The Performance of CryoSat-2 LRM Level-2 Datasets over the Mediterranean Egyptian Coasts

Mohamed El Tokhey, Tamer Sorour, Mohamed Elhabiby, Yasser Mogahed, Hilal Salloum
Public Works Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt

Abstract— Although the primary goal of ESA's CryoSat-2 is dedicated to support cryosphere science, but also CryoSat-2 is operating over ocean, providing valuable sea surface heights (SSHs) measurements, suited for oceanography and geodesy researches. Hence, its ability to contribute to such applications has to be investigated. On the other hand, the main challenge in utilizing and linking the official CryoSat-2 level-2 dataset with other altimetric datasets, for the suited marine researches, arise from the remaining errors in the provided SSHs, not accounted for by the mission's inner calibration. The main goal of this work aims to assess the performance of CryoSat-2 LRM level 2 dataset over the Mediterranean Egyptian coasts. This was performed by evaluating the ability of the provided dataset to produce a mean sea surface (MSS) model, comparable to the available global model. The absolute bias in the provided dataset has been estimated first. The accurate stacked Jason-2 SSHs were used as control points for calibration and validation, highlighting the efficiency of using such method for regional absolute calibration. Also, the estimated MSS has been compared with the global MSS model. Results reveal that the provided CryoSat-2 SSHs in the GDR LRM level-2 baseline-B product contain an absolute bias of about -93.1 cm w.r.t. stacked Jason-2 SSHs. Results also indicate that the CryoSat-2 dataset from the GDR level-2, can be used to estimate a MSS model in the Mediterranean Egyptian coasts accurate to about 3 cm w.r.t. stacked Jason-2 SSHs and with good agreement with the global MSS model to about 5 cm.

Index Terms— Altimetry, CryoSat-2 LRM, Absolute calibration, Validation, Mediterranean Egyptian coasts, MSS.

1 Introduction

CryoSat-2 satellite mission was launched on 8 April 2010 by the European Space Agency (ESA). The main goal of CryoSat-2 is dedicated to precise monitoring of the variations in the thickness of marine ice and ice sheets. Besides the necessary measurements to meet the main goal that supported cryosphere science, CryoSat -2 provides valuable sea surface height measurements.

CryoSat-2 radar altimetry instrument is called SIRAL (Synthetic Aperture Interferometric Radar Altimeter). It has been designed to operate in three measurement modes and to switch among these modes autonomously as the satellite flies over a predetermined geographical mode mask. Over the oceans and relatively smooth ice sheet interiors, CryoSat-2 operates like a traditional radar altimeter in Low Resolution Mode (LRM). But, unlike most radar altimeters that observe the surface at nadir, CryoSat can observe off-nadir. The second mode, the Synthetic Aperture Radar (SAR), is used over ocean areas where floating marine ice is prevalent in addition to a few small test areas. The third mode, SAR interferometry (SARIN), is used around ice sheet margins and over mountain glaciers as well as a few test areas [1].

Taking into account that CryoSat-2 operates in LRM over oceans, with a long repeat cycle of 369 days, it accumulates a very dense ground tracks. Consequently, CryoSat-2 LRM dataset provides important sea surface height measurements, suited for geodetic applications [2]. Hence, its ability to contribute to such applications has to be investigated.

On the other hand, CryoSat-2 LRM, as a traditional radar altimeter (fig. 1), measures the time taken by a radar pulse to travel from the satellite to the sea surface and then back to the satellite receiver, to derive the measured range using the precise satellite location. Then the sea surface height (SSH) is computed by (1) as the difference between the satellite altitude (H_{alt}), and the measured range (R), after applying the necessary corrections (Δr_i), to remove the instrumental errors and geophysical effects.

