1984) using ECMWF meteorological data (ibid.) . In case of absence of the actual meteorological data the original correction from the fast-delivery data is taken.

c_{ion}: Ionospheric correction from IRI95 model (Bilitza, 1996)

7.2 QLOPR Crossover Statistics

The table shows the statistics of SSH crossover differences,which were computed in the same way as described above (chapter 6).

Day	Mean (cm)	RMS (cm)	No. Crossover
30-Jun-1997	0.2	13.3	50
01-Jul-1997	3.8	11.0	38
02-Jul-1997	6.1	14.2	56
03-Jul-1997	2.2	12.3	52
04-Jul-1997	-4.4	12.2	35
05-Jul-1997	6.1	16.0	28
06-Jul-1997	-0.4	8.6	50
07-Jul-1997	-3.5	9.7	54
08-Jul-1997	4.7	16.9	46
09-Jul-1997	2.9	10.3	53
10-Jul-1997	3.5	10.5	55
11-Jul-1997	2.2	13.4	52
12-Jul-1997	-0.3	12.3	60
13-Jul-1997	2.2	8.2	49
Mean	1.7	11.9	48

The first remarkable divergence to the crossover statistics of the ROPR is the higher number of crossovers. The reason for this is the missing fast-delivery data from Prince Albert ground station in the ROPR. Moreover, it has to be noted that many crossovers are located in ice-covered areas. In open ocean areas the crossovers are grouped on latitude bands, thus the crossover differences are representative for comparison studies only, but not suitable for further investigations.

7.3 Collinear Analysis between ROPR and QLOPR

Collinear tracks between ROPR and QLOPR were compared by subtrackting QLOPR sea surface heights from ROPR sea surface heights. The statistics were generated for each day of the investigation period in order to compare the results with the statistics of the crossover differences. In order to distinguish between the influences of orbit and corrected range two additional statistics were generated. The radial orbit difference was computed from ROPR interpolated satellite height minus QLOPR interpolated satellite height. It should be noted that these differences were calculated at single altimeter points, which is not comparable to the differences given in the table before (see chapter 4), in which the differences are made at normal points with a 30 seconds time spacing. Additional, the statistics of ROPR corrected ranges minus QLOPR corrected ranges were also listed. This means in detail:

$$ssh(ROPR) - ssh(QLOPR) = h_{sat}(ROPR) - h_{alt\_c}(ROPR) - h_{sat}(QLOPR) + h_{alt\_c}(QLOPR)$$

$$= \{h_{sat}(ROPR) - h_{sat}(QLOPR)\} - \{h_{alt\_c}(ROPR) - h_{alt\_c}(QLOPR)\}$$

Day	ssh difference		radial orbit differ.		RA range differ.	
	Mean (cm)	RMS (cm)	Mean (cm)	RMS (cm)	Mean (cm)	RMS (cm)
30-Jun-1997	3.4	7.8	0.0	4.9	-3.4	6.0
01-Jul-1997	3.4	7.6	0.1	6.6	-3.3	7.6
02-Jul-1997	2.8	9.1	-0.4	7.8	-3.1	7.1
03-Jul-1997	3.6	7.8	0.2	5.7	-3.3	5.4
04-Jul-1997	4.8	6.9	-0.1	4.8	-4.9	5.4
05-Jul-1997	4.6	7.6	-0.3	5.3	-4.9	5.1
06-Jul-1997	5.8	8.3	1.4	9.0	-4.4	8.4
07-Jul-1997	6.3	12.0	1.4	13.3	-4.9	8.3
08-Jul-1997	5.5	8.2	0.2	5.5	-5.3	6.0
09-Jul-1997	5.4	9.1	0.3	6.5	-5.2	6.3
10-Jul-1997	8.2	12.3	0.2	5.3	-8.0	10.4
11-Jul-1997	6.1	8.2	0.6	5.0	-5.5	6.5
12-Jul-1997	4.7	8.3	-0.2	6.5	-4.9	5.6
13-Jul-1997	6.1	7.4	0.6	5.1	-5.5	5.3
Mean	4.9	8.9	0.1	6.7	-4.8	6.8

Some statements can be concluded from the table above. The mean values of the radial orbit differences vary slightly around 0, only at the interchange between July 6 and July 7 higher variations appear, maybe due to a track containing corrupt PRARE or laser information. The mean values of the ssh differences are in general caused by the mean values of the range differences. In this context first a 16 mm jump from July 3 to July 4 is visible, which is caused by the SPTR correction (see chapter 7.1). With the assumption that all path delay and tidal corrections are equal for ROPR and QLOPR, the corrected ranges of the investigation period from ROPR should be larger than the QLOPR ranges due to USO drift and SPTR range correction. This is, however, not convenient for the wet and dry tropospheric correction, which introduce a bias of -6 to -8 cm to the corrected altimeter ranges. This means that a bias between ROPR and QLOPR is caused by the USO drift and SPTR range correction, which are only applied for QLOPR, and by the tropospheric corrections. This statement, however, has to be seen independently from an assumption concerning a bias to an absolute reference.

