IMPROVED ERS AND ENVISAT PRECISE ORBIT DETERMINATION

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ABSTRACT

For over a decade, the Delft precise ERS-1 and ERS-2 orbits have been used in many scientific investigations based on ERS altimeter and interferometric SAR data. This orbit computation is now continued for Envisat, with an unprecedented accuracy due to better tracking data and lower force model errors. Orbit errors due to inaccuracies in the Earth's gravity model, which have been the main focus of research during the 1990s, have been reduced to a lower level than those incurred by errors in measurement modelling and non-gravitational force modelling.

We have compared several models and methods in order to investigate and where possible reduce each of the error sources. When reprocessing the tracking data over the solar maximum period of the past years, frequent large and unpredictable changes in thermospheric density form the dominant remaining source of orbit error, for which accurate modelling remains a difficulty. Nevertheless, the quality of our Envisat precise orbits already rivals that of TOPEX/Poseidon and Jason. The orbit quality will likely further improve as solar activity continues to drop towards solar minimum.

Key words: ERS-2; Envisat; Orbit; SLR; DORIS; Radar Altimeter; Gravity field model; non-gravitational forces;.

1. INTRODUCTION

Precise orbital positions of the satellite are essential elements in the processing of ERS and Envisat radar altimeter and interferometric SAR data. In radar altimetry, the orbital altitude is required to relate observations of the distance between the instrument and the radar-reflecting surface to a terrestrial reference surface. Even though the orbit is no longer the dominant error source in altimetry processing, any improvement in its accuracy will directly increase the fidelity of the altimeter science data. In order to generate SAR interferograms, the difference in position between two or more successive SAR image acquisitions is required at a high precision.

The DEOS institute at Delft University of Technology has been involved with the computation of precise orbits for ERS since the start of the ERS-1 mission. The Delft orbits, generated using the GEODYN software [1] and made available through ftp, have been used in many scientific investigations based on ERS altimeter and interferometric SAR data processing. With the launch of Envisat, DEOS has been involved in the validation of the Envisat orbit products and continues to compute its precise orbits on a regular basis.

The orbit determination is based on models of the forces acting on the satellite, where selected parameters of these models are adjusted, along with an initial satellite position and velocity. This adjustment is done in order to make the resulting orbit fit to the tracking data in a least-squares sense. The most important force models include the Earth's irregular gravity field, the effects of tides on the gravity field, aerodynamic drag by the upper atmosphere, and radiation pressure forces from the Sun and Earth. Gravity effects from the Moon, Sun and planets are also taken into account.

All three satellites carry identical laser retro-reflector arrays for tracking with sub-centimetre accuracy by around 30 laser ranging stations. The SLR tracking is subject to weather conditions, and the global coverage is far from complete. However, the unambiguous high-accuracy range-measurements have proven vital for the ERS altimetry missions [2], and now provide an ideal synergy with the radiometric tracking on Envisat.

Radiometric orbit tracking has been provided by the German PRARE system on ERS-2, after a failure of that instrument on ERS-1. The latency in the availability of the PRARE data has rendered it unsuitable for orbit determination in support of operational altimetry applications. In addition, the PRARE tracking network has degraded severely over time. For this reason, altimeter data has been used as auxiliary tracking data in the orbit determination of the ERS satellites in Delft. On Envisat, the primary tracking instrument is the French-build DORIS receiver, using the Doppler shift of transmissions from a network of approximately 50 beacons. This dense dataset ensures that precise orbits can be obtained without having to use the altimeter data.

Details of the models and parameterisation used in the DEOS precise orbit determination for ERS can be found in [3, 4]. Orbits computed according to that description,

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referred to as DGM-E04 orbits, are now available for the entire global ERS altimetry mission, from the launch of ERS-1 in July 1991 to the failure of the second tape recorder on ERS-2 in June 2003.

The launch of Envisat has warranted a detailed new look at orbit determination models and methods. This paper will describe this investigation, which has focused on tracking data availability, external events affecting the orbit accuracy, dynamic models and parameterisation schemes. The selected new procedures can to a large extent also introduce an orbit improvement for the ERS satellites over the DGM-E04 orbits, which results in a significant upgrade of this long-term altimetry dataset.

