**CALVAL**

# Error budget of Envisat Altimetry Mission - V3 reprocessing version

Reference : CLS.DOS/NT/2018.233

Nomenclature : CLS-NT-06-233 SALP-RP-MA-EA-23233-CLS

Issue : 1rev 0

Date : 25/06/2018 June 25, 2018

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| Chronology Issues : | | |
|---|---|---|
| Issue : | Date : | Reason for change : |
| 1.0 | 25/06/2018 | Created |

| People involved in this issue: | | | | |
|---|---|---|---|---|
| | **AUTHORS** | **COMPANY** | **DATE** | **INITIALS** |
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| Index sheet : | |
|---|---|
| Context | |
| Keywords | |
| hyperlink | |

| Distribution : | | |
|---|---|---|
| Company | Means of distribution | Names |
| CNES | mail | N. Picot, T. Guinle |
| ESA | mail | P. Femenias |

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# 1. Introduction

This document is a synthesis of the error budget estimated for the whole mission for Envisat altimeter (RA-2) level 2 OFL products. This takes into account the homogeneous reprocessed v3 data set, achieved in March 2018. Estimating the error budget in altimetry is a hard work principally because of the lack of absolute reference. It can however be estimated by comparing corrections from different sources of estimation (typically measurements/models or measurements/in situ data,...).

The global Envisat altimeter error budget (for level 2 OFL products) changed during the mission lifetime considering corrections improvements (this effect is much reduced thanks to the reprocessing exercise), on aging of devices or geophysical interannual effects. The table hereafter sums up the Envisat altimeter error budget for year 2018 compared to the specifications allowed budget. Each figure of the table is associated to a small paragraph including:

- comments on the method used to quantify them
- comments on the stability of the given value.
- reference documents.

Particular events:

- In 2012, Envisat was entirely on its drifting phase. The 35 day cycle reduced to a 30day pseudo cycle with a small drift estimated to +/-1.7km per cycle maximum at respectively 50deg Latitude N/S, whereas it does not drift at 38deg N and S. Note that the drift was observed to be higher than the one theoretically expected (+/-600m per cycle maximum was expected). The impact on the data was already described in last year yearly report. Only a weak impact is noticed in the data quality (the visible impact concerns the SLA standard deviation) and the new Mean Sea Surface was shown to erase almost all this impact (see [5]).
- The Envisat whole mission reprocessing ended on March 2018. The ground processing chains had been upgraded to support reprocessing, this new standard is called V3. The impact of this new version is detailed in [9].
- On April, 8th 2012, the communication with Envisat mission was definitively lost. Its data quality remained stable and very good until the end. The end of operation was announced in May 2012; this Error Bugdet document has been updated after the end of the mission, thanks to delayed time reprocessing and improvement of the global altimetric system.

# 2. Term by term altimetric error budget

## 2.1. Altimeter noise

A slight seasonal signal is visible on the mean RMS of Ku 20Hz. Higher values correspond to higher waves occurring during the austral winter. The mean value is about 9.1 cm. This value represents a rough estimation of the 20 Hz altimeter noise (Zanife et al. 2003 [16], Vincent et al. 2003a [15]). Assuming that the 20Hz measurements have uncorrelated noise, it corresponds to a noise of about 2 cm at 1Hz.