$$SSH = H_{alt} - R - \sum_i \Delta r_i \tag{1}$$

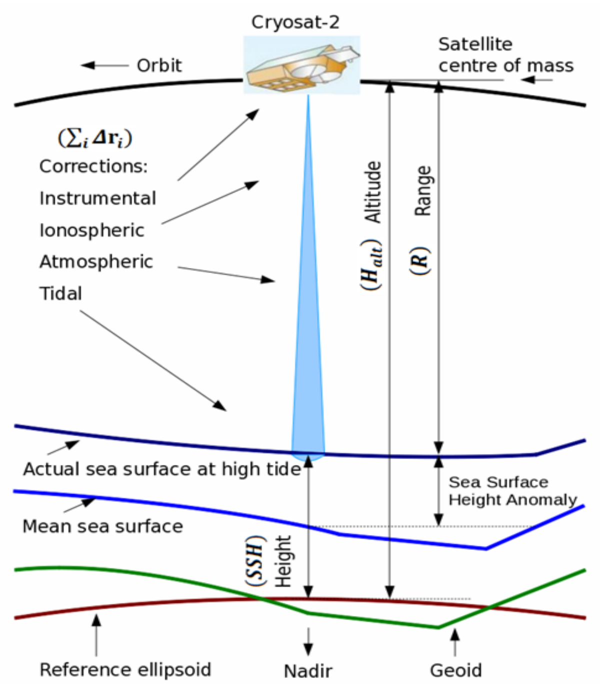

Fig. 1. Basic altimetry terms and applicable corrections over open ocean. (After Bouzinac 2014, [1]).

ISSN 2229-5518

Hence, the computed sea surface height may still contain some errors, not accounted for by the mission's inner calibration, mainly come from errors in measuring the arrival time of the return pulse or its processing, errors in satellite orbit or satellite center of mass. Also the weakness of the used models for removing the geophysical effects, in some areas, affects the computed sea surface height. Consequently, the CryoSat-2 LRM product provided by the agency will present systematic differences, in absolute sense, with other missions' products. This will form the main challenge in linking CryoSat-2 dataset with other altimetric datasets, along with the challenge in the accurate employment of CryoSat-2 LRM dataset itself, in the suited marine researches.

The systematic errors in satellite altimetry SSH can be estimated by methods of external calibration, in which the derived SSH from the mission dataset are compared with the SSH derived independently, over a sufficient long time period. Calibration methods are mainly classified as relative and absolute calibration [3].

The relative calibration approaches depend on crossover adjustment scenario with other satellite altimetry datasets, to derive mainly the relative range bias along with analyzing and removing the other remained errors through the calibration procedures. Such approaches are used in dual missions crossover scenario e.g. [4], [5], and also in multi missions crossover scenario, mostly inside the global altimetric datasets centers e.g. [3], [6].

In contrast, the absolute approaches depend on comparing the sea surface heights obtained from altimetric mission with that from fixed sites; to derive the absolute difference. In-situ data obtained by GPS equipped buoys or GPS-linked tide gauges, and due to the geographical location of these fixed sites under the tracks of the exact repeat missions, are mainly used to calibrate such altimetry missions e.g. [7], [8], [9].

However, other regional calibration approaches, comparable to the in-situ absolute calibration, may be used. The stacked points of Topex/Poseidon SSHs, as a reference mission followed on by Jason-1/2, were used as control points to estimate the bias and tilt in altimetry missions with long repeat cycle e.g. [10], [11]. Also, a new regional calibration approach, was introduced by [12], and based on a succession of accurate mean sea surface profiles combining several missions.

The most conducted research to estimate the remaining errors in CryoSat-2 LRM dataset, have been applied globally using the relative calibration approaches, either by employing the dual missions crossover scenario e.g. [13], [14], or by employing the multi missions crossover scenario e.g. [3], [15]. The overall assessment results of such researches, show significant errors in the provided CryoSat-2 LRM dataset which have to be taken into account, to ensure consistency with other altimetric datasets. Also, the CryoSat-2 technical reports, published by the ESA [16], announced that some identified errors are still under investigation even in the announced Baseline-C product

The main goal of this work aims to assess the performance of CryoSat-2 LRM level 2 dataset over the Mediterranean Egyptian coasts. This will be through evaluating the difference of CryoSat-2 dataset with the stacked Jason-2 SSHs, as a reference mission, to estimate the absolute bias in the provided datasets. Then, the ability of the provided data to produce a mean sea surface model, comparable to the available global models, will be evaluated.

Hence, such work also aims, to provide useful conclusions, for altimetric users, who want to utilize the official CryoSat-2 level 2 dataset, along with highlighting the efficiency of employing the stacked Jason-2 SSHs for regional absolute calibration.