2. DATA AND EVENT MONITORING

The quality of a computed orbit is determined by the quality of the underlying tracking data and models. Therefore the processing and monitoring of both the tracking data and geophysical data used by the models is an important tool, both in the Envisat orbit determination and for the validation of the final orbit. These aspects are described in the sections below. In the future, this information will be used to generate an orbit quality flag, which can be used to edit the altimeter data.

2.1. Tracking data

Laser tracking of Envisat began on 10 April 2002, at 19:28 UTC by SLR stations near Riga, Latvia and Helsinki, Finland. The number of SLR stations actively tracking Envisat in any given week has varied between approximately 10 and 30, depending on weather as well as operational conditions at the stations. Because of the weather restrictions on laser tracking, and the disproportionally large fraction of stations in Europe, there is a yearly minimum in laser tracking during the Northern Hemisphere winter. The number of SLR passes per orbital revolution has varied between 0.65 and 1.35, when averaged over each 35-day repeat cycle.

The DORIS system does not have these weather and operational restrictions. It operates in radio-wavelengths and the beacons are designed to operate for long durations with little human intervention. There were several issues with both the ground and space segment of Envisat in the first months after launch however, which limited the DORIS data availability. Most of these problems have now been solved and the nearly 50 beacons are currently providing data for 8 to 9 DORIS passes on average per orbital revolution.

More important than the absolute tracking data quantities are the occurrences of long duration gaps in the tracking data. Figure 1a shows all gaps in DORIS and SLR, since the start of the mission, which are longer in duration than one hour. For SLR tracking, gaps with a duration of several hours occur very frequently. Since the station coverage is very inhomogeneous, it frequently takes several revolutions before the satellite passes over another station. SLR tracking gaps longer than half a day are very rare however. These usually only occur right after manoeuvres or geomagnetic storms, when the orbit predictions that the stations use to target their lasers tend to be less reliable.

For the DORIS system, the ground beacon network runs independently of the satellite operations. Due to the large number of stations, there is a high degree of build-in robustness. The failure of one or even a few beacons only has a small impact on orbit determination results. Any DORIS data gaps shown in Figure 1a are directly the result of issues of the Envisat satellite, its DORIS instrument, or the ground segment. Since early 2003, these data gaps have become relatively infrequent. Their occurrence does, however, strongly affect the orbit precision, especially when they coincide with manoeuvres and SLR data gaps, as has happened for example in cycles 9, 12 and 16.

2.2. Geophysical effects on satellite drag

Most of the dynamic models used in orbit determination, such as the gravity field, exhibit more or less constant error characteristics over time. Similar errors are introduced from cycle to cycle and year to year. The drag force, however, depends on a model of the density of the thermosphere, which has large variations with solar and geomagnetic activity. These are related to sunspot regions, solar flares and coronal mass ejections. There are especially large uncertainties in density during the peak years of the 11-year solar activity cycle. The density model uses ground-based observations as proxies for the solar EUV and geomagnetic heating input into the atmosphere. Figure 1b shows the $F_{10.7}$ proxy for solar activity and A_p for geomagnetic activity. Note that daily A_p values are shown here, even though 3-hourly values of a_p or the related k_p value are used in density models for precise orbit determination purposes.

The Envisat mission was launched close to the end of the peak in the 11-year solar activity cycle. Over the mission lifetime up to now, $F_{10.7}$ can be seen to be steadily decreasing in Figure 1b, even though large variations with a periodicity of approximately 27-days (the solar rotation period) are visible. It is expected that $F_{10.7}$ will continue to decrease to around 70 by the year 2007, when the Sun and thereby the Earth's upper atmosphere have reached a more steady, inactive state. At that point, the magnitude of the drag force will be more than one order of magnitude less than at launch, and almost two orders of magnitude lower than during the extreme solar-magnetic storm at the end of October 2003. This event, coinciding with an orbit manoeuvre and SLR data gap, has significantly impacted the orbit accuracy of Envisat.

2.3. Orbit maintenance manoeuvres

Orbit maintenance manoeuvres are used to keep Envisat within its 1 km deadband from a nominal groundtrack.

