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ESA Sea Level CCI

Validation Report: WP2200 Orbit Calculation

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| Reference: | CLS-DOS-NT-12-52 |
| Nomenclature: | SLCCI-VR-20 |
| Issue: | 1. 1 |
| Date: | Mar. 12, 12 |

| Chronology Issues: | | | |
| --- | --- | --- | --- |
| Issue: | Date: | Reason for change: | Author |
| Rev 0 | 15/09/11 | Creation | M. Ablain |
| Rev 1 | 27/01/11 | Update with new RRDP concerning CNES GDR-D orbit | M. Ablain |
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| People involved in this issue: | | |
| Written by (\*): | M. Ablain (CLS)  S. Rudenko (GFZ)  T. Schoene (GFZ) | Date + Initials:( visa or ref) |
| Checked by (\*): | G. Timms (Logica) | Date + Initial:( visa ou ref) |
| Approved by (\*): | G. Larnicol (CLS) | Date + Initial:( visa ou ref) |
| Application authorized by (\*): | ESA | Date + Initial:( visa ou ref) |

*\*In the opposite box: Last and First name of the person + company if different from CLS*

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| Index Sheet: | |
| Context: | Baghera tool, project ACT-OCEAN |
| Keywords: | Oceanography, sea level |
| Hyperlink: |  |

| Distribution: | | |
| --- | --- | --- |
| Company | Means of distribution | Names |
| CLS | Notification |  |

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| List of items to be confirmed or to be defined |

Lists of TBC:

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Lists of TBD:

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| Applicable documents |

AD Sea level CCI project Management Plan  
CLS-DOS-NT-10-013

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| Reference documents |

RD 1 Manuel du processus Documentation  
CLS-DOC

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# Introduction

The main objective of this document is to provide the analysis of the RRDP reports dedicated to the orbit calculation (WP2200) in order to estimate the best orbit solutions to improve the sea-level calculation for climate applications.

This document discuss the impact of all new algorithms separating the different climate applications defined in the sea level CCI URD (User Requirement Document) and separating the several temporal scales related with climate applications. A clearly and easily understandable impact indicator has been defined and is described in annex of this document (see Appendix B -)."

The following RRDP have been performed for ERS-1 and ERS-2 missions:

* Comparison of Reaper combined orbit with GFZ Reaper orbit: [RRDP\_WP2200\_Orbit\_COMBINEDReaper\_vs\_GFZReaper\_11-08-29.pdf](ftp://slcci_team:%2fextcci2011-@ftp.esa-sealevel-cci.org/Data/RRDP/RRDP_WP2200_Orbit_COMBINEDReaper_vs_GFZReaper_11-08-29.pdf)
* Comparison of Reaper ESOC orbit with GFZ Reaper orbit: [RRDP\_WP2200\_Orbit\_ESOCReaper\_vs\_GFZReaper\_11-08-29.pdf](ftp://slcci_team:%2fextcci2011-@ftp.esa-sealevel-cci.org/Data/RRDP/RRDP_WP2200_Orbit_ESOCReaper_vs_GFZReaper_11-08-29.pdf)
* Comparison of GFZ Reaper orbit with DEOS orbit based on the DGM-E04 gravity field model currently used in the AVISO products: [RRDP\_WP2200\_Orbit\_GFZReaper\_vs\_DEOS\_11-08-26.pdf](ftp://slcci_team:%2fextcci2011-@ftp.esa-sealevel-cci.org/Data/RRDP/RRDP_WP2200_Orbit_GFZReaper_vs_DEOS_11-08-26.pdf)
* Comparison of GFZ SLCCI orbit with the Reaper combined orbit based: [RRDP\_WP2200\_Orbit\_GFZslcci\_vs\_COMBINEDReaper\_11-09-06.pdf](ftp://slcci_team:%2fextcci2011-@ftp.esa-sealevel-cci.org/Data/RRDP/RRDP_WP2200_Orbit_GFZslcci_vs_COMBINEDReaper_11-09-06.pdf)

and the following RRDP has been performed for Envisat, Jason-1 and Jason-2:

[RRDP\_WP2200\_Orbit\_ESOCv7\_vs\_CNESGdrC\_11-08-26.pdf](ftp://slcci_team:%2fextcci2011-@ftp.esa-sealevel-cci.org/Data/RRDP/RRDP_WP2200_Orbit_ESOCv7_vs_CNESGdrC_11-08-26.pdf)

[RRDP\_WP2200\_Orbit\_CNESgdrD\_vs\_CNESgdrC\_12-01-24.pdf](ftp://slcci_team:%2fextcci2011-@ftp.esa-sealevel-cci.org/Data/RRDP/RRDP_WP2200_Orbit_CNESgdrD_vs_CNESgdrC_12-01-24.pdf)

The Reaper orbits have been uploaded from the following ftp site: <ftp://dgn6.esoc.esa.int/reaper/>. The orbits are computed in the LPOD2005 terrestrial reference frame using the models and input data described in the poster presentation ”Improvements in ERS-1 and ERS-2 precise orbit determination” by S. Rudenko, M. Otten,P. Visser, R. Scharroo and T. Schoene, presented at the European Geosciences Union (EGU) General Assembly2011, Vienna, Austria, 3-8 April 2011 and available as file <ftp://dgn6.esoc.esa.int/reaper/poster_EGU-2011.pdf> (S. Rudenko, M. Otten, P. Visser, R. Scharroo, T. Schoene, New improved homogeneous orbits of ERS-1 and ERS-2 satellites, Advances in Space Research, 2011, submitted).