2 USED DATA AND AREA UNDER STUDY

The used datasets in this work include the CryoSat-2 LRM dataset from the GDR Level-2 baseline B product, covering the third cycle of the mission (between 19-June-2012 and 22-June-2013) provided by ESA. In addition to the data under investigation i.e. CryoSat-2 LRM, also the stacked Jason-2 SSHs (between April-2012 to Aug-2013) provided by Physical Oceanography Distributed Active Archive Center-NASA (PO-DAAC), were used only for calibration and validation. Currently, Jason-2 is considered as a reference mission, after Topex/Poseidon and Jason-1, and benefit from the continuous absolute calibration at the in situ calibration sites.

The area under study is located in the Mediterranean coastal region of Egypt, bounded by 30°N to 34°N in latitude and 22°E to 37°E in longitude. Since the area under study was relatively small, and to obtain more representative results in estimating the absolute bias, It was decided to perform the regional absolute calibration over larger area, 30°N to 37°N in latitude (i.e. the Eastern Mediterranean basin), to permit of using more Jason-2 points.

3 METHODOLOGY

The ability of the CryoSat-2 LRM level-2 dataset to produce a MSS model, comparable to the available global model, was assessed by estimating the absolute bias in the provided dataset first. The accurate stacked Jason-2 SSHs were used for calibration and validation. Later, the comparison with global MSS model, DTU13 MSS generated by Technical University of Denmark [17], was performed.

The processing procedures are based on using the corrected SSHs of the 1-Hz measurements through the remove-restore-technique, and can be summarized as follow:

1. Extract the valid corrected SSHs from CryoSat-2 LRM level-2 dataset in the 1-Hz measurements from 20-Hz.
2. Remove data over land to obtain only ocean data.
3. Remove the contribution of geopotential model (N_{GGM})., to get the reduced SSHs ($SSH^{red\text{-}GGM}$) by the formula:

$$SSH^{red-GGM} = SSH - N_{GGM} \quad (2)$$

4. Apply 3RMS tests and local filter.
5. Gridding using the weighted mean method, power two, employing the formula:

$$\overline{X} = \sum_i \frac{x_i}{r_i^2} \Big/ \sum_i \frac{1}{r_i^2} \quad (3)$$

   Where X bar is the interpolated value, i is the number of neighbor points, x_i is the neighbor point value and r_i^2 is the square distance between the neighbor and interpolated point.
6. Restore the contribution of geopotential model (N_{GGM}),

to obtain the CryoSat-2 biased SSHs model.

7. Estimate the absolute difference (ΔSSH) with stacked Jason-2 SSHs by the formula:

$$\Delta SSH = J2^{SSH} - Cr^{BiasMod} \quad (4)$$

Where $J2^{SSH}$ represents the accurate stacked Jason-2 SSHs and $Cr^{Bias\ Mod}$ represents their interpolated values from the CryoSat-2 biased SSHs model.

8. Apply the estimated bias to the original CryoSat-2 SSH and reprocess to produce the MSS from CryoSat-2 data.
9. Validate the estimated MSS against the DTU13 MSS global model.

4 ESTIMATING THE ABSOLUTE BIAS

Estimating the absolute bias was performed in a larger area than the Mideterranean Egyptian coasts, covering the Eastern Mediterranean basin, i.e. bounded by 30°N to 37°N in latitude and 22°E to 37°E in longitude.

CryoSat-2 LRM level-2 dataset contains the corrected SSH at 20-Hz measurements, with no information about range and altitude in each measurement. The first preprocessing step was to derive the 1-Hz measurements by averaging the 20-Hz measurements. Also, an editing criteria was applied (based on removing any measurement which assigned with errors or invalid correction) to get the valid corrected SSHs.

Since the CryoSat-2 LRM dataset contain measurements over land, it was necessary to be removed. The surface type and ocean depth assigned in CryoSat-2 product are based on the 2'x2' MACESS model computed in 2004 by [18]. Also, the ocean depth is assigned only to the first 1-Hz measurements of the 20-Hz measurements. So, to remove data over land, it was better to use the DTU10 bathymetry model, generated by Technical University of Denmark in 1'x1' resolution. The depth for each measurement point was interpolated from the DTU10 bathymetry model. Then, measurements with depth above -10 m were removed to obtain only ocean data.

