REAPER: ERS-1 and ERS-2 Orbit Validation Report

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Chapter 1

Introduction

This documents contains the orbit validation results performed at ESOC as well as the altimeter validation results performed by Remko Scharroo of Altimetrics LCC.

The orbit and altimeter validation results in this report are based on the following solutions: from DEOS for ERS-1 solution number four and for ERS-2 solution number three, from GFZ for ERS-1 and ERS-2 solution number four (updated), from ESOC for ERS-1 and ERS-2 solution number three. The combination solution is based on the latest solution from the three analysis centres expect from GFZ were solution number three was used as solution four was delivered after the combination generation process was started.

Chapter 2 and 3 contain the ERS-1 and ERS-2 orbit validation results. Chapter 4 contains the altimter validation results and Chapter 5 contains the Conclusions.

Based on the altimeter validation results for ERS-1 and ERS-2 the combined orbit is recommended to be used for the REAPER reprocessing.

Chapter 2

ERS-1 Orbit Validation

This Chapter will contain all the ERS-1 orbit validation results.

The tables below list the yearly mean and *rms* orbit difference between the four different orbit solution for ERS-1. Outliers have been removed from the mean and *rms* computation. The editing criteria applied were if the total mean orbit difference was greater then 1 metre or if the total *rms* orbit difference was greater then 1.5 metre then the daily value was not used for the yearly mean or *rms* computation.

	1991	1992	1993	1994	1995	1996
mean						
radial	0.19	0.31	0.22	0.21	0.25	0.23
along	-2.40	1.86	0.87	0.75	0.57	2.00
cross	1.67	0.11	-0.29	0.17	-0.18	-0.11
rms						
radial	6.05	3.60	2.19	1.72	1.58	1.82
along	39.64	22.20	13.96	10.67	8.51	9.17
cross	33.72	28.00	18.89	11.16	8.62	9.49

Table 2.1: Yearly mean and *rms* orbit difference in centimetres for ERS-1 between DEOS and GFZ. Orbit difference is calculated as DEOS-GFZ.

	1991	1992	1993	1994	1995	1996
mean						
radial	0.58	0.10	0.06	0.05	0.05	0.03
along	1.49	-0.68	-0.06	2.68	1.53	0.51
cross	1.36	-0.12	-0.62	-0.13	-0.22	-0.36
rms						
radial	6.48	3.64	2.25	1.77	1.71	1.80
along	37.28	23.97	15.00	11.62	10.59	8.13
cross	29.79	17.51	11.73	8.44	8.14	6.81

Table 2.2: Yearly mean and *rms* orbit difference in centimetres for ERS-1 between DEOS and ESOC. Orbit difference is calculated as DEOS-ESOC.

	1991	1992	1993	1994	1995	1996
mean						
radial	0.13	0.08	0.02	0.07	0.05	0.02
along	-1.17	-0.29	0.50	0.50	0.47	1.27
cross	2.07	-0.08	-0.48	-0.16	-0.22	-0.34
rms						
radial	4.10	2.84	1.59	1.21	1.04	1.42
along	22.26	14.63	8.19	6.11	5.03	6.78
cross	24.62	17.02	9.51	5.83	5.01	5.96

Table 2.3: Yearly mean and *rms* orbit difference in centimetres for ERS-1 between DEOS and Combination. Orbit difference is calculated as DEOS-Combination.

	1991	1992	1993	1994	1995	1996
mean						
radial	-0.08	-0.25	-0.15	-0.16	-0.22	-0.18
along	2.14	-1.51	-1.10	1.66	0.79	-1.56
cross	-1.52	-0.51	-0.50	0.07	-0.05	-0.24
rms						
radial	7.27	3.41	2.21	1.83	1.79	1.93
along	39.64	24.55	15.44	12.05	10.20	9.38
cross	30.95	23.02	17.02	9.94	7.49	7.95

Table 2.4: Yearly mean and *rms* orbit difference in centimetres for ERS-1 between GFZ and ESOC. Orbit difference is calculated as GFZ-ESOC.

	1991	1992	1993	1994	1995	1996
mean						
radial	-0.11	-0.34	-0.19	-0.17	-0.20	-0.18
along	0.66	-1.24	-0.25	-0.38	-0.07	-0.87
cross	0.44	-0.10	-0.31	-0.27	-0.05	-0.24
rms						
radial	4.81	2.35	1.38	1.13	1.02	1.12
along	25.29	13.89	8.36	6.49	4.63	5.67
cross	26.19	17.93	14.40	7.00	4.51	5.44

Table 2.5: Yearly mean and *rms* orbit difference in centimetres for ERS-1 between GFZ and Combination. Orbit difference is calculated as GFZ-Combination.

	1991	1992	1993	1994	1995	1996
mean						
radial	0.03	0.03	-0.01	-0.00	0.02	-0.01
along	-0.37	1.03	1.17	-2.09	-1.14	0.88
cross	0.79	-0.01	0.29	-0.36	-0.00	0.06
rms						
radial	5.38	3.00	1.77	1.40	1.36	1.37
along	33.83	21.36	13.96	10.47	9.10	8.06
cross	31.32	17.08	11.18	7.17	6.14	6.26

Table 2.6: Yearly mean and *rms* orbit difference in centimetres for ERS-1 between ESOC and Combination. Orbit difference is calculated as ESOC-Combination.

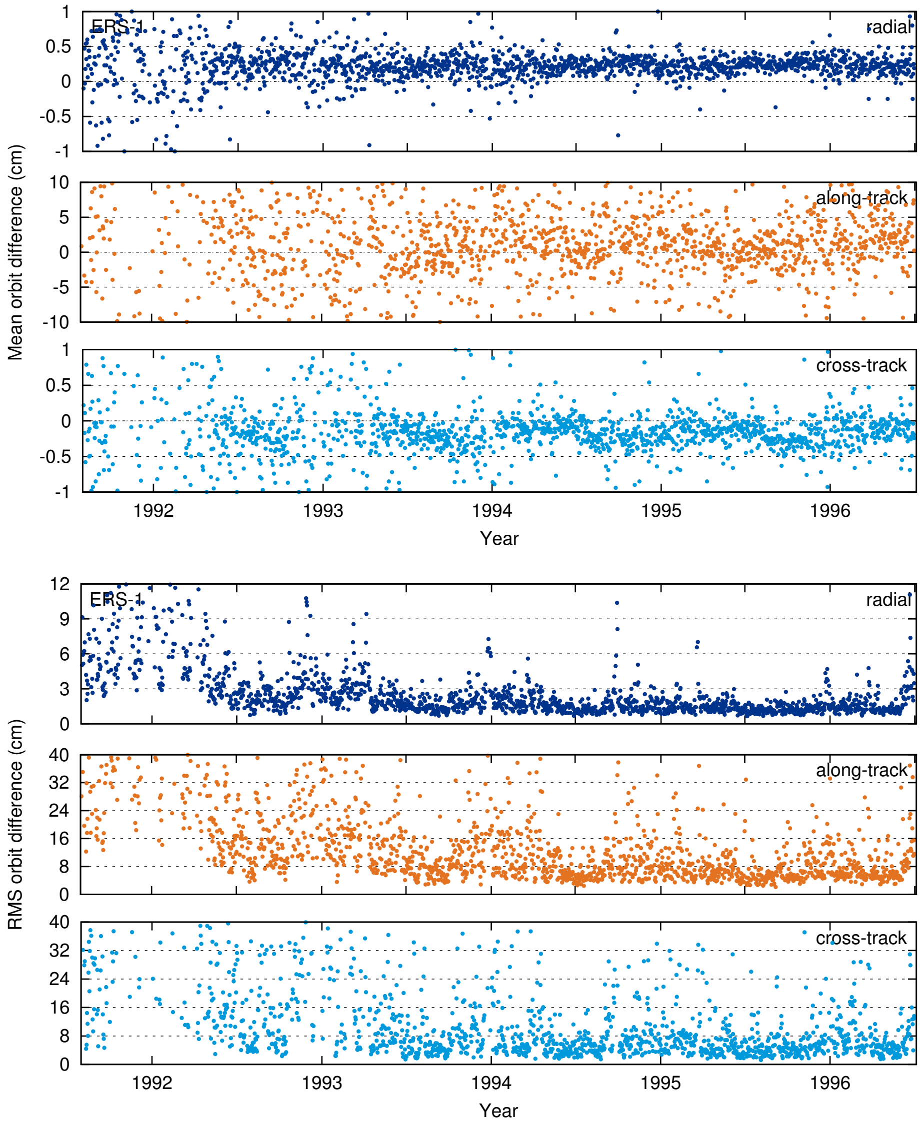


Figure 2.1: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-1 between DEOS and GFZ. Orbit difference is calculated as DEOS-GFZ.

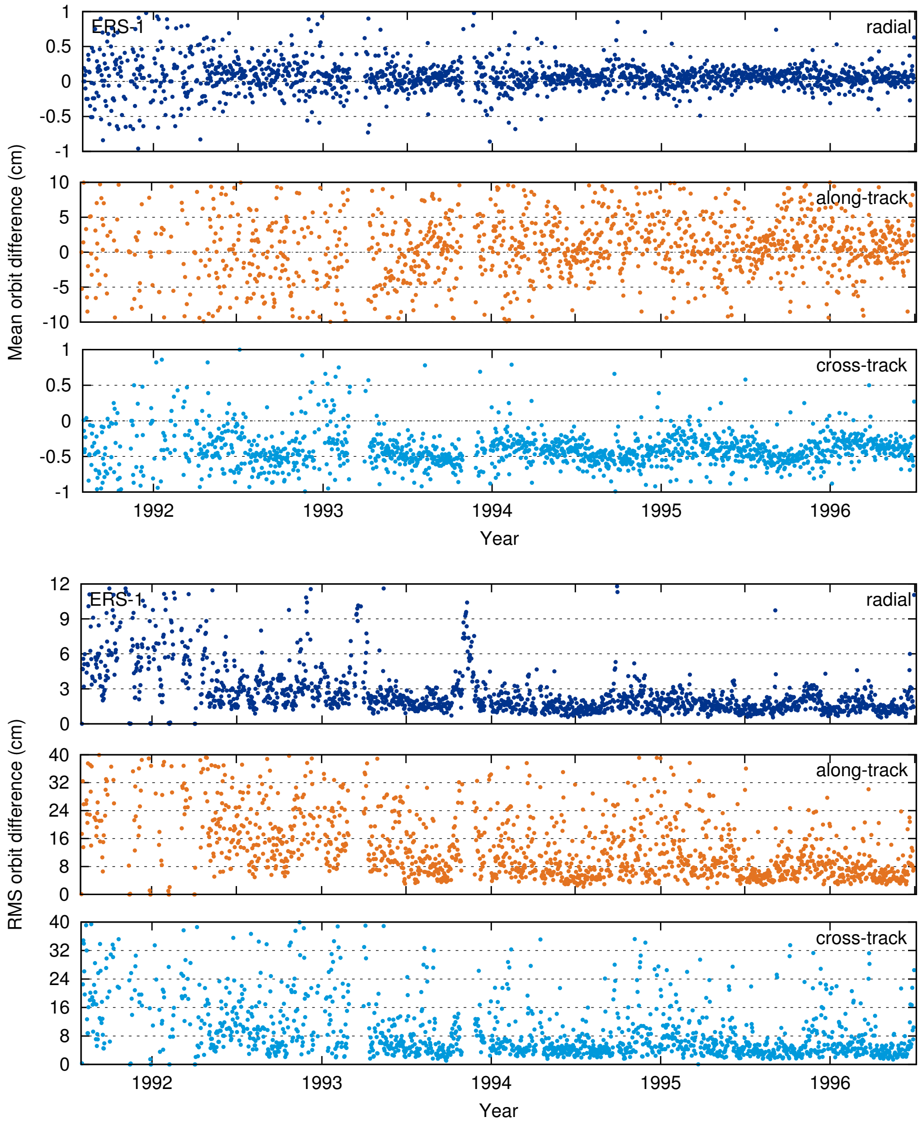


Figure 2.2: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-1 between DEOS and ESOC. Orbit difference is calculated as DEOS-ESOC.

