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Global Calibration of Jason-2 by Multi-Mission Crossover Analysis

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Abstract

Multi-mission altimeter observations are successfully used for global cross calibration of altimeters. The approach utilizes a least squares adjustment minimizing single and dual satellite crossover differences as well as consecutive differences of the radial component of single satellites. The method is applied to obtain a characterization of the radial errors of the first year of OSTM/Jason-2 data. A mean relative range bias of about 7.5 ± 0.2 cm with respect to Jason-1 was computed. The radial errors show increased auto-correlation at the orbit revolution period which is related to geographically correlated error pattern with up to about 2 cm amplitude.

1. Introduction

The OSTM/Jason-2 satellite was launched in June 2008 as a follow-on mission to TOPEX/Poseidon and Jason-1 in the same orbit as its predecessors. The mission is conducted under cooperation between United States and Europe involving the French Space Agency CNES, the United States National Aeronautics and Space Administration (NASA), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), and the National Oceanic and Atmospheric Administration (NOAA). Jason-2 is based on Jason-1 state of the art, including improvements in payload technology, data processing, and algorithms. For sea-surface height accuracy a globally averaged RMS of 3.4 cm is feasible (AVISO 2009).

Within the first mission phase of about 20 cycles (roughly 200 days) both Jason satellites were orbiting in formation, following the same ground track with a time delay of about one minute only. This first phase was dedicated to validation and calibration of the new mission with respect to Jason-1. In February 2009 the Jason-1 orbit was moved to measure on an interleaved ground track in order to allow higher spatial and an improved temporal resolution.

An accurate calibration is essential for many applications, especially for long-term studies of global and regional sea-level change – necessarily based on more than one altimeter mission. Within their formation flight phase a direct comparison of Jason-1 and Jason-2 measurements could be performed, as shown by (Ablain, et al. 2008) or (Chambers, et al. 2003). However, the duration of the formation flight phase was too short to identify small instrumental drifts. To monitor the long term accuracy and stability in situ calibration sites are indispensible. Such sites are operated in Harvest (Haines, et al. 2003), Corsica (Bonnefond, Exertier, et al. 2003), Gavdos (Ioannides, et al. 2009), and Bass Strait (Watson, White, et al. 2004). All these locations provide valuable information on the absolute range bias – but the results differ by a

few centimetres (Bonnefond, Desai, et al. 2008). The reason may be a different number of overflights, different equipments at the calibration sites, but could also be due to specific local conditions for the environmental or geophysical corrections. Finally, systematic, geographically correlated orbit errors could explain part of the range bias differences between the calibrations sites. In contrast to in-situ calibrations, a crossover analysis provides relative, but global calibration results and allows the estimation of geographically distributed error pattern. Furthermore, since this method does not directly need simultaneous measurements at nearly the same position, the approach is independent of the satellites orbit configuration. As a consequence, the calibration can be continued even after the orbit shift of Jason-1 and can be extended as a continuous cross-calibration over the whole mission lifetime.
As the presented approach provides globally distributed and continuously available range corrections, these can be used to connect multiple missions with different orbit characteristics to one single virtual mission with optimal temporal and spatial data distribution. This is essential for many applications like ocean tide modeling or sea level analyses.

After a short overview on the data used within the study, this paper will introduce the method of multi-mission crossover analysis which has been applied for the Jason-2 calibration followed by its results. These are divided in four groups: (i) time series of radial errors, (ii) range bias, (iii) differences in the centre-of-origin realization per mission cycle, and (iv) geographically correlated mean errors.

Tab. 1: Input data used in multi-mission crossover analysis

Mission (Cycle)	Source	Corrections, Replacements
Jason-1 (239-280)	GDR-C PODAAC/ AVISO	JMR radiometer, with replacement product (239-259) smoothed two-frequency ionosphere FES2004 (Lyard, et al. 2006)[1] Dynamic Atmospheric Correction, DAC (Pascual, et al. 2008)
Jason-2 (001-040)	GDR-T AVISO	AMR radiometer smoothed two-frequency ionosphere FES2004, same as for Jason-1 DAC, same as for Jason-1
Envisat (070-081)	GDR-C ESA/CNES	MWR JPL GIM model, IRI reduction to orbit height after (Iijima, et al. 1999) FES2004, same as for Jason-1 DAC, same as for Jason-1
GFO[2] (219-222)	GDR NOAA	no MWR data available, model based on NCEP data JPL GIM model (IRI reduction), same as for Envisat FES2004, same as for Jason-1 DAC, same as for Jason-1

[1] Long periodic tides corrected after (Lefèvre 2009)
[2] GFO radar altimeter is turned off during eclipse periods (since march 2007)

2. Altimeter Data

Within this paper a global calibration of Jason-2 mission is performed by means of a multi-mission crossover analysis. The results are computed for a time period of about one year starting 2008-07-12 and ending 2009-08-12. Data from various altimetry missions are used: in addition to Jason-1 and Jason-2 data, measurements from Envisat and GFO (only in 2008). In order to get consistent calibration results it is necessary to harmonize these data sets as far as possible. To achieve this, identical reference ellipsoids are used as well as same geophysical corrections whenever possible. *Tab. 1* is showing a summary of the input data. The FES2004 model was produced by LEGOS and CLS Space Oceanography Division and distributed by AVISO, with support from CNES. The Dynamic Atmospheric Corrections (DAC) are produced by CLS Space Oceanography Division using the Mog2D model from LEGOS and distributed by AVISO, with support from CNES.