DEOS preliminary ERS-1 and ERS-2 orbits are based on the DGM-E04 gravity field model and SLR and OPR altimeter crossovers and normal points. They have been uploaded from the following ftp sites <http://www.deos.tudelft.nl/ers/precorbs/> for ERS-1 and ERS-2.

The GFZ SLCCI orbit solutions are available on the ftp site: ftp://ftp.esa-sealevel-cci.org/Data/WP2200. The orbit was computed in the ITRF2008 reference frame using the models defined in “Sergei Rudenko and Tilo Schoene. Definition of common standards for ERS-1, ERS-2, Envisat, TOPEX/Poseidon, Jason-1 and Jason-2 precise orbit determination. Report for the ESA Climate Change Initiative Sea Level Project. April 15, 2011, updated on May 16, 2011 ».

The CNES GDR-D orbit solutions have been provided by CNES in the framework of the SALP project. For more information see the Lucas Cerri’ presentation made during the San Diego OSTST (October 2011): <http://www.aviso.oceanobs.com/fileadmin/documents/OSTST/>

# Global Mean Sea Level

## Long-term evolution

### Validation diagnoses used

The validation diagnosis of the long-term sea-level evolution (A201-a) allows us to evaluate the impact on the global MSL trend using successively the different orbit solutions. Their impact is also analyzed separating descending and ascending passes (A201-b): the reduction of the MSL trend differences is a good quality criterion to determine which correction is the best. Cross-comparison of MSL trends between altimetric missions collocated on the same period (B001) and the comparison with in-situ measurements (tide gauge C001) also give a relevant indication to know whether the potential drift of altimeter MSL is reduced or not with new correction (C001).

### Orbit solutions dedicated to ERS-1 and ERS-2

For ERS-1 and ERS-2, the impact of the new orbits derived from REAPER and SLCCI projects tested is significant for the global MSL in comparison with the DEOS orbit (based on the DGM-E04 gravity field model) currently used in the sea-level AVISO products. The global MSL trend differences range from +0.5 to +0.9 mm/yr for ERS-1 and from -0.2 to -0.4 mm/yr for ERS-2. The stronger impact on ERS-1 is likely due to the shorter altimetry period: 4 years for ERS-1 (October 1992 -June 1996) instead of 8 years for ERS-2 (May 1995- July 2003). The following table shows the global MSL trends obtained with the different orbit solutions:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Altimetry missions | DEOS DGM-E04 (Reference) | GFZ Reaper | ESOC Reaper | COMBINED Reaper | GFZ SLCCI |
| ERS-1 | 6.3 mm/yr | 7.0 mm/yr  (+0.7 / DEOS) | 6.9 mm/yr  (+0.6 /DEOS) | 6.8 mm/yr  (+0.5/DEOS) | 7.2 mm/yr  (+0.9 / DEOS) |
| ERS-2 | 2.7 mm/yr | 2.5 mm/yr  (-0.2/DEOS) | 2.4 mm/yr  (-0.3/DEOS) | 2.3 mm/yr  (-0.4/DEOS) | 2.3 mm/yr  (-0.4/DEOS) |

Table : [Diagnosis A201-a] Impact of the orbit solutions on global MSL trends for ERS-1 and ERS-2

We observed that the ascending/descending trend differences are maximal with the former orbit solution (DEOS DGM-E04): 2.5 mm/yr for ERS-1 and 1.8 mm/yr for ERS-2. These differences are reduced using the Reaper orbits. On average, the COMBINED Reaper solution provides the best results, but not that for ERS-2 orbit ESOC Reaper and GFZ solutions provides results as good as the COMBINED solution. The following table shows the absolute MSL trend differences obtained between ascending passes and descending passes with the different orbit solutions:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Altimetry missions | DEOS DGM-E04 (Reference) | GFZ Reaper | ESOC Reaper | COMBINED Reaper | GFZ SLCCI |
| ERS-1 | = 2.5 mm/yr | =0.5 mm/yr | =1.6 mm/yr | =1.0 mm/yr | =2.7 mm/yr |
| ERS-2 | =1.8 mm/yr | =1.2 mm/yr | =0.1 mm/yr | =0.1 mm/yr | =0.1 mm/yr |

Table : [Diagnosis A201-b] Global MSL trend differences between ascending and descending passes for ERS-1 and ERS-2 orbit solutions

The comparison with tide gauges clearly highlights that all the new Reaper and GFZ SLCCI orbit solutions significantly reduce the MSL drift between altimetry and tide gauges in comparison with the DEOS orbit currently used in AVISO products. It is clearly displayed for ERS-1 mission with a decrease close to 2.5 mm/yr at tide gauges location. These results (displayed in the following table) demonstrate that new Reaper orbits are likely better in terms of MSL trend. However the accuracy of the tide-gauge and altimetry comparisons is not good for ERS-1 due to the short time series. The sensitivity of the method is high. For instance, adding last cycle 53 which is suspect in terms of sea-level bias, the drift increases by 2 mm/yr whatever the orbit solutions. For ERS-2, the time series being longer, the accuracy of the method is close to 1 mm/yr. Such levels of accuracy do not allow us to determine which Reaper or SLCCI orbit solutions is the best one in terms of long-term evolution using tide-gauge and altimetry comparisons.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Altimetry missions | DEOS DGM-E04 - Tide Gauge (Reference) | GFZ Reaper - Tide Gauge | ESOC Reaper - Tide Gauge | COMBINED Reaper - Tide Gauge | GFZ SLCCI - Tide Gauge |
| ERS-1 | =+2.8mm/yr | =+0.3 mm/yr | =+0.2 mm/yr | =+0.0 mm/yr | =-0.7 mm/yr |
| ERS-2 | =-1.2mm/yr | =-0.6mm/yr | = -0.1mm/yr | =-0.8mm/yr | =-0.4mm/yr |