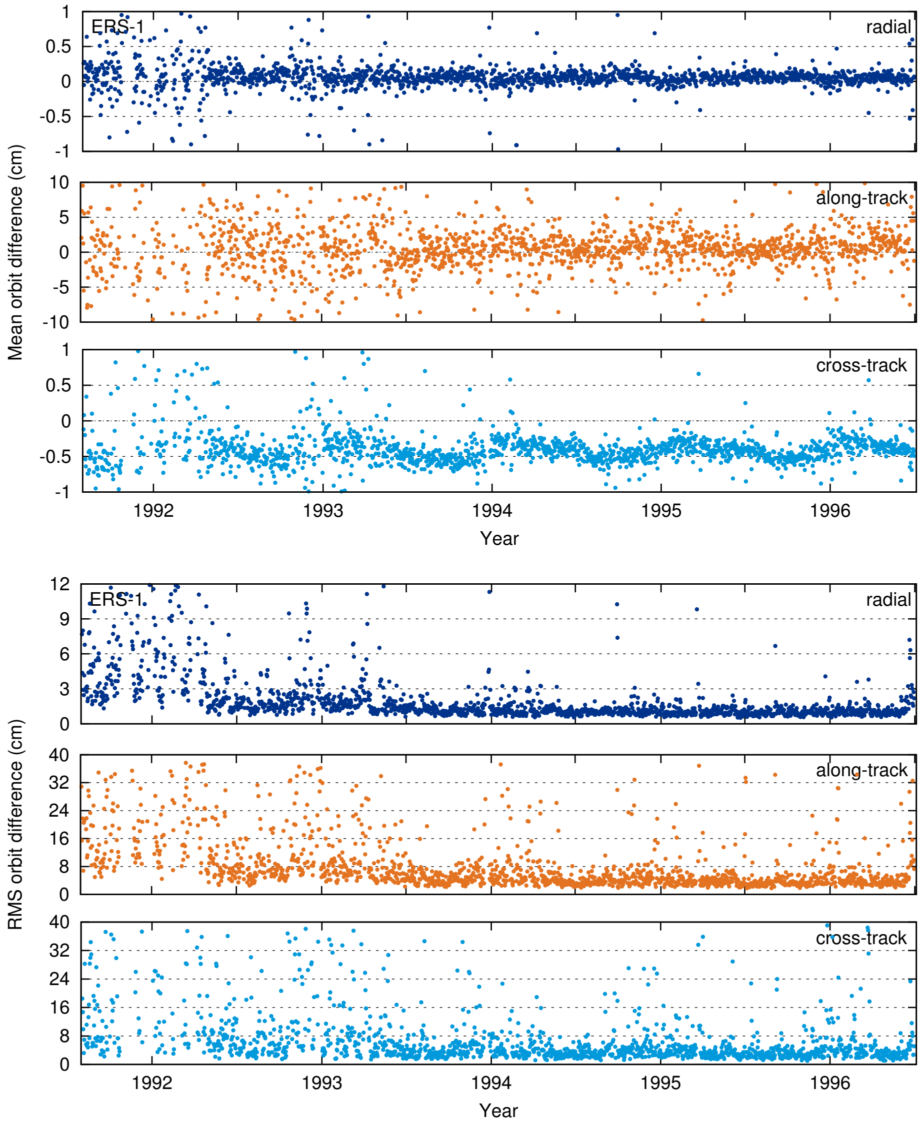


Figure 2.3: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-1 between DEOS and Combination. Orbit difference is calculated as DEOS-Combination.

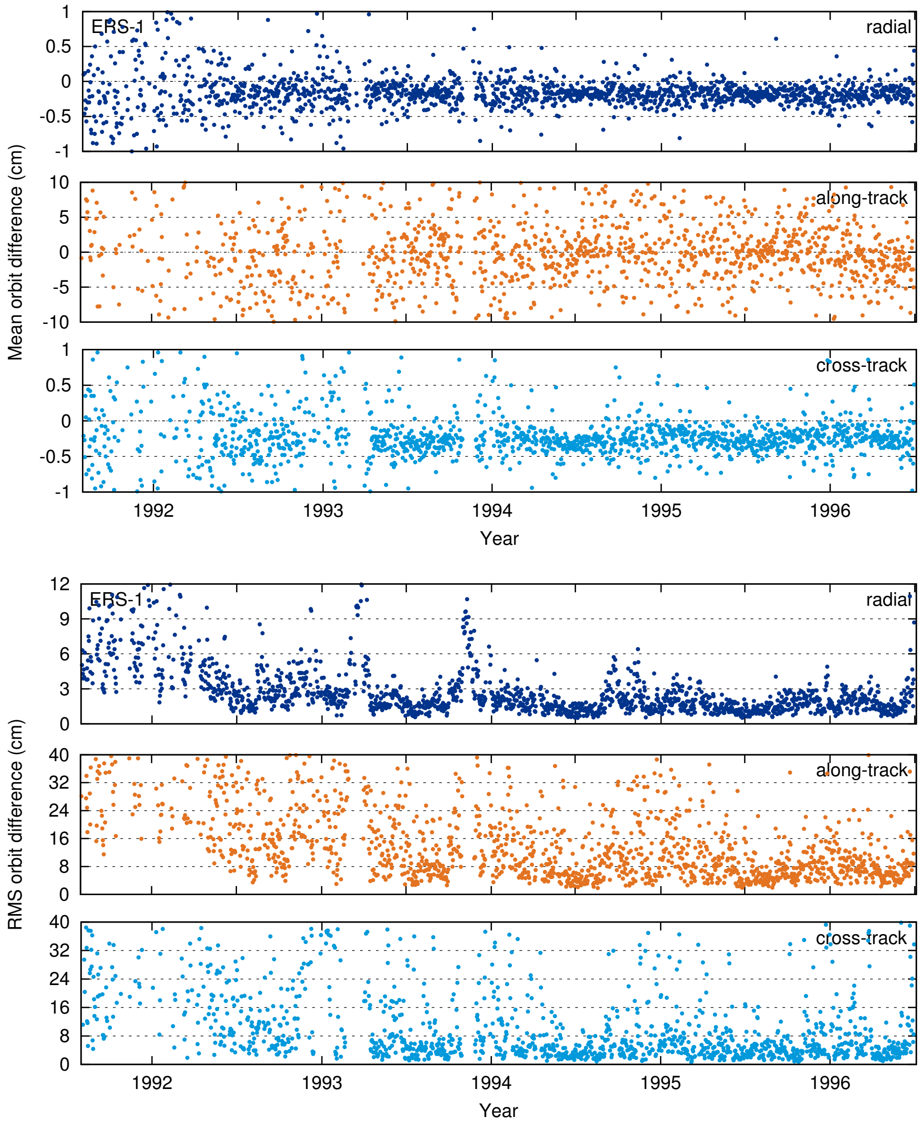
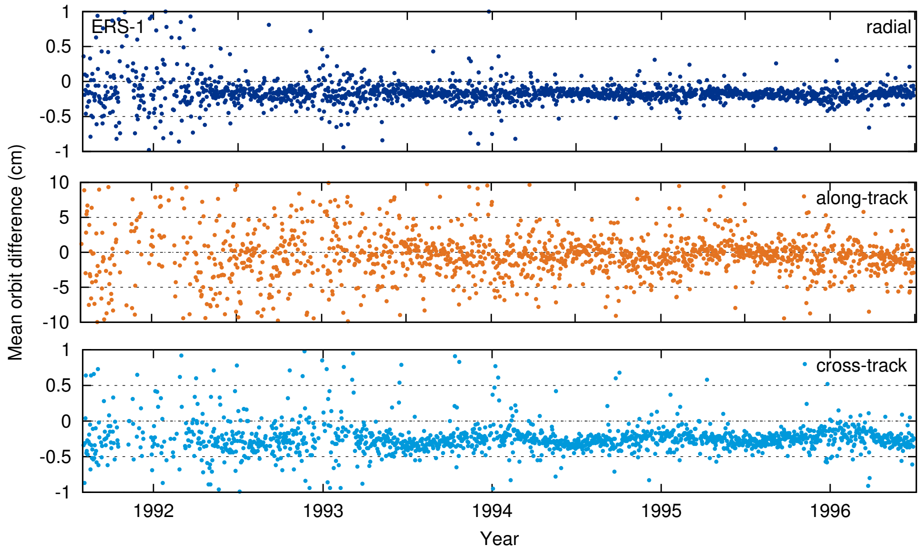


Figure 2.4: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-1 between GFZ and ESOC. Orbit difference is calculated as GFZ-ESOC.



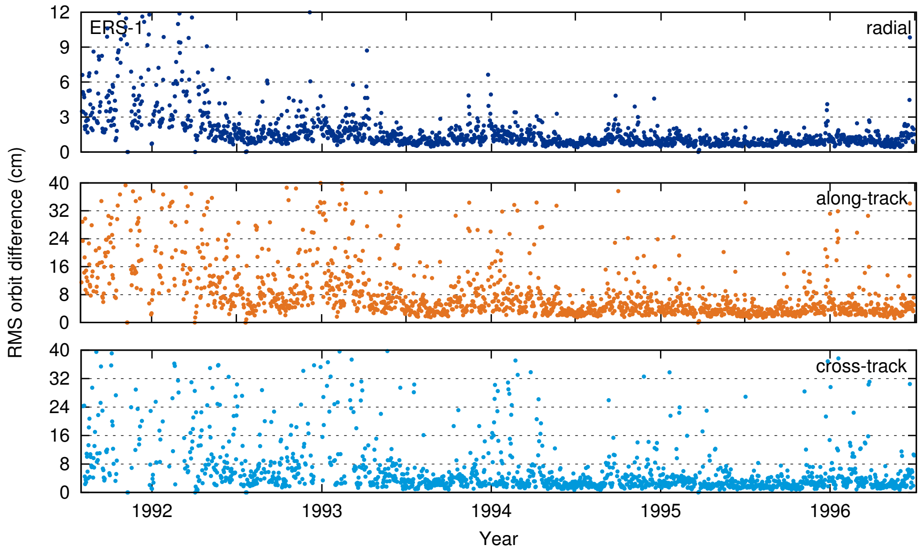


Figure 2.5: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-1 between GFZ and Combination. Orbit difference is calculated as GFZ-Combination.

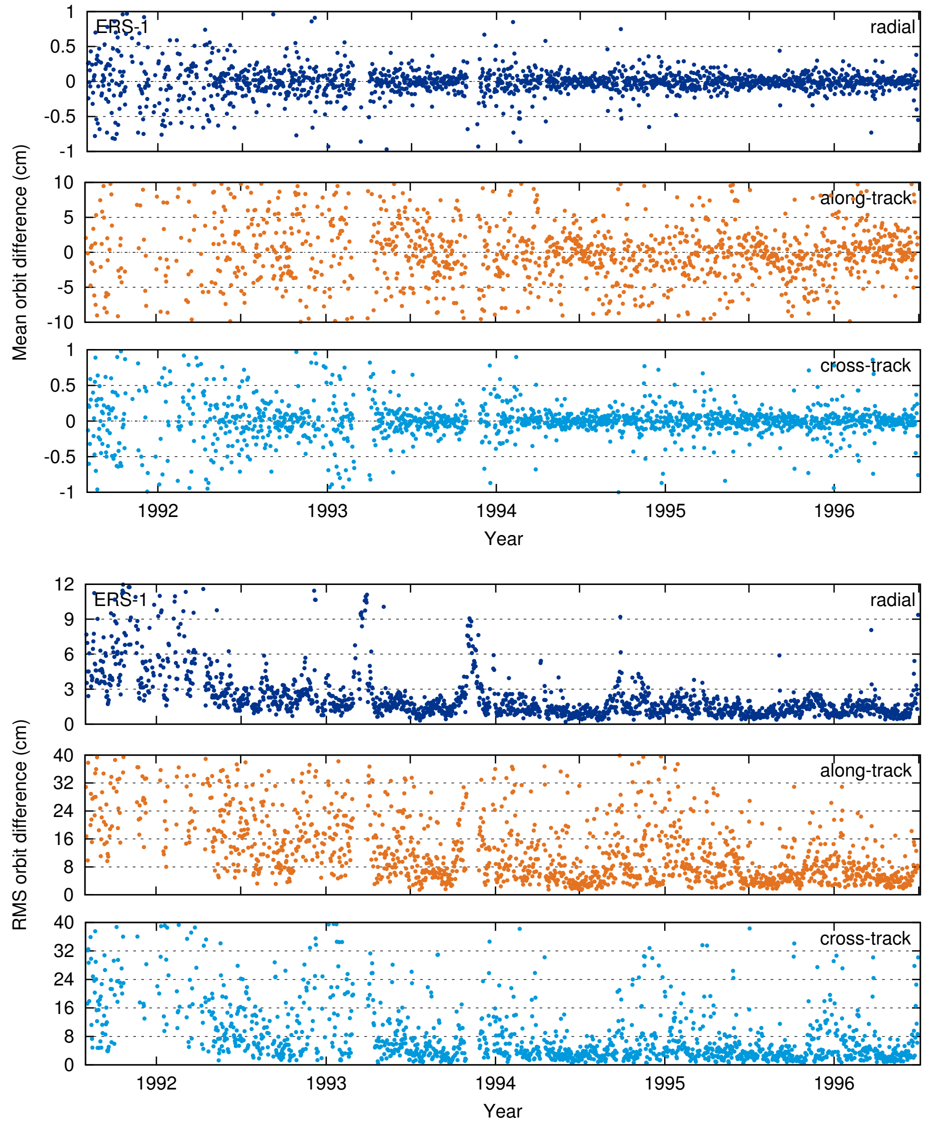


Figure 2.6: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-1 between ESOC and Combination. Orbit difference is calculated as ESOC-Combination.