3. Multi-Mission Crossover Analysis

The crossover analysis takes advantage of the redundancy that the sea surface height at the intersection of two crossing passes can be observed twice. The method has been used for many years and proved to be a powerful tool for identifying errors in the altimeter sensors (Kozel, et al. 1994), the radial component of the satellite orbits (Klokocnik, et al. 2000) or in geophysical correction models (Gaspar, et al. 1994). In this study the crossover analysis is used to perform a relative calibration of the Jason-2 range measurements w.r.t. contemporaneous altimeter missions. In general, the sea level serves as reference – not in an absolute but in a relative sense and for a period of a few days only, such that sea level variations can be neglected. Without sea level variations, all altimeter systems should observe the same sea surface. The differences in sea surface heights, realized as crossover differences, are attributed by a least squares adjustment to the radial errors of the altimeter systems under investigation (without assigning orbital or instrumental causes or deficiencies in geophysical models).

The particular aspect of the present analysis is that radial errors are not estimated by a functional model (e.g. polynomials, Fourier series). Instead individual error components are introduced at every crossing of the two intersecting passes. To let the time series of these radial errors obey a certain degree of smoothness, the adjustment minimizes not only the crossover differences but also all differences between consecutive errors of the individual missions. For details see (Bosch and Savcenko 2006) and (Bosch, et al. in preparation). Crossover and consecutive differences are weighted according to (i) the standard deviation obtained from the interpolation of sea surface heights to the crossover position, (ii) the time delay between the crossing sea level measurements or between the consecutive errors, and (iii) the performance differences of the different missions. In order to obtain an objective weighting scheme between all altimeter missions and for the relative weighting between crossover and consecutive differences the stochastic model of the adjustment was extended by a Variance Component Estimation (VCE) as described in (Koch and Kusche 2002). This procedure is still under investigation. Realistic variance components could be reached in case there are no systematic errors in the data (see *Fig. 5* in section 6). If there are only two missions the VCE is not as robust, especially in the presence of unknown systematic errors.

The crossover analysis is segmented and performed for each 10 day cycle with 3 day overlap to neighbouring cycles. For each analysis period single- and dual-satellite crossover differences were computed between all missions in all combinations. The time difference between the measurements is limited to three days to minimize the influences of sea level variability. Even so, the number of crossovers per analysis period varies between some 20,000 (three missions) up to more than 120,000 (five missions). For the life time of Jason-2 three missions are available for most of the time providing about 30,000 to 60,000 valid crossovers per cycle. Based on a 3-σ criterion of the crossover differences, between 1 and 2.5% of all available crossovers were marked as outliers and excluded from the processing. For most of the cycles the variance of crossovers could be reduced by more than 90%, from originally around 20 cm RMS to approximately 4 cm.

In can be shown (Bosch, et al. in preparation) that the normal equation system of the present adjustment has a rank defect of 1. The necessary regularisation is achieved by applying a single constraint to the errors of a reference mission. In this investigation, Jason-1 is used as reference mission. For every analysis period the sum of all errors (or the mean bias) of Jason-1 is forced to zero. Consequently all estimated errors are relative to Jason-1. It should be emphasized that such a constraint does not inhibit temporal as well as geographically correlated variations of the radial errors of Jason-1 itself.

4. Radial Errors for Jason-2

The outputs of the multi-mission crossover analysis are time series of radial errors for every mission and every analysis period covering 16 days each. The errors within the 3 days overlapping periods in general coincide except for a few millimetres with the error estimates within the central 10-day periods. The redundant estimates are therefore skipped such that the final error time series compiles only the errors of the concatenated 10-day periods. The left panel of *Fig. 1* shows a small subset of the radial errors of Jason-2 and Jason-1 for a time period of only five hours. The similarity of the errors and a mean offset of about 7 to 8 cm between the two missions are obvious. As Jason-1 serves as reference mission within the least squares adjustment, the radial errors of this mission scatter around zero. The high correlation between the two time series is mainly due to the formation flight constellation: the two satellites measure the same signal in space and time. They are equipped with nearly identical instruments, processed with the same algorithms and have comparable orbital accuracy.