Following the remove-restore technique, the contribution of the global geopotential model has been removed employing the EGM-2008 generated by [19], in (2), to get the reduced SSHs i.e. CryoSat-2 SSHs were referenced to EGM-2008.

The resulted reduced SSHs were submitted to 3RMS tests to remove any remained blunder. Furthermore, to obtain more homogeneity and consistency among the used data, a local filter was applied. The used local filter based on an iterative code, in which the reduced SSH value for each point has been compared with its interpolated value from the nearest 10 points. The point has been removed if the difference exceeded the 3 standard deviation. The local filter had been applied until no data have been removed. Table 1 represents the statistics of SSHs and SSHs reduced EGM-2008 along tracks, after 3RMS and filtering process in the Eastern Mideterranean..

The reduced SSHs resulted after 3RMS tests and filtering process have been gridded on 1'x1' grid by the method of weighted means, power two, as in (3), using the nearest 10 points. The resulted reduced SSHs grids have been smoothed using a simple average filter within 20 Km, to reduce time variability of SSHs.

To obtain the biased SSH model, referenced to EGM-2008, the contribution of EGM-2008 have been restored for each grid.

TABLE 1
STATISTICS OF SSHS AND REDUCED SSHS ALONG TRACKS, AFTER 3RMS AND FILTERING PROCESS IN THE EASTERN MEDITERRANEAN [UNIT IN M].

	Min.	Max.	Mean	Std.
SSHs	-0.186	36.620	13.339	± 6.162
SSHs $^{red\ EGM08}$	-1.603	-0.410	-0.887	± 0.123

Actually the CryoSat-2 SSHs biased model represents the MSS referenced to EGM-2008, estimated from CryoStat-2, but with systematic errors. Table 2 presents the statistics of the reduced SSHs grid and the biased SSHs model in the Eastern Mideterranean.

Finally, the most accurate stacked Jason-2 SSHs points (i.e. not close to coasts or relate to shallow water), and also exist in LRM mask area, have been interpolated from the computed CryoSat-2 biased SSHs model. Then, the differences between the stacked Jason-2 SSHs and their interpolated values are computed by (4). Table 3 presents the Statistics of the difference between stacked Jason-2 SSHs and CryoSat-2 biased SSHs model referenced to EGM2008, in the Eastern Mediterranean.

TABLE 2
STATISTICS OF REDUCED SSHS GRID AND THE BIASED SSHS MODEL REFERENCED TO EGM2008, IN THE EASTERN MEDITERRANEAN [UNIT IN M].

	Min.	Max.	Mean	Std.
SSHs $^{red\ EGM08}$	-1.163	-0.594	-0.896	± 0.089
SSHs	-0.031	37.152	14.808	± 7.526

Table 3 indicates that CryoSat-2 LRM baseline-B product provides SSHs lower than the actual SSHs provided by Jason-2 by about 93.1 cm in the mean term. Trials to minimize the obtained difference using four and five parameters transformation models, in addition to 1st, 2nd and 3rd order polynomial models, resulted in no gain in the accuracy of the difference. Consequenty, it can be considered that the absolute bias in CryoSat-2 LRM SSHs, from level-2 baseline-B product, is about (-93.1) cm w.r.t. stacked Jason-2 SSHs.

TABLE 3
STATISTICS OF THE DIFFERENCE BETWEEN STACKED JASON-2 SSHS AND CRYOSAT-2 BIASED SSHS MODEL REFERENCED TO EGM2008, IN THE EASTERN MEDITERRANEAN [UNIT IN M].

	Min.	Max.	Mean	Std.
$J2^{SSH}$ – $Cr^{Bias\ Mod}$	-0.853	1.034	0.931	± 0.031

It is necessary to mention here to the results of other studies conducted on the same CryoSat-2 product used in this study. The LRM range bias w.r.t. Jason-2 is -23.4 cm as estimated by [14]. Also the orbit offset is -70.4 cm as applied by [15] to the sea level anomaly derived from CryoSat-2 SSHs. Hence, the esti-

ISSN 2229-5518

mated absolute bias in this work seems to be relatively in line with the results of other calibration approaches applied globally. The difference is in the range of less than 1 cm, which may be related to the area under study.