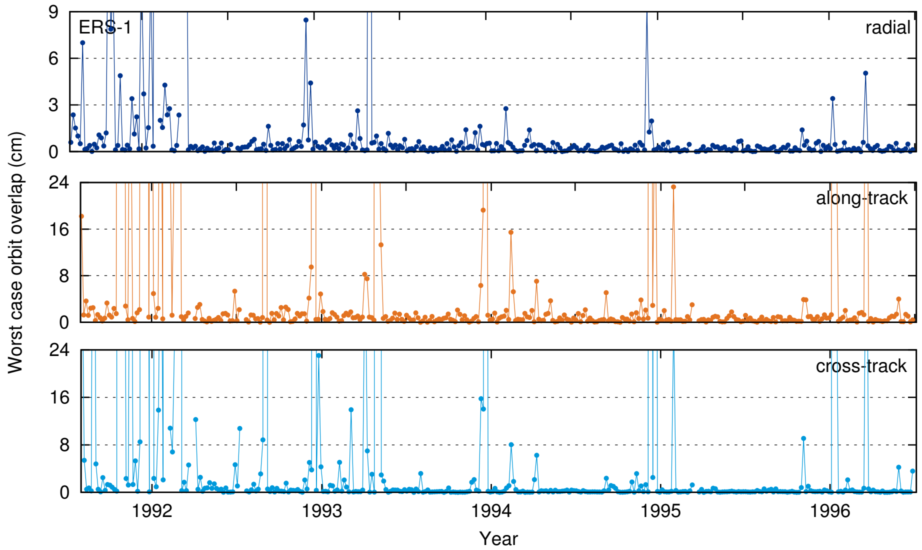


Figure 2.7: Worst case orbit overlap in centimetres for ERS-1 Combination solution.

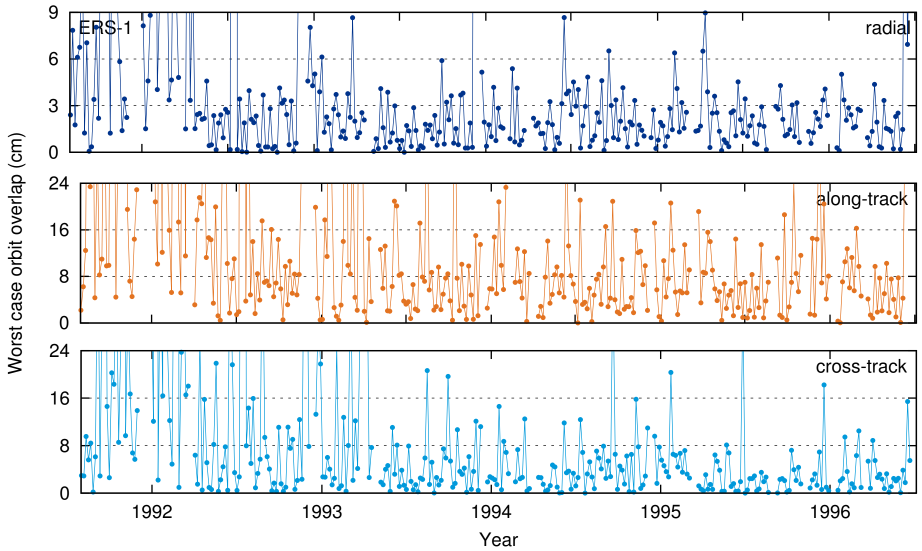


Figure 2.8: Worst case orbit overlap in centimetres for ERS-1 DEOS solution.

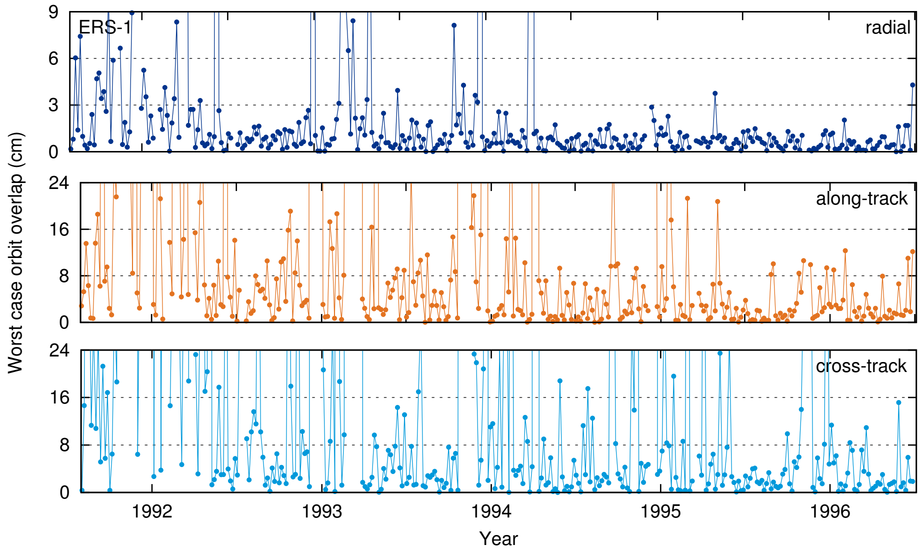


Figure 2.9: Worst case orbit overlap in centimetres for ERS-1 ESOC solution.

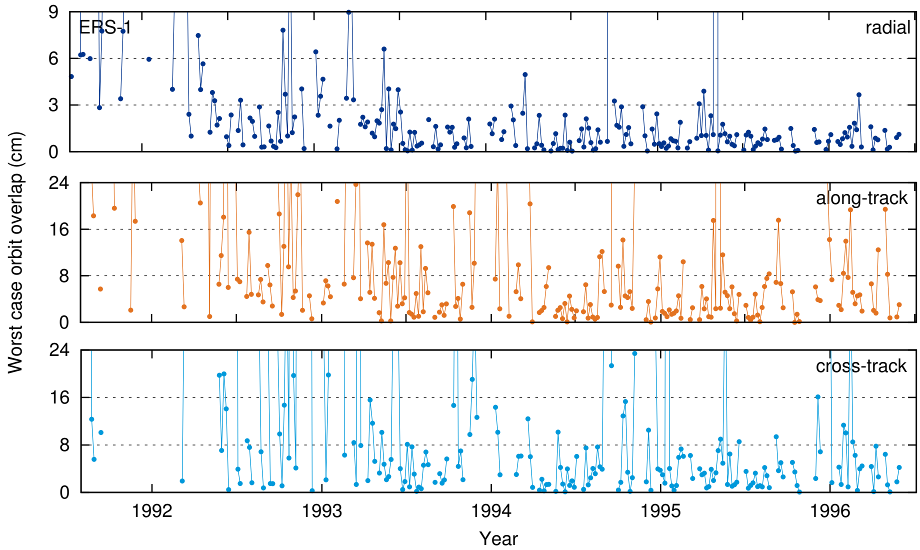


Figure 2.10: Worst case orbit overlap in centimetres for ERS-1 GFZ solution.

Chapter 3

ERS-2 Orbit Validation

This Chapter will contain all the ERS-2 orbit validation results.

The tables below list the yearly mean and *rms* orbit difference between the four different orbit solution for ERS-2. Outliers have been removed from the mean and *rms* computation. The editing criteria applied were if the total mean orbit difference was greater then 1 metre or if the total *rms* orbit difference was greater then 1.5 metre then the daily value was not used for the yearly mean or *rms* computation.

	1995	1996	1997	1998	1999	2000	2001	2002	2003
mean									
radial	0.24	0.22	0.21	0.23	0.23	0.34	0.20	0.33	0.25
along	0.65	1.83	0.74	0.13	0.34	-0.46	0.74	0.09	0.22
cross	-0.17	-0.15	-0.13	-0.03	-0.14	-0.31	-0.08	0.07	-0.13
rms									
radial	1.67	1.48	1.27	1.94	2.14	4.01	3.18	2.82	2.24
along	9.31	6.05	5.33	8.44	11.58	20.42	15.59	11.51	10.04
cross	12.20	7.49	5.50	10.12	11.77	17.53	15.34	10.16	7.33

Table 3.1: Yearly mean and *rms* orbit difference in centimetres for ERS-2 between DEOS and GFZ. Orbit difference is calculated as DEOS-GFZ.

	1995	1996	1997	1998	1999	2000	2001	2002	2003
mean									
radial	0.07	0.07	0.05	0.04	0.02	0.06	0.04	0.04	0.01
along	1.07	1.78	0.52	-0.36	-0.37	-4.14	-0.77	0.37	-0.05
cross	-0.24	-0.28	-0.41	-0.27	-0.02	-0.25	-0.68	-0.21	-0.27
rms									
radial	1.81	1.93	1.74	1.98	2.50	4.25	3.87	3.74	2.32
along	10.77	9.10	9.79	11.33	14.20	23.86	20.82	17.57	10.16
cross	13.00	8.53	6.14	7.94	12.23	15.46	14.93	9.63	6.87

Table 3.2: Yearly mean and *rms* orbit difference in centimetres for ERS-2 between DEOS and ESOC. Orbit difference is calculated as DEOS-ESOC.

	1995	1996	1997	1998	1999	2000	2001	2002	2003
mean									
radial	0.06	0.06	0.04	0.02	0.03	0.07	0.02	0.05	0.01
along	-0.57	1.24	0.52	0.32	0.29	-1.55	-0.03	-0.08	0.07
cross	-0.51	-0.35	-0.05	-0.10	-0.31	-0.26	-0.60	-0.20	-0.28
rms									
radial	1.29	1.10	0.91	1.28	1.55	2.93	2.38	2.06	1.49
along	6.82	3.81	3.29	4.99	6.75	13.05	9.15	7.30	5.95
cross	10.57	5.34	3.79	6.08	8.32	11.64	10.60	6.06	4.76

Table 3.3: Yearly mean and *rms* orbit difference in centimetres for ERS-2 between DEOS and Combination. Orbit difference is calculated as DEOS-Combination.

	1995	1996	1997	1998	1999	2000	2001	2002	2003
mean									
radial	-0.17	-0.16	-0.15	-0.19	-0.23	-0.34	-0.26	-0.28	-0.24
along	0.27	-0.12	-0.15	-0.30	-0.74	-3.39	-1.15	0.32	-0.09
cross	-0.31	-0.21	-0.26	-0.26	-0.43	-0.01	-0.09	-0.26	-0.14
rms									
radial	1.61	1.73	1.85	2.25	2.55	3.96	3.75	3.53	2.16
along	8.64	8.18	9.96	12.21	15.32	23.38	21.60	17.39	11.04
cross	4.83	4.29	4.87	8.81	10.04	14.49	13.15	8.56	4.85

Table 3.4: Yearly mean and *rms* orbit difference in centimetres for ERS-2 between GFZ and ESOC. Orbit difference is calculated as GFZ-ESOC.

	1995	1996	1997	1998	1999	2000	2001	2002	2003
mean									
radial	-0.18	-0.17	-0.16	-0.20	-0.22	-0.32	-0.28	-0.27	-0.24
along	-0.84	-0.65	-0.09	0.03	-0.02	-1.21	-0.35	-0.20	-0.15
cross	-0.38	-0.27	-0.09	-0.07	-0.19	0.08	-0.36	-0.23	-0.15
rms									
radial	0.96	0.94	0.99	1.31	1.87	2.58	2.25	1.89	1.30
along	5.36	3.26	3.30	5.22	7.91	11.71	9.73	7.11	5.63
cross	4.18	2.93	3.28	6.00	7.15	11.54	7.88	6.14	3.46

Table 3.5: Yearly mean and *rms* orbit difference in centimetres for ERS-2 between GFZ and Combination. Orbit difference is calculated as GFZ-Combination.

	1995	1996	1997	1998	1999	2000	2001	2002	2003
mean									
radial	-0.00	-0.00	-0.01	-0.00	0.01	0.00	-0.01	0.01	-0.00
along	-1.55	-0.83	0.04	0.28	0.39	2.14	1.68	-0.38	0.04
cross	-0.01	-0.04	0.33	0.22	0.10	0.09	0.11	0.01	-0.03
rms									
radial	1.33	1.46	1.45	1.66	2.04	3.45	3.26	3.16	1.79
along	8.90	7.77	9.21	10.71	13.07	22.08	19.16	16.09	8.78
cross	5.52	4.72	4.67	7.04	8.26	13.96	11.78	7.30	3.85

Table 3.6: Yearly mean and *rms* orbit difference in centimetres for ERS-2 between ESOC and Combination. Orbit difference is calculated as ESOC-Combination.