Table : [Diagnosis C001] Impact of the orbit solutions on global MSL drift detected with tide gauges for ERS-1 and ERS-2 orbit solutions (ERS-1 cycle 53 has been removed)

### Orbit solutions dedicated to Envisat and Jason-1

ESOC-V7 orbit solution reduces the global MSL trend for Jason-1 and Envisat altimetry missions by respectively -0.11 mm/yr and -0.24 mm/yr which is a significant impact. A similar result is obtained with the Envisat CNES GDR-D orbit with a global MSL trend reduction of 0.18 mm/yr whereas the impact is almost null for Jason-1 (+0.05 m/yr). The following table shows the global MSL trends obtained with the different orbit solutions:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Altimetry missions | CNES GDR-C (Reference) | ESOC V7 | CNES GDR-D | GFZ SLCCI |
| Envisat | 0.81 mm/yr | 0.57 mm/yr  (-0.24/GDR-C) | 0.60 mm/yr  (-0.18/GDR-C) | Not yet processed |
| Jason-1 | 2.42 mm/yr | 2.31 mm/yr  (-0.11/GDR-C) | 2.47 mm/yr  (+0.05/GDR-C) | Not yet processed |

Table : [Diagnosis A201-a] Impact of the orbit solutions on global MSL trends for Envisat and Jason-1

ESOC-V7 and CNEs GDR-D orbit solutions allow us to reduce significantly the ascending and descending MSL trend differences. This result is a good quality indicator of these both orbit solutions in terms of long-term stability. The following table shows the absolute MSL trend differences obtained between ascending passes and descending passes with the different orbit solutions:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Altimetry missions | CNES GDR-C (Reference) | ESOC V7 | CNES GDR-D | GFZ SLCCI |
| Envisat | =0.43 mm/yr | =0.01 mm/yr | =-0.10 mm/yr | Not yet processed |
| Jason-1 | =0.62 mm/yr | =0.12 mm/yr | =-0.15 mm/yr | Not yet processed |

Table : [Diagnosis A201-b] Global MSL trend differences between ascending and descending passes for Envisat and Jason-1 orbit solutions

The comparison with tide gauges does not display significant results (see the following table). Indeed, the accuracy of the tide-gauge and altimetry comparisons is likely to be close to 0.5 mm/yr for Envisat and Jason-1, and the impact of new orbit (ESOC v7) is lower than 0.2 mm/yr. Therefore it is difficult to demonstrate which orbit is the best with this diagnosis in terms of long-term evolution.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Altimetry missions | CNES GDR-C (Reference) | ESOC V7 | CNES GDR-D | GFZ SLCCI |
| Envisat | =-1.5mm/yr | =-1.4mm/yr | =-1.4mm/yr | Not yet processed |
| Jason-1 | =+0.1mm/yr | =+0.1mm/yr | =+0.1mm/yr | Not yet processed |

Table : [Diagnosis C001] Impact of the orbit solutions on global MSL drift detected with tide gauges for Envisat and Jason-1 orbit solutions

## Inter-Annual signals

### Validation diagnoses used

The monitoring of the differences between both corrections (A001) but also of the variance differences of SLA (A202) may provide information concerning the impact of the studied correction on the global MSL at inter-annual time scales.

### Orbit solutions dedicated to ERS-1 and ERS-2

ERS-1 period is too short (4 years) to detect any inter-annual differences due to new orbits. For ERS-2, the 8-year period is long enough but no variation at temporal scales higher than 1 year is clearly observed.

### Orbit solutions dedicated to Envisat and Jason-1

For Jason-1 and Envisat, no variation at inter-annual scale is clearly observed.

## Annual and semi-annuals signals

### Validation diagnoses used

The periodograms of differences between the orbit solutions allow us to determine the impact of the studied correction at annual and semi-annual scales (A003). Analyzing the sea-level periodograms (A206), we can describe the impact on the MSL calculation. The comparison with in-situ measurements (tide gauge) also gives a relevant indication of whether the periodic signals are reduced or not with the new correction (C003): a reduced annual or semi-annual signal is a good indication of a better correction.

### Orbit solutions dedicated to ERS-1 and ERS-2

For ERS-1 and ERS-2, the annual signal amplitude of global MSL increases with new Reaper and SLCCI orbits from 1.0 and 1.5 mm (see following table) which is a significant impact. The annual signal amplitude of global MSL for these missions ranges from 0.8 to 0.9 cm with Reaper orbits instead of 0.7-0.8 cm with DEOS DGM-E04 reference orbit.

Concerning the semi-annual signal amplitude of global MSL, the impact is very low between 0.1 and 0.2 mm. It’s not significant enough to be described in more details.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Altimetry missions | DEOS DGM-E04 (Reference) | GFZ Reaper | ESOC Reaper | COMBINED Reaper | GFZ SLCCI |
| ERS-1 | 0.70 cm | 0.80 cm | 0.85 cm | 0.80 cm | 0.80 cm |
| ERS-2 | 0.75 cm | 0.85 cm | 0.90 cm | 0.90 cm | 0.85 cm |

Table : [Diagnosis A206] Impact on the annual signal amplitude of global MSL of ERS-1 and ERS-2 orbit solutions

For the annual signal, the comparison with tide-gauges may provide in theory an interesting external information in order to know whether the amplitude increase of the annual signal observed with Reaper orbits is relevant or not at tide-gauge locations. In practice, the diagnoses have been performed (C003) but they do not currently provide consistent results: more accurate investigation is needed.

