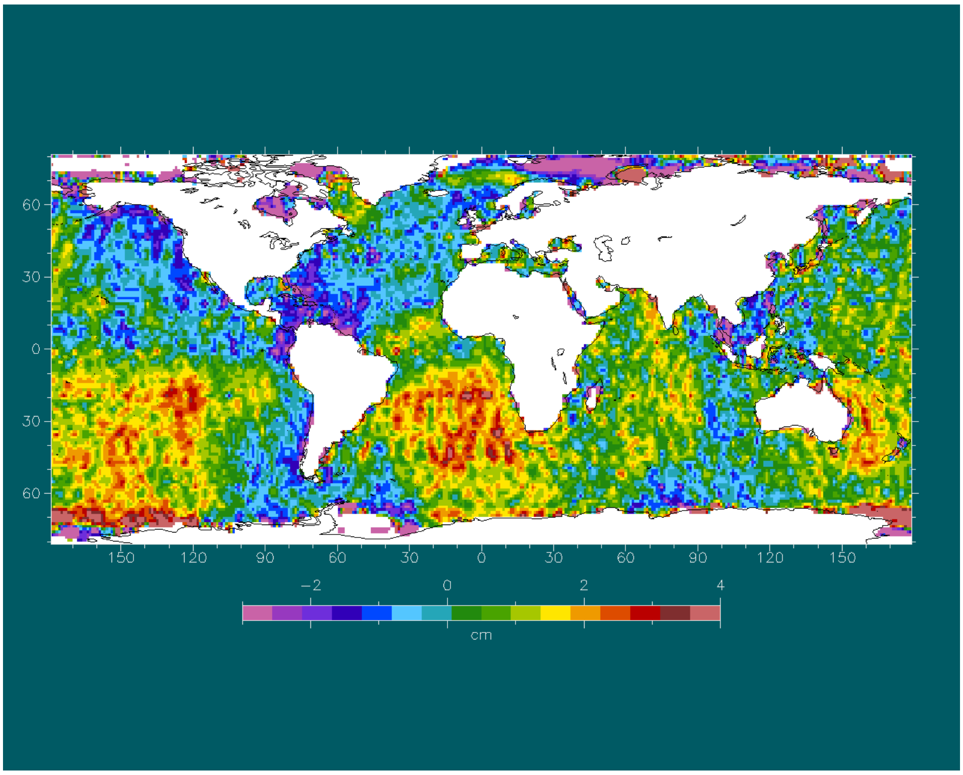
REAPER

Re-scoping of ERS Altimetry Data Set Reprocessing

ERS Orbit Validation Report

Document ID: DOPS-SYS-TN-101-OPS-GN

Authors:
Michiel Otten and Pieter Visser



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Rene Zandbergen
March 20, 2019

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Chapter 1

Introduction

This documents contains the orbit validation results performed at ESOC as part of the REAPER POD extension activity performed in 2018 by Delft University of Technology (TUD) and the Navigation Support Office at ESA/ESOC.

The orbit and altimeter validation results in this report are based on the following solutions: from Delft Universty of Technology for ERS-1 Delivery number 3 and for ERS-2 Delivery number 3, from ESOC for ERS-1 Delivery number 2 and ERS-2 Delivery number 1. The combination solution is based on the latest solution from the two analysis centres.

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

Based on the altimeter validation results for ERS-1 and ERS-2 the Delft University of Technology orbit is recommended to be used as the reference for the new REAPER orbits.

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 three 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	-0.03	0.10	0.08	0.06	0.06	0.08
along	5.65	3.48	2.63	3.79	2.27	0.00
cross	-1.13	-0.33	-0.39	-0.45	-0.44	-0.31
rms						
radial	5.46	3.77	2.78	2.29	2.08	1.91
along	37.02	25.73	19.11	15.37	13.03	11.20
cross	34.05	22.41	14.51	11.79	10.21	9.64

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

	1991	1992	1993	1994	1995	1996
mean						
radial	0.42	0.17	0.09	0.07	0.08	0.08
along	-1.07	-0.08	-0.17	0.70	0.84	0.25
cross	-0.41	-0.38	-0.26	-0.42	-0.54	-0.37
rms						
radial	3.47	2.57	1.69	1.50	1.28	1.10
along	10.32	8.01	4.92	4.90	4.01	3.12
cross	18.69	11.23	6.66	5.06	4.18	3.09

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

	1991	1992	1993	1994	1995	1996
mean						
radial	0.13	0.02	0.00	0.00	0.02	-0.01
along	-6.07	-3.57	-2.37	-2.87	-2.03	0.25
cross	0.90	-0.07	-0.11	0.14	-0.10	-0.07
rms						
radial	4.51	3.16	2.13	1.66	1.62	1.57
along	34.73	24.08	17.10	13.63	11.65	9.96
cross	32.84	20.78	13.23	10.56	9.20	8.22

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

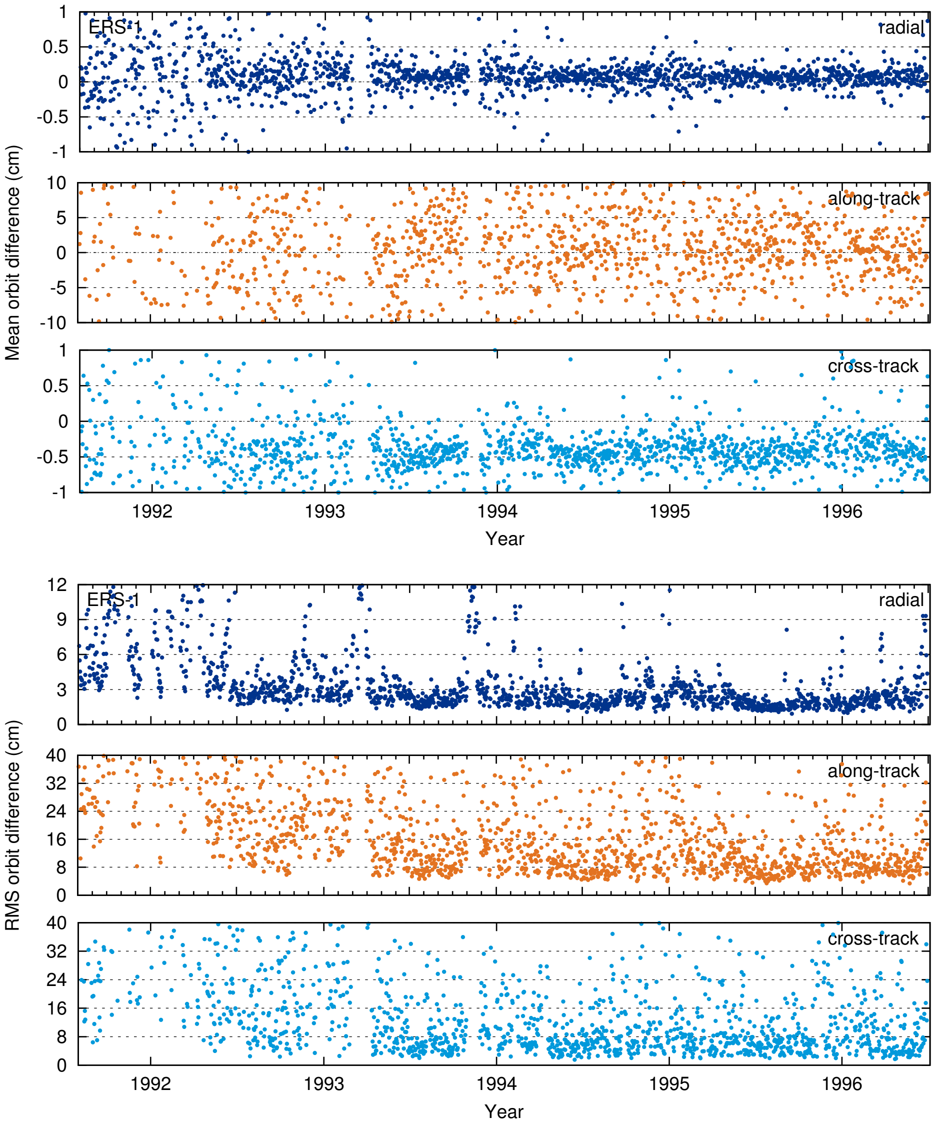


Figure 2.1: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-1 between TUD and ESOC. Orbit difference is calculated as TUD-ESOC.