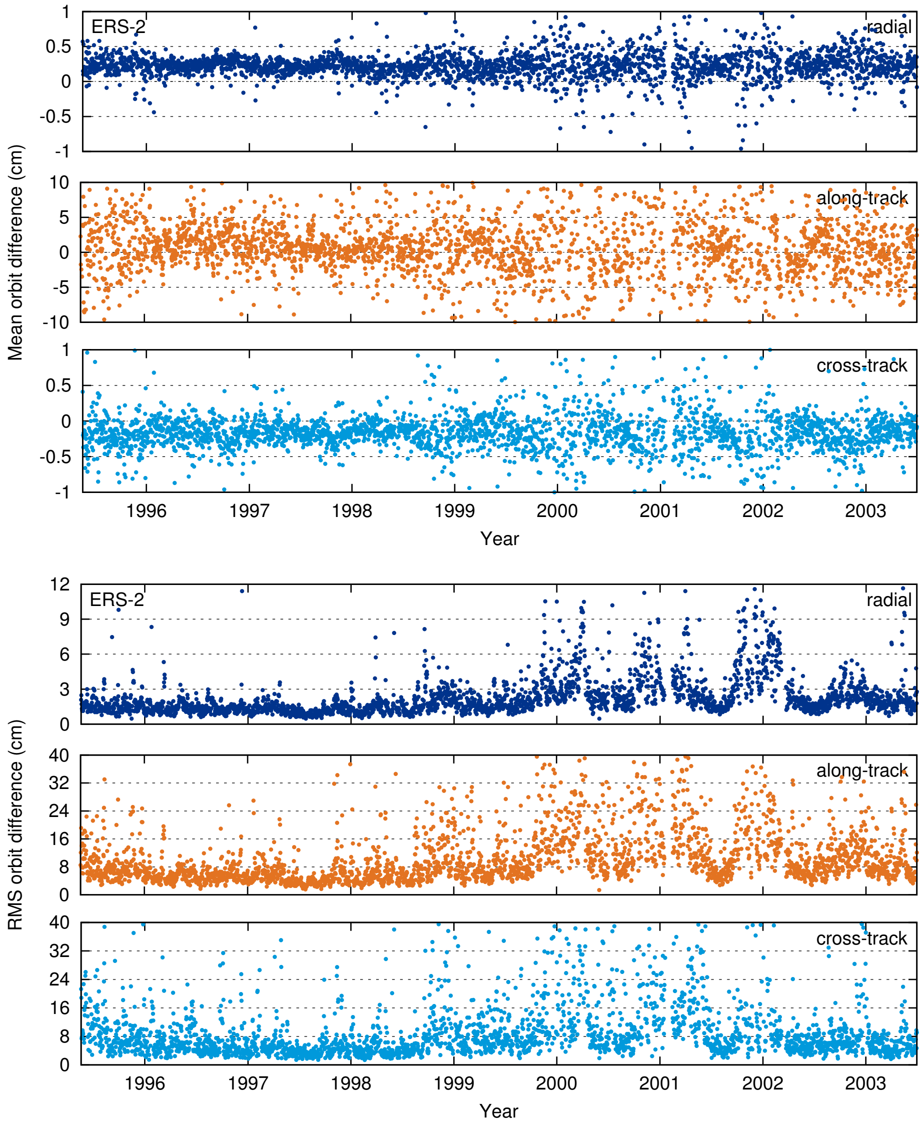


Figure 3.1: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-2 between DEOS and GFZ. Orbit difference is calculated as DEOS-GFZ.

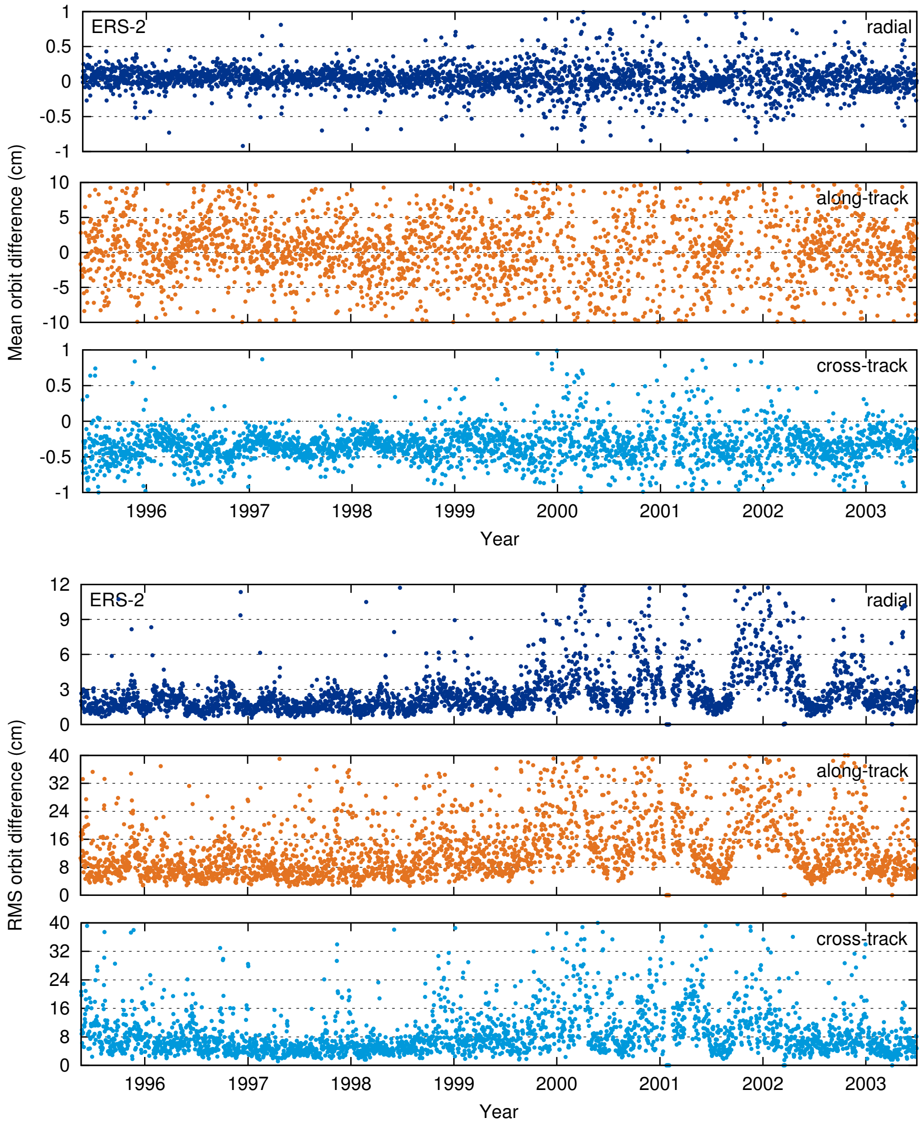


Figure 3.2: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-2 between DEOS and ESOC. Orbit difference is calculated as DEOS-ESOC.

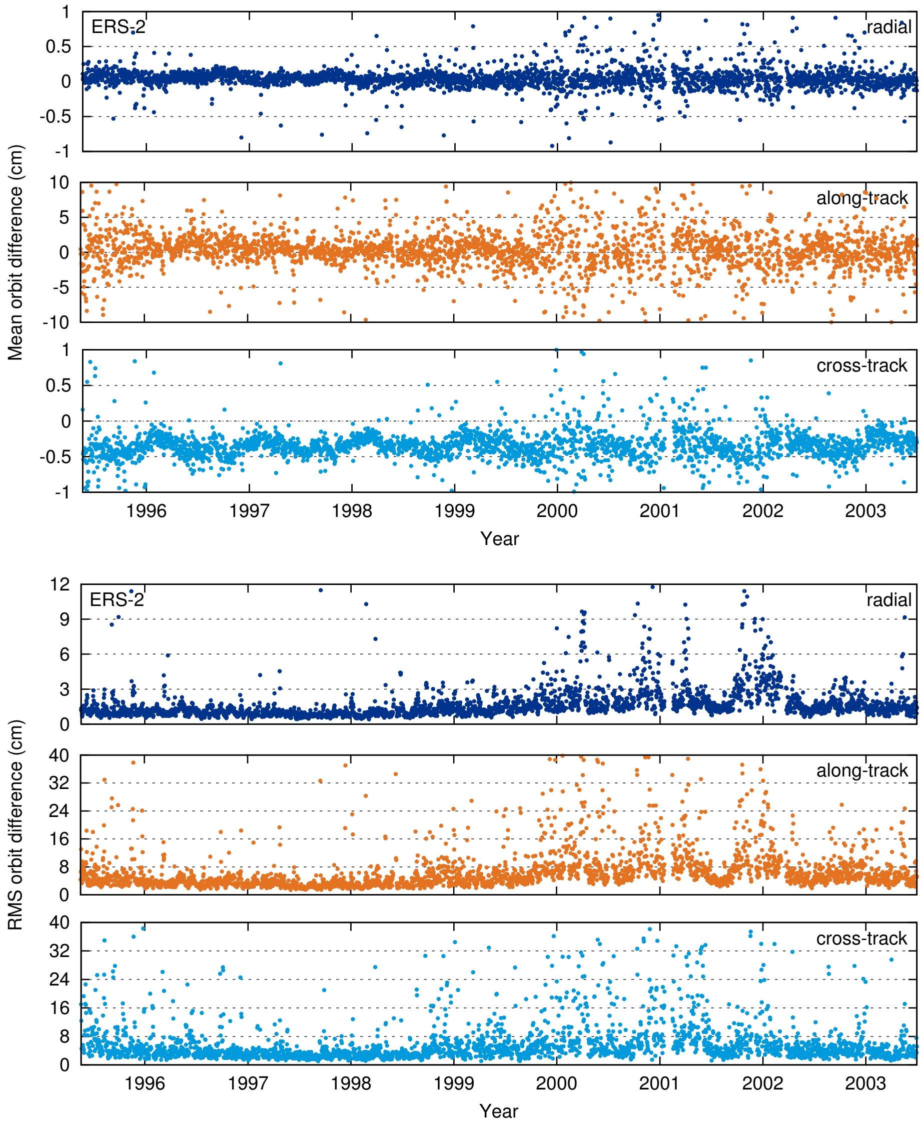


Figure 3.3: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-2 between DEOS and Combination. Orbit difference is calculated as DEOS-Combination.

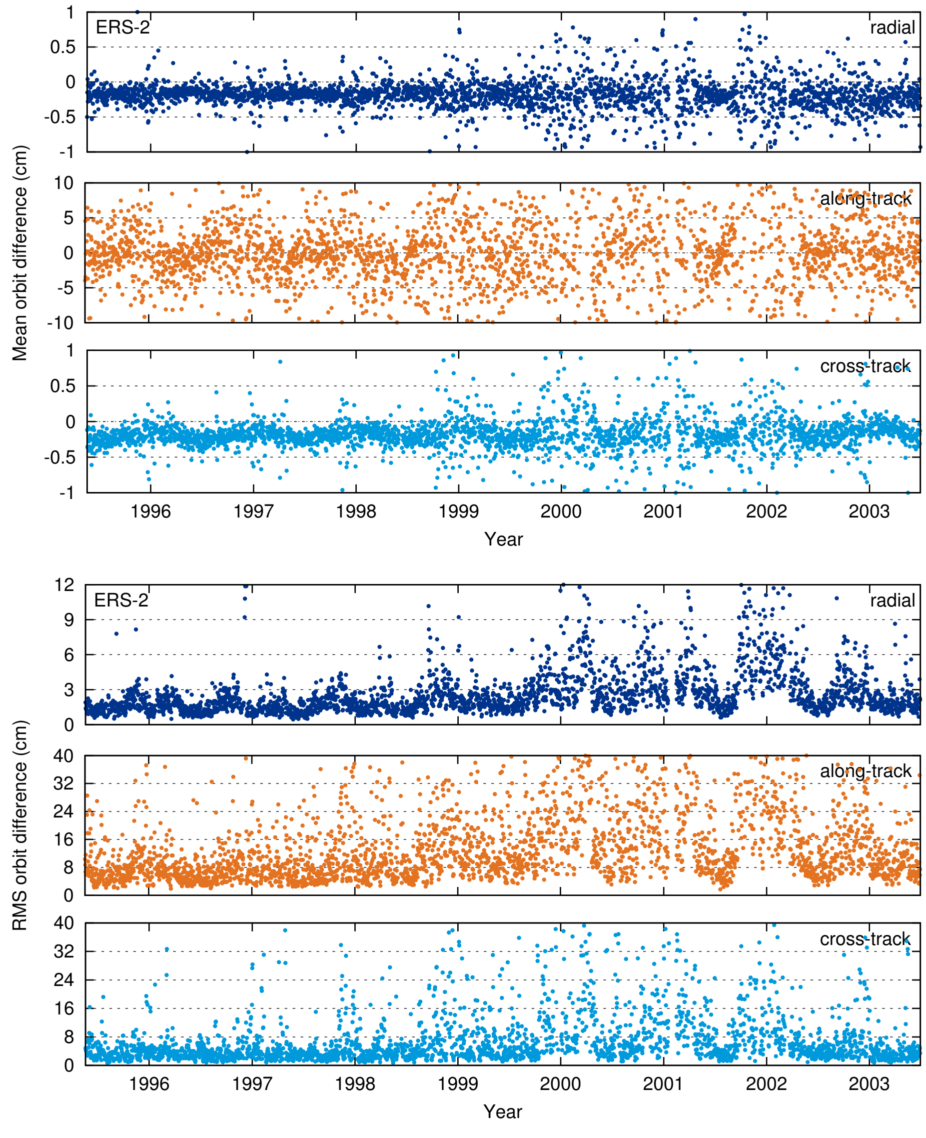


Figure 3.4: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-2 between GFZ and ESOC. Orbit difference is calculated as GFZ-ESOC.