The complete time series for Jason-2 consist of more than 850,000 error estimates with an average sampling distance of about 15 seconds (over ocean area only). This rather dense sampling available for a period of about 400 days allows a reliable statistical characterisation of the errors by means of empirical auto-covariance functions as shown in *Fig. 1* (right side) for both Jason satellites. The two auto-covariance functions are very close to each other with variances of about 400 mm^2 (corresponding to about 2.0 cm standard deviation) and relative maxima after the first and second orbital revolution (with a period of approximately 6746 sec). Obviously, these maxima imply increasing correlations between measurements on neighbouring ground tracks – an early indication of geographically correlated error patterns to be discussed in detail below.

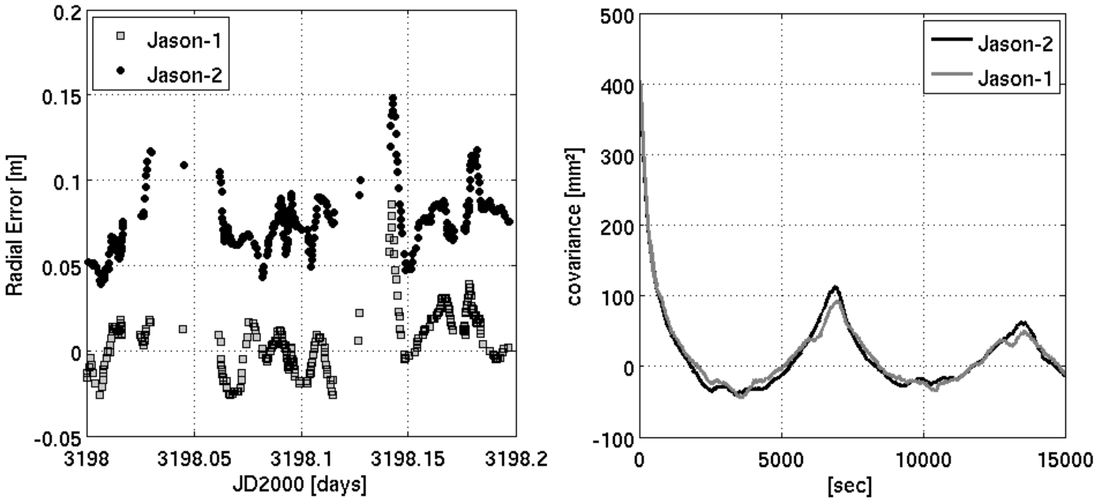

Fig. 1: Subset (approx. 5h) of time series of radial errors for Jason-1 and Jason-2 within formation flight phase (left side) and associated empirical auto-covariance functions computed from the complete time series of 20 cycles (right side). The gaps in the radial error time series are due to land outages.

It is also possible to compute cross-covariance functions between the Jason-1 and Jason-2 radial errors. In *Fig. 2* this is shown for two different cycles, 248, before and 262 after the orbit manoeuvres of Jason-1. Within the formation flight phase there is a peak cross correlation of about 0.8. It appears around a time lag of approximately one minute – which was the time difference the two satellites were following each other over the same ground track. The peak in the cross correlation disappears after the orbit shift when both satellites were flying over interleaved ground tracks. This is a further indicator for geographically correlated errors (rather similar for both missions).

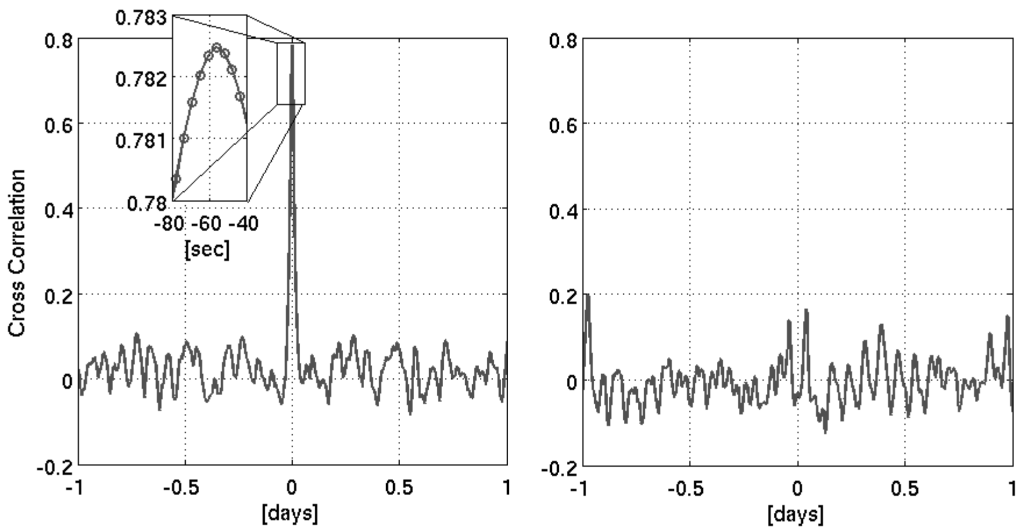

Fig. 2: Empirical Cross-Covariance between Jason-1 and Jason-2 for different mission phases: left plot for cycle 248 within formation flight phase and right plot for cycle 262 with interleaved ground tracks.