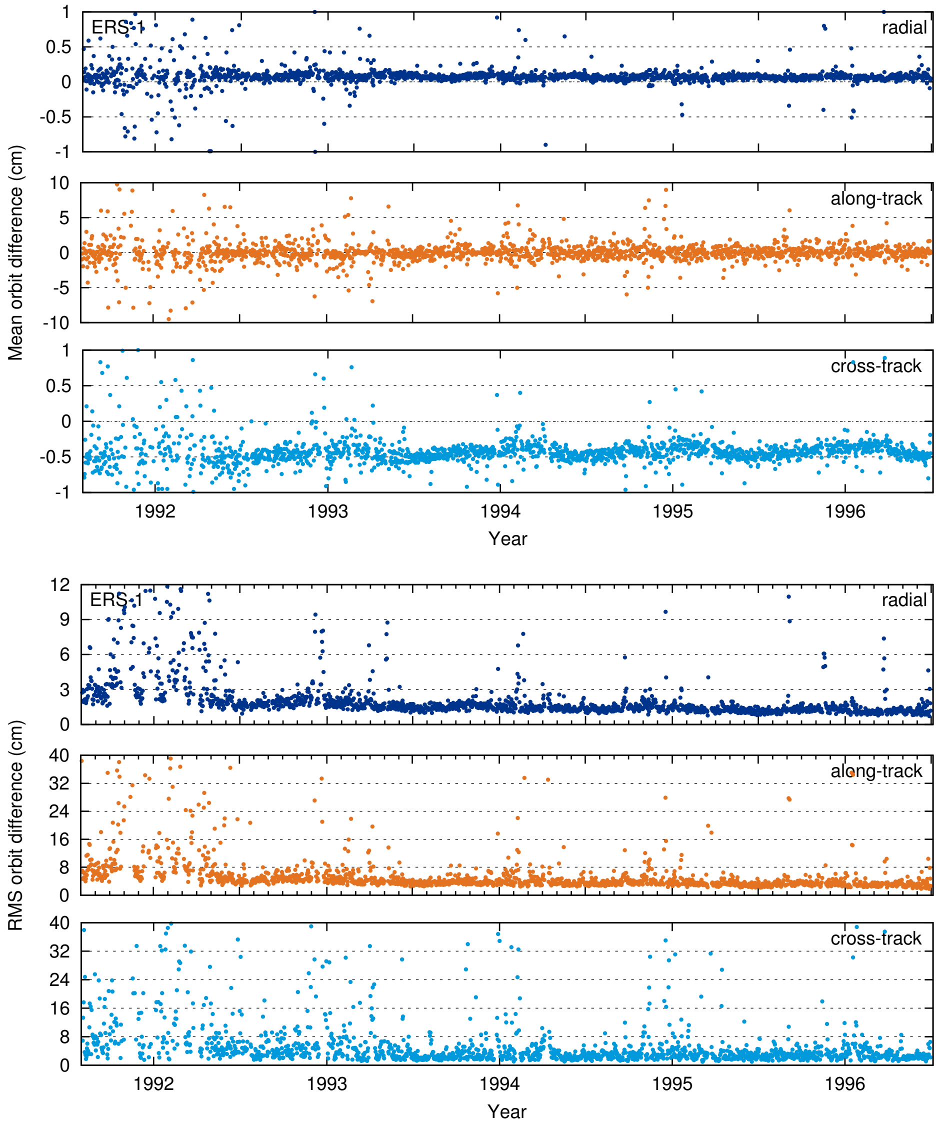


Figure 2.2: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-1 between TUD and Combination. Orbit difference is calculated as TUD-Combination.

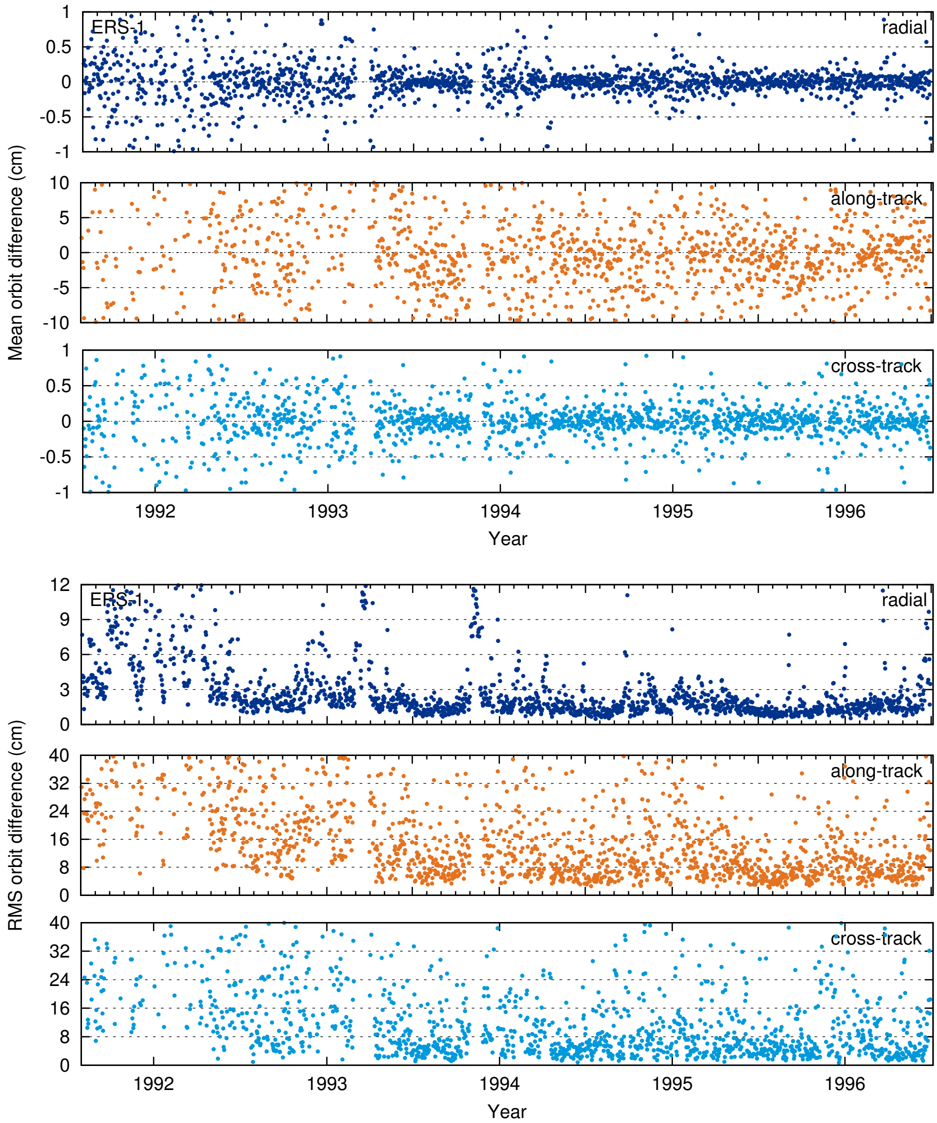


Figure 2.3: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-1 between ESOC and Combination. Orbit difference is calculated as ESOC-Combination.