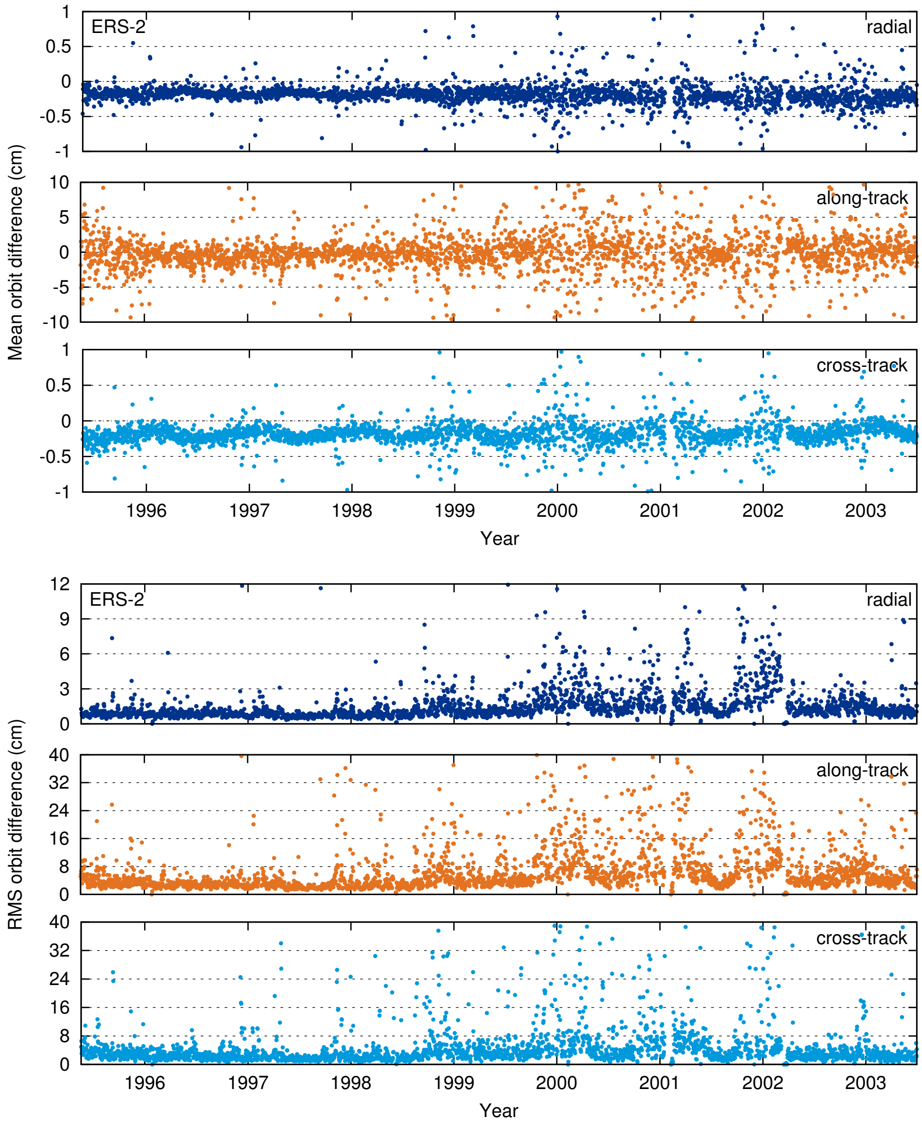


Figure 3.5: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-2 between GFZ and Combination. Orbit difference is calculated as GFZ-Combination.

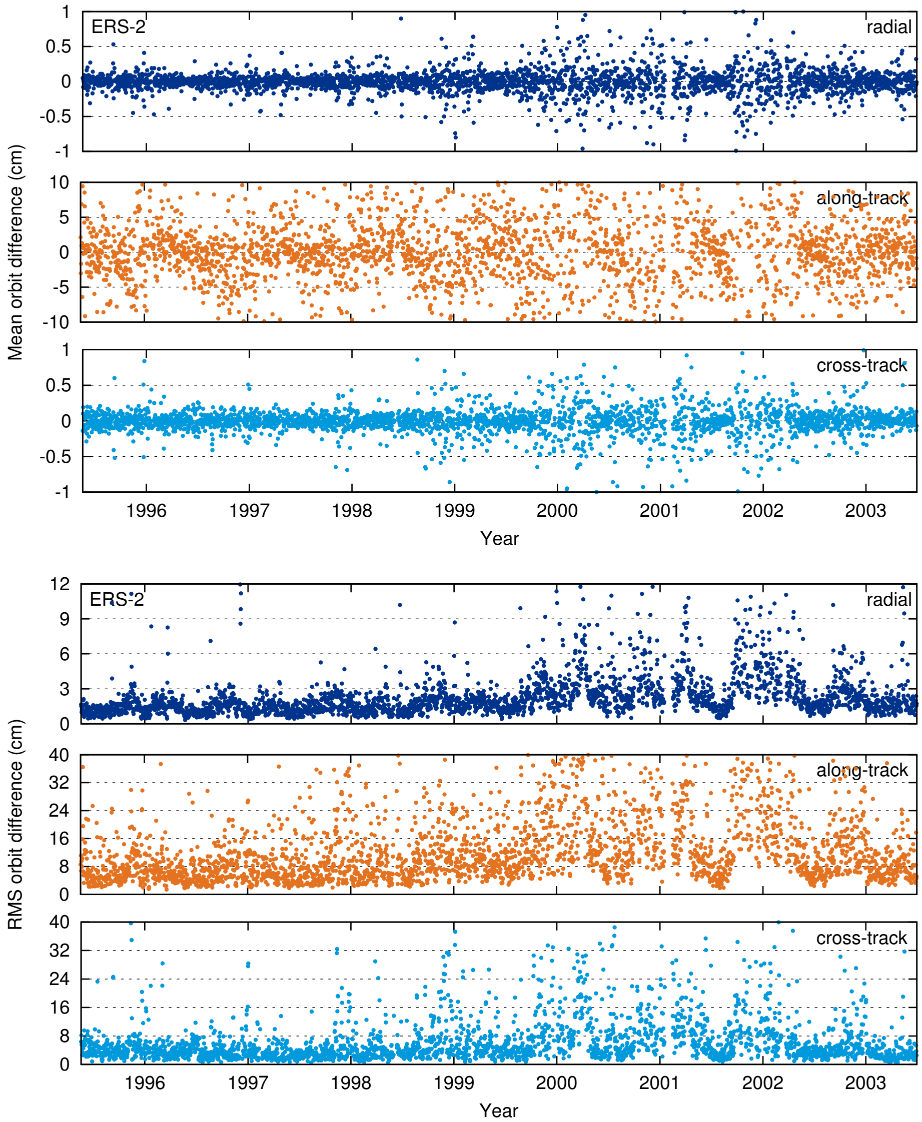


Figure 3.6: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-2 between ESOC and Combination. Orbit difference is calculated as ESOC-Combination.

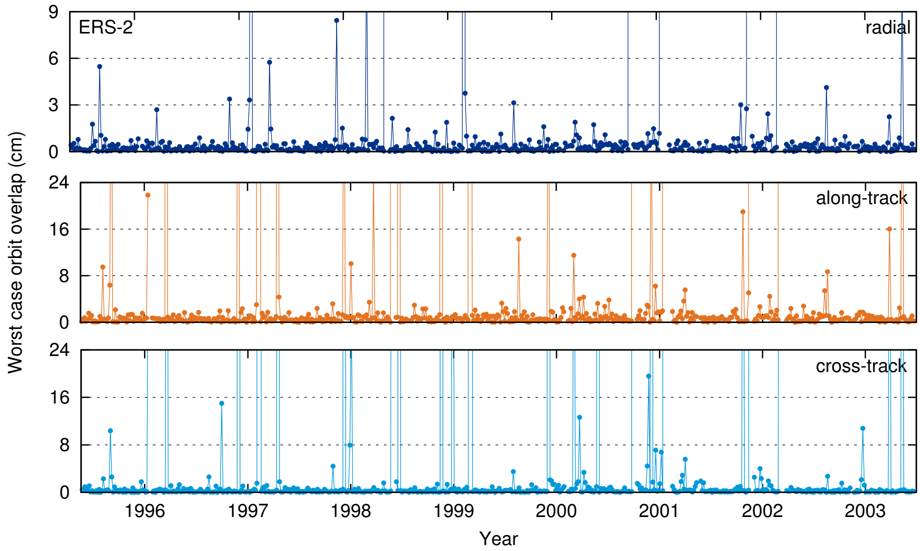


Figure 3.7: Worst case orbit overlap in centimetres for ERS-2 Combination solution.

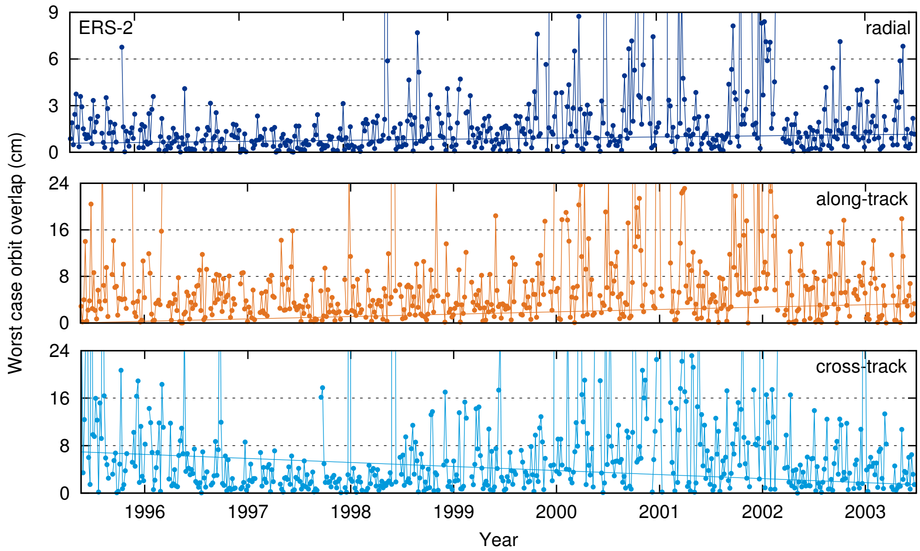


Figure 3.8: Worst case orbit overlap in centimetres for ERS-2 DEOS solution.

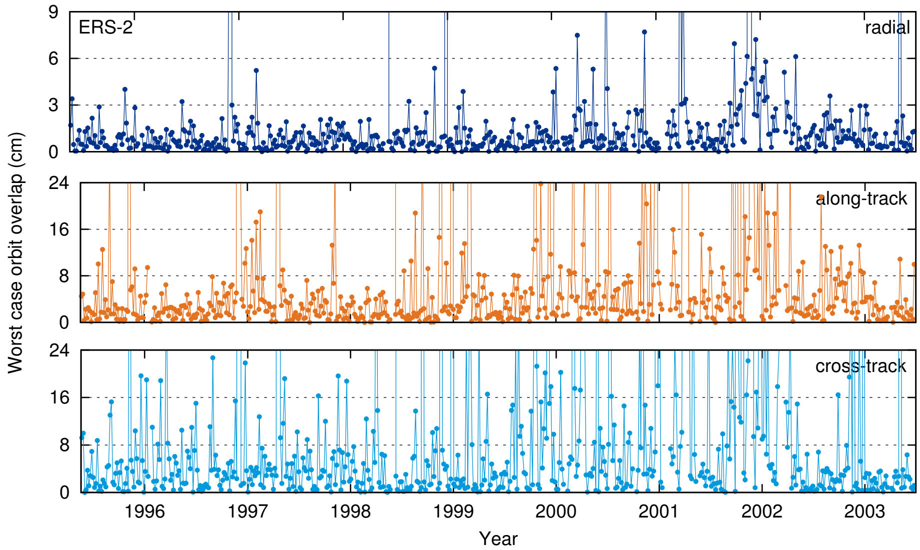


Figure 3.9: Worst case orbit overlap in centimetres for ERS-2 ESOC solution.

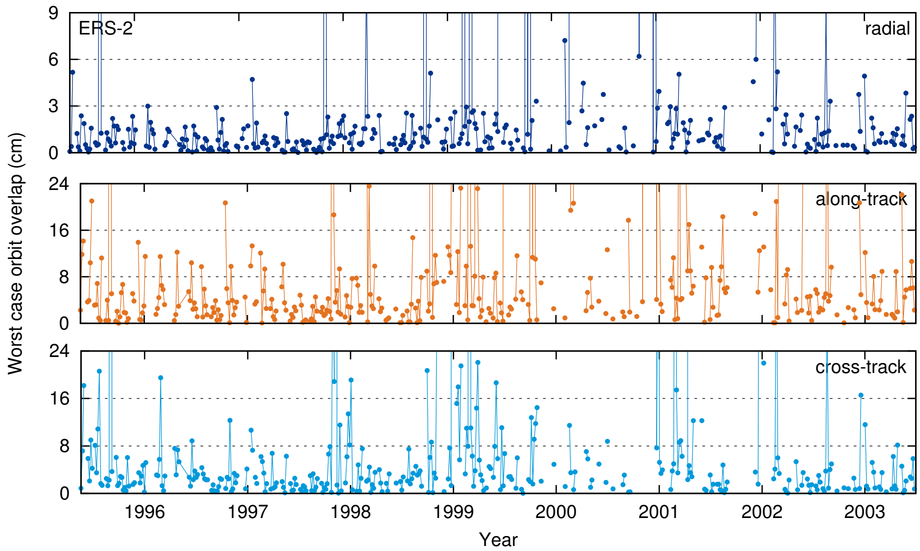


Figure 3.10: Worst case orbit overlap in centimetres for ERS-2 GFZ solution.

Chapter 4

ERS-1 and ERS-2 Altimeter Validation

4.1 Crossover statistics

Let us first look at the crossover statistics as a function of time. This will identify where there are periods that could potentially be improved. Because I am using crossovers, I actually know that there are altimeter measurements for those periods. So unlike a straightforward orbit comparison, here we see the actual impact on the altimeter products.