**The High frequency content of range parameter (noise level) remains stable over the mission.**

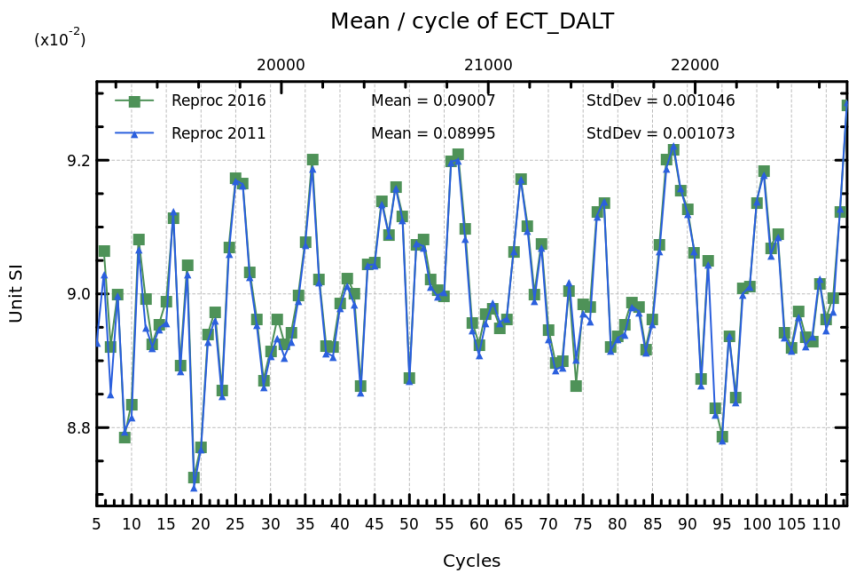


Figure 1: *Mean of range standard deviation at 18Hz, averaged by cycle*

## 2.2. Sea State Bias

Estimating the absolute sea state bias correction error is relatively difficult (see [12]). Since most SSB estimators are computed as a function of SWH and altimeter Wind Speed, the first approach is to use a Gaussian assumption, and a direct dependence between the random noises on the input parameters. Our current knowledge on SWH and SIG0 is synthesized in chapter 5.3 and 5.4 of [12].

This don't represent an absolute reference but long term monitoring mean and standard deviation of SSB give information on stability of this parameter. Studies concerning the SSB noise was also performed and explained during SLOOP project ([4]). This sea state bias mean is stable around -14cm with an annual cycle linked to the seasonal repartition of high/small waves. The standard deviation of SSB (including ocean variability) is now homogeneous on the whole time series, using the 2007 Labroue Non Parametric Bias. The standard deviation is between 6cm and 7.5cm according to a seasonnal signal and 6.3cm for 2012.

For the V3 reprocessing, a new SSB has been computed, to take into account the large scale evolutions du to the v3 standards (orbit, wet tropospheric correction, SWH...). The differences of computation change correlation between SSB and SWH and introduces a 2.1cm bias on SLA (from 13.8cm to 15.9cm), illustrated on 2.

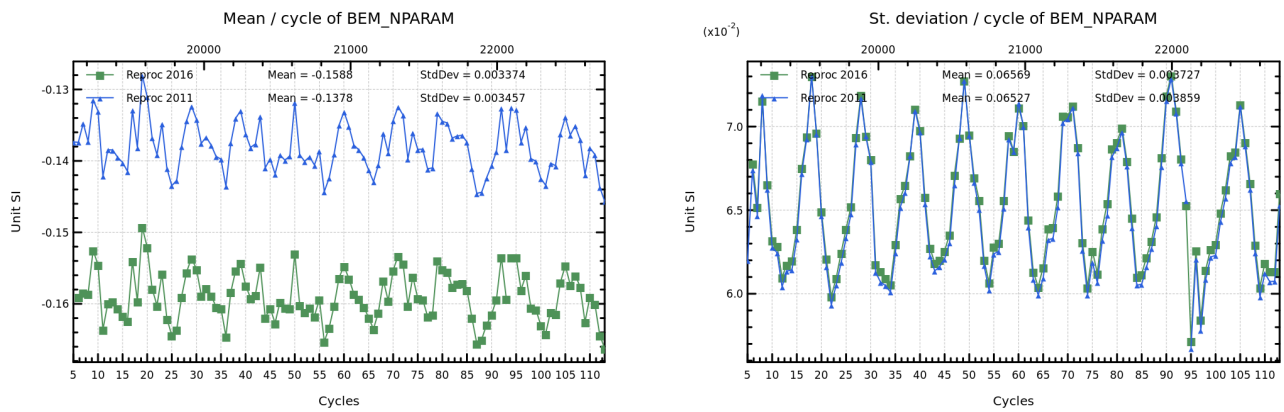


Figure 2: *Mean and Std. Dev of Sea State Bias by cycle in meters (SI)*

## 2.3. Ionospheric correction

Due to the S-Band loss on January 17th 2008, the bifrequency ionospheric correction is no longer available. A comparison to the GIM model ionospheric correction during 2007 and a cross comparison between Envisat and Jason-1/2 and the GIM model during 2010 enables to get an acceptable value. The comparison to the GIM model ionospheric correction during year 2007 gives a standard deviation of 0.7 cm. As described in Envisat Yearly report 2010, a 280km Lanczos Low pass filter enables to reduce this variability to 0.4 cm. Cross comparison of bifrequency ionosphere to the same GIM model ionospheric correction for Jason-1/2 shows that the statistics are rising slowly. This is related to the slight increase of solar activity.
**The ionosphere quality is affected by the S-Band loss from January 2008 onwards. For the v3 reprocessing, the quality of the GIM ionosphere correction continues to be slightly degraded whereas it was stable until 2011.** In fact, the degradation starts to be observable after cycle 100 at crossovers as seen on figure 7.