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 three 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	0.05	0.06	0.03	0.05	0.08	-0.02	0.07	0.10	0.09
along	1.38	-0.07	0.27	1.35	1.18	-0.94	0.04	1.36	3.21
cross	-0.55	-0.46	-0.24	-0.20	-0.53	-0.15	-0.37	-0.38	-0.21
rms									
radial	2.54	2.03	2.49	2.72	2.84	3.99	3.65	3.93	2.90
along	14.09	10.09	12.16	12.47	14.65	23.33	20.90	17.96	15.66
cross	8.40	7.11	5.00	6.63	8.79	10.77	10.02	7.65	5.60
	2004	2005	2006	2007	2008	2009	2010	2011	
mean									
radial	0.10	0.05	0.06	0.07	0.07	0.06	0.11	-0.03	
along	-0.10	0.08	-0.47	1.36	0.51	0.14	0.41	1.01	
cross	-0.26	-0.31	-0.29	-0.31	-0.30	-0.29	-0.30	-0.49	
rms									
radial	2.85	2.38	2.24	2.40	1.79	1.89	2.12	3.10	
along	15.59	11.65	11.22	11.02	6.89	8.29	10.18	15.46	
cross	7.37	5.09	5.40	5.64	3.89	3.86	4.45	6.84	

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

	1995	1996	1997	1998	1999	2000	2001	2002	2003
mean									
radial	0.05	0.06	0.06	0.06	0.07	0.09	0.07	0.08	0.06
along	0.61	0.29	-0.18	-0.23	0.12	0.71	0.39	0.26	0.22
cross	-0.34	-0.42	-0.19	-0.33	-0.67	-0.29	-0.49	-0.38	-0.30
rms									
radial	1.58	1.34	1.35	1.46	1.54	2.29	2.15	1.88	1.41
along	4.21	3.71	3.40	4.16	4.35	6.60	5.94	5.10	3.96
cross	2.60	2.36	1.68	2.48	2.94	4.06	4.03	2.82	3.58
	2004	2005	2006	2007	2008	2009	2010	2011	
mean									
radial	0.04	0.07	0.06	0.06	0.09	0.07	0.07	0.06	
along	0.40	-0.19	0.21	0.15	-0.33	0.02	0.18	0.68	
cross	-0.27	-0.31	-0.32	-0.32	-0.27	-0.28	-0.31	-0.68	
rms									
radial	1.18	1.03	0.97	1.05	1.07	0.91	1.12	1.74	
along	3.26	2.56	3.60	2.66	2.76	2.09	2.85	3.57	
cross	4.05	2.12	2.17	2.31	2.25	1.76	2.62	3.49	

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

	1995	1996	1997	1998	1999	2000	2001	2002	2003
mean									
radial	-0.01	0.00	0.01	0.00	-0.03	-0.06	-0.04	-0.04	-0.02
along	-1.51	0.17	-0.70	-1.96	-0.75	0.10	0.68	-1.21	-2.86
cross	0.15	0.04	0.01	0.00	0.03	0.11	0.01	0.06	-0.21
rms									
radial	1.87	1.52	1.88	2.23	2.44	3.52	3.22	3.41	2.64
along	12.81	9.34	11.14	11.51	14.16	22.27	20.91	16.80	14.77
cross	7.83	6.70	4.42	6.15	8.41	10.11	8.86	6.78	5.02
	2004	2005	2006	2007	2008	2009	2010	2011	
mean									
radial	-0.06	-0.02	0.00	0.00	-0.01	0.00	-0.04	0.08	
along	0.12	-0.36	0.40	-1.37	-0.57	-0.10	-0.25	-0.85	
cross	-0.01	0.04	0.01	0.01	0.03	-0.01	-0.01	0.17	
rms									
radial	2.62	2.17	1.97	2.14	1.55	1.65	1.95	2.98	
along	15.19	11.92	10.76	10.79	6.59	8.13	10.10	15.60	
cross	6.82	4.76	5.00	5.55	3.45	3.66	4.05	6.10	

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

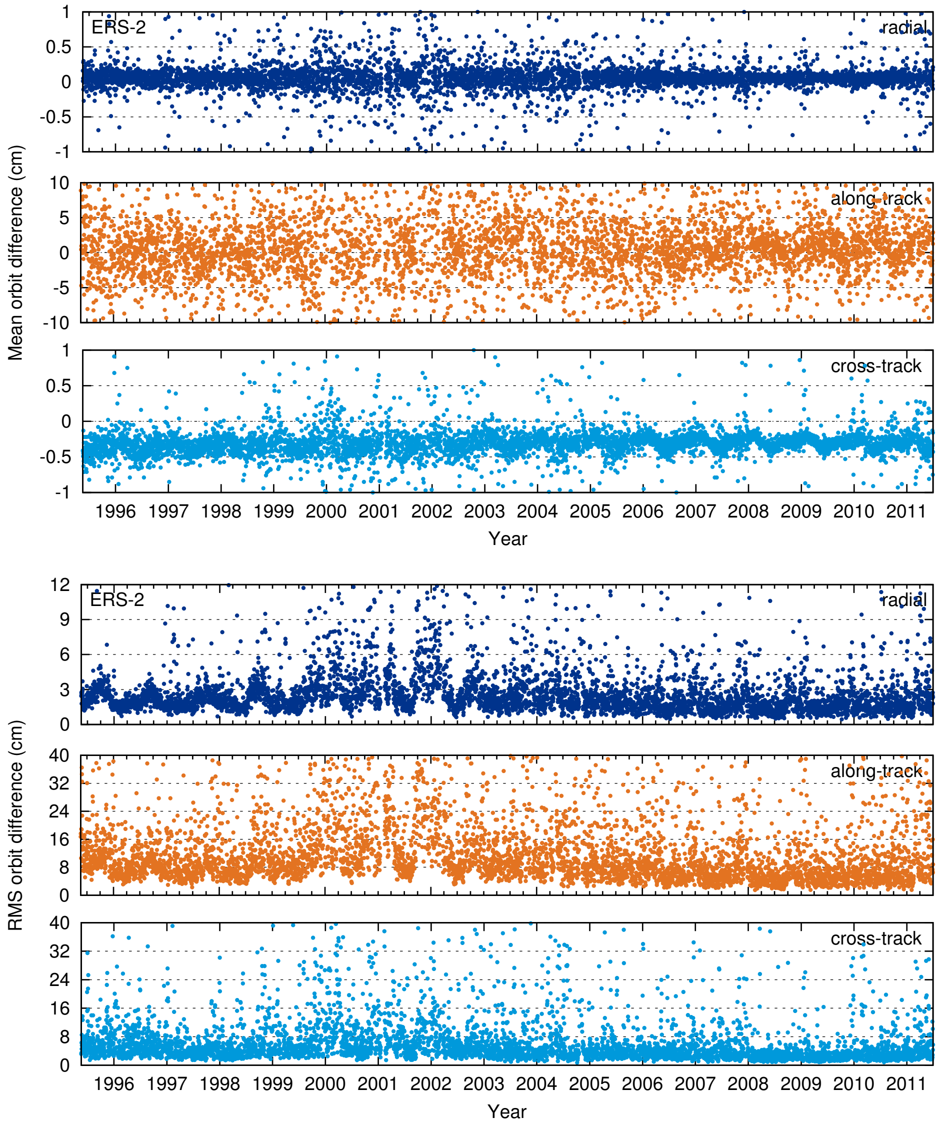


Figure 3.1: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-2 between TUD and ESOC. Orbit difference is calculated as TUD-ESOC.

