DTU Space
National Space Institute

Cryosat Plus for ocean

CP40

Product Validation Report

Sea Floor Bathymetry

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PVR Version 1.0

December 17th 2014

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Document history.

Version	Date	Comments
0.8	12 september 2014	
0.9	24 October 2014	Results revised as input data were corrected (range correction error corrected by ESA)
1.0	17 December 2014	Corrections from ESA review implemented

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1. Background

This task of the CryoSat+ for Ocean (CP4O) contract deals with the use of Cryosat-2 SAR data to detect ocean bathymetry features, in particular the mapping of sea mounts, which should benefit from the finer along-track resolution of SAR altimeters and the closely spaced tracks of the Cryosat-2 mission. This documents is closely related to the ATBD giving the theoretical base for the study.

As for the Coastal Ocean, the SAR re-tracking needed for mapping sea mounts will be the same as for Open Ocean. The only addition to the processing is the need for further along-track processing and filtering to achieve the S/N needed to retrieve small gravity signals associated with underwater bathymetry.

2. Cryosat-2 dataset

A total of 472 Cryosat-2 SAR tracks have been processed under the new mask by ESA (B. Lucas and S. Dinardo, personal comunication) using the SAMOSA-3 SAR altimetry retracker following an unpublished method described by Dinardo and provided to the author as part of the CP40 project.