5. Relative Range Bias

The estimated radial errors x_i have an individual time stamp and are attached to the known crossover locations (φ_i, λ_i). Thus, a decomposition of these errors in a relative range bias (Δr) and common centre-of-origin shifts (Δx, Δy, Δz) is straightforward. This post-processing is performed for every mission and every cycle by means of a least squares adjustment with the following model for the radial errors x_i:

$$x_i + v_{xi} = \Delta r + \Delta x \cos\varphi_i \cos\lambda_i + \Delta y \cos\varphi_i \sin\lambda_i + \Delta z \sin\varphi_i$$

The values Δr can become rather large (a few decimetres) and accommodate to first order the relative range biases between the altimeters caused, for example, by electronic path delays. As Δr affects the radial direction, it may in addition absorb small scale differences between different tracking systems used within the orbit computation (Bosch and Savcenko 2006). Each value represents a 10-day mean and a global average. *Fig. 3* shows for every cycle the range biases of Jason-2 relative to Jason-1 (the reference mission). The long-term mean value (for 38 Cycles) is 7.5 cm with a standard deviation of 0.2 cm calculated from the scatter of the single cycle solutions. A temporal drift of approximately -2.4 mm/year could be computed though it is not significant. There is also no significant difference between the mean range bias of the formation flight phase (cycles 240-259) and afterwards (cycles 262-280). Thus, on the basis of the present observation period a time-constant range bias for Jason-2 can be assumed. Taking into account the global mean relative range bias of Jason-1 (9.7 cm w.r.t. TOPEX) known from previous cross-calibrations between Jason-1 and TOPEX mission (Bosch, et al. in preparation) and considering the absolute range bias of 1.5 cm for TOPEX which is included in the used MGDR data set (AVISO 1996), an absolute range bias of 15.7 cm is computed for Jason-2. This value agrees very well to the absolute calibration result of Jason-2 performed for the first 15 cycles at Bass Strait which is stated to be 15.95 ± 0.85 cm (Watson, Neil, et al. 2009). Differences to the results from other in-situ cal/val sites do not exceed 3 cm and are in the same order of magnitude than these results among each other.

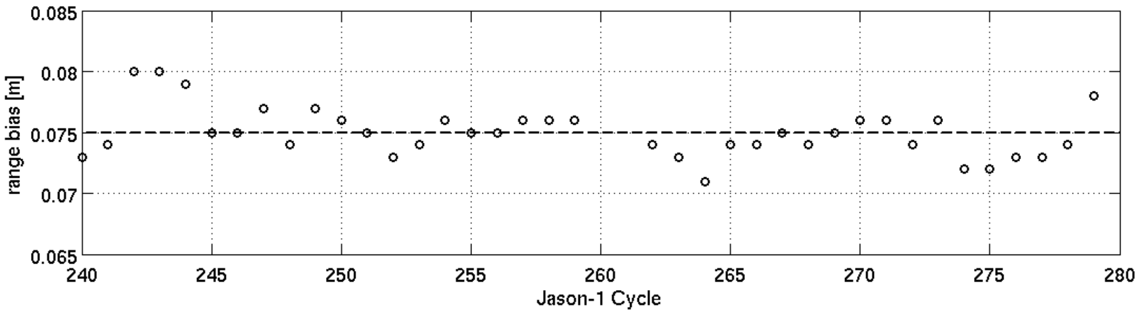

Fig. 3: Cycle based Relative Range Bias of Jason-2

Most of the range differences between Jason-1 and Jason-2 are due to a truncation effect in the pulse repetition frequency (PRF) and differences in the characterization parameters of the two missions (Desjonqueres 2009). Thus, a great part of the range bias could be explained by modelling errors included in the GDR-T data set. In the next version of GDR data these two effects will be removed.

6. Centre-of-Origin Realizations

In addition to the relative range biases, the post-processing reveals systematic differences in the center-of-origin realization of the mission orbits which are shown in *Fig. 4*. GFO is not included here as this mission is only available up to September 2009 (cycle 245). Only in the very first four cycles a contribution from GFO could be seen. Afterwards the VCE reduces the influence of GFO by assigning a high sigma to these data (*Fig. 5*).