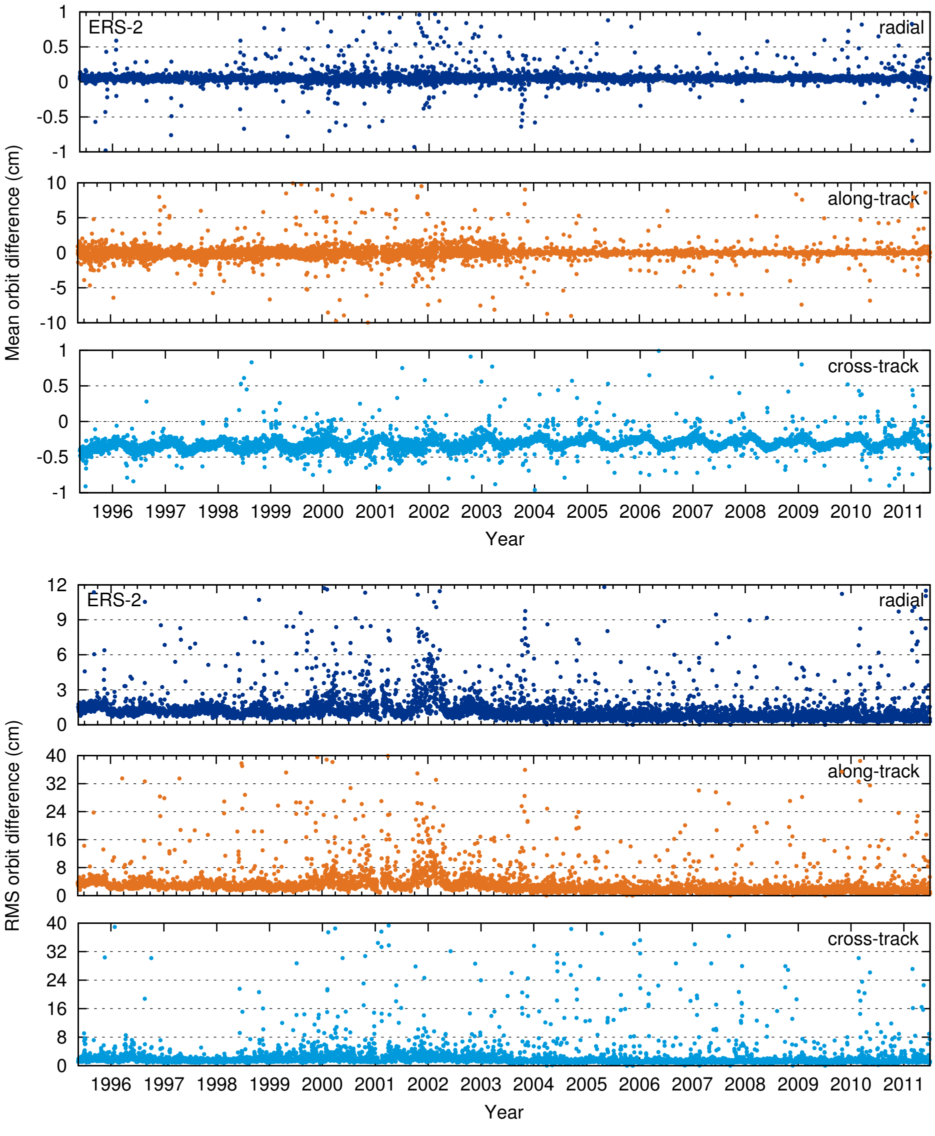


Figure 3.2: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-2 between TUD and Combination. Orbit difference is calculated as TUD-Combination.

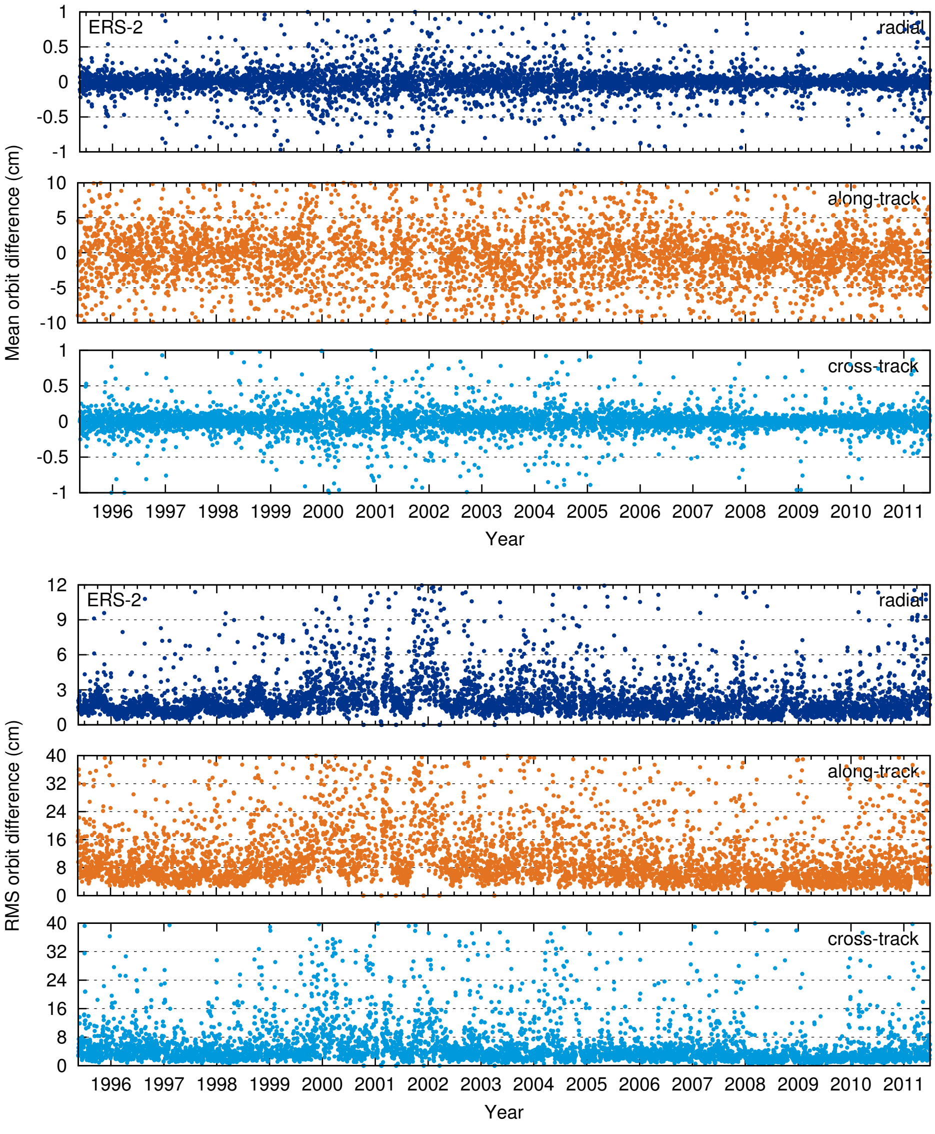


Figure 3.3: Daily mean (top) and *rms* (bottom) orbit difference in centimetres for ERS-2 between ESOC and Combination. Orbit difference is calculated as ESOC-Combination.

Chapter 4

ERS-1 and ERS-2 Altimeter Validation

4.1 Crossover statistics

Let us 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. The two following plots (4.1 and 4.2) show for ERS-1 and ERS-2 the crossover statistics per month starting from the start of the processing period. The ERS-1 and ERS-2 crossover rms has been improved over the entire period for both the new combination solution as well as the TUD solution. Overall the TUD solution performs the best with the fewest outliers compared to all previous solutions.

4.2 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 4.3 and 4.4 show the mean crossover height differences. There is a clear improvement for the combination solution as well as the TUD solution compared to the original REAPER combination for both ERS-1 and ERS-2. The rms of the mean of crossover (in cm) for ERS-1 is 2.3, 2.3, 2.5 and 2.5 for REAPERv1, TUD, ESOC and the new combination solution. For ERS-2 the mean of crossover (in cm) is 2.1, 2.1, 2.3 and 2.2 for REAPERv1, TUD, ESOC and the new combination solution.