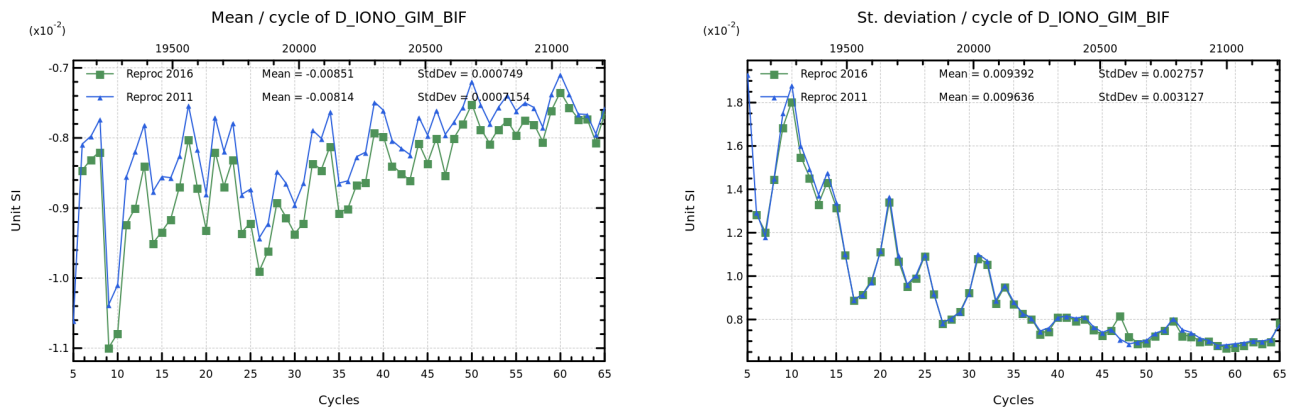


Figure 3: *Mean and Std. Dev of BIRF - GIM ionospheric correction by cycle*

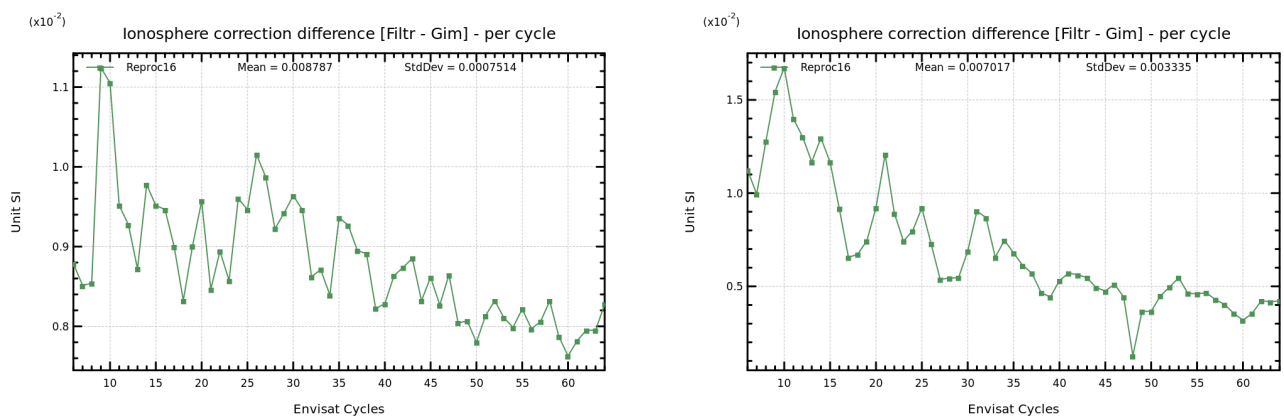


Figure 4: *Mean and Std. Dev of FILTR - GIM ionospheric correction by cycle*

Since the S-Band loss, Envisat iono correction was efficiently replaced by the JPL GIM model. But the solar activity (reprensented by a higher value of the mean correction) is increasing again since mid 2009 following a 11 year period signal (see 5 left hand plot). The monitoring of the difference iono GIM-Bifrequency correction on Jason-1 and Jason-2 (see 5 right hand plot) enlights that the error on the model is higher when the solar activity increases (around 5mm more than in 2008). The GIM model is known to be less efficient at the end of the Envisat data set as observed on the signature on 6 plot compared to 7.