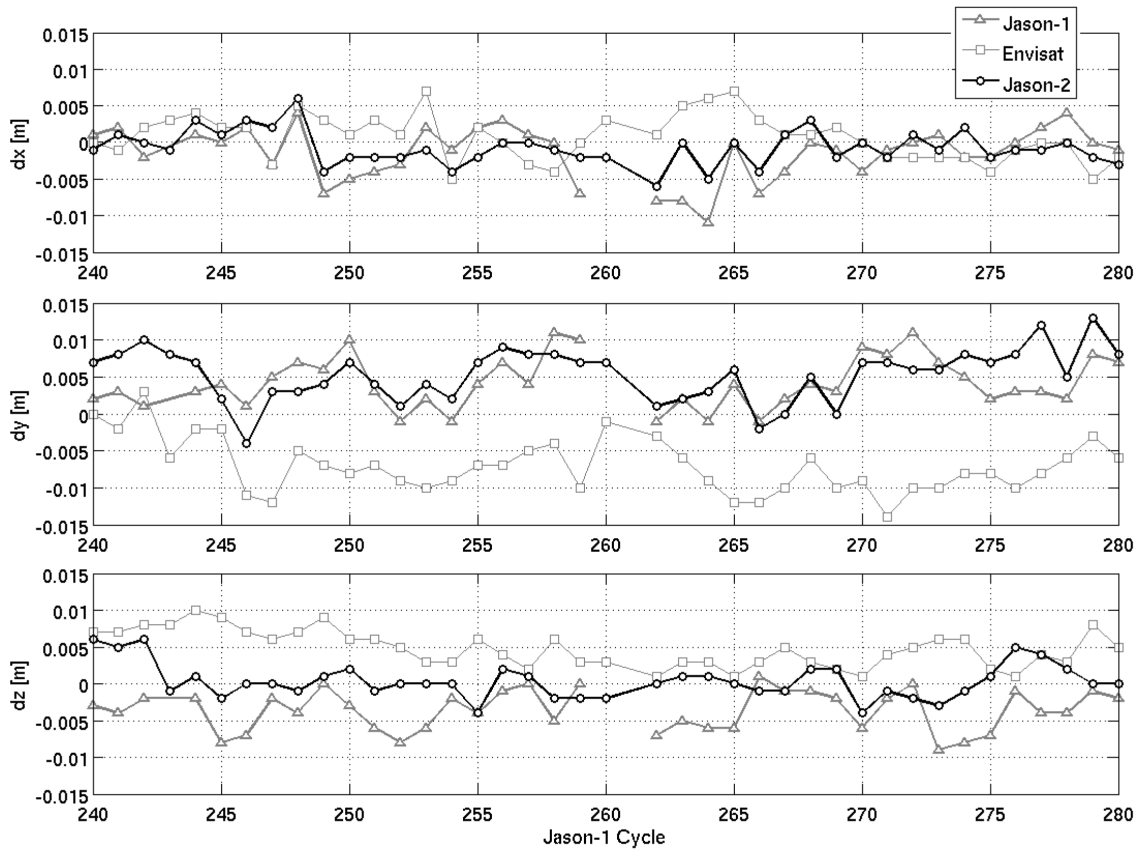

Fig. 4: Differences in the center-of-origin realization for Jason-1, Jason-2 and Envisat

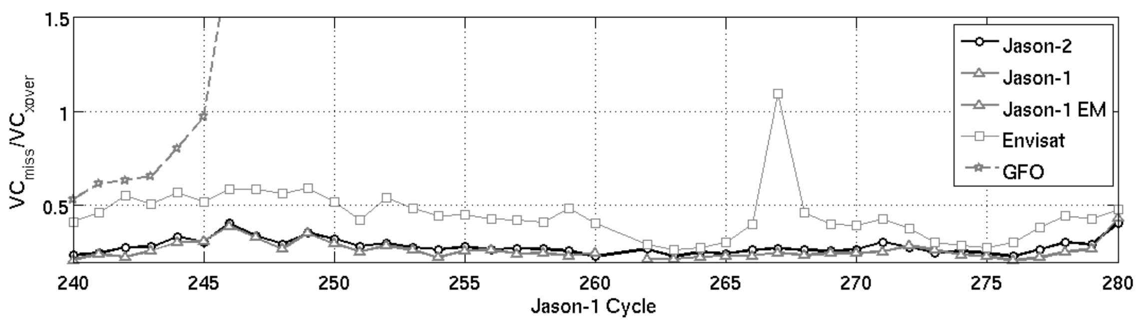

Fig. 5: Variance Components for all missions. The relative values which are shown indicate the weighting between crossovers and consecutive differences for each mission. The outlier for Envisat in Cycle 267 is due to missing data (geophysical corrections).

For the Jason-2 lifetime, the Δx, Δy, Δz values for all remaining missions hardly exceed 1 cm except for Envisat reaching 1.5 cm in the y-component. However, care should be taken for interpreting these results. In contrast to the mean radial error which was forced to have a zero mean for the reference mission Jason-1, the centre-of-origin shifts are assigned by the crossover adjustment without fixing the origin for any of the mission orbits. Since there are only three missions, this assignment may not be as reliable as desired. In *Fig. 4* there are time intervals in which the estimated shifts of Envisat and Jason-1 seem to compensate each other (in particular for the y- and z-component) indicating that the analysis is not able to separate the shifts from these two missions. As a consequence, relative centre-of-origin shifts between the mission are build and shown in *Fig. 6*.