The plots compare the time series of the crossover statistics on different time intervals. I have experimented with showing the difference of the RMS values between the REAPER and DGM-E04 orbits, which is shown in the plots 4.1 and 4.2. In those plots negative numbers are an improvement of the RMS crossover difference, positive are worsening. This representation shows very well where we made improvements, and where we should be able to improve.

The best was to view the impact of the new orbits is to look at the plots of the weekly statistics (the daily ones are a bit noisy), see plot 4.1 and 4.2. The colours used for the orbit solutions are consistent throughout the all plots: orange for the DEOS DGM-E04 orbit; blue, dark green, red and magenta for the DEOS, ESOC, GFZ and combined orbit solutions, respectively.

The ERS-1 crossover RMS has been improved by about 3 mm across the different solutions. At the time of the Bergen symposium, the beginning of the ERS-1 mission saw no improvements, but that has changed now. In fact, there we now see the largest reduction in crossover RMS, between 1 and 2 cm.

The combined ERS-1 orbit performs the best with the fewest increase of crossover RMS compared to the reference orbit. The only critical weeks for this solution are those starting on: - 1992-04-21 and 1994-04-12, which are at the end and beginning of a data outage, and thus have poor statistical significance. - 1994-10-04 and 1995-03-21, which are periods of very little data and can likewise be ignored. The other solutions each have several periods of deterioration that are not in the combined orbit.

The ERS-2 crossover RMS has improved even more, by about 5 mm for the entire period. Particularly during the period of high solar activity at the end of 2001 and first half of 2002 we see a lot of improvement. By the time of the Bergen symposium the GFZ orbits performed much better than all others, now the DEOS and combined orbits have achieved the same level of accuracy. The ESOC orbits, however, perform significantly worse, with the most cases of increase of RMS compared to the DEOS orbits. It is comforting to note that the combined orbit never exceeds the original crossover RMS by more than 1 mm.

Finally, the table below shows that the RMS crossover differences are the lowest in the combined orbit solution, and that the variance reduces by about $3cm^2$ compared to the DGM-E04 reference orbit. The combined orbit can hence be considered the best not only for the overall period for both satellites, but even for every annual period.

ERS-1	all	1991	1992	1993	1994	1995	1996
Sol.							
DGM	8.28	13.77	9.88	7.74	7.67	7.39	6.90
DEOS	7.69	11.78	9.49	7.18	7.19	6.92	6.46
GFZ	7.71	13.53	8.98	7.27	7.22	6.93	6.34
ESOC	7.86	12.63	9.11	7.79	7.25	6.89	6.38
COMBI	7.53	11.33	8.57	7.12	7.14	6.85	6.30

Table 4.1: ERS-1 overall and annual crossover RMS values (cm) (after 3.5-sigma editing)

ERS-2	all	1995	1996	1997	1998	1999	2000	2001	2002	2003
Sol.										
DGM	7.31	6.78	6.45	6.53	6.73	6.98	8.45	8.87	8.33	6.60
DEOS	6.44	6.25	5.93	5.99	6.12	6.12	7.23	7.32	6.86	5.98
GFZ	6.64	6.27	5.92	6.03	6.25	6.47	7.78	7.87	6.87	6.10
ESOC	6.93	6.28	6.09	6.14	6.24	6.48	8.33	8.41	8.18	6.17
COMBI	6.40	6.17	5.85	6.01	6.05	6.11	7.06	7.20	6.97	5.87

Table 4.2: ERS-2 overall and annual crossover RMS values (cm) (after 3.5-sigma editing)

4.2 Apparent time tag bias

The daily and weekly statistics for each solution are plotted in plots 4.3 and 4.4.

I looked at the impact of the new orbits on the apparent time tag bias. As you know, I always apply a time tag bias to the ERS-1 and ERS-2 time tags before interpolating the orbits. Those values are -1.5 and -1.3 ms, respectively. The plots show overall very little impact on the apparent timing bias. The DEOS solution shows the most consistency in this statistic, although I have no explanation why that would be the case.

The values below are the mean time tag biases for the ERS-1 and ERS-2 missions including the aforementioned corrections (in ms):

	DGM	DEOS	GFZ	ESOC	COMBI
ERS-1	-1.716	-1.630	-1.657	-1.643	-1.673
ERS-2	-1.253	-1.261	-1.289	-1.285	-1.264

Table 4.3: ERS-1 and ERS-2 mean time tag bias for all solutions.

This may suggest that the time tag bias of ERS-1 is actually closer to -1.7 ms, but otherwise, the orbit solutions do not change this story much.

4.3 Geographically correlated orbit error

After creating the single satellite crossovers, I averaged them in time as a function of location. If you look at the averaged crossover differences, you get the anti-correlated orbit error. The plots 4.5 and 4.6 show the mean crossover height differences. There is a clear improvement in all the REAPER orbits over the DGM-E04 baseline: much less trackiness. This can mostly be contributed to the improvement of the gravity field from DGM-E04 (an ERS-tailored model based on JGM-3) to the current GRACE-based EIGEN-CG03. Since geographical patterns are dominated by any remaining errors in the gravity field, they differ very little among the new orbits, using a common gravity field solution.

Looking at the ERS-1 results, we notice that the DEOS and GFZ solutions create a clear north-south hemispherical separation between positive (south) and negative (north) values. This correlates well with the observation above that the time tag bias in ERS-1 is still underestimated and should be increased with -0.2 ms to -1.7 ms. The ESOC orbit seems to add an additional long-wave length feature with higher values near the 180 meridian.

The ERS-2 results, averaged over a longer period, including a period of strong solar activity, show signs of ascending-descending (night-day) difference correlated with the ionospheric correction. The pattern of two bands with negative values along the geomagnetic equator is quite clear and suggest that the TEC during day (high) is overestimated.

	DGM	DEOS	GFZ	ESOC	COMBI
ERS-1 mean diff	1.73	1.14	1.31	1.18	1.24
ERS-2 mean diff	1.55	0.98	1.04	1.15	1.07
ERS-1 mean SLA	2.55	2.64	2.61	2.56	2.63
ERS-2 mean SLA	1.72	1.76	1.85	2.06	1.72

Table 4.4: RMS of mean crossover difference and RMS about mean of mean sea level anomaly. Values in cm.

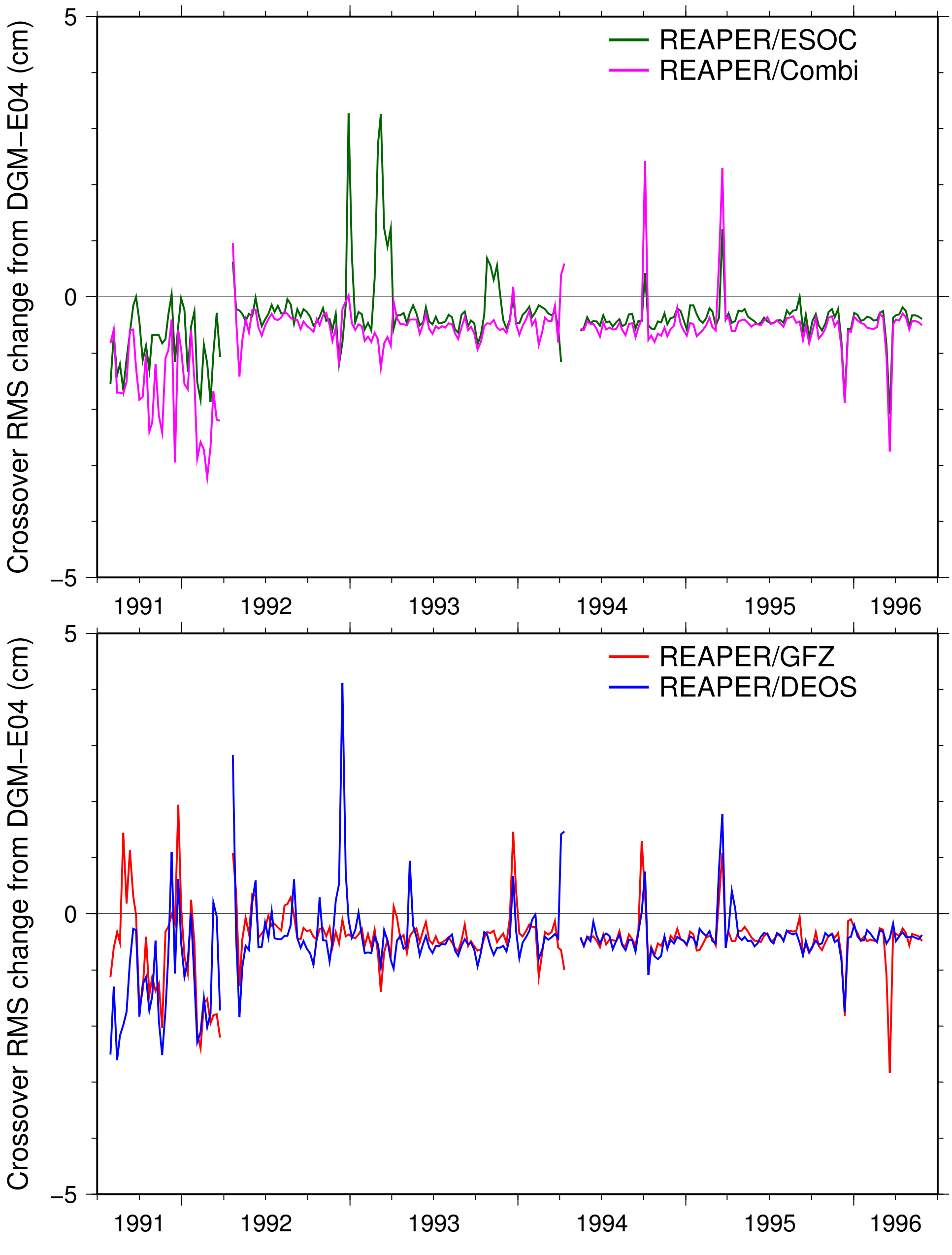


Figure 4.1: rms crossover improvement for the ERS-1 REAPER solutions over the DGM-E04 solution in cm.

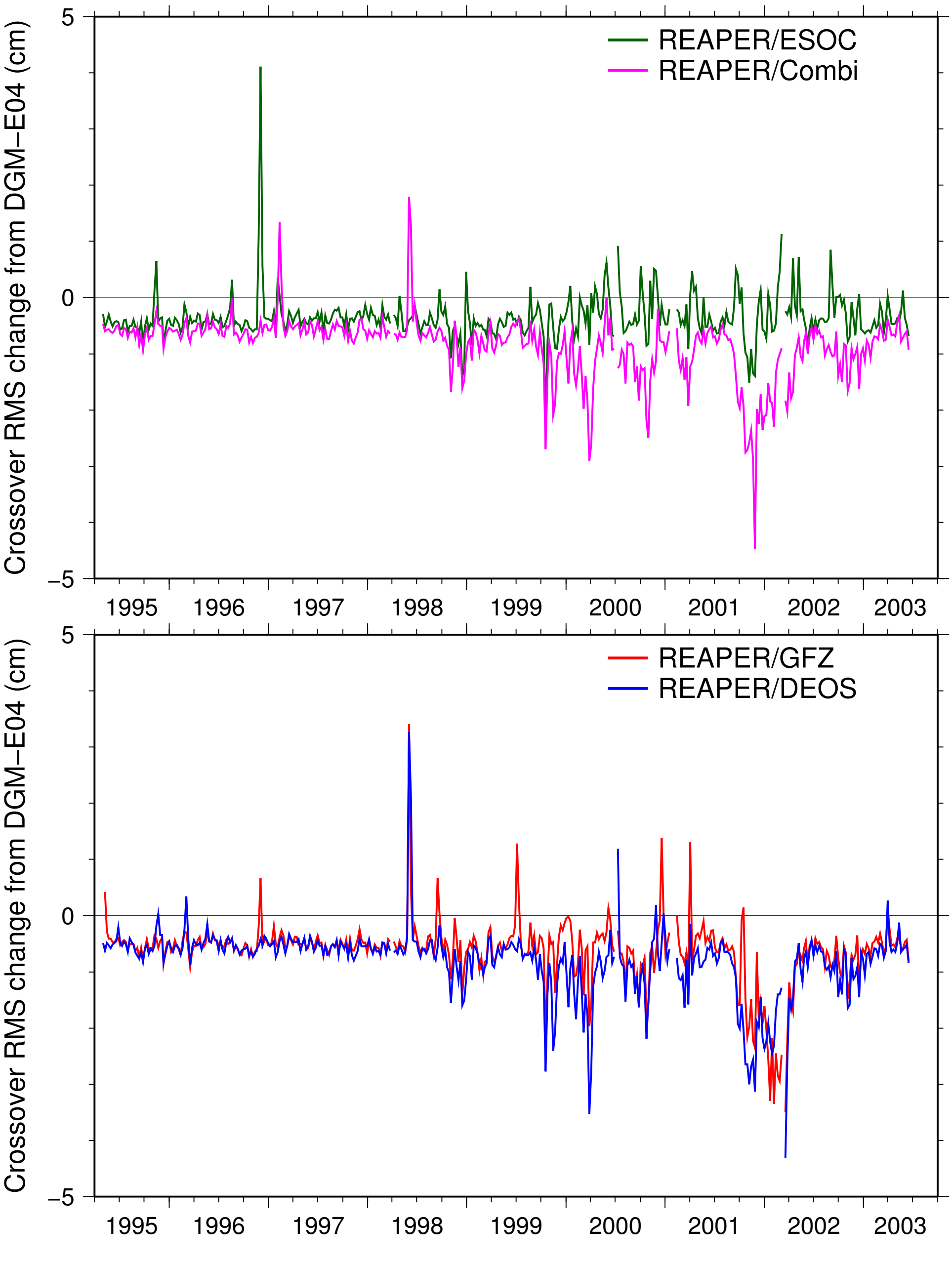


Figure 4.2: rms crossover improvement of the ERS-2 REAPER solutions over the DGM-E04 solution ib cm.