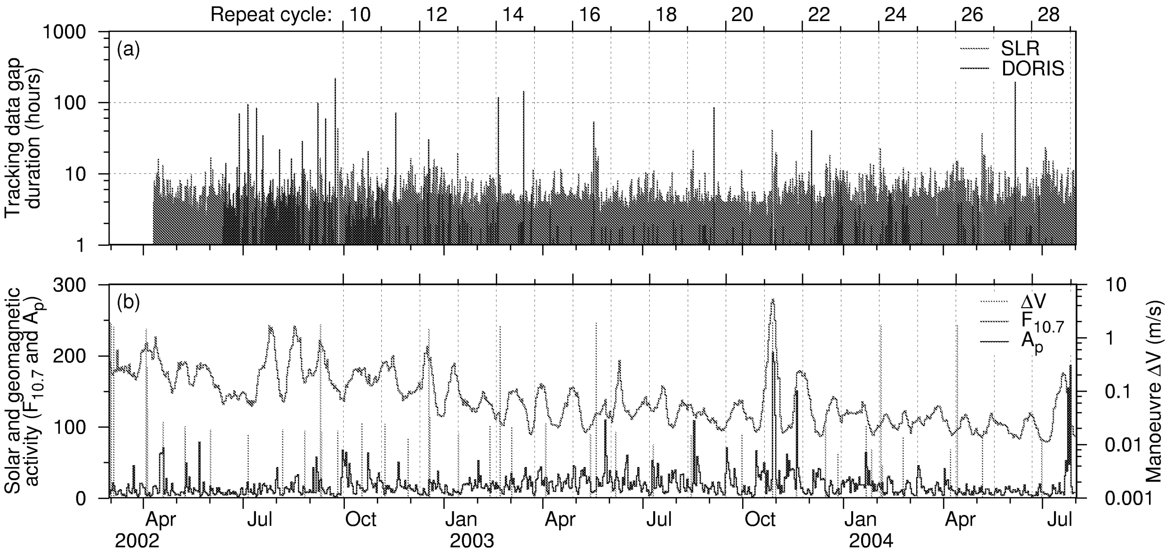

Figure 1. Timelines of important contributors to degraded orbit quality for Envisat: (a) Tracking data gaps in SLR and DORIS. (b) Solar and geomagnetic activity proxies $F_{10.7}$ and A_p proxies, and orbit-maintenance manoeuvres.

Drag perturbations are the largest in-plane accelerations, which have to be countered by regular orbit-raising manoeuvres. Out-of-plane orbit manoeuvres require much more energy, but occur less frequently. They are required to counter the effect of solar radiation pressure and solar and lunar gravity on the inclination of the orbit plane. It requires no explanation that such manoeuvres are disruptive events in the precise orbit determination. The manoeuvres are usually handled by estimation of a three-component acceleration for the duration of one integration time-step. For the larger out-of-plane manoeuvres, the tracking data is often not strong enough to constrain this estimation, and the orbit determination arcs have to be split at the manoeuvre instance itself. In any case, the orbit is often poorly determined when the time-span between two or more successive manoeuvres is small (less than a day).

3. MODEL AND ORBIT COMPARISONS

The models, methods and parameterisations which are used in the current ERS-2 and Envisat orbits are for a large part derived from the DGM-E04 ERS orbits described in detail in [3]. The models and methods which have changed for the improved orbit determination of ERS-2 and Envisat are summarised and compared in table 1.

The selection of new models started with an extensive orbit comparison activity by the Envisat Orbit Verification Team (OVT). At the end of the validation phase, the OVT recommendations were adopted by CNES for processing the precise orbits which appear on the altimeter GDR products. We have continued the evaluation of new models as they have become available. Most notable are the GRACE gravity models.

This section will discuss the performance of various models and strategies for the orbit determination of Envisat. The orbit determination was tested for Envisat cycle 18, which occurred during a period of moderate solar activity, few tracking data gaps and contained only one in-plane orbit manoeuvre.

Several orbit quality criteria are use in the comparison, of which the results are summarised in table 2. None of these criteria can give a direct estimate of the orbit accuracy. The difference of overlapping orbit arcs in the radial direction is a measure of consistency in the orbit solution from arc to arc. However, because systematic errors in tracking data and force models are similar in all arcs, this statistic can only provide a lower bound on the orbit precision during the overlap periods. On the other hand, the ends of the arcs, which are used in the overlaps, are considered less accurate than the centre of the arcs.