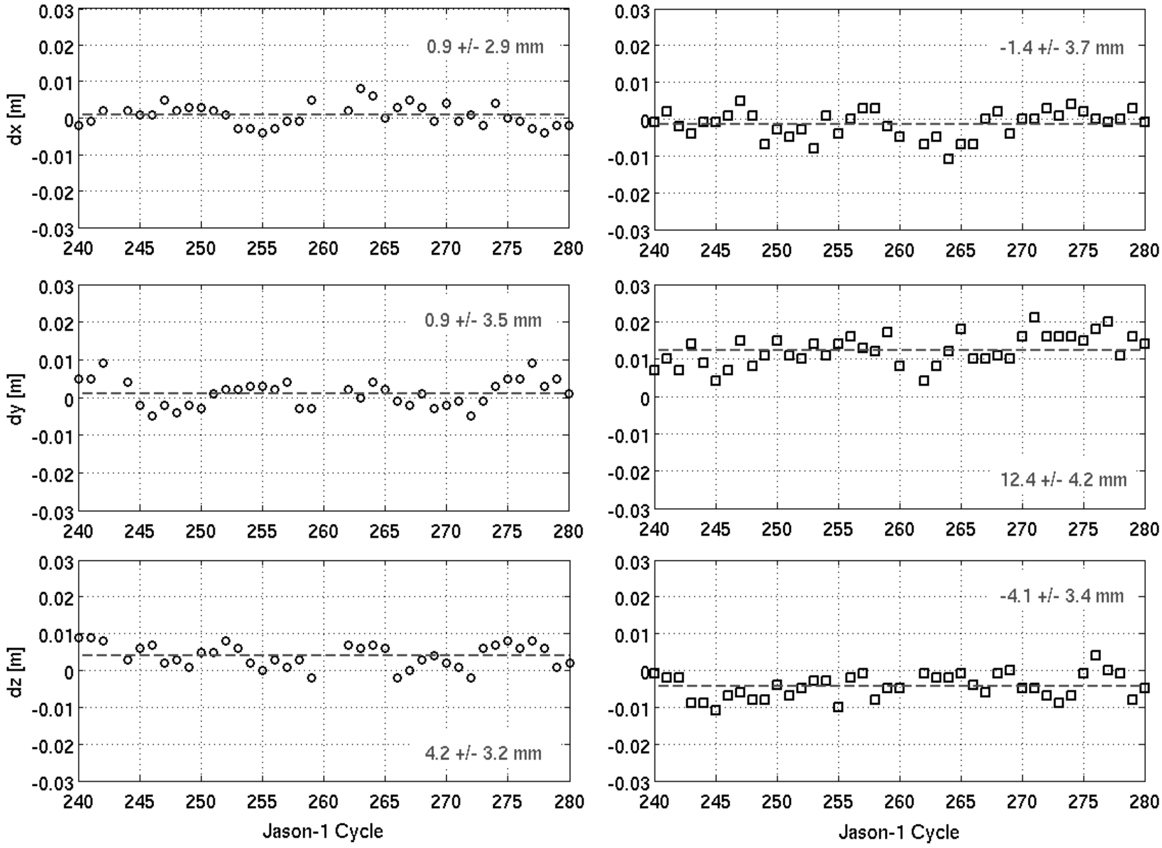

Fig. 6: Jason-2 relative center-of-origin differences w.r.t. Jason-1 (left panel) and w.r.t. Envisat (right panel). Significant differences could be seen between the two Jason in dz and between Jason-2 and Envisat in dy and dz.

The bottom left panel shows that there is a 4 mm difference in the z-component of the center-of-origin realization between Jason-1 and Jason-2 orbits. The source for this difference is under further investigation, considering that for most of the cycles there are correlations of 0.3 and 0.6 between Δr and Δz caused by the uneven land-ocean distribution on northern and southern hemisphere.

The discrepancies between the two Jason satellites are quite small; however, the difference in y-shift between Jason-2 and Envisat is clearly significant and exceeds 12 mm. In contrast to the Jason-2 satellite Envisat has no GPS tracking such that systematic differences between the GPS tracking network realization and the Laser and DORIS networks could map into the y-shift observed here. Other potential explanations are differences in the modeling of the satellites surface forces within the orbit computation of Jason and Envisat (mainly radiation pressure and albedo).