5 MSS Model Estimation and Validation

To produce the MSS of CryoSat-2 LRM level-2 dataset, the original dataset have been reprocessed, in the same methodology, after removing the estimated absolute bias. Fig. 2 represents the MSS model referenced to EGM2008, produced from CryoSat-2 LRM level-2 dataset over the Eastern Mediterranean basin.

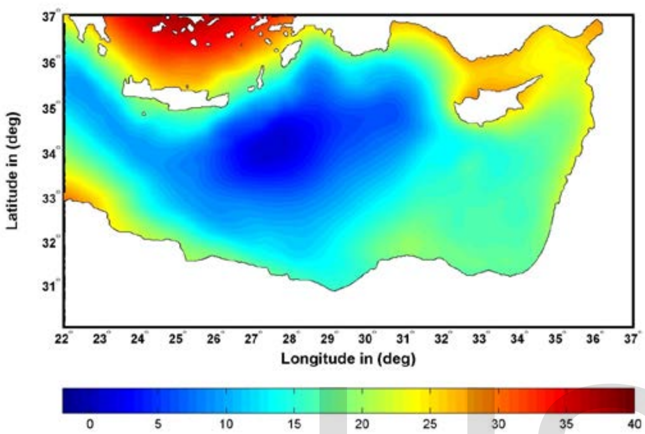

Fig. 2. Final MSS model computed from CryoSat-2 referenced to EGM2008. [Unit in m]

Taking into account that the MSS model estimated from CryoSat-2 will be assessed over the Mediterranean Egyptian coasts, table 4 represents the statistics of the estimated MSS reduced EGM 2008 and the estimated MSS model, only over the Mediterranean Egyptian coasts.

The validation of the estimated MSS model was performed through comparisons with the stacked Jason-2 SSHs and the

TABLE 4
Statistics of the Estimated MSS Reduced EGM 2008 and the Estimated MSS Model over the Mediterranean Egyptian Coasts. [Unit in m]

	Min.	Max.	Mean	Std.
$MSS^{Cr\ red\ EGM08}$	- 0.104	0.302	0.093	± 0.073
MSS^{Cr}	0.957	30.268	13.738	± 4.797

DTU13 MSS. For the comparison, stacked Jason-2 points and the 1' x 1' DTU13 MSS points in the Mediterranean Egyptian coasts were interpolated from the estimated MSS model, and the differences were computed. Table 5 represents the statistics of the differences between stacked Jason-2, DTU13 MSS and the estimated MSS model from CryoSat-2 in the Mediterranean Egyptian coasts. Also the differences with stacked Jason-2 and DTU13 MSS are presented in fig. 3 and fig. 4 respectively.

TABLE 5
Statistics of the Differences between Stacked Jason-2, DTU13 MSS and the Estimated MSS Model from CryoSat-2 in the Mediterranean Egyptian Coasts. [Unit in m]

	Min.	Max.	Mean	Std.
$J_2 - MSS^{Cr}$	-0.093	0.119	0.001	± 0.032
$MSS^{DTU} - MSS^{Cr}$	-0.541	0.209	-0.040	± 0.052

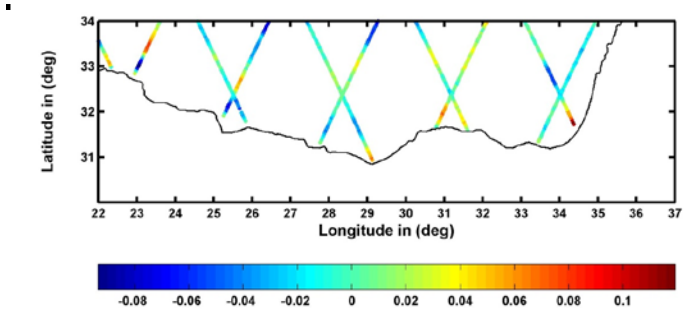

Fig. 3. Difference between stacked Jason-2 SSHs and the computed MSS. [Unit in m]

It is evident from table 5, that the estimated MSS model is accurate to about 3 cm w.r.t. stacked Jason-2 SSHs, and also with good agreement with the DTU13 MSS to about 5 cm. The maximum and minimum values of the differences are related to regions close to the coastline and shallow water; where the estimated model and DTU13 MSS model relatively suffer from errors. Such results also indicate the efficiency of the estimated absolute bias, along with the used method to estimate it.