Since the SLR and DORIS data are both used in the orbit determination, lower residuals indicate a better fit in table 2. The SLR residuals are especially valuable, since they provide a direct range measurement, with a very low error. Only measurements from the nine most stable and reliable SLR stations have been used in table 2. The statistics on sea height differences at altimeter crossover points are the only independent data source for evaluating orbit error. However, the crossovers also contain large contributions due to sea surface variability and errors in the altimeter measurement corrections. Nevertheless, the crossover RMS is the most useful statistic for relative comparison of orbit quality. The mean of the crossovers represents a systematic difference between ascending (night-time) and descending (day-time) tracks, and therefore could represent an offset of the orbit in the inertial X-Y plane, with respect to the centre of mass of the Earth.

	ERS-1/2 DGM-E04 orbits	new ERS-2 orbits	Envisat orbits
Gravity field	DGM-E04	EIGEN-GRACE01S	EIGEN-GRACE01S
Tides	EGM-96	PGS7751E	PGS7751E
Station positions	LSC98-C01	ITRF-2000	ITRF-2000
Surface forces	Box-wing panels	ANGARA ERS-2	ANGARA Envisat
Thermosphere	DTM, MSIS-86	MSIS-86	MSIS-86
Drag scale factor sub-arc	6 hours	3 hours	1/4 orbit
1-cpr acceleration sub-arc	22 hours	12 hours	12 hours
SLR a-priori sigma	5 cm + station specific	4 cm + station specific	4 cm + station specific
DORIS a-priori sigma	–	–	0.2 mm/s

Table 1. Comparison of force models, force model parameterisations and data weights for the DGM-E04 orbits and the improved ERS-2 and Envisat orbits. Only changes with respect to the setup of [3] are represented in this table.

		Overlap RMS	Residual RMS		Crossovers	
		Radial (cm)	SLR (cm)	DORIS (mm/s)	mean (cm)	RMS (cm)
(a)	*Gravity field model*					
	JGM-3	1.72	4.86	0.5887	-1.68	9.22
	EGM-96	0.97	4.64	0.5761	-1.51	8.57
	DGM-E04	1.30	3.73	0.5636	-1.48	7.35
	GRIM5-S1	0.58	2.52	0.5541	-1.03	7.32
	EIGEN-GRACE01S	0.61	2.27	0.5545	-0.83	7.05
	EIGEN-GRACE02S	0.58	2.13	0.5541	-0.88	7.04
(b)	*Aerodynamic drag models*					
	Panels, MSIS-86	0.54	2.12	0.5539	-0.93	7.05
	ANGARA, MSIS-86	0.60	2.13	0.5540	-0.89	7.04
	ANGARA, MSIS-86, HWM-93	0.58	2.13	0.5541	-0.88	7.04
	ANGARA, DTM-94	0.63	2.25	0.5560	-0.93	7.06
	ANGARA, NRLMSISE-00	0.58	2.15	0.5541	-0.94	7.04
(c)	*Radiation pressure models*					
	Sun and Earth: panels	0.60	2.09	0.5532	-0.99	7.06
	Sun: ANGARA, Earth: panels	0.58	2.13	0.5541	-0.88	7.04
	Sun and Earth: ANGARA	0.60	2.13	0.5537	-0.85	7.06
(d)	*Drag scale factors estimated per day*					
	4 (every 6 hours)	0.58	2.13	0.5541	-0.88	7.04
	8 (every 3 hours)	0.58	1.99	0.5521	-0.97	7.04
	16 (every 90 minutes)	0.59	1.94	0.5510	-0.99	7.04
	32 (every 45 minutes)	0.51	1.75	0.5508	-1.00	7.04
	64 (every 22.5 minutes)	0.51	1.67	0.5518	-0.92	7.03
(e)	*Tracking data a-priori standard deviations (relative weighting)*					
	SLR: 4 cm, DORIS:10.000 mm/s	2.96	1.78	0.5901	-1.08	7.60
	SLR: 4 cm, DORIS: 1.000 mm/s	1.33	1.80	0.5598	-1.21	7.21
	SLR: 4 cm, DORIS: 0.600 mm/s	1.06	1.84	0.5578	-1.09	7.18
	SLR: 4 cm, DORIS: 0.400 mm/s	0.87	1.88	0.5564	-0.94	7.11
	SLR: 4 cm, DORIS: 0.200 mm/s	0.66	2.02	0.5541	-0.77	7.06
	SLR: 4 cm, DORIS: 0.010 mm/s	0.67	4.53	0.5484	-0.59	7.93
	SLR: 4 cm, DORIS: 0.001 mm/s	0.67	4.61	0.5484	-0.59	7.94
(f)	*GDR orbit*					
	Envisat RA-2 GDR (CNES POE orbit)				-1.48	7.38