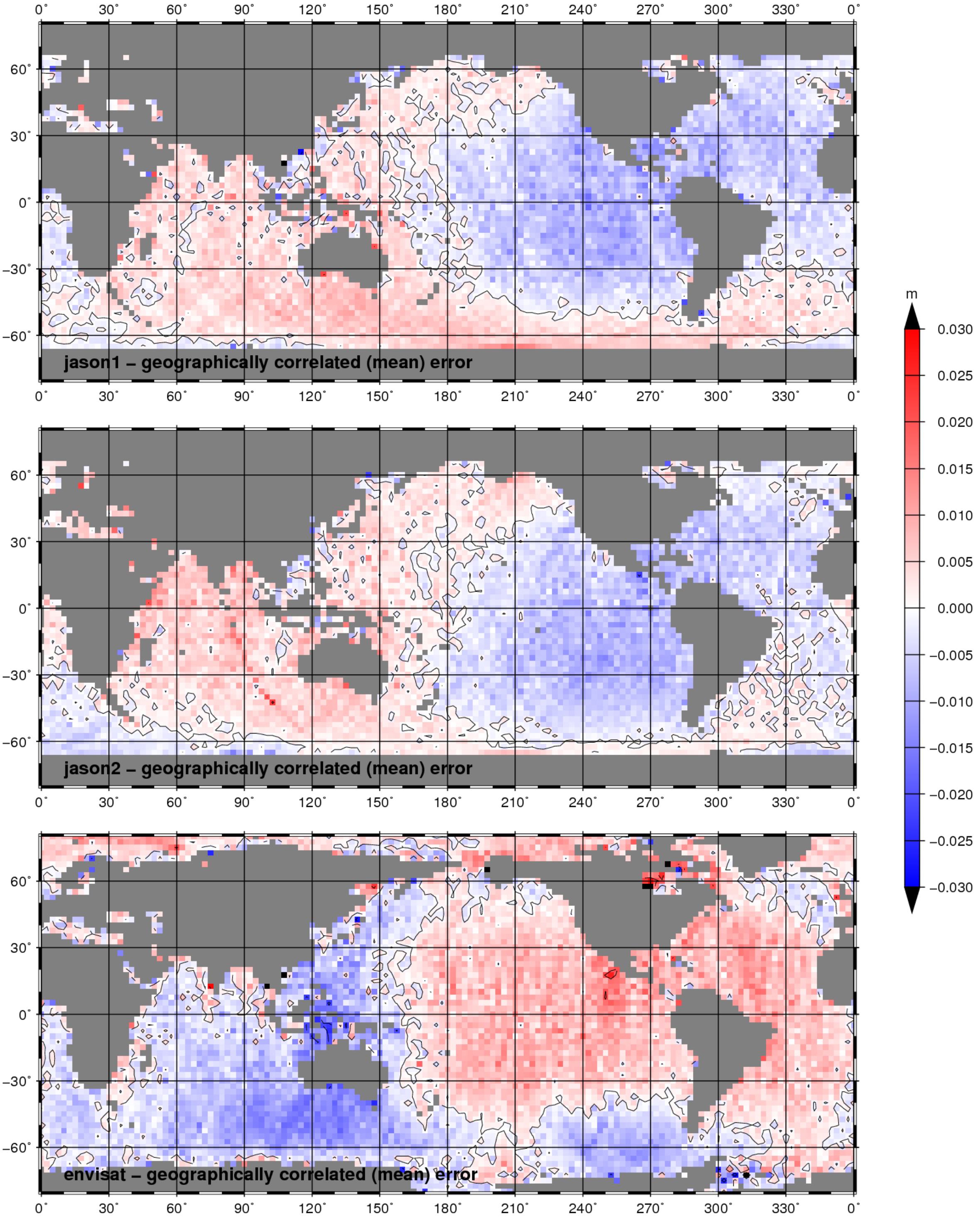

Fig. 7: Geographically correlated mean errors for Jason-1 (top), Jason-2 (middle), and Envisat (bottom). The estimated range bias for each mission is already subtracted from the data.

7. Geographically correlated errors

Error components having the same sign for ascending and descending passes are called geographically correlated errors (GCE). It is very important to know these types of errors because they map directly in the sea surface heights, but are not visible in single-satellite crossovers. For their visualization the radial errors of each mission were gridded and averaged over 2.5°×2.5° cells separately for ascending and descending passes. These mean values represent mean radial errors of ascending Δr^{asc} and descending Δr^{desc} passes and were subsequently used to compute cell by cell the mean GCE $\Delta\gamma$ and the variable error $\Delta\delta$ from the following formulae (Rosborough 1986)

$$\Delta\gamma = (\Delta r^{asc} + \Delta r^{desc}) / 2$$

$$\Delta\delta = (\Delta r^{asc} - \Delta r^{desc}) / 2$$

Fig. 7 shows the distribution of the mean GCE for all three missions. The amplitudes reach RMS values of 5.4 mm, 5.0 mm, and 7.5 mm for Jason-1, Jason-2, and Envisat respectively. For all missions the GCE amplitudes take maxima of approximately ± 3 cm. The error patterns for the two Jason resemble each other with a minimum around the East Pacific region and a maximum South of Australia. A direct comparison shows that the Jason-2 minimum is shifted a bit more in the northern direction than the Jason-1 minimum. In contrast, Envisat has GCE pattern with nearly opposite signs.