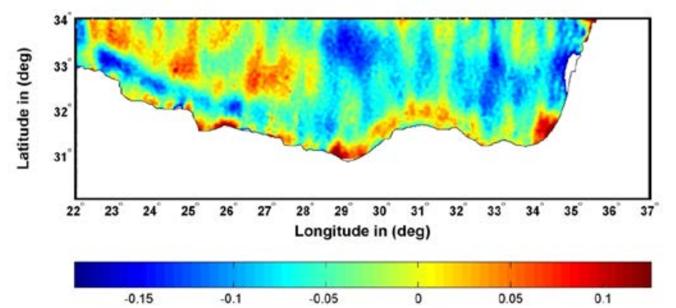

Fig. 4. Difference between DTU13 MSS and computed MSS from CryoSat-2. [Unit in m]

6 Conclusions

Based on the performed assessment of the performance of CryoSat-2 LRM level-2 dataset over the Mediterranean Egyptian coasts, the following conclusions can be drawn:

Using the stacked Jason-2 SSHs as control points, to perform regional absolute calibration for CryoSat-2 LRM dataset, is an efficient calibration method, comparable to the relative calibration methods applied globally. The difference is in the range of

ISSN 2229-5518

less than 1 cm in the Eastern Mediterranean basin. Hence, such regional calibration method can be applied anywhere for any altimetric mission of long repeat cycle.

The provided SSH in the official CryoSat-2 LRM dataset from the GDR level-2 baseline-B product must be raised by 93.1 cm, to remove the absolute bias w.r.t. the current reference mission (i.e. Jason-2). While the absolute bias was obtained for baseline-B product in this work, before the availability of the baseline-C product, the above absolute calibration method can be applied for the baseline-C product.

CryoSat-2 LRM level-2 dataset can be used to estimate a MSS model in the Mediterranean Egyptian coasts accurate to about 3 cm w.r.t. Stacked Jason-2 SSHs, and with good agreement with the global MSS model to about 5 cm. Hence, CryoSat-2 LRM level-2 dataset can be used for marine applications, not only over open ocean, but also over coastal areas in the range of the above accuracy, after taking into account the absolute bias in the provided dataset.

References

[1] C. Bouzinac, "CryoSat Product Handbook". European Space Agency., official CryoSat documents, available at https://earth.esa.int/documents/10174/125272/CryoSat_Product_Handbook (last accessed 18 Jan. 2016).

[2] M. El Tokhey, T. Sorour, M. Elhabiby, Y. Mogahed and H. Salloum. "Assessment of Combination the New Altimetric GM for Modeling Eastern Mediterranean Marine Geoid in the Presence of High Resolution GGMs". Presented at the AEAS 42nd Annual International Conference, ASU, Cairo, Egypt, 27-29 Dec. 2015.

[3] W. Bosch, D. Dettmering and C. Schwatke, "Multi-Mission Cross-Calibration of Satellite Altimeters: Constructing a Long-Term Data Record for Global and Regional Sea Level Change Studies". Remote Sensing, vol. 6, no. 3, pp. 2255-2281, 2014. doi:10.3390/rs6032255.

[4] P.Y. Le Traon and F. Ogor, "ERS-1/2 Orbit Improvement Using TOPEX/POSEIDON: The 2 cm Challenge". J. Geophysical Ressearch, vol. 103, no. C4, pp 8045–8057, 1998.

[5] A. Ollivier, Y. Faugere, M. Ablain, N. Picot, P. Femenias and J. Benveniste, "ENVISAT Ocean Altimeter Becoming Relevant for Mean Sea Level Trend Studies". Marine Geodesy, vol 35, pp 1118–1136, 2012.