Table 2. Results of the orbit tests in the model and parameter comparison for Envisat cycle 18.

3.1. Gravity field

The comparison of gravity field models is summarised in table 2a. It includes two models which have been long-time reference fields, but did not have any ERS data included in their generation. These are JGM-3 [5] and EGM96 [6]. They return SLR residuals of 4–5 cm for Envisat, and a crossover RMS close to 9 cm. A version of JGM-3 tuned with ERS altimetry from the tandem phase is DGM-E04 [3]. This model, which has long been the standard for ERS orbit determination in Delft, does much better, returning a crossover RMS of 7.35 cm. The GRIM5-S1 model [7] is the best performing pre-CHAMP and GRACE model available. It is based on a large quantity of satellite tracking data, including the ERS satellites. This results not only in a crossover RMS which is slightly better than that for DGM-E04, but also in much-reduced SLR and DORIS residuals, indicating that it removes along- and cross-track errors as well as the radial orbit errors which had already been largely removed by DGM-E04. Finally, the first two static gravity fields from the GRACE mission build by GFZ-Potsdam are EIGEN-GRACE01S and EIGEN-GRACE02S [8]. The preliminary EIGEN-GRACE01S model, based just on a small amount of GRACE data, already outperforms all previous models. The fact that these results are achieved based on a model that does not contain ERS or Envisat data is very good news for future missions in new orbits, such as Cryosat. No gravity field tuning will be necessary for such missions. The second GFZ static GRACE-only model, EIGEN-GRACE02S, released just in time to be taken into account for this comparison, shows that a slight improvement is still possible, which is best visible in the SLR fit. Note that no CHAMP gravity field models were included in the comparison. In our experience, static gravity models including CHAMP data have shown no significant benefit for ERS and Envisat orbit determination over their predecessor models.

3.2. Non-gravitational force models

The relative performance of non-gravitational force models is presented in table 2, sections b and c. Two representations of the satellite geometry and surface properties were compared. A relatively simple panel model provided by the CNES Envisat POD team, and an ANGARA model [9], developed by DEOS in cooperation with ESOC and HTG. The performance of these models was tested for aerodynamic drag, solar radiation pressure and Earth radiation pressure. A similar comparison for the ERS-2 models [9] showed that although the ANGARA models are better at representing subtle variations in the accelerations than the panel models, there does not seem to be a net effect on the precise orbits. This conclusion also seems to apply to Envisat. The differences in the orbit quality indicators of table 2 is very small. Any difference in the accelerations between the different models has an effect on the orbit that can be easily absorbed in the empirical accelerations and scale factors.

The same is true for the thermospheric models. The MSIS-86 model [10] is the most widely used today. It is tested here also in combination with a horizontal wind model HWM-93 [11], which has a second order effect on the aerodynamic perturbations. Alternatives for MSIS-86 are its follow-on NRLMSISE-00 [12], and the French DTM94 [13]. Although the model outputs vary more greatly than was the case in the panel/ANGARA comparison, the errors in the models are mostly absorbed by the empirical force model parameters. Again, the differences on the Envisat orbit statistics are small: the MSIS-type models only slightly outperform the DTM94 model.