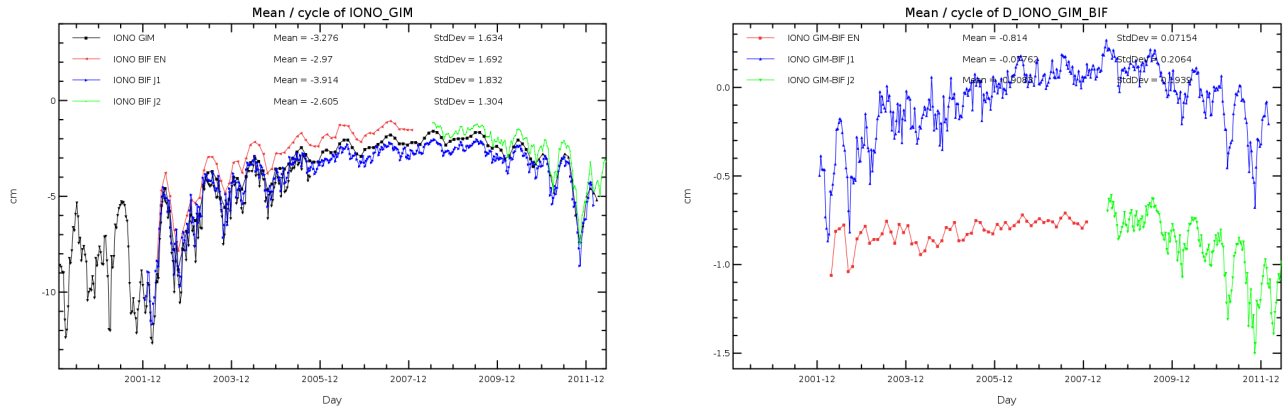


Figure 5: *Ionospheric content over the 11 last years observed by different missions (left). Difference to GIM reference (right).*

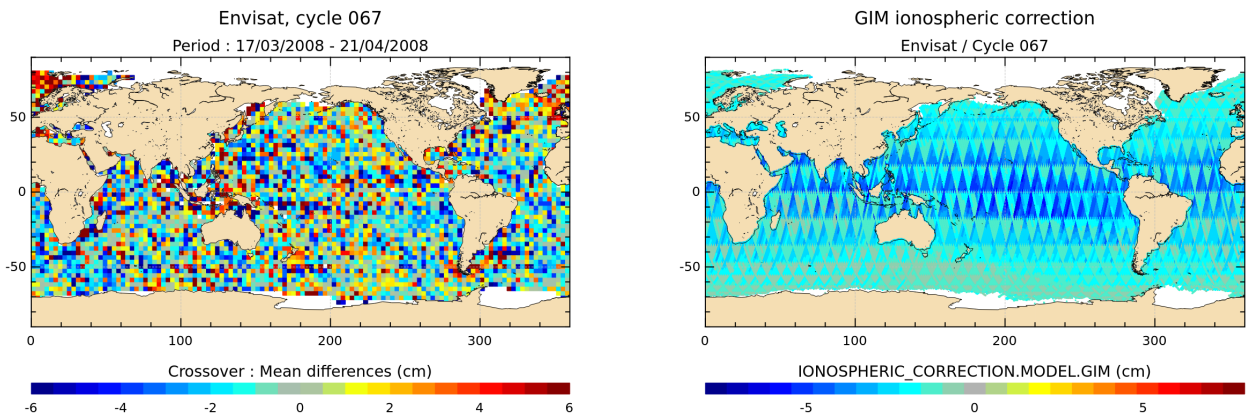


Figure 6: *Cycle 67, march 2008: SSH at crossovers (left). GIM ionospheric correction (right).*