### Orbit solutions dedicated to Envisat and Jason-1

Concerning Jason-1 and Envisat, the impact of new ESOC V7 and CNES GDR-D orbit solutions is not significant on the amplitude of annual and semi-annual signals (< 0.2 mm) in comparison with CNES GDR-C orbit solution (reference).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Altimetry missions | CNES GDR-C (Reference) | ESOC V7 | CNES GDR-D | GFZ SLCCI |
| Envisat | 0.75 cm | 0.73 cm | 0.75 cm | Not yet processed |
| Jason-1 | 0.65 cm | 0.65 cm | 0.65 cm processed | Not yet processed |

Table : [Diagnosis A206] Impact on the annual signal amplitude of global MSL of Envisat and Jason-1 orbit solutions

# Regional Mean Sea Level

## Long-term evolution

### Validation diagnoses used

The validation diagnosis of the regional trend of sea-level differences using successively two orbit solutions (A204-a) allows us to evaluate the impact of the different corrections on the local MSL trends. Their impact is also analyzed separating descending and ascending passes (A204-b): the reduction of the MSL trend differences is a good quality criterion to determine the best correction. Cross-comparison of MSL trends evolution between altimetry missions collocated on the same period (B202) also gives a relevant indication of whether the potential MSL drift is reduced or not with the studied correction (C001).

### Orbit solutions dedicated to ERS-1 and ERS-2

Maps of regional MSL trend differences using successively all the ERS-1 and ERS-2 orbit solutions (A204) highlight significant differences at regional scales.

The new Reaper orbits display strong hemispheric MSL differences between ±8 mm/yr for ERS-1 and ±3 mm/yr for ERS-2 (see following figures) in comparison with DEOS DGM-E04 orbit. LPOD2005 – an extension of the International Terrestrial Reference Frame (ITRF 2005) for SLR-based POD - used in Reaper orbits mainly explains this hemispheric strong impact. The new gravity field used in Reaper orbits has probably also an impact (see further). There is an opposite impact between ERS-1 and ERS-2 not explained at the moment, but as described further in this section, it is likely to be an error in the reference orbit solution (DEOS DGM-E04).

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Figure : [Diagnosis A204-a] Maps of MSL trend differences using successively GFZ Reaper and DEOS (reference) orbit solutions in the MSL calculation for ERS-1 (on left) and ERS-2 (on right).

The comparison of COMBINED and ESOC Reaper orbit solutions with GFZ Reaper orbit solution also displays significant regional differences in terms of regional MSL trends (displayed between COMBINED and GFZ orbit solutions on following figures). The differences are stronger for ERS-1 (±5 mm/yr) than for ERS-2 (±2 mm/yr), but it is likely due to the shorter period on ERS-1. The structure of these MSL trend differences is the same for both missions with hemispheric structures (North/South) depending on the longitudes. The signature of this signal is likely due to the slightly different parameterization and minor differences in some models used to calculate these orbit solutions. All Reaper orbit solutions were computed using the same static EIGEN-GL04S gravity field model with annual and semi-annual variations up to degree and order 50 from EIGEN-GL04S-ANNUAL gravity field model.

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Figure : [Diagnosis A204-a] Maps of MSL trend differences using successively COMBINED and GFZ Reaper orbit solutions in the MSL calculation for ERS-1 (on left) and ERS-2 (on right).

In addition, the GFZ SLCCI orbit solutions have been directly compared to the COMBINED Reaper orbit. This comparison is interesting since new standards have been applied on GFZ SLCCI orbit as ITRF2008 (Altamimi et al.,2011) and SLRF2008 (Pavlis,2009) for missing stations coordinates. The trend differences observed for both missions are strong (±4 mm/yr for ERS-1 and ±2 mm/yr for ERS-2) with similar large geographical structures. This means that the impact of new standards on orbit calculation is strong for regional climate application at basin scales. But no diagnosis currently performed in RRDP allows us to determine which orbit solution is the best.

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Figure : [Diagnosis A204-a] Maps of MSL trend differences using successively GFZ SLCCI and COMBINED Reaper orbit solutions in the MSL calculation for ERS-1 (on left) and ERS-2 (on right).

Over a long enough period, the North and South global MSL trends have to converge and finally to be very close. Therefore, the analysis of the consistency of the MSL evolution between these both hemispheres is a good quality criterion to determine which orbit solution is the best.

The MSL trend differences between South and North hemispheres have been calculated and displayed in the following table (thanks to validation diagnoses A201-c). Although the ERS-1 period is quite short, we clearly observed a best consistency of MSL trend differences with Reaper and SLCCI orbit solutions. Similar results are obtained for ERS-2 with a significant consistency improvement of hemispheric MSL trends thanks to Reaper and SLCCI orbit solutions. For ERS-1 and ERS-2, COMBINED and ESOC Reaper orbit solutions provide the best results. Reaper and SLCCI GFZ orbit solution provide an improvement in comparison with the reference orbit (DEOS) but not as much as ESOC or COMBINED Reaper orbit solutions.

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| Altimetry missions | DEOS DGM-E04 (Reference) | GFZ Reaper | ESOC Reaper | COMBINED Reaper | GFZ SLCCI |
| ERS-1 | =-3.0 mm/yr | =+2.1 mm/yr | =+1.5 mm/yr | =+1.1 mm/yr | =+2.0 mm/yr |
| ERS-2 | =+3.9 mm/yr | =+1.8 mm/yr | =+0.6 mm/yr | =+1.2 mm/yr | =+1.6 mm/yr |

Table [Diagnosis A201-c]: Global MSL trend differences between North and South hemispheres for ERS-1 and ERS-2 orbit solutions

Note that the cross-calibration between ERS-1 and ERS-2 is not relevant to estimate regional MSL trend differences between both missions due to the very short common period: 1 year only.