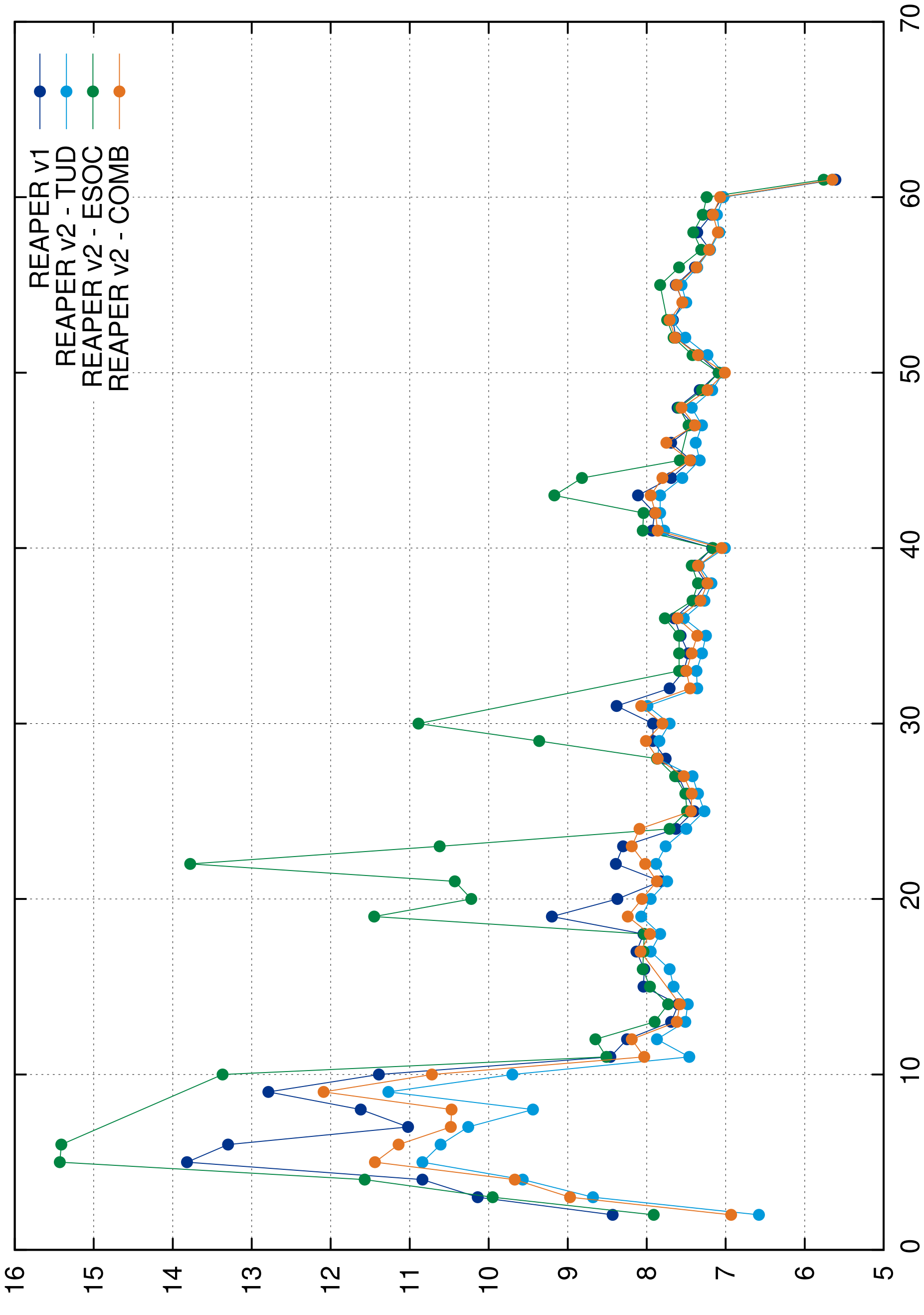


Figure 4.1: rms crossover for the ERS-1 new REAPER solutions compared to the old REAPER combination solution in cm.