3.3. Force model parameterisation

As mentioned in the introduction, a common practice in precise orbit determination is to estimate force model parameters, which help reduce orbit error. The most effective and common estimated parameters are scale factors for the drag force and sinusoidal empirical accelerations in the along- and cross-track direction, with a frequency of once per revolution. These parameters can be defined to be piece-wise constant over an estimation interval which is shorter than the total orbital arc. When reducing the length of these sub-arc intervals, the orbit solution starts to rely less on the original dynamic models and more on the tracking data, moving to a so-called reduced-dynamic solution. In order to test the effect of changes in the parameterisation, various lengths of the drag scale factor estimation interval are compared in table 2d.

It is clear that when reducing this time-interval the DORIS and especially the SLR residuals reduce dramatically. This makes perfect sense, because the orbit solution is given more freedom in order to better fit this tracking data. Only when the interval becomes very short (22.5 minutes), the DORIS residuals start to become slightly higher again. It is likely that the short-duration drag scale factors adversely affect the estimation of the DORIS per pass frequency offset and tropospheric scale parameters estimates at this point. An expected decrease in the radial overlap RMS is also notable, signifying a better consistency at the ends of the orbit arcs. However, there is no improvement visible in the crossover statistics. This might indicate that although the orbit is adjusted to better fit the data over the laser stations, there is no significant improvement outside their coverage.

The lack of improvement with a reduced-dynamic orbit determination strategy for Envisat seems disappointing compared with results obtained earlier for Envisat, and for example for the Jason satellite [14]. However, it should be noted that in the past these strategies have always been demonstrated using gravity field models containing considerable residual gravity field model error. In this test, we have used the very accurate EIGEN-GRACE02S gravity field model. The trade-off between a dynamic and reduced-dynamic strategy is always based on the balance between the quality of the tracking data and the quality of the force models. It seems that with the GRACE gravity field, the orbit quality measured in terms of crossover RMS has become rather insensitive to the level of force model parameterisation.

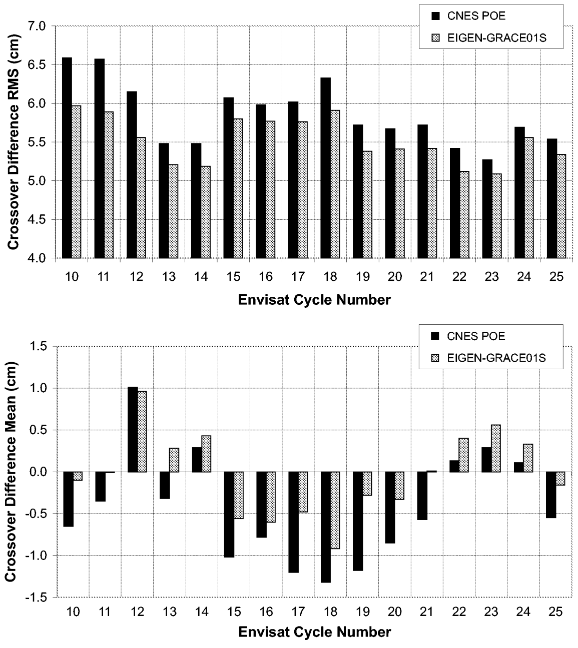

Figure 2. Crossover RMS (top) and mean values for Envisat cycles 10–25.

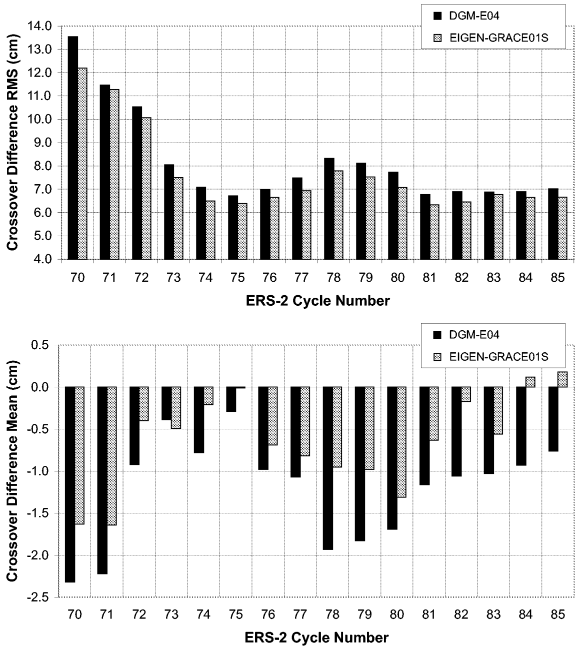

Figure 3. Crossover RMS (top) and mean values for ERS-2 cycles 70–85.