### Orbit solutions dedicated to Envisat and Jason-1

Maps of regional MSL trend differences using successively the ESOC-V7, CNES GDR-D and CNES GDR-C orbit solutions (A204) highlight significant differences at regional scales. The impact is stronger for Envisat (±3 mm/yr) than Jason-1 (±1 mm/yr).

Large positive and negative structures of trend differences are observed (see following figures) but these structures are not correlated between both missions. The impact mainly depends of longitudes for Envisat, whereas for Jason-1 are positive in North Atlantic and more and less positive in the West Pacific. These spatial patterns are typically the signature of gravity fields which are not the same for new orbit solutions and CNES GDR-C orbit. However we do not observed exactly the same impact between ESOC V7 and CNES GDR-D orbits solutions whereas gravity fields are similar.

Focusing at the regional MSL trend consistency between Jason-1 and Envisat after selecting the same period (validation diagnosis B002), we clearly observed that this consistency is significantly improved between both missions using ESOC V7 orbit solution in the MSL calculation (see Figure 5). The large positive patterns observed using CNES CDR-C orbit in the West Pacific and in the Indian Ocean, have been significantly reduced with ESOC V7 solution. It remains significant differences between both missions (using ESOC V7 solution), but the spatial scale of patterns is smaller. Therefore it is likely due to the contribution of other altimetry components rather than the orbit as for instance the wet tropospheric or the ionospheric corrections.

Finally, the analysis of the MSL evolution consistency between each hemisphere (see Table 10) highlights an improved result for Jason-1 using ESOC-V7 (+0.4 mm/yr) instead of CNES GDR-C orbit (+1.1 mm/yr). For Envisat there is no impact: it is an expected result, since previous maps don’t display any latitude dependence between both orbit solutions.

In conclusion, these analyses give a good confidence in orbit ESOC V7 orbit solution to improve the regional MSL trend differences.

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Figure : [Diagnosis A204-a] Maps of MSL trend differences using successively ESOC v7 and CNES GDR-C (reference) orbit solutions (on top) and using successively preliminary CNES GDR-D and CNES GDR-C orbit solutions (on bottom) in the MSL calculation for Envisat (on left) and Jason-1 (on right).

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| X:\DiffGrids_REF.png | X:\DiffGrids_ETU.png |
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Figure : [Diagnosis A204-a] Maps of MSL trend differences between Envisat and Jason-1 (over the same altimetry period) using successively CNES GDR-C (on left) and ESOC v7 orbit solutions (on top right) and the preliminary orbit GDR-D orbit solutions (on bottom right) in the MSL calculation.

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| --- | --- | --- | --- | --- |
| Altimetry missions | CNES GDR-C (Reference) | ESOC V7 | CNES GDR-D | GFZ SLCCI |
| Envisat | =+1.0 mm/yr | =+1.1 mm/yr | =+1.5 mm/yr | Not yet processed |
| Jason-1 | =+1.1 mm/yr | =+0.4 mm/yr | =+0.3 mm/yr | Not yet processed |

Table : [Diagnosis A201-c] Global MSL trend differences between North and South hemispheres for Jason-1 and Envisat orbit solutions

## Annual and semi-annuals signals

### Validation diagnoses used

The analyses of periodic signals of regional mean sea level are performed thanks to diagnosis A205 where the difference of amplitudes and phases between SLA using successively 2 orbit solutions are mapped for annual and semi-annual signals. These diagnoses allow us to characterize the local or regional impact of new orbit solution.

The comparison with in-situ measurements (temperature and salinity profiles for instance) could also give a relevant indication of whether the periodic signals are better estimated or not with the studied correction (at the moment this diagnosis has not been yet processed).

### Orbit solutions dedicated to ERS-1 and ERS-2

Concerning ERS-1 and ERS-2, regional amplitudes and phases of annual and semi-annual signals are significantly modified using new Reaper and SLCCI orbit solutions in comparison with reference one (DEOS DGM-E04). On the following figures (Figure 6 and Figure 7), the amplitude differences and phase differences of annual and semi-annual signals have been mapped using successively GFZ Reaper and DEOS DGM-E04 orbit solutions in MSL calculation. Similar structures are observed for ERS-1 and ERS-2, for amplitude and phase differences and for annual and semi-annual signals. For annual signal, amplitude differences reach ± 1.5 cm in some large areas as the central Pacific Ocean with phase differences close to 1 month (~ 30 degrees). For semi-annual signal, differences are smaller but still significant as for instance in the East tropical Pacific Ocean where the amplitude differences are close to -1 cm.

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Figure : [Diagnosis A205] Amplitude differences (on left) and phase differences (on right) of regional MSL annual signals using successively GFZ Reaper and DEOS DGM-E04 orbit solutions in the MSL calculation for ERS-1 (on top) and ERS-2 (on bottom).

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Figure [Diagnosis A205]: Amplitude differences (on left) and phase differences (on right) of regional MSL semi-annual signals using successively GFZ Reaper and DEOS DGM-E04 orbit solutions in the MSL calculation for ERS-1 (on top) and ERS-2 (on bottom).

Comparing COMBINED or ESOC Reaper orbits with GFZ Reaper solution, very strong differences are highlighted concerning the amplitude of the annual signal (see following figures). Same structures are observed for ERS-1 and ERS-2. The amplitude differences are between ±2 cm and depend on the latitudes. We also observe phase differences close to 1 month in the South hemisphere.

No validation diagnosis produced in the RRDP report is able to demonstrate which orbit solution provides the best results concerning the estimation of periodic signal. We can just exclude the reference orbit (DEOS-DGLM04) which does not use the recent standards. As the impact between GFZ and ESOC/COMBINED orbits is very strong, it seems necessary to perform thorough investigations.