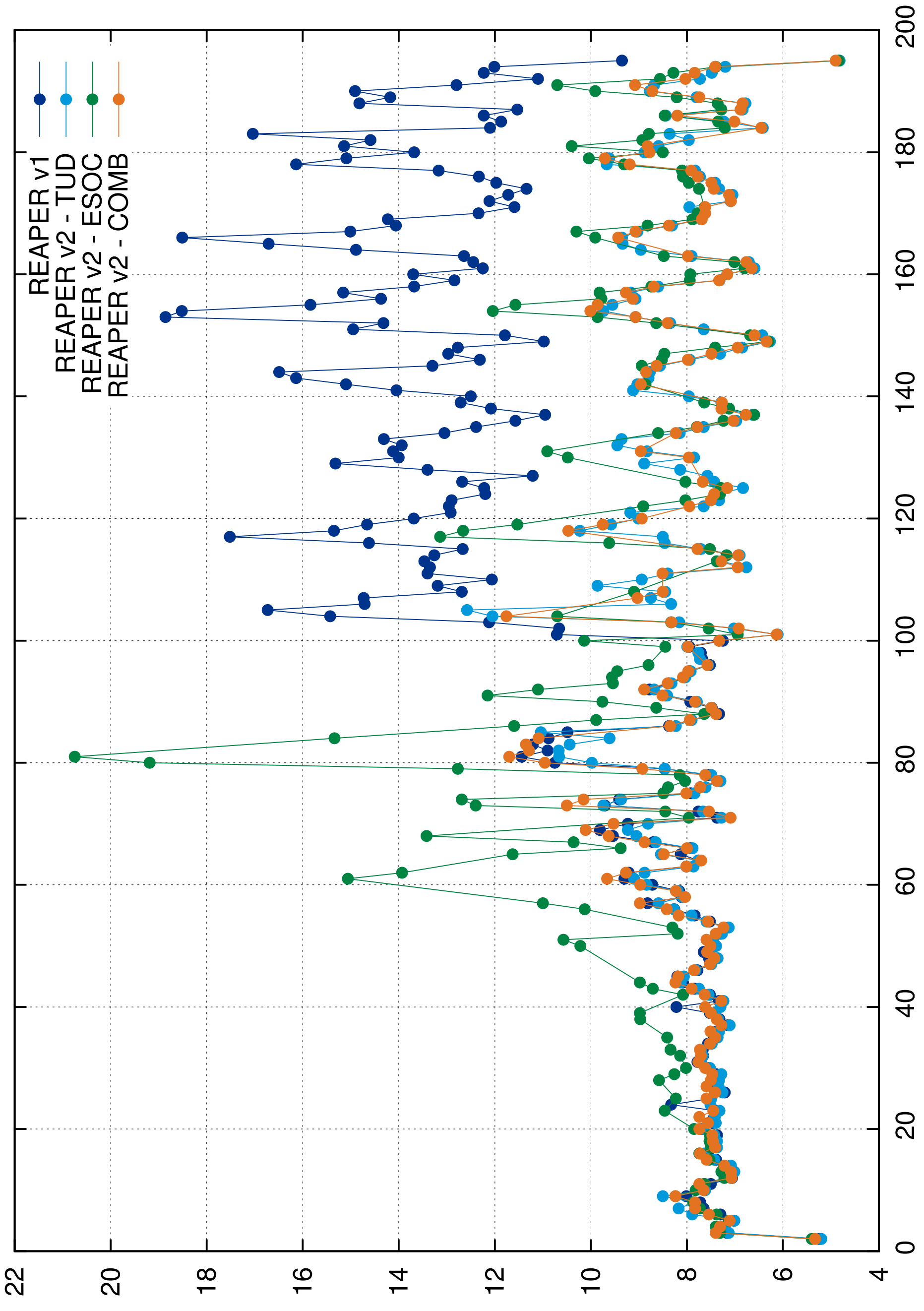
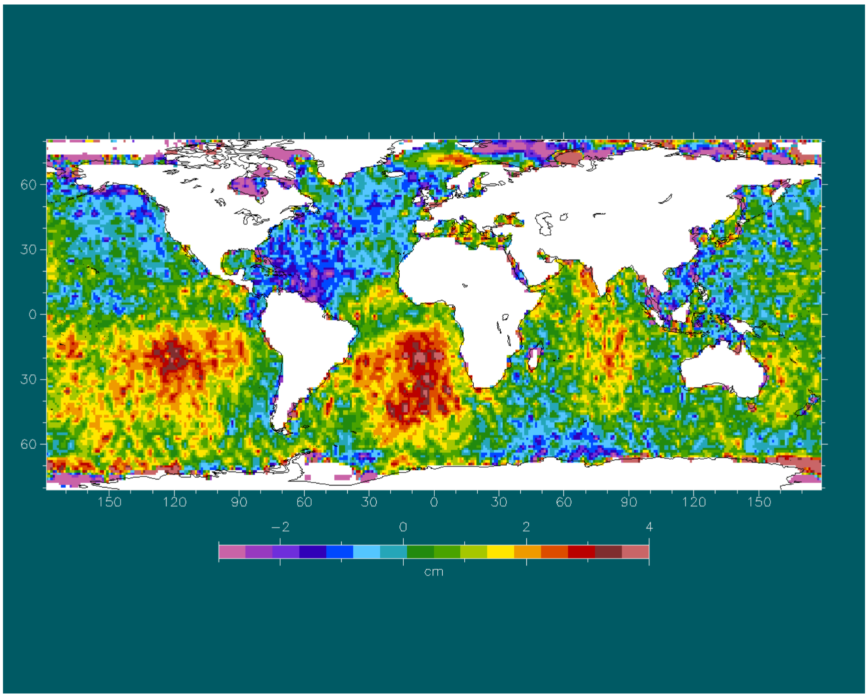
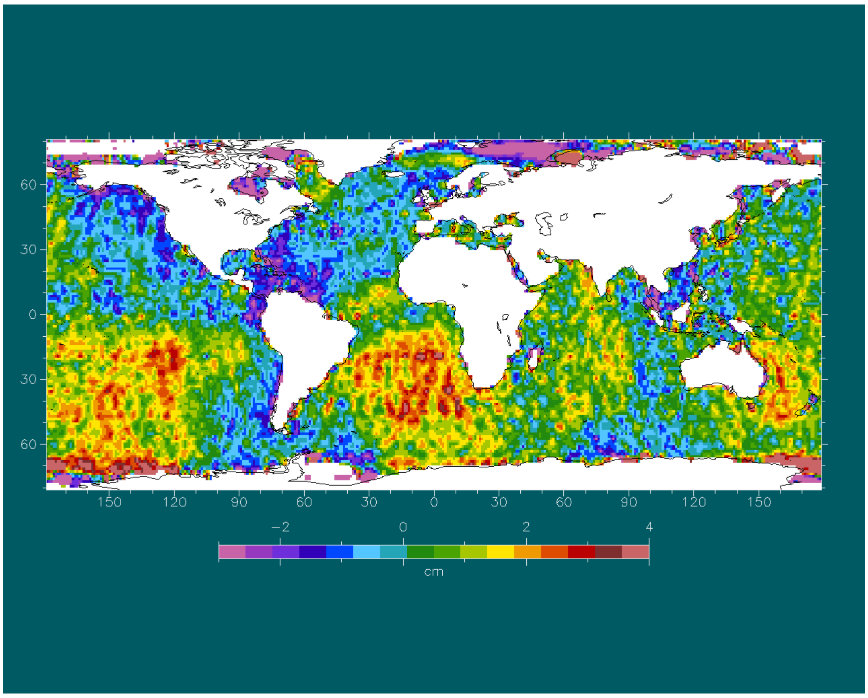
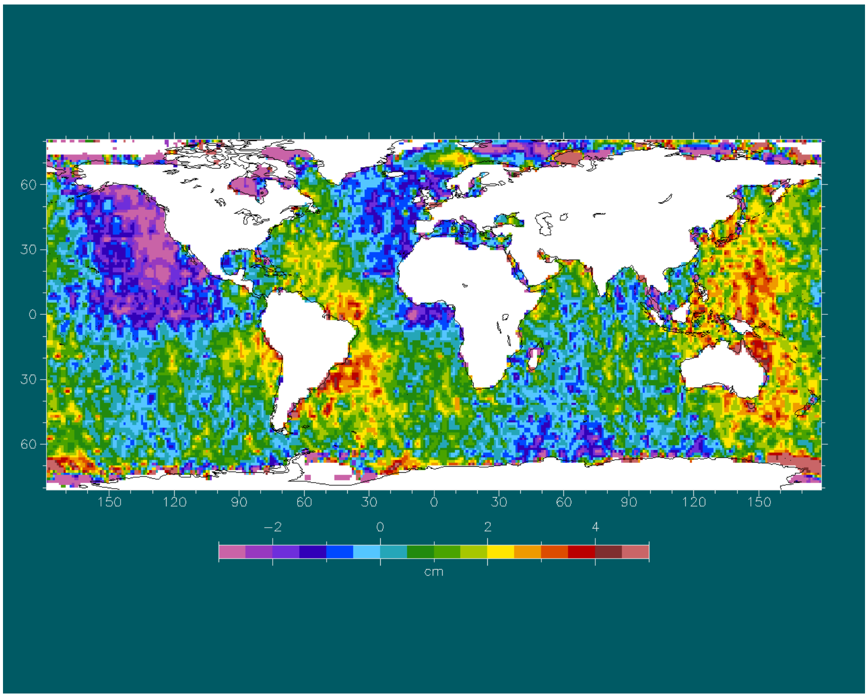


Figure 4.2: rms crossover for the ERS-2 new REAPER solutions compared to the old REAPER combination solution in cm.