[6] R. Scharroo, E. Leuliette, J. Lillibridge, D. Byrne, M. Naeije and G. Mitchum, "RADS: Consistent Multi-Mission Products". in Proc. of the Symposium on 20 Years of Progress in Radar Altimetry, Venice, 20-28 September 2012, Eur. Space Agency Spec. Publ., ESA SP-710, p. 4 pp., 2013.

[7] P. Bonnefond, P. Exertier, O. Laurain, Y. Menard, A. Orsoni, G. Jan and E. Jeansou. "Absolute Calibration of Jason-1 and TOPEX/Poseidon Altimeter in Corsica". Marine Geodesy, vol. 26, pp 261–284, 2003.

[8] C. Watson, N. White, J. Church, J. Beardsley, M. King and R. Coleman, "On-going Monitoring of Absolute Bias from the Australian In-situ Calibration Sites: Bass Strait and Storm Bay". Presented at the OSTST Meeting, Boulder, CO, USA, 8–11 October 2013.

[9] S.P. Mertikas, R.T. Loannides, I.N. Tziavos, G.S. Vergos, W. Hausleitner, X. Frantzis, A. Tripolitsiotis, P. Partsinevelos and D. Andrikopoulos, "Statistical Models and Latest Results in the Determination of the Absolute Bias for the Radar Altimeters of Jason Satellites Using the Gavdos Facility". Marine Geodesy, vol. 33, pp 114–149, 2010.

[10] V.M. Kotzev, L.G. Pashova, I.N. Tziavos, G.S. Vergos and R.S, Grebenitcharsky, "Multi-Satellite Marine Geoid for the Black Sea". Compt rend Acad bulg Sci, vol. 62, no. 5, pp 621-630, 2009.

[11] V.D. Andritsanos, G.S. Vergos, I.N. Tziavos, E.C. Pavlis and S.P. Mertikas, "A High Resolution Geoid for the Establishment of the Gavdos Multi-Satellite Calibration Site". International Association of Geodesy Symposia, Vol. 123 Sideris (ed.), "Gravity Geoid and Geodynamics 2000", Springer - Verlag Berlin Heidelberg, pp. 347-354, 2001.

[12] M. Cancet, B. Haines, P. Bonnefond, E. Jeansou, F. Lyard and P. Femenias, "Regional CALVAL of Jason-2 and ENVISAT in Corsica and at Harvest". Presented at the OSTST Meeting, Boulder, CO, USA, 8–11 October 2013.

[13] D. Dettmering and W. Bosch, "Performance of ESA CryoSat-2 GDR Data Over Open Ocean", In: L. Ouwehand (Ed.) Proceedings of "CryoSat Third User Workshop", March 2013, Dresden, Germany, ESA SP-717 (CD-ROM), ISBN 978-92-9221-281-0, ESA/ESTEC, 2014

[14] M. Naeije, E. Schrama and R. Scharroo, "Validation LRM&FDM Level2 Ocean Data", Presented at the CryoSat QWG-4 meeting, ESRIN, Frascati, Italy, 21-23 May 2013.

[15] R. Scharroo and M. Naeije, "CryoSat-2 Pseudo LRM Technique". Presented at the CryoSat QWG-4 final meeting, ESRIN, Frascati, Italy, 30 June -2 July 2014.

[16] ESA, "CryoSat Data Quality Status Summary", Tech. Rep. CS-TN-ESA-GS-808 Version 8, European Space Agency,05 November 2014

[17] O.B. Andersen, L. Stenseng and P. Knudsen, "The DTU13 MSS (Mean Sea Surface) and MDT (Mean Dynamic Topography) from 20 Years of Satellite Altimetry", The 3rd International Gravity Field Service (IGFS) General Assembly, Shanghai, China, June 30 - July 6, 2014

[18] D. Defrenne and J. Benveniste, "A Global Land Elevation and Ocean Bathymetry Model from Radar Altimetry". QWG meeting minutes ,March 2004.

[19] Pavlis N.K., Holmes S.A., Kenyon S.C., Factor J.K.; "An Earth Gravitational Model to Degree 2160: EGM2008", presented at the 2008 General Assembly of the European Geosciences Union, Vienna, Austria, April 13-18, 2008.