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Figure : [Diagnosis A205] Amplitude differences (on left) and phase differences (on right) of regional MSL annual signals using successively ESOC Reaper and GFZ Reaper orbit solutions in the MSL calculation for ERS-1 (on top) and ERS-2 (on bottom).

Comparing COMBINED Reaper and GFZ SLCCI orbit solutions, we observed smaller differences lower than 0.5 mm of amplitude. However, concerning annual signals, they are well correlated at large spatial scales and with exactly the same structures for both missions as displayed in the following maps. This means that new standards applied on GFZ SLCCI orbit solutions have a coherent impact on periodic signals but it is not currently possible to determine if it is realistic or not.

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Figure : [Diagnosis A205] Amplitude differences of regional MSL annual signals using successively GFZ SLCCI and COMBINED Reaper orbit solutions in the MSL calculation for ERS-1 (on left) and ERS-2 (on right).

### Orbit solutions dedicated to Envisat and Jason-1

For Envisat and Jason-1 the impact of new orbit solutions (ESOC and CNES) on annual signal and semi-annual of regional MSL is lower than for ERS-2. Amplitude differences are lower than 0.5 cm for annual signal and 0.2 cm for semi-annual signal, but we detect stronger phase differences for semi-annual signal (until 1 month in south hemisphere) than for annual signal. Therefore the impact of new ESOC-V7 orbit is low (but not null).

As previously, it’s not possible to determine which orbit improves the estimation of periodic signal with validation diagnosis performed in the RRDP report at the moment. In this case, it is more difficult since the impact is low.

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Figure : [Diagnosis A205] Amplitude differences (on left) and phase differences (on right) of regional MSL annual signals using successively ESOC-V7 and CNES GDR-C orbit solutions in the MSL calculation for Envisat (on top) and Jason-1 (on bottom).

## Coastal areas

For coastal areas, the impact of orbit solutions is the same that for global ocean as a result of long correlation distances of orbit (several thousands of kilometers).

## High latitudes

The impact of orbit calculation in high latitudes is strong especially concerning the estimation of regional MSL trends.

# Mesoscale

## Validation diagnoses used

Sea-level analyses at crossover points and with along-track data allow us to detect improvements at short temporal scales (< 2 months) for mesoscale application. The most relevant diagnoses performed in RRDP are the monitoring and the map of the variance SSH differences using successively 2 different orbit solutions in the sea-level calculation.

Diagnoses A102, A103 and A104 display the map and the long-term monitoring of SSH differences at crossover points (mean and variance): the reduction of variance and the reduction of geographical biases indicate a better internal consistency of sea-level between ascending and descending passes within a 10-day window.

Diagnoses A203 and A209 (A209 not yet processed) display the map and the long-term monitoring of SSH variance differences relative to a mean sea surface (MSS): the reduction of variance indicates a better consistency with the MSS. Most of the time, it demonstrates an improvement of sea-level computation. But in some few cases, the variance increase can also indicate a systematic error in the MSS due to geographical bias for instance not taken into account.

## Orbit solutions dedicated to ERS-1 and ERS-2

The improvement of sea-level estimation for short temporal signal (> 20 days) is very significant using new Reaper and SLCCI orbits in comparison with the reference orbit (DEOS DGM-E04).  
The crossovers validation diagnoses display a very strong improvement for ERS-1 and ERS-2 in terms of variance reduction and geographical bias reduction. We have plotted, for instance, the map of variance reduction (A104) for ERS-1 and ERS-2 using GFZ Reaper orbit instead of reference orbit in the SSH calculation (see following figures).

This strong improvement provided by new Reaper orbit is mainly due to the new standards used in the orbit calculation as the new model of the Earth gravity field.

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Figure : [Diagnosis A104] Maps of SSH variance differences using successively GFZ Reaper and DEOS (reference) orbit solutions in the SSH calculation for ERS-1 (on left) and ERS-2 (on right).

Comparing the Reaper orbits together, we obtained the best results with COMBINED solution with a significant variance reduction for both missions (see following figure). GFZ and ESOC solutions are closer although GFZ solutions provide better results at the end of the ERS-2 period.

Therefore these analyses show that COMBINED orbit significantly increases the ERS-1 and ERS-2 SSH performances: it is the best orbit solution for ERS-1 and ERS-2 to improve the sea-level calculation at short temporal scale.

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Figure : [Diagnosis A104] Maps of SSH variance differences using successively GFZ Reaper and DEOS (reference) orbit solutions in the SSH calculation for ERS-1 (on left) and ERS-2 (on right).

Comparing the GFZ SLCCI and COMBINED Reaper orbit solutions together, we also obtained a better consistency of sea-level calculation at crossovers with the COMBINED orbit. The following maps display clearly a global lower SSH variance at crossovers using COMBINED instead of GFZ SLCCI orbits. The temporal evolution of these variance differences (diagnoses A102) does not depend on the period.

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Figure : [Diagnosis A104] Maps of SSH variance differences using successively GFZ SLCCI and COMBINED Reaper orbit solutions in the SSH calculation for ERS-1 (on left) and ERS-2 (on right).

The last result is not in agreement with another diagnosis (not performed in RRDP reports) allowing us to measure the consistency of radial orbit components between ascending and descending passes at crossovers. Crossover height differences were computed using an iterative process (Wisse et al., 1995). Crossover height differences are generally due to sea level changes between the two epochs, satellite orbit height errors as well as the errors of used tide models, altimeter range corrections etc. (Scharroo, 2002, p.14). The root-mean-square (RMS) value of the crossover differences is a measure of the cumulative height errors. When the same altimeter data corrections are used for the crossover analysis of different orbits and only orbits are replaced, the value of RMS crossover differences is an indication of orbit quality at the given time interval of crossover computation: smaller crossover RMS height difference indicates better orbit quality. The following table gives the mean values of crossover RMS height differences computed at 7-day interval for different orbit solutions over the period from September 1992 till June 1996 for ERS-1 and from May 1995 till July 2003 for ERS-2.