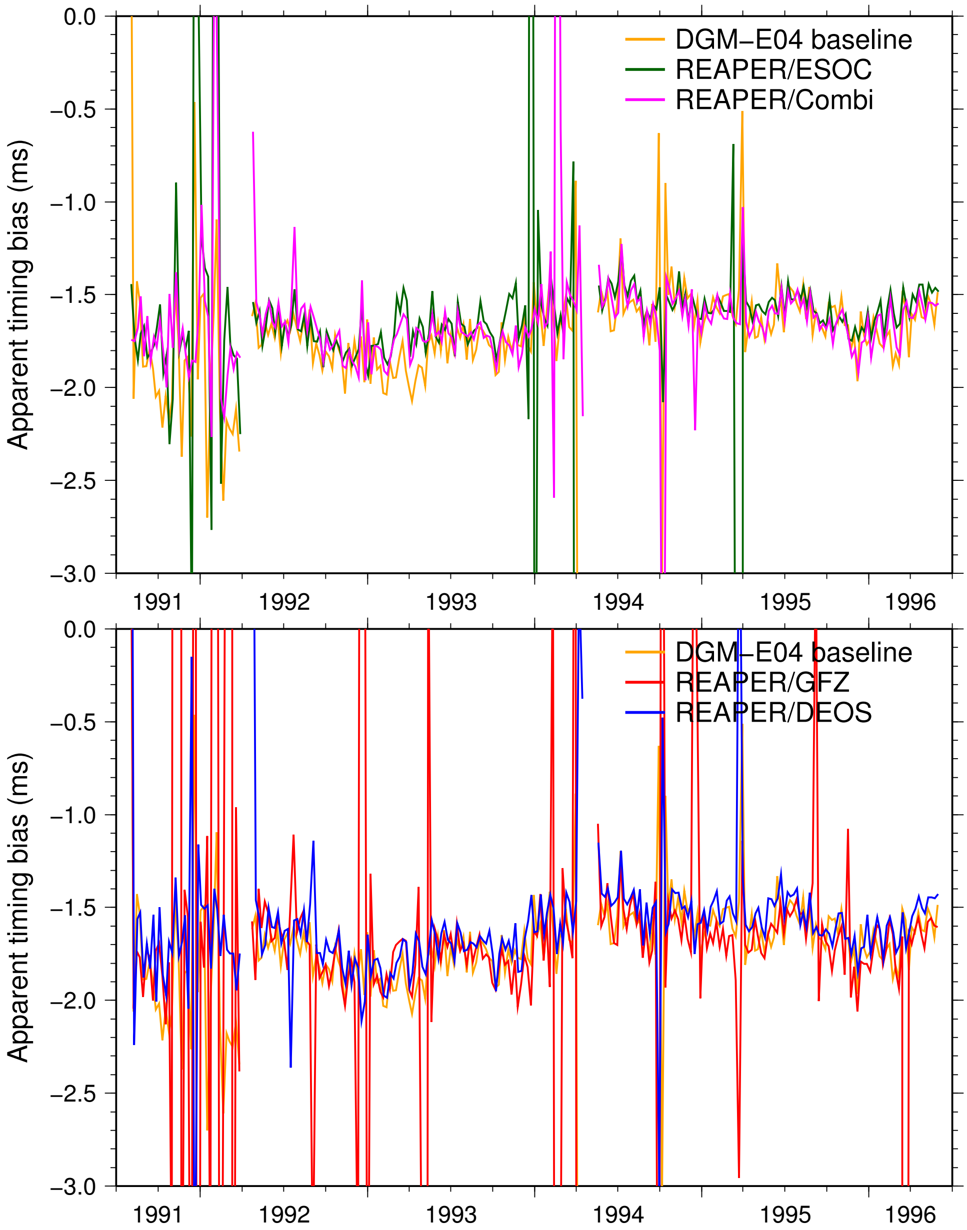


Figure 4.3: ERS-1 apparent timing bias in ms for the REAPER solutions and the DGM-E04 reference solution

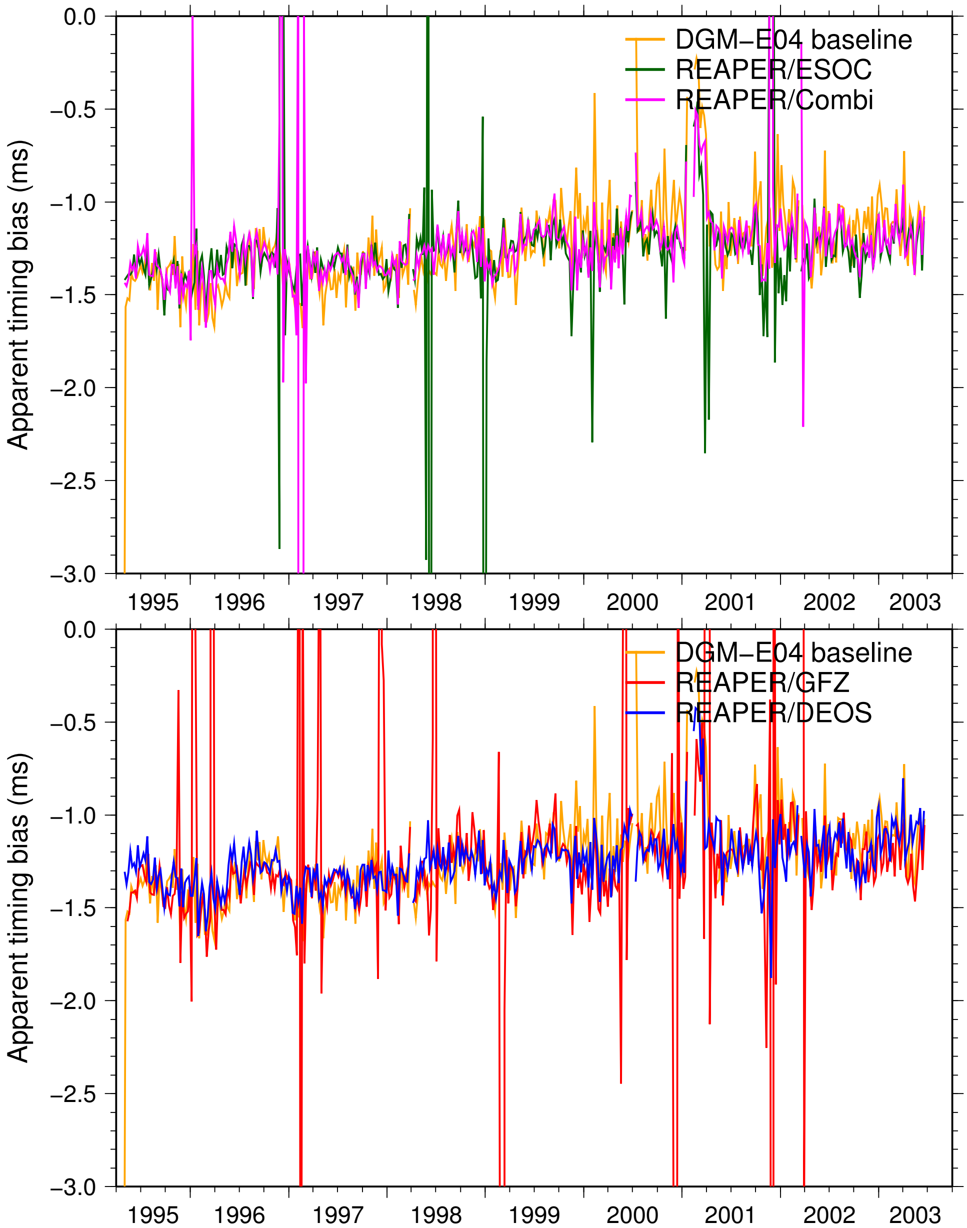
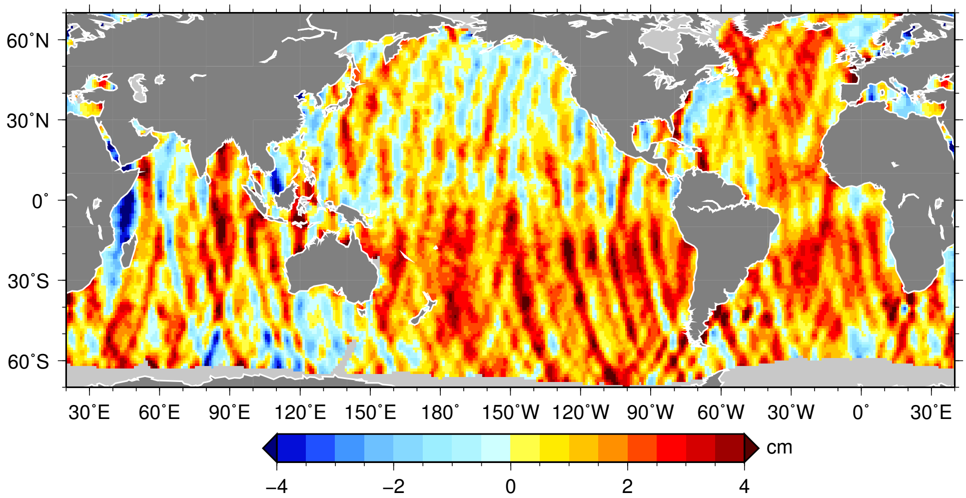
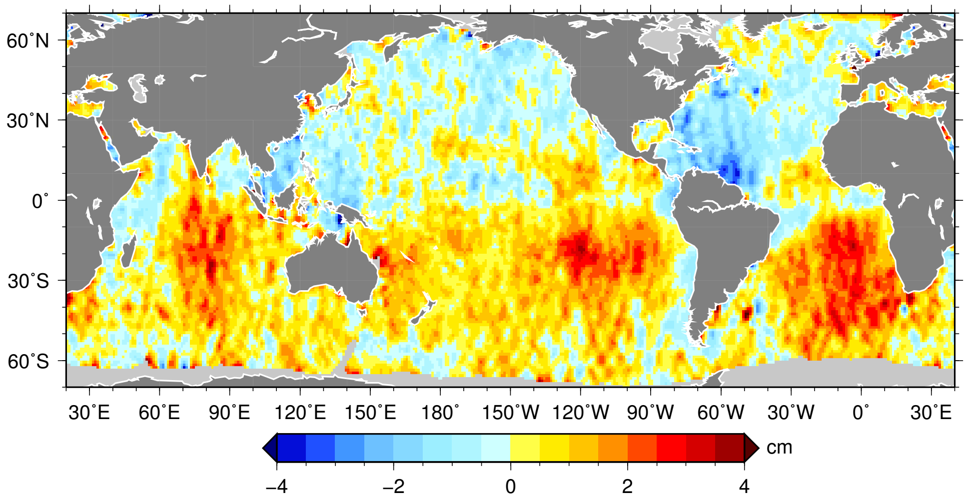
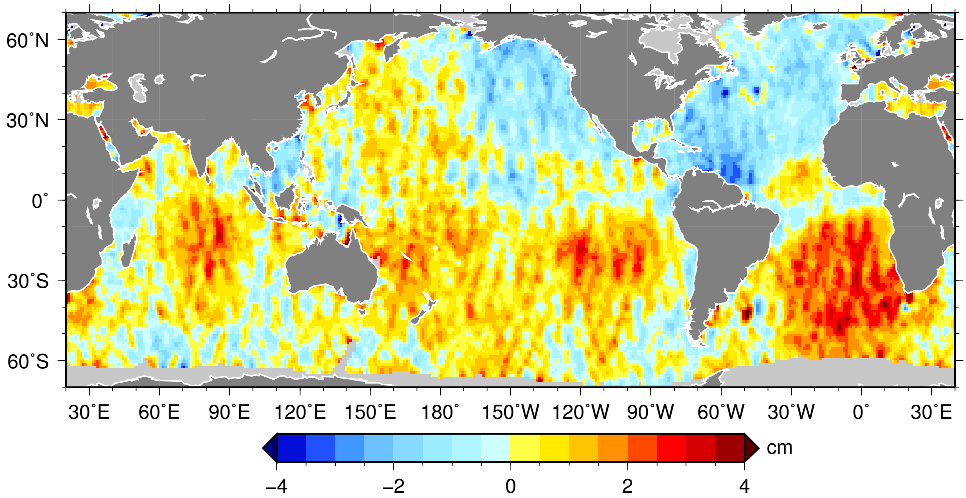
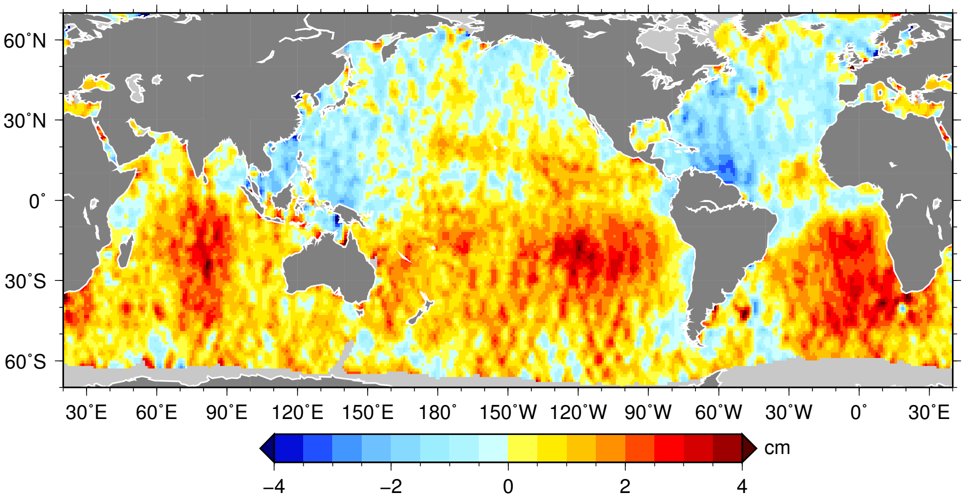