With only three missions it may be possible, that the analysis procedure assigns GCE errors with opposing sign if the data of two or more missions are inconsistent. Therefore it is again recommended to use the GCE estimates only in a relative sense. Building the GCE-differences between pairs of missions, only a low relative error pattern (up to 1 cm) results for Jason-2-Jason-1 with a slight latitude dependency. In contrast, the difference between Jason-2 and Envisat reach more than three centimeters and shows mainly a y-shift (*see Fig. 8).* These results confirm the Δx-, Δy-, and Δz- shifts shown in *Fig. 6*. In order to find the origin of these differences further investigations are necessary.

8. Conclusion

In order to calibrate the new OSTM/Jason-2 radar altimeter, a multi-mission crossover analysis was performed with Jason-1, Jason-2 and Envisat during Jason-2's first year. The analysis is based on single and dual satellite crossover differences performed in all combinations. A highly redundant least squares adjustment then provides a time series of consecutive radial errors without introducing any functional error model. A global mean range bias of 7.5 ± 0.2 cm (w.r.t. Jason-1) is estimated for the GDR-T data – in accordance to calibration results of other groups. Moreover, the statistical properties of radial errors were characterized by empirical covariance functions. It was demonstrated that the analysis can identify differences in the center-of-origin realization. For the two Jason satellites the results are rather consistent, but systematic differences in comparison with Envisat were revealed. The geographical distribution of errors indicate large-scale, geographically correlated error pattern with amplitudes for Jason-2 remaining everywhere smaller than approximately 2 cm and RMS of 0.5 cm.

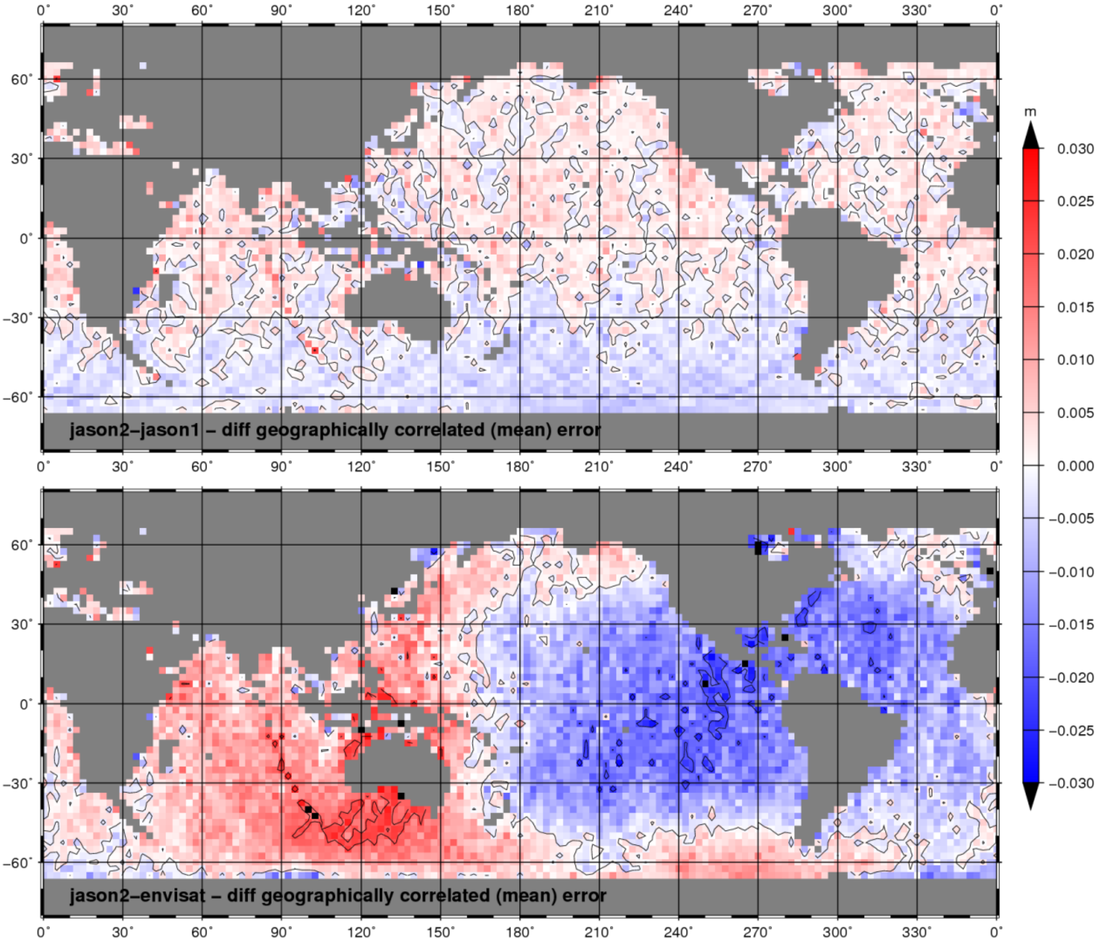

Fig. 8: Differences of geographically correlated errors for Jason-2: on the top w.r.t. Jason-1 and on the bottom w.r.t. Envisat

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