7.4 Gradient tests

Gradients tests of ROPR and QLOPR were performed for the entire investigation period with respect to a 1.5-year sea surface model (SSH_L96319) which is based on ERS-2 OPR02 altimeter data. The table displays the statistics of 3 seperate analysis: Case A shows the RMS differences of computed along-track sea surface heights from ROPR and QLOPR minus the interpolated sea surface heights from the model. The next test (case B) reveals the RMS of the gradients of the computed along-track sea surface heights. At least, for case C the gradients of the differences between the computed along-track sea surface heights and the interpolated model sea surface heights were calculated and a statistic analysis was performed. A small RMS in case C represents a good agreement between the along-track sea surface heights and the model.

	ROPR		QLOPR	
	Mean	RMS	Mean	RMS
case A [cm]	10.5	40.9	4.9	37.9
case B [cm/km]	0.0	2.47	0.0	2.45
case C [cm/km]	0.0	1.64	0.0	1.63

Case A shows that the SSH differences with respect to the long-period sea surface model have higher variations for ROPR than for QLOPR. The higher mean value results from the shorter corrected range for ROPR (see chapter 7.3). Case B exibits a slightly higher variation for ROPR, maybe one reason for this is the higher noise due to missing corrections like actual meterological corrections, USO drift and SPTR range correction. Case C shows that the along-track sea surface heights from ROPR are on the same level of agreement as the QLOPR along-track sea surface heights with respect to the model sea surface heigths.

8. Conclusion

For the investigation period from June 30 to July 13, 1997 several quality tests were performed concerning the orbit determination and the altimetry. Internal and external checks concerning the orbit determination revealed a good and stable quality of RPD orbit, which is comparable to the quality of PRL orbit. Although the altimeter tracks from Prince Albert ground station are missing in the ROPR, the quality is slighly worse by a few cm than QLOPR, which has been demonstrated by the RMS differences at crossover points and the gradient tests. The tropospheric corrections of ROPR ranges are based on look-up tables and model assumptions only, also missing are the USO drift and SPTR range correction. Thus, a bias of approx. 5 cm and slighly higher noise are included in the ROPR altimeter ranges, which was pointed out by collinear analysis. Better coverage of ROPR data can be obtained if altimeter data from Prince Albert ground station will be available within 3 hours after acquisition, as well as the data from the other 3 ground stations.

9. References

9.1 Applicable Documents

ERS-D-GPM-31200; The German PAF for ERS; *Altimeter and Orbit Global Products Manual*; issue July 14, 1997.

ERS-D-STD-31101; The German PAF for ERS; *ERS Standards used at D-PAF*; issue September 1996.

9.2 Publications

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Bilitza D. (1996); *International Reference Ionosphere 1995*; pers. communication.

Gruber Th., Anzenhofer M., Rentsch M., and Romaneeßen E. (1997); *Improvements of D-PAF Altimeter Products*; Third ERS Symposium, Florence, Italy, March 17-21, 1997.

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Le Provost C., Lyard F., Molines J.M., Genco M.L., Rabilloud F. (1996); *A hydrodynamic ocean tide model improved by assimilating a satellite altimeter derived data set*; in press at Journal of Geophysical Research.

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Tapley B.D., Lundberg J.B., and Born G.H. (1982); *The Seasat Altimeter Wet Tropospheric Range Correction revised*; Marine Geodesy 8, 221-248.

Zhu, S.Y., Reigber, Ch., and Massmann F.-H. (1991); *Some Improvements of the Solid Earth Tide Model*; Manuscripta Geodaetica 16, 215-220.

Abbreviations

CIO	Conventional International Origin
CIRA	COSPAR International Reference Atmosphere
CIS	Conventional Inertial System
CTS	Conventional Terrestrial System
D-PAF	German Processing and Archiving Facility for ERS
DMA	Defence Mapping Agency
ECMWF	European Centre for Medium-Range Weather Forcasting
ERS	European Remote Sensing Satellite
ESA	European Space Agency
FES	Grenoble Finite Element Solution
GFZ	GeoForschungsZentrum Potsdam
GPS	Global Positioning System
GRGS	Groupe de Recherche de Geodesie Spatiale
IAU	International Astronomical Union
IERS	International Earth Rotation Service
IRI95	International Reference Ionosphere 1995
ITRF	International Terrestrial Reference System
JPL	Jet Propulsion Laboratory
LRDPF	Low-Rate Data Processing Facility
NIMA	National Imagery Mapping Agency
QLOPR	Quick-Look Ocean Product Record
PDO	PRARE Doppler
PGM	Potsdam Gravity Model
PRA	PRARE Range
PRARE	Precise Range and Range Rate Equipment
PRL	Preliminary Orbit
RA	Radar Altimeter
RA-FD	Radar Altimeter Fast-Delivery Data
RPD	Rapid Orbit
ROPR	Rapid Ocean Product Record
SLR	Satellite Laser Ranging
SPTR	Single Path Target Response
USO	Ultra Stable Oscillator
UTC	Universal Time Coordinated
WGS	World Geodetic System