3.4. Relative DORIS/SLR data weight

Table 2e finally shows the effect of changing the relative DORIS/SLR data weighting in the orbit determination. The data weight is usually expressed in terms of the a-priori standard deviation (sigma) for a certain measurement type. In this case, the SLR data sigma has been kept fixed at 4.0 cm with a station-dependent factor of 1–20 cm added in a root-sum-square sense to account for differences in SLR station performance and knowledge of a-priori station coordinates. For the DORIS system, the sigma is varied between 10 mm/s for a solution that is close to SLR-only, to 0.001 mm/s for an approximation of a DORIS-only orbit.

It is clear both from the radial overlap RMS as well as the crossover statistics, that there is an optimum in the orbit quality when using a DORIS sigma of approximately 0.2 mm/s. This result demonstrates the excellent synergy between the two tracking data types. Note however that at the two extremes, SLR-only and DORIS-only, the resulting orbits still result in quite reasonable orbit quality statistics. It seems that even with only one of the two tracking systems, a radial orbit precision better than 10 cm RMS can quite easily be reached.

3.5. Cycle-to-cycle behaviour of crossover statistics

The long-term behaviour of the crossover difference RMS and mean for Envisat is shown in figure 2. In this figure, the CNES POE orbit which is made available on the RA-2 GDR dataset is compared with the Delft EIGEN-GRACE01S solution. Note that Envisat RA-2 data for cycles 10, 11 and 12 were only made available using a preliminary version of the GDR processing software, while cycles 13, 14 and 15 were only partly available at the time this analysis was performed.

The RMS of the crossovers shows that the Delft solution is consistently more accurate than the GDR orbits. The difference can be attributed for the largest part to the use of the GRACE gravity model in Delft, while the GRIM5-S1 model is used by CNES. There also seems to be a considerable long-term variation in the crossover RMS which is consistent for both orbits. The source of this variation is difficult to pin down, because variations in sea surface variability and altimeter media corrections, as well as several aspects of orbit modelling could play a part here. In the mean of the crossovers however, a sinusoidal variation is visible with an amplitude of approximately 1.5 cm and a period of approximately one year. Recall that the mean of the crossover differences represents a systematic offset between the ascending and descending tracks. It is therefore likely that such a signal represents a miscentring of the orbit in inertial space [15], although errors in the ionospheric corrections could also have such a signature. Although the centring of the Delft orbits seems to be better than that of the CNES POE, further investigation is required in order to identify and possibly remove the source of this variation. It is likely that orbit centring variations have a component in the direction of the Earth's spin axis as well, and could therefore adversely influence the reliability of climatological studies based on altimeter data.

The same analysis of crossover statistics was done for ERS-2 cycles 70–85. Figure 3 compares the RMS and mean of the crossovers when using the Delft DGM-E04 and the new EIGEN-GRACE01S solutions. Note however that for ERS, the altimeter data is used as tracking

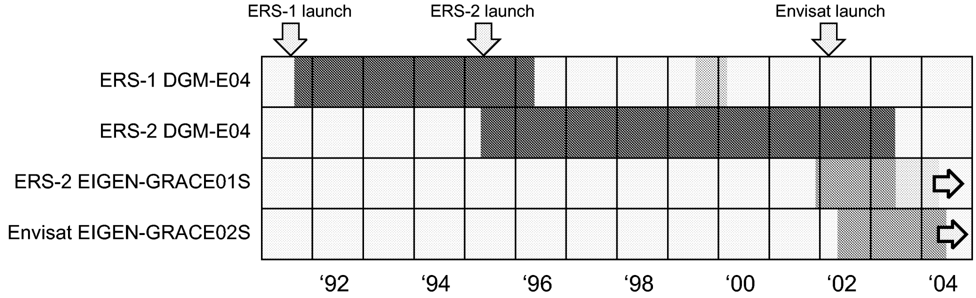

Figure 4. Timeline highlighting the availability of the various Delft orbit solutions for ERS-1, ERS-2 and Envisat. The lighter shades indicate orbit solutions for use in InSAR processing, based on SLR data only, for periods when the RA instrument was not active or not delivering global data.