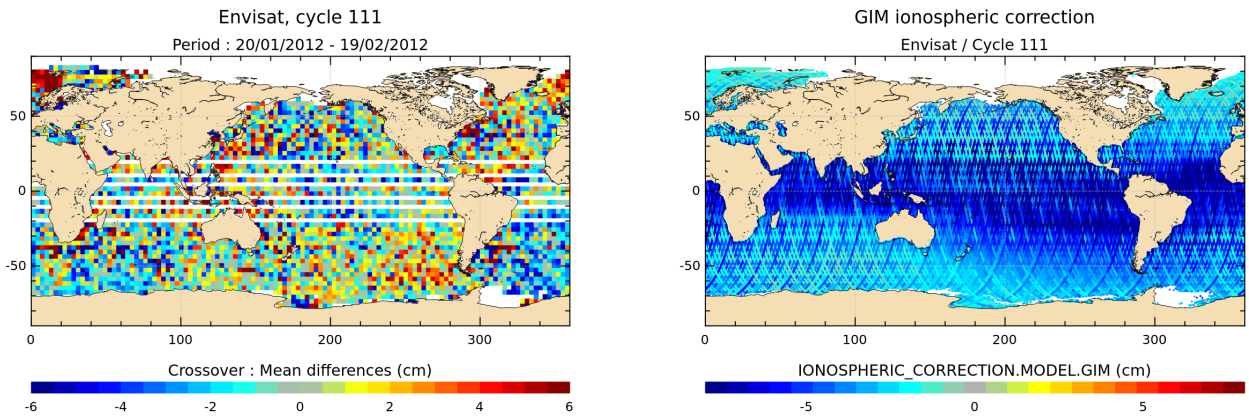


Figure 7: *Cycle 111, february 2012: SSH at crossovers (left). GIM ionospheric correction (right).*

## 2.4. Dry troposphere

See Salstein et al. (2008) [10].

## 2.5. Wet troposphere

The quality of wet tropospheric correction can be analysed differenciating the various inhomogeneity on the bias or on the variability, by comparing the radiometer correction to the model one. Two models are considered:
- the operational ECMWF model and
- the reprocessed ERA-Interim model (also available in the products since v3 reprocessing)

With the first reference, the variability obsereved can include the effect of the MWR aging but it also includes ECMWF model changes.
With the second one, the model is homogeneous and the jumps are only due to MWR aging, anomalies, or geophysical content.

For the major part of the mission, the bias between model and MWR is rather stable around 1.5cm, whith slightly higher values (2cm) before cycle 12 (beginning 2003) Globally, the MWR performences are better than ECMWF (1.5cm$^2$) as illustrated by the graph 8. This is much better than with the v2.1+ reprocessing. Concerning the average stability, it is responsible for a non negligieble part of the Mean Sea Level uncertainty (Ablain et al. 2010 [1]), around 0.6mm/year on Envisat as explained in ([6]).

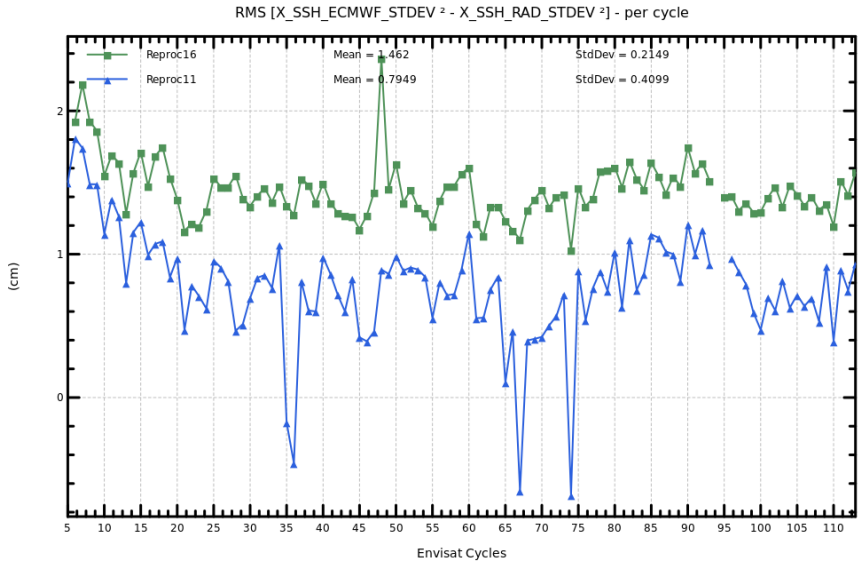


Figure 8: *RMS loss using ECMWF instead of MWR at crossovers, monitored by cycle. For V3 (Reprocessing 2016) and V2.1+ (2011).*