60
30
0
30
60
150 120 90 60 30 0 30 60 90 120 150
−2 0 2 4
cm


60
30
0
30
60
150 120 90 60 30 0 30 60 90 120 150
−2 0 2 4
cm



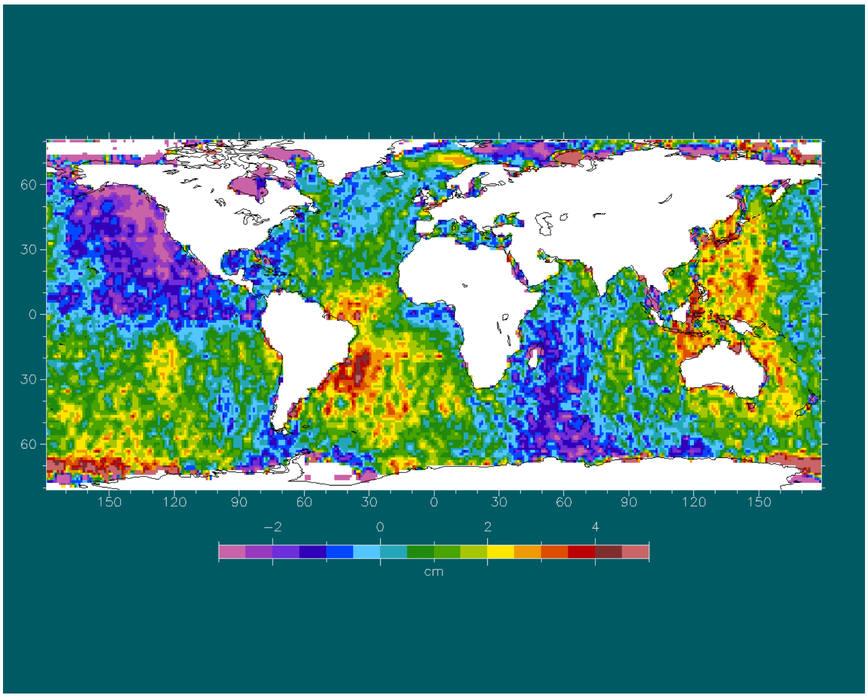
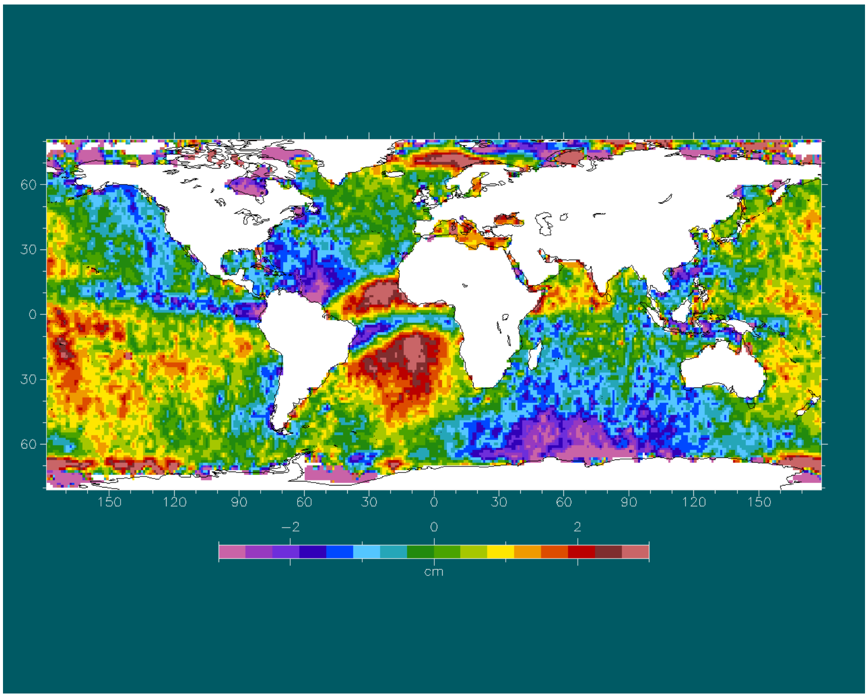
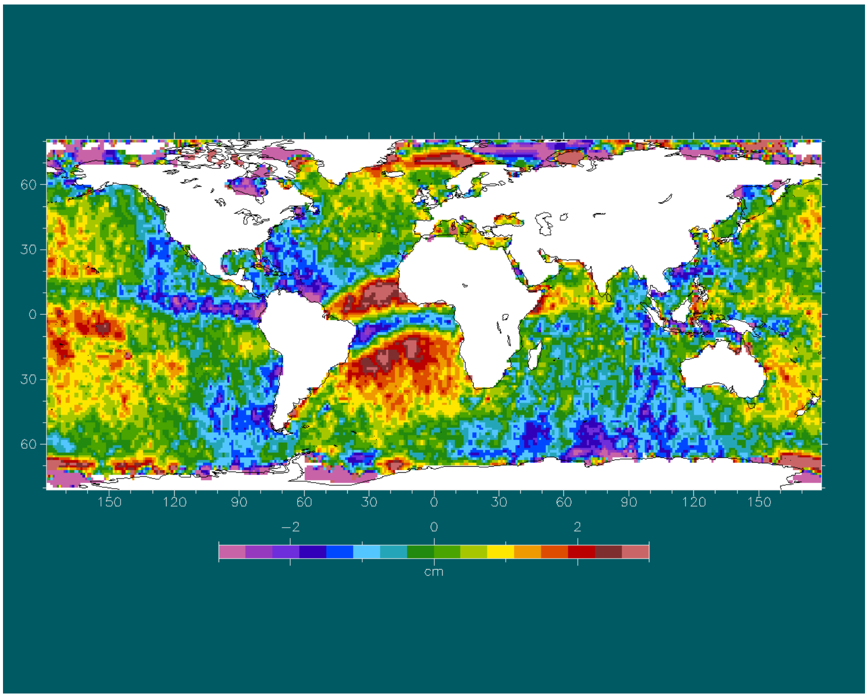


Figure 4.3: Mean crossover height differences computed using different orbits: REAPER v1, and three REAPER v2 orbits (TUD, ESOC and combined one (from top to bottom)) for ERS-1


60
30
0
30
60
150
120
90
60
30
0
30
60
90
120
150
−2
0
2
cm


60
30
0
30
60
150
120
90
60
30
0
30
60
90
120
150
−2
0
2
cm

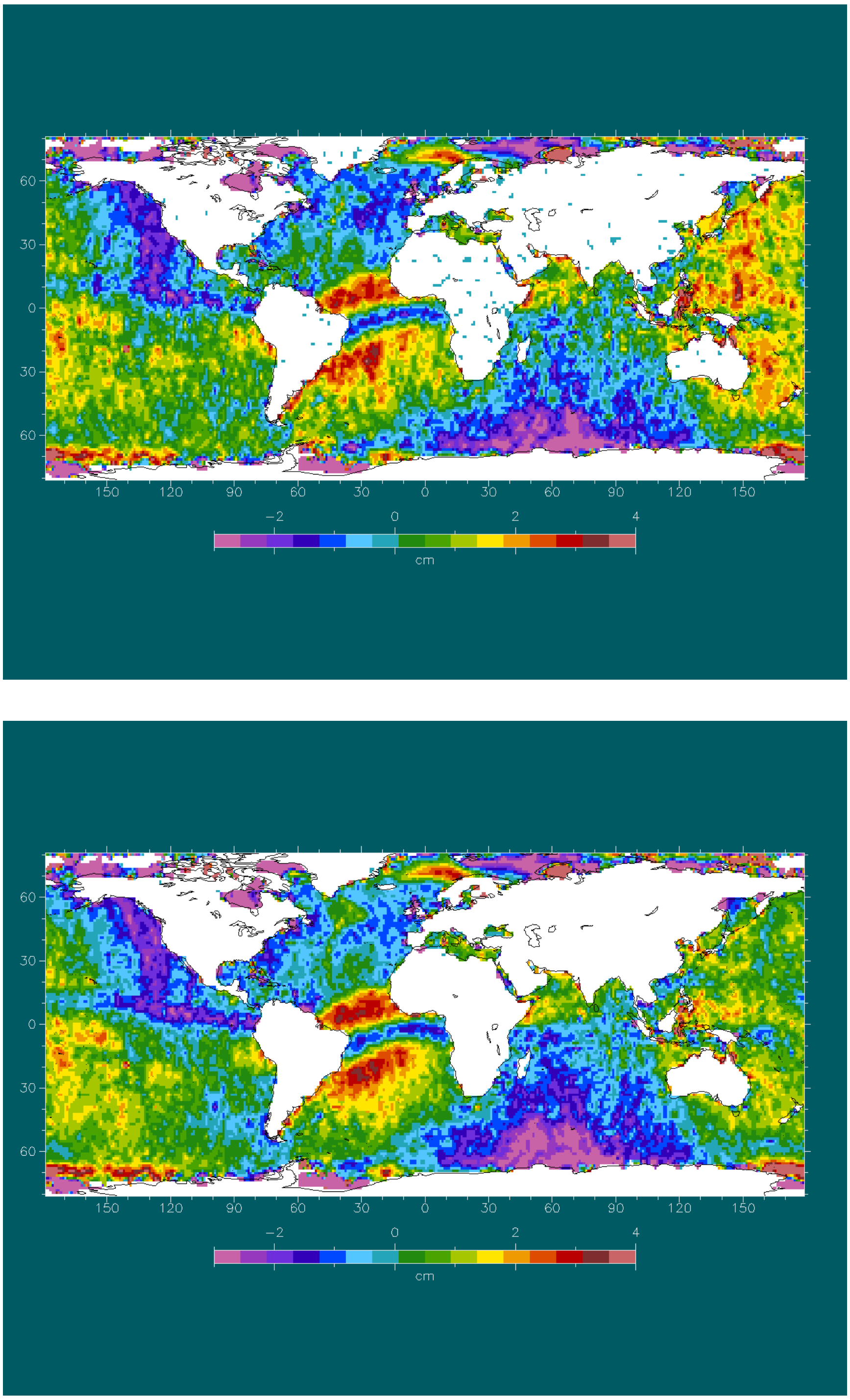


Figure 4.4: Mean crossover height differences computed using different orbits: REAPER v1, and three REAPER v2 orbits (TUD, ESOC and combined one from top to bottom)) for ERS-2