data in the orbit determination, and can not be used as an independent data type. Nevertheless, figure 3 shows that the EIGEN-GRACE01S orbits are consistently better than the DGM-E04 orbits. As for Envisat, the variation between cycles is much larger than the differences between the two solutions. Especially cycles 70, 71 and 72 show abnormally large crossover difference statistics. ERS-2 shows the same variation in the crossover means as Envisat. Note also that the overall magnitude of the crossovers for ERS-2 is much higher than for Envisat. This can be attributed to several of the improvements in the Envisat RA-2/MWR/DORIS payload over the equivalent instruments on ERS. Most notable are probably the dual-frequency ionosphere correction and improved orbit tracking by DORIS.

3.6. ERS and Envisat orbit performance

The accuracy of precise satellite orbits can not be measured exactly without an independent, unambiguous additional tracking measurement. Since such a measurement is not available for ERS and Envisat, it is only possible to make an estimate of the orbit accuracies. A conservative estimate is that the ERS-2 EIGEN-GRACE01S radial orbit accuracy is now at the level of 4 cm RMS, under normal solar activity conditions. Due to the limited tracking information content of the SLR and altimetry data used in ERS orbit determination, the orbit quality is rather sensitive to disturbed conditions in the thermosphere. At high solar activity and during geomagnetic storms, the orbit quality is therefore often degraded, while at low solar activity, when substantial SLR tracking is available, the orbits are exceptionally good. For Envisat, the orbit quality is more consistent, thanks to the DORIS tracking. The radial orbit error is estimated at 2–3 cm RMS, comparable to the accuracy of the SLR/DORIS orbits on the TOPEX/Poseidon and Jason-1 altimetry GDR data.

4. AVAILABILITY OF THE ORBITS

The Delft orbit files for ERS and Envisat can be freely downloaded in ODR format, together with software tools to read and interpolate these files. The web address is http://www.deos.tudelft.nl/ers/precorbs/orbits/. There is currently a latency of 1–3 months in the availability of the precise orbits. The availability over time for the old and new generation orbits is visualised in figure 4. Note that after the tape-recorder failure on ERS-2 in June 2003, DEOS has stopped the generation and distribution of fast-delivery orbits. SLR-only orbits for ERS-2 will remain available as long as there is adequate SLR tracking, in support of the InSAR community.

Since the EIGEN-GRACE01S orbits are only available starting with ERS-2 cycle 70, and no DGM-E04 orbits are available for Envisat, there is currently no consistent continuing time-series of ERS-1, ERS-2 and Envisat altimetry available. This is of importance for local climate studies. Since the different gravity models introduce different geographically correlated orbit errors, the switch from DGM-E04 to EIGEN-GRACE01S introduces location-dependent jumps in the time-series of several centimetres.

5. CONCLUSIONS

The new Delft ERS-2 and Envisat EIGEN-GRACE01S orbits significantly outperform the widely-used DGM-E04 and GDR orbit solutions. Radial orbit errors are now estimated at 4 cm RMS for ERS-2 and 2.5 to 3 cm RMS for Envisat, respectively. Special care has to be taken to monitor gaps in the tracking data, manoeuvres and variations in the thermospheric density due to solar and geomagnetic activity. Degraded orbits due to such events could be flagged in the future, so that affected altimeter data can be easily edited when necessary.

An extensive orbit comparison campaign was performed to find the optimal models and parameterisations for use in the orbit determination of Envisat. The GRACE gravity mission is the main cause of the improved orbit accuracy, which applies to ERS-2 as well. For Envisat, the orbit accuracy in terms of the RMS altimeter crossover differences is in fact relatively insensitive to the degree of reduced-dynamic parameterisation, when the EIGEN-GRACE02S gravity model is used. The DORIS and SLR measurements each have their unique contribution to the orbit determination problem. Using either one these data types, orbits that meet the Envisat accuracy specifications can be computed. However, a combination of SLR and

DORIS data results in the best possible orbit solution. Together with the improved GRACE gravity model, this tracking combination has made it possible to meet the ambitious goal of 3 cm Envisat orbits.

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