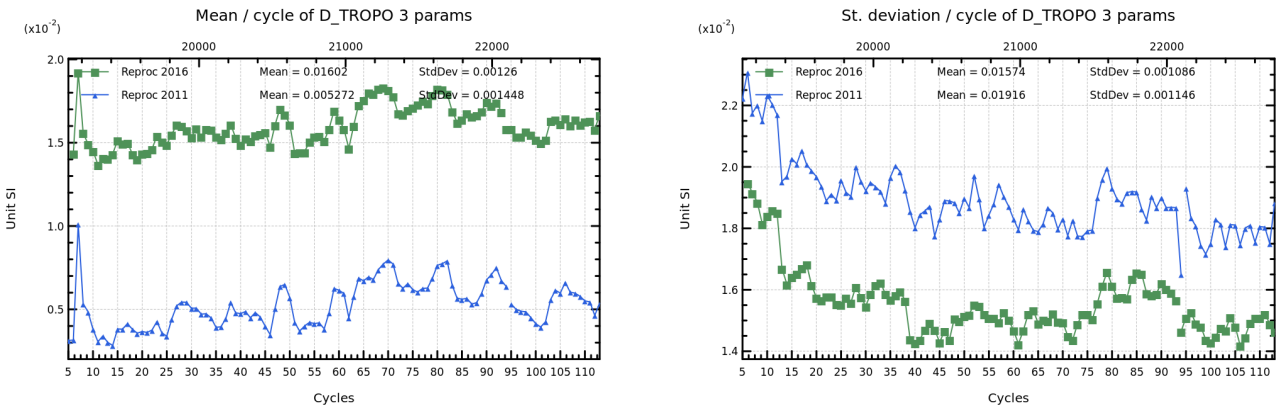


Figure 9: *Mean and Std. Dev of [radiometer-model] correction by cycle*

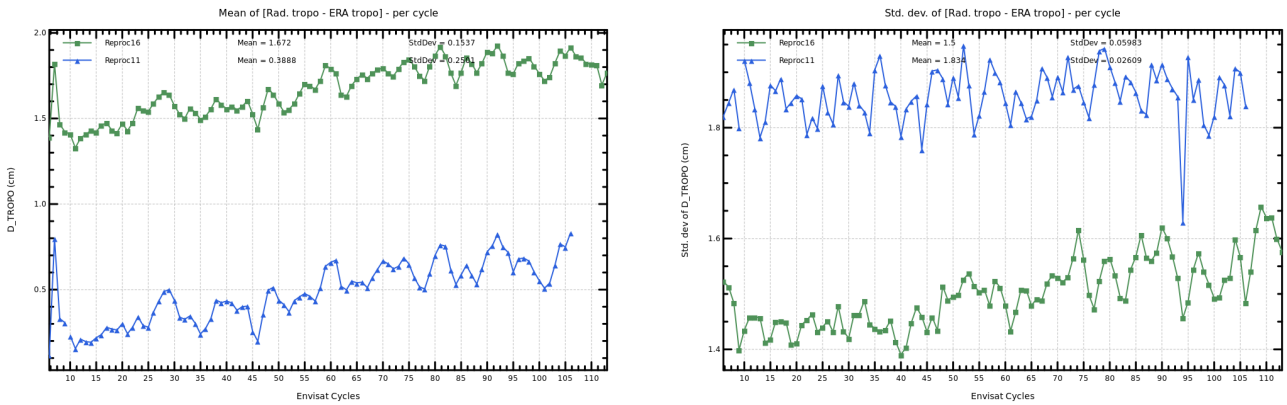


Figure 10: *Mean and Std. Dev of [radiometer-ERA model] correction by cycle*

## 2.6. Range drift/SSH

Thanks to the previous v2.1 reprocessing updates, the accuracy of Envisat Mean Sea Level trend is now more realistic as detailled in Ollivier et al. 2012 [7]. The stability of the SSH stability can also be assessed by in situ data, as described in Valladeau and Leageais et al, 2012 [14].
Still some errors remain on the mission which was not dedicated to climate studies and mainly due to altimeter and/or radiometer instrumental errors.

## 2.7. Radial Orbit Error

Absolute orbit quality is hard to determine, a criteria is the rms based on laser data. After the increase of 2010 (from around 1.5 to 1.9cm), the rms slightly decreased at the beginning of 2011 but increased to the end to reach 1.8cm. In 2012, the same phenomenon is observed, a slight decresase, reaching 1.2cm.
This increase could be due to a quality degradation of some stations included in the laser network. Furthermore, an internal quality criteria can also be given, based on consecutive orbits overlap comparison. This rms is reduced to around 0.6 cm for 2010 (1cm in 2009). The rms based on high elevation laser data gives a more reliable metric to assess the orbit quality. Orbit quality is stable despite the change to the drifting phase orbit and the slight increase of the solar activity.