## Orbit solutions dedicated to Envisat and Jason-1

Concerning Jason-1 and Envisat, the impact at short temporal scales of using new orbit solutions (ESCO V7 and CNES GDR-D) instead of CNES GDR-C one is low. The analyses at crossover points do not display strong variance differences. We only observe a low variance increase or reduction in some large areas. We also observed that CNES orbit solutions (GDR-D and GDR-C) provide more homogenous maps of SSH crossovers in terms of variance differences than the ESOC orbit solutions. But it’s not really possible to recommend one of them to improve mesoscale applications.

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Figure : [Diagnosis A104] Maps of SSH variance differences using successively ESOC-V7 and CNES-GDR-C (reference) orbit solutions in the SSH calculation for Envisat (on left) and Jason-1 (on right).

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Figure : [Diagnosis A104] Maps of SSH variance differences using successively preliminary CNEs GDR-D and CNES-GDR-C (reference) orbit solutions in the SSH calculation for Envisat (on left) and Jason-1 (on right).

## Coastal areas

For coastal areas, the impact of orbit solutions is the same that for global ocean as a result of long correlation distances of orbit (several thousands of kilometers).

## High latitudes

The impact of orbit calculation at high latitudes to improve the sea-level calculation for mesoscale applications is the same as in global ocean for orbit solutions tested in RRDP reports.

# Conclusions and recommendations

**For ERS-1 and ERS-2:** on average the COMBINED Reaper orbits provide the best results for all the climatic applications with a significant improvement of the sea-level estimation in comparison with DEOS DGM-E04 orbit currently used in AVISO products. However, concerning some impacts on periodic signals or regional trends which are strong, we cannot determine which orbit solution is the best. For instance, the GFZ SLCCI orbit solutions containing new orbit standards (as ITRF2008) provide regional trends significantly different.

* Therefore we recommend to use the COMBINED Reaper orbit solutions since these orbit solutions display the best results in terms of consistency of ascending and descending passes as well as crossovers points as on long-term trends. However the GFZ SLCCI orbits solution clearly show interesting signals at basin scales which might be realistic.

**For Envisat, Jason-1 and Jason-2:** ESOC-V7 and preliminary CNES GDR-D orbit solutions significantly improves the estimation of regional sea-level trends with a strong reduction of longitudinal features (especially on Envisat). For the global MSL trend (only Envisat), we also detect a significant impact but it’s not possible to determine which orbit solution is the best. The impact on other climatic applications is null or low and it is also difficult to determine which orbit solution is the best.

* Although ESOC-V7 and preliminary CNES GDR-D orbit solutions provide similar improvements for scientific application, we recommend to use the preliminary CNES GDR-D orbit solution since it is available over a longer period until December 2012 included for Jason-1, Envisat but also Jason-2.

1. Synthesis

This section synthesizes the impact of all the new algorithms dedicated to the orbit computation for each altimetric mission and separating the different climate applications defined in the sea level CCI URD (User Requirement Document). The impact is also estimated for several temporal scales impacting climate studies for each application.

In order to have a clear view of these potential impacts, the information is summarized in tables (1 table per altimetry missions). An impact indicator clearly and easily comprehensible has been defined with 3 levels: significant impact, low impact, no impact detected. Each level is represented by a different color box.

The choice of a value indicator (significant, low or null) is quite subjective. As it depends on the application (Global MSL, regional MSL, mesoscale…), the rule to classify this impact has been defined in annex of this document (see appendix).

## ERS-1

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| ERS-1 [October 1992 -June 1996] | | | | | |
| Climate  Applications | Temporal Scales | Round Robin Data Package (RRDP) | | | |
| GFZ Reaper versus DEOS | ESOC Reaper versus GFZ Reaper | COMBINED Reaper / GFZ Reaper | GFZ SLCCI versus COMBINED Reaper |
| Global Mean Sea Level | Long-term evolution (trend) | + |  |  | - |
| Inter annual signals (> 1 year) |  |  |  |  |
| Annual and semi-annual Signals | + |  |  |  |
| Regional Mean Sea Level | Long-term evolution (trend) | + |  |  |  |
| Annual and semi-annual Signals | + |  |  |  |
| Mesoscale | Signals < 2 months | + | - | + | - |
| Specific regional areas of main interest for climate studies: | | | | | |
| Coastal areas | Long-term evolution (trend) | No specific impact of orbit calculation in coastal areas | | | |
| Signals < 2 months |
| High latitudes | Long-term evolution (trend) | + |  |  |  |
| Signals < 2 months | + | - | + | - |
|  |  |  |  |  |  |
|  | Legend : | Significant impact | Low impact | No impact detected | Not yet evaluated |
|  |  | + | : Positive impact (low) | | |
|  |  | - | : Negative impact (significant) | | |
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## ERS-2