Chapter 5

Conclusions

The new REAPER combination solution shows for ERS-1 and ERS-2 a superior performance when compared to the previous REAPER combination orbit. Furthermore, the extension of the ERS-2 solution until mid 2011 now means that for the first time for both missions a single uniform solution is available that covers the full missions' duration for which altimeter data is available.

While this report concludes the REAPER activity, further work on the ERS orbit solutions will be undertaken by ESOC as an internally funded activity. This has the aim to achieve a further improvement, which is considered still to be possible. Any resulting improved orbits, and a corresponding combination, will be made available to the user community.

Appendix A

Format Description

The daily sp3 files for the ESOC and combination solution have the following naming convention: YYMMDD.$<$ *centre* $>$.sp3 in which YY is the 2 digit year, MM the month and DD the day of the start of the file (the first epoch of the file in GPS time) each of the daily files is exactly 24 hours long and has a 1-minute sampling interval and $<$ *centre* $>$ is either esoc or comb respectively. For the TUD daily sp3 files the naming convention is xxo.YYMMDD.sp3 for ERS-1 and adr.YYMMDD.sp3 for ERS-2 with the above mentioned convention for YY,MM and DD.

The formal error estimation files have the following naming convention: formal.YYMMDD for both ERS-1 and ERS-2.

A.1 SP3 orbit format

The format description of the SP3 files can be found at the following location: ftp://igs.org/pub/data/format/sp3c.txt

A.2 Formal error estimation

The formal errors are based on the inverse of the normal matrix of all estimated parameters in the orbit determination process (initial position and velocity, drag parameters, solar radiation pressure coefficient, empirical accelerations, manoeuvres if applicable, measurement biases, etc.: see the EXCEL sheet with the orbit setup). When computing the normal matrix all correlations and constraints imposed on the estimated parameters are taken into account, and use is made of the observation weights (again please see the EXCEL sheet with the orbit setup). The parameter uncertainties and their correlations are then propagated to position and velocity uncertainties using the variational equations that represent the partial derivatives of the position and velocity coordinates to the estimated parameters.

Column	Description
1	GPS time (YYMMDDHHMMSS.0)
2	Formal error J2000 position X coordinate (cm)
3	Formal error J2000 position Y coordinate (cm)
4	Formal error J2000 position Z coordinate (cm)
5	Formal error J2000 velocity X coordinate (cm/s)
6	Formal error J2000 velocity Y coordinate (cm/s)
7	Formal error J2000 velocity Z coordinate (cm/s)
8	Formal error radial position coordinate (cm)
9	Formal error along-track position coordinate (cm)
10	Formal error cross-track position coordinate (cm)
11	Formal error radial velocity coordinate (cm/s)
12	Formal error along-track velocity coordinate (cm/s)
13	Formal error cross-track velocity coordinate (cm/s)

Table A.1: Format description of the TUD formal error estimates.

Please note that formal errors have not been calibrated and are in general optimistic. These formal errors thus do not always realistically represent the real error level. However, the formal errors provide relative quality information and can be used to identify periods when orbit quality can be less (e.g. close to manoeuvre periods).

Appendix B

Processing standards overview

	ESOC Update 22.08.2018	DEOS Update 28.08.2018
Software		
Name and version	NAPEOS version 4.2	GEODYN 0712
Arc cut		
Arc lengths	7 Day Arcs (with 24 Hour overlap on each side)	5.5 days with 24-hr overlaps on each side
Handle of Manoeuvers	Estimated	Estimated
Additional margins		
Reference System		
Polar motion and UT1	IERS bulletin C04 series with IERS daily and sub-daily corrections	IERS bulletin C04
Precesion and Nutation model	IERS Conventions 2010	
SLR coordinates	ITRF2014	ITRF2014
PRARE coordinates		TU Delft estimated
Displacement of reference points		
Earth tides	IERS2010 Standards	IERS2003 solid earth tides
Atmospheric loading	NONE	NONE
Ocean loading	EOT11a	GOT4.10
Pole tides	IERS2010 Standards	IERS2003
Satellite reference		
Mass and center of gravity	Post-Launch values from Control Centre	Post-Launch values from ESOC
Attitude Model	Theoretical attitude model (yaw-steering)	Nominal law (=yaw-steering)
Gravity		
Gravity field (static)	EIGEN.GRGS.RL03.v2.coef	EIGEN.GRGS.RLO3.v2.coef (80x80 part)
Gravity field (time varying)	Annual+Semi Annual 80x80 from EIGEN.GRGS.RL03.v2.coef	Annual+Semi Annual 80x80 from EIGEN.GRGS.RL03.v2.coef
Earth tides	IERS2010 Standards	IERS2003 standards
Pole tide	IERS2010 Standards	IERS2003 standards
Ocean tides	EOT11a all constituent up to degree/order 50	GOT4.10
Atmospheric tides	NONE	none
Atmospheric gravity	AOD1B rl06 80x80 at 3hrs	AOD1B rl06 80x80 at 3hrs
Third bodies	All planets, Sun and Moon DE-405	All planets, Sun and Moon DE-405
Surface forces and empirical		
Radiation Pressure model	ANGARA or box/wing model	box/wing model
Radiation pressure scale coefficient	fixed	fixed
Earth radiation	applied (albedo and IR from ANGARA model)	applied
Atmospheric density model	MSIS-90	MSIS-86
Drag coefficients	10 per day	8 per day (+ 3-hr time correlation constraints)
1/rev empiricals	Every 12 Hours	Every 11 hours, filled up around maneuvers (+ 11 hr time correlation constr.)
SLR measurements		
Data Taken From	CDDIS	CDDIS and EDC
Troposphere correction	Mendes-Pavlis following IERS 2003 update	Mendes-Pavlis
Retroreflector correction	fixed offset value per satellite according to ILRS website values	fixed offset value per satellite according to ILRS website values
Biases	NONE	Range biases estimated for some stations and passes
Weight	4.0 cm	10 cm
Elevation angle cutoff	NONE	10 degrees
Downweighting law	NONE	NONE
Altimeter Data		
Data Taken From	RADS Database	RADS Databasee
Crossovers		10 cm
Altimeter heights (normal points)		10 cm
Biases		One altimeter time bias per arc
Biases (Cont'd)		One altimeter sea level height bias per arc
Relativistic corrections	IERS Conventions 2010	IERS Conventions 2003
Prare measurements		
Data Taken From		GFZ
Troposphere correction		Hopfield model,scale factor biases estimated
Retroreflector correction		Fixed pre-launch offset values
Biases		Range biases per station per arc estimated
Biases (Cont'd)		Pass dependent tropospheric scale factors
Biases (Cont'd)		One overall PRARE time bias per arc
Weight		10 cm (PRARE range), 0.1 cm/s (PRARE Doppler)
Elevation angle cutoff		10 degrees
Downweighting law		NONE