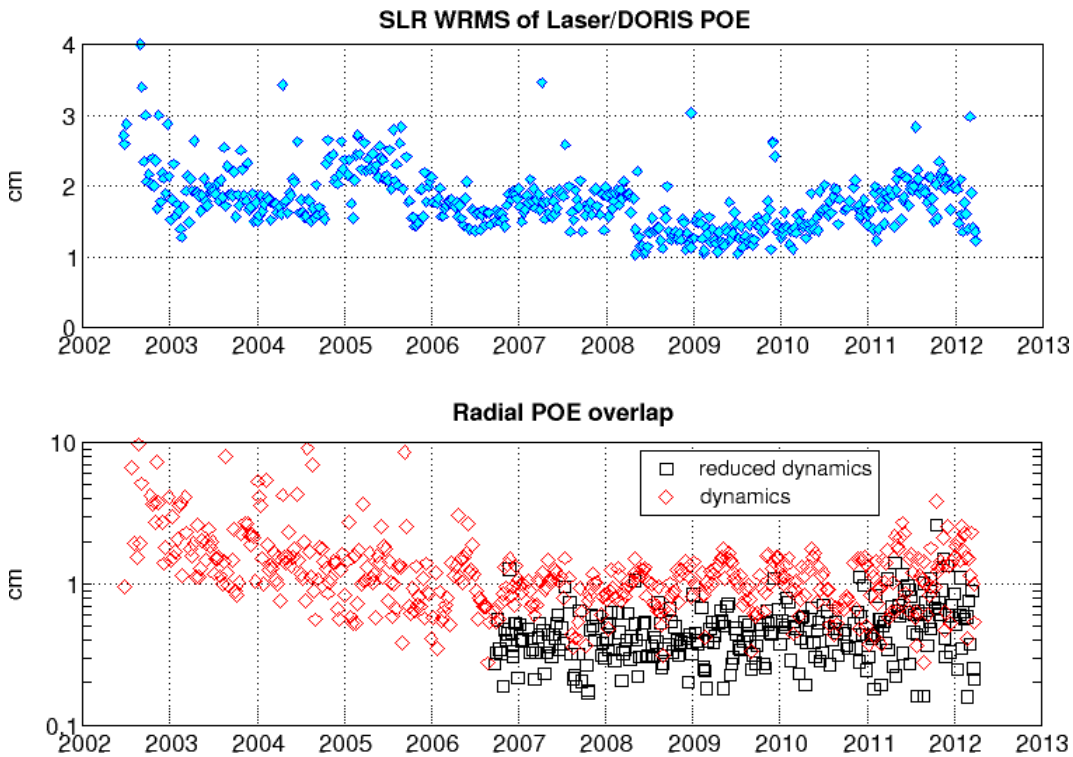


Figure 11: *Intrinsic POD quality criterion for Envisat (courtesy P. Yaya)*

## 2.8. Significant Wave Height

The SWH in V3 dataset is corrected with reference to the previous reprocessing thanks to Look Up tables taking into account the retracking errors depending on the SWH height (see [9]).

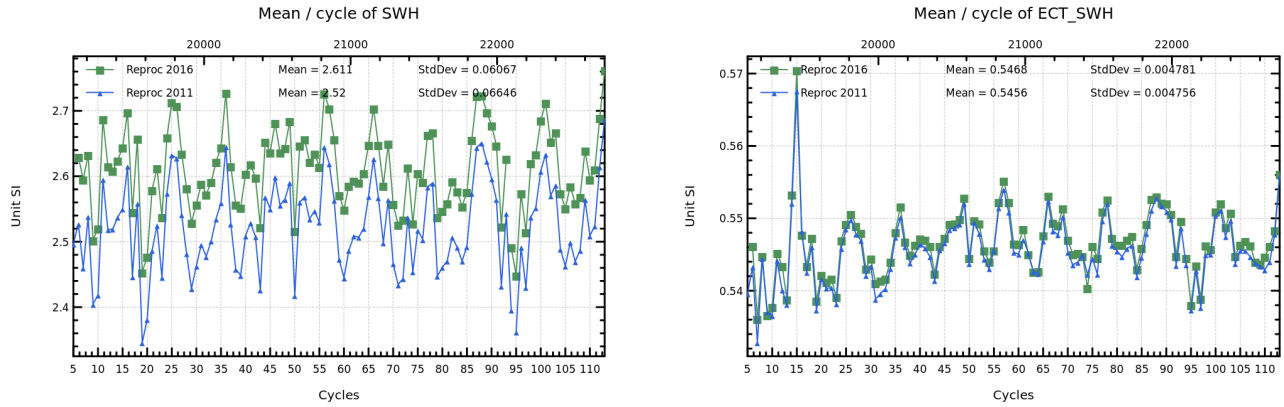


Figure 12: *Left) Mean Wave Height by cycle Right) Sdt. dev. of Wave Height by cycle*