Figure 4.4: ERS-2 apparent timing bias in ms for the REAPER solutions and the DGM-E04 reference solution


60˚N
30˚N
0˚
30˚S
60˚S
30˚E 60˚E 90˚E 120˚E 150˚E 180˚ 150˚W 120˚W 90˚W 60˚W 30˚W 0˚ 30˚E
cm
−4 −2 0 2 4


60˚N
30˚N
0˚
30˚S
60˚S
30˚E 60˚E 90˚E 120˚E 150˚E 180˚ 150˚W 120˚W 90˚W 60˚W 30˚W 0˚ 30˚E
cm
−4 −2 0 2 4


60˚N
30˚N
0˚
30˚S
60˚S
30˚E 60˚E 90˚E 120˚E 150˚E 180˚ 150˚W 120˚W 90˚W 60˚W 30˚W 0˚ 30˚E
cm
−4 −2 0 2 4



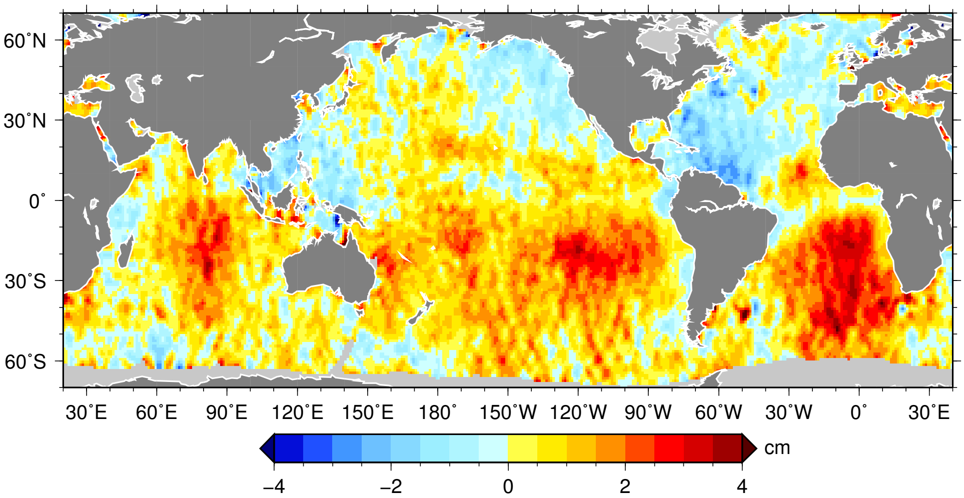
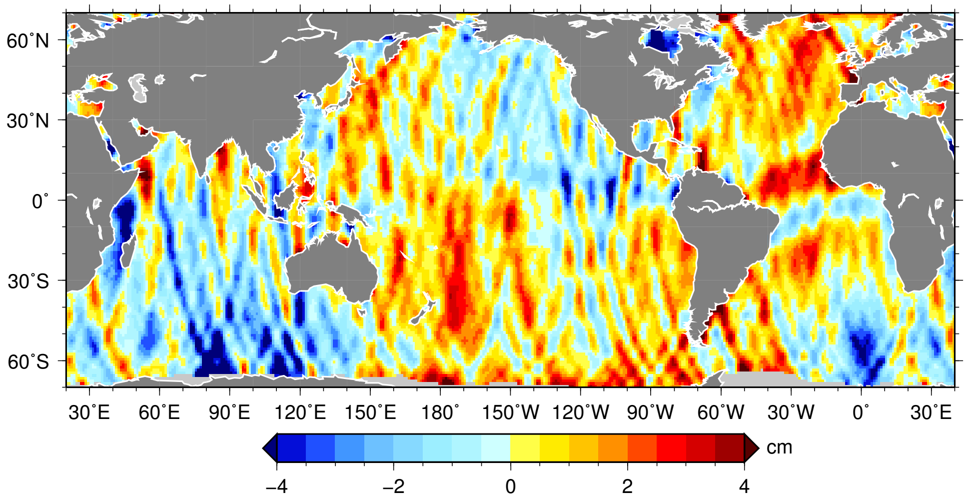
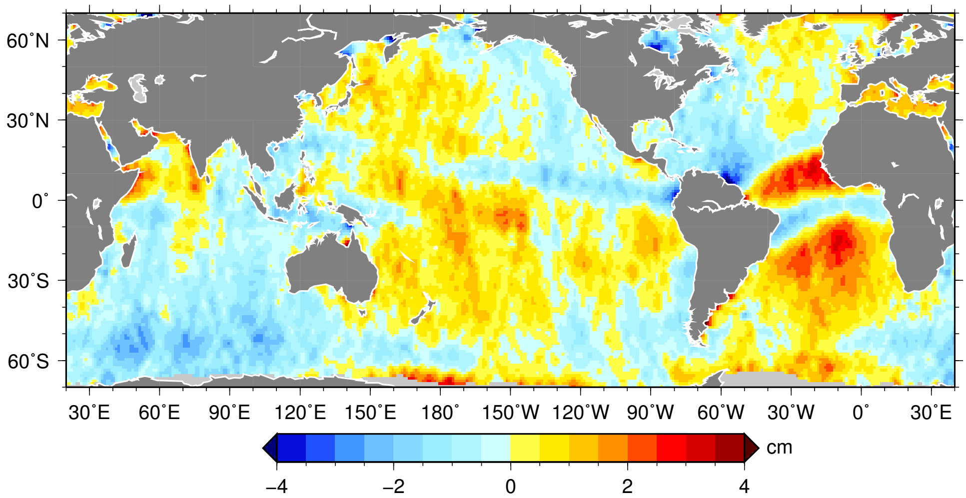
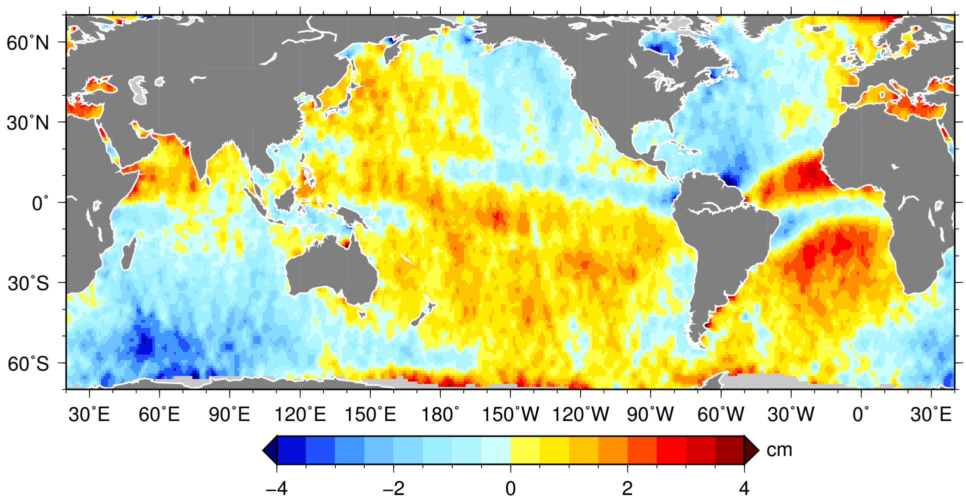
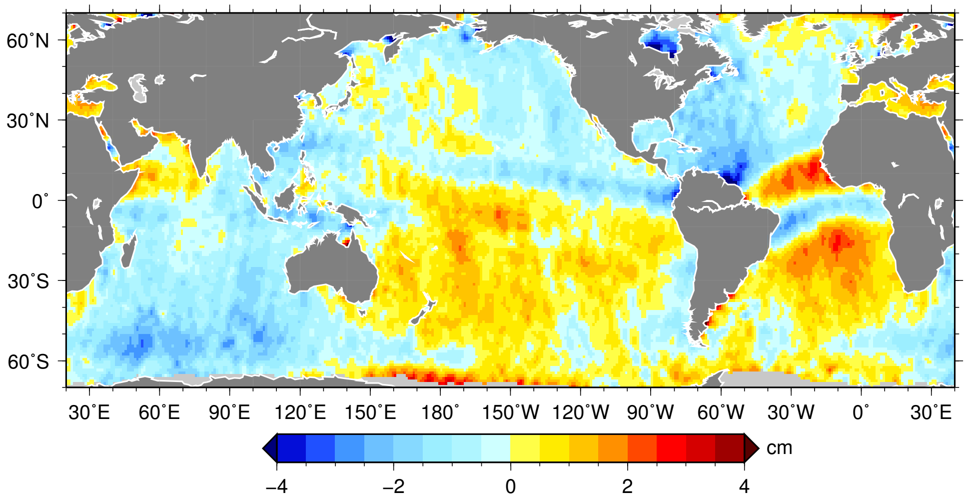


Figure 4.5: Mean crossover height differences computed using different orbits: DGM-E04, and four REAPER orbits (DEOS, ESOC, GFZ and combined one (from top to bottom)) for ERS-1


60°N
30°N
0°
30°S
60°S
30°E 60°E 90°E 120°E 150°E 180° 150°W 120°W 90°W 60°W 30°W 0° 30°E
cm
−4 −2 0 2 4


60°N
30°N
0°
30°S
60°S
30°E 60°E 90°E 120°E 150°E 180° 150°W 120°W 90°W 60°W 30°W 0° 30°E
cm
−4 −2 0 2 4


60°N
30°N
0°
30°S
60°S
30°E 60°E 90°E 120°E 150°E 180° 150°W 120°W 90°W 60°W 30°W 0° 30°E
cm
−4 −2 0 2 4



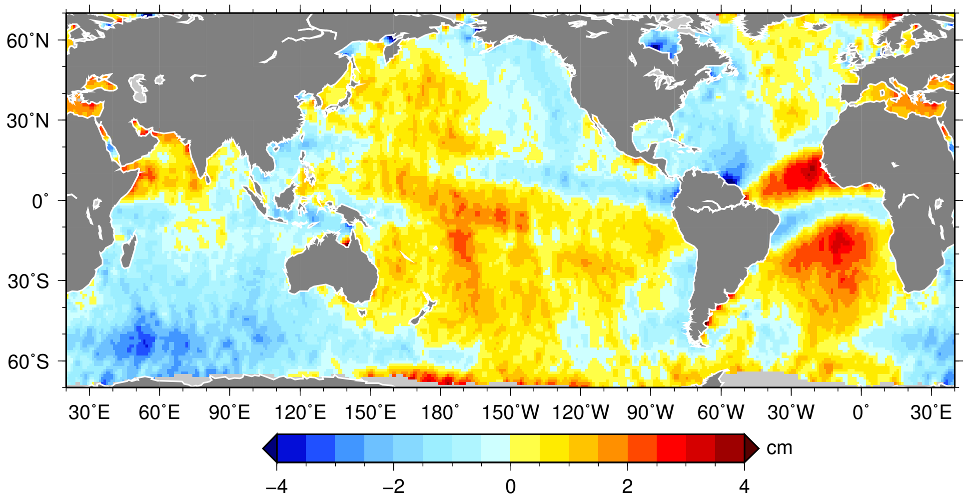


Figure 4.6: Mean crossover height differences computed using different orbits: DGM-E04, and four REAPER orbits (DEOS, ESOC, GFZ and combined one (from top to bottom)) for ERS-2

Chapter 5

Conclusions

Concerning the differences between the orbit performances:

- Of the independent solutions, the DEOS orbit has the lowest crossover RMS as well as the lowest RMS sea level anomaly during most of the two missions. This suggests that those orbits have the lowest short-wavelength orbit error (1- and 2-cpr mostly).

- The combined solution for both missions performs even better overall.

- In terms of height stability, important for sea level change studies, the combined solution for ERS-1 and ERS-2 is the most consistent. The ERS-2 ESOC orbits, though seemingly more consistent with the DGM-E04 orbit in their seasonal variation, show a slight decline not observed in any of the other orbits.

- The apparent timing bias, partly responsible for a 2-cpr orbit error, is estimated about 0.2 ms short for ERS-1. Suggested values for ERS-1 and ERS-2 are approximately -1.7 and -1.3 ms, respectively.

- Owing to the use of the same gravity field in all new orbit solutions, the geographically correlated orbit errors are very close between the different solutions.