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| --- | --- | --- | --- | --- | --- |
| ERS-2 [May 1995 -July 2003] | | | | | |
| Climate  Applications | Temporal Scales | Round Robin Data Package (RRDP) | | | |
| GFZ Reaper versus DEOS | ESOC Reaper versus GFZ Reaper | COMBINED Reaper / GFZ Reaper | GFZ SLCCI versus COMBINED Reaper |
| Global Mean Sea Level | Long-term evolution (trend) | + |  |  |  |
| Inter annual signals (> 1 year) |  |  |  |  |
| Annual and semi-annual Signals | + |  |  |  |
| Regional Mean Sea Level | Long-term evolution (trend) | + |  |  |  |
| Annual and semi-annual Signals | + |  |  |  |
| Mesoscale | Signals < 2 months | + | - | + | - |
| Specific regional areas of main interest for climate studies: | | | | | |
| Coastal areas | Long-term evolution (trend) | No specific impact of orbit calculation in coastal areas | | | |
| Signals < 2 months |
| High latitudes | Long-term evolution (trend) | + |  |  |  |
| Signals < 2 months | + | - | + |  |
|  |  |  |  |  |  |
|  | Legend : | Significant impact | Low impact | No impact detected | Not yet evaluated |
|  |  | + | : Positive impact (low) | | |
|  |  | - | : Negative impact (significant) | | |

## Envisat

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Envisat [October 2002- December 2010] | | | | | |
| Climate  Applications | Temporal Scales | Round Robin Data Package (RRDP) | | | |
| ESOC V7 versus CNES GDR-C | CNES GDR-D versus CNES GDR-C | GFZ SLCCI versus GFZ Reaper |  |
| Global Mean Sea Level | Long-term evolution (trend) |  |  |  |  |
| Inter annual signals (> 1 year) |  |  |  |  |
| Annual and semi-annual Signals |  |  |  |  |
| Regional Mean Sea Level | Long-term evolution (trend) | + | + |  |  |
| Annual and semi-annual Signals |  |  |  |  |
| Mesoscale | Signals < 2 months |  |  |  |  |
| Specific regional areas of main interest for climate studies: | | | | | |
| Coastal areas | Long-term evolution (trend) | No specific impact of orbit calculation in coastal areas | | | |
| Signals < 2 months |
| High latitudes | Long-term evolution (trend) |  |  |  |  |
| Signals < 2 months |  |  |  |  |
|  |  |  |  |  |  |
|  | Legend : | Significant impact | Low impact | No impact detected | Not yet evaluated |
|  |  | + | : Positive impact (low) | | |
|  |  | - | : Negative impact (significant) | | |

## Jason-1

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Jason-1 [January 2002- December 2010] | | | | | |
| Climate  Applications | Temporal Scales | Round Robin Data Package (RRDP) | | | |
| ESOC V7 versus CNES GDR-C | CNES GDR-D versus CNES GDR-C | GFZ SLCCI versus GFZ Reaper |  |
| Global Mean Sea Level | Long-term evolution (trend) | + |  |  |  |
| Inter annual signals (> 1 year) |  |  |  |  |
| Annual and semi-annual Signals |  |  |  |  |
| Regional Mean Sea Level | Long-term evolution (trend) | + | + |  |  |
| Annual and semi-annual Signals |  |  |  |  |
| Mesoscale | Signals < 2 months |  |  |  |  |
| Specific regional areas of main interest for climate studies: | | | | | |
| Coastal areas | Long-term evolution (trend) | No specific impact of orbit calculation in coastal areas | | | |
| Signals < 2 months |
| High latitudes | Long-term evolution (trend) | + |  |  |  |
| Signals < 2 months |  |  |  |  |
|  |  |  |  |  |  |
|  |  | Significant impact | Low impact | No impact detected | Not yet evaluated |
|  |  | + | : Positive impact (low) | | |
|  |  | - | : Negative impact (significant) | | |

## Jason-2 / TOPEX/Poseidon / GFO

No orbit solution has been tested in the RRDP procedure for these altimetry missions.

1. Definition of the indicator value

In this table, the choice of the indicator value is defined for each climate applications and temporal scales. The thresholds defined here are valid for time series long enough (> 7 years). If time series is too short, the thresholds have to be majored.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Climate  Applications | Temporal Scales | Definition of the indicator value | | |
| Significant impact | Low impact | No impact detected |
| Global Mean Sea Level | Long-term evolution (trend) | Trend >0.15 mm/yr | Trend> 0.05 mm/yr | Trend< 0.05 mm/yr |
| Inter annual signals (> 1 year) | Amplitude> 0.5 mm | Amplitude> 0.2 mm | Amplitude< 0.2 mm |
| Annual and semi-annual Signals | Amplitude> 1 mm | Amplitude> 0.2 mm | Amplitude< 0.2 mm |
| Regional Mean Sea Level | Long-term evolution (trend) | Trend > 0.5 mm/yr | Trend> 0.1 mm/yr | Trend< 0.1 mm/yr |
| Annual and semi-annual Signals | Amplitude> 5 mm | Amplitude> 0.5 mm | Amplitude< 0.5 mm |
| Mesoscale | Signals < 2 months | Crossovers Variance differences > 1 cm² | Crossovers Variance differences > 0.2 cm² | Crossovers Variance differences < 0.2 cm² |
| Specific regional areas of main interest for climate studies: | | | | |
| Coastal areas | Long-term evolution (trend) | Trend > 0.5 mm/yr | Trend> 0.1 mm/yr | Trend< 0.1 mm/yr |
| Signals < 2 months | Crossovers Variance differences > 1 cm² | Crossovers Variance differences > 0.2 cm² | Crossovers Variance differences < 0.2 cm² |
| High latitudes | Long-term evolution (trend) | Trend > 0.5 mm/yr | Trend> 0.1 mm/yr | Trend< 0.1 mm/yr |
| Signals < 2 months | Crossovers Variance differences > 1 cm² | Crossovers Variance differences > 0.2 cm² | Crossovers Variance differences < 0.2 cm² |

1. List of acronyms

|  |  |
| --- | --- |
| TBC | To be confirmed |
| TBD | To be defined |
| AD | Applicable Document |
| RD | Reference Document |