## 2.9. Wind speed

Obtained from a comparison between Sigma0 derived winds obtained with v1.0 tables and ECMWF gaussian grids wind outputs, with ocean data only (see editing specifications in Envisat Yearly report 2010 [5]). In 2012, a paper was also written on the stability of this parameter, evidencing a drift at the beginning of Envisat's period (Ablain et al. 2012 [2]).

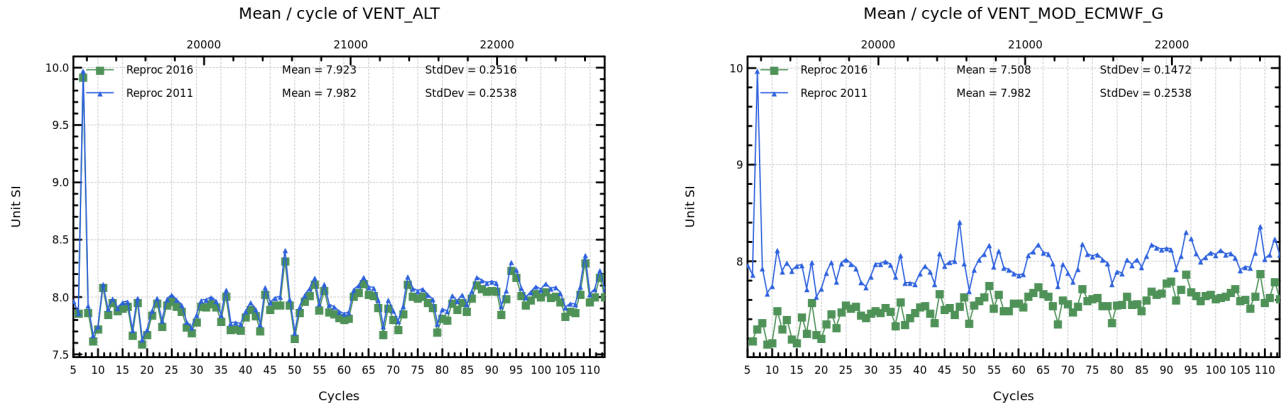


Figure 13: *Mean of Left) Altimetric Wind Speed Right) ECMWF Gaussian Wind Model, by cycle*

| Envisat Altimetry | Specified | Observed | Comments |
|---|---|---|---|
| **Altimeter noise** | 4.5cm | 2cm | Altimeter noise computed on post launch data (see 2.1/) |
| **Sea State Bias** | 2cm | 0.5cm | SSB error estimated from differences between different empirical models. Value at 2 m SWH. (see 2.2/) |
| **Ionosphere** | 0.2cm | 0.7cm | Derived from cross-sensor comparisons (see 2.3/) |
| **Dry troposphere** | 0.7cm | 0.7cm | From uncertainties in ECMWF atmospheric fields used to derive the correction. Value at 2-3 hPa sea level pression. (see 2.4/) |
| **Wet troposphere** | 1.4cm | 1.5cm | Comparisons with ECMWF correction. (see 2.5/) |
| **Total range error (TRE):** $\sqrt{\sum Terms^2}$ | **5cm** | **2.9cm** | |
| **Range drift/SSH** | $<$ 0.5cm/y | 0.2cm/y | From in situ tide gauge comparison over 2005-2010 (see 2.6/) |
| **Radial Orbit error (ROE)** | 2cm | 1.7cm | From POD operational monitoring (see 2.7/) |
| **Sea height error:** $\sqrt{(TRE)^2 + (ROE)^2}$ | **5.4cm** | **3.5cm** | |
| **Significant Wave Height** | 5% or 25 cm | 25cm | Comparison versus ECMWF WAM global value (see 2.8/) |
| **Wind Speed** | 2.0m/s | 1.3m/s | Comparison versus ECMWF global fields (see 2.9/) |