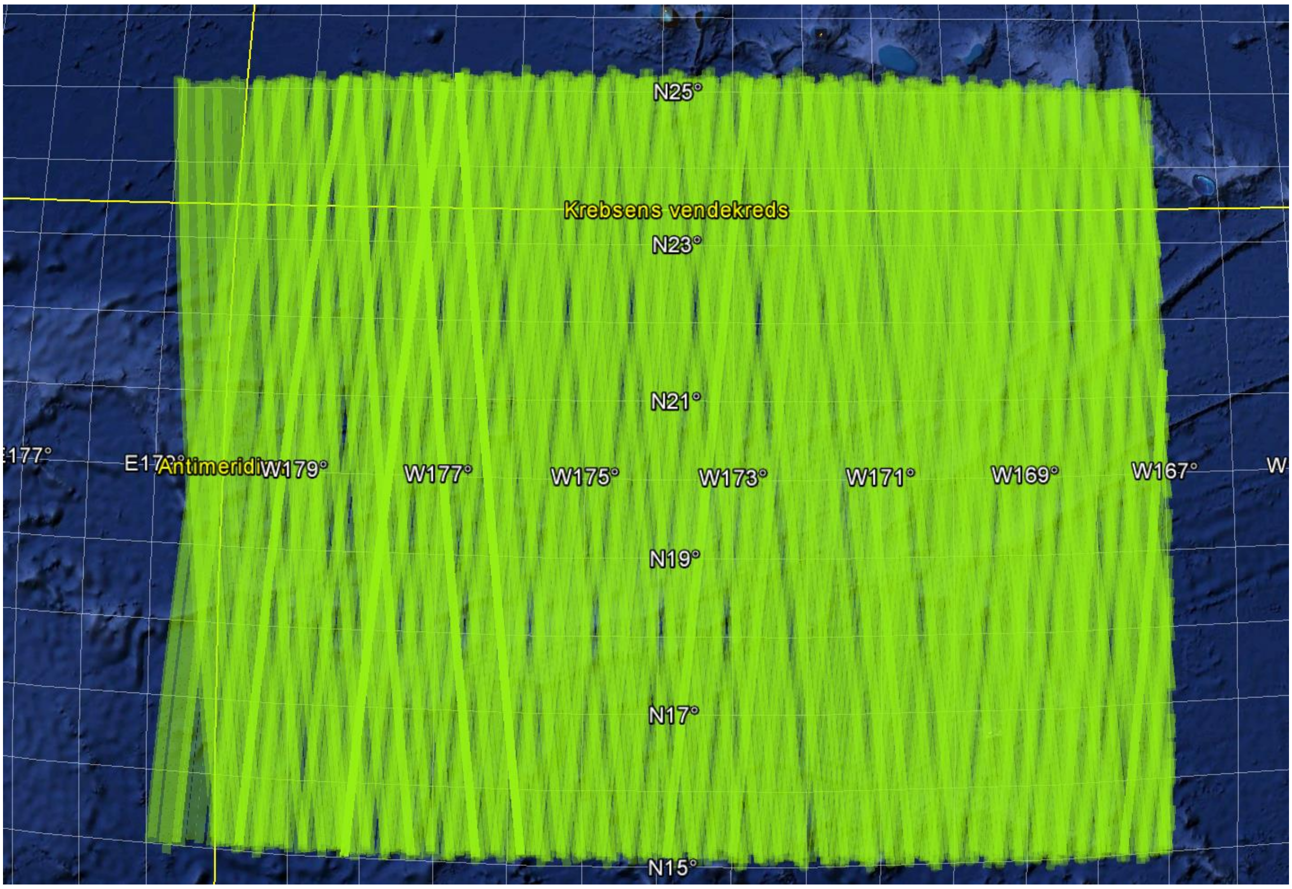

Figure 1. The region investigated for the sea floor bathymetry project and the Cryosat-2 SAR data processed by ESA.

The data span the period of October 2012 until January 2014 and data were delivered a s 1 Hz and 20 Hz uncorrected sea surface height anomalies with 1 Hz range corrections which was linearly interpolated to the 20 Hz sea surface height observations to give the 20 Hz corrected sea surface height observations. The Data and region close to Hawaii is shown in Figure 1.

2.1 Range corrections and processing

Assuming the range and geophysical corrections used are identical to the corrections described in the Cryosat-2 handbook the sea surface height anomaly, h, is given by

$$h = hobs - \Delta hdry - \Delta hwet - \Delta hiono - \Delta hssb - htides - hatm - hgeoid - Rretrakbias$$

where all corrections are sea surface height corrections and something that should be removed from the height (Andersen and Scharroo, 2011). In the following we assumed that the all range and geophysical corrections were present and within given bounds.

No sea state bias correction is given with the provided L1b data and hence it was derived empirically.

We applied the following linear correction based on the significant waveheight. The coefficients for this are similar to what is applied by RADS (Scharroo, personal communication).

$$\Delta hssb = -0.045 * SWH$$

As for the geoid correction the geoid/MSS correction applied with the data was updated with the EGM 2008 geoid.

An ad-hoc retracker bias was determined using the difference to the DTU10Mean sea surface (Andersen et al., 2009). Here, the difference for the data over the given region was found to be

$$R_{retrackbias} = 69.8 \text{ cm}$$

This value was subsequently removed from the sea surface height observations and hence the mean value of all observations was zero relatively to the DTU10MSS. Naturally this $R_{retrackbias}$ might include a lot of other contributions like seasonal variability, mean sea surface error, possible reference ellipsoid differences etc.

The observed retracker bias agrees very well with the bias in the “known Cryosat-2 biases” for Cryosat-2 Baseline-B SAR altimetry of 67 cm (Parrinello, 2013)

Data provided were occasionally lacking some of the range corrections. An editing of bad correction of the range corrections were done by requiring that the sum of all range corrections should be between -1 and -4 meters.

2.2 Input data statistics

	Time period	Std dev on ALL edited data	Nb of Points after editing	1 Hz std dev (Noise in RADS)
20 Hz (provided)	2013	11.9	1603779	-
1 Hz (provided)	2013	8.5	80206	-
1 Hz (computed)	2013	8.4	79982	1.8
2 Hz (computed)	2013	8.9	134602	1.9
4 Hz (computed)	2013	9.0	269371	2.1
1Hz RADS	2011	8.0	82700	3.1
1 HZ RADS RDSAR	2013	8.5	81901	3.1

Table 1. The data retracked using the ESA SAMOSA3 implementation. All range corrections have been applied. In the table the standard deviation on all data are given and the standard deviation within 1 Hz. The standard deviation of all data will reflect the standard deviation of the geophysical signal as well.

A total of 472 tracks of ERS-1 containing 1 Hz values and 20 Hz values processed Cryosat-2 data were **provided** by ESA for the region 179E – 168W/192E and between 15 N and 25 N. Statistics of these are shown in Table 1. These were equally distributed as ascending and descending tracks. Assuming a total of 236 ascentind tracks within the box of 19 degrees longitude equalizing 2000 km.

An editing relative to the DTU10MSS was performed requiring that all individual points should not deviate from this with more than 1 meter. This follows the suggestion by (Cheng and Andersen, 2015). The statistics of the **provided** data are presented after editing. The provided data were then used to **compute** 1,2 and 4 Hz data (se statistics in Table 1)

The track to track distance is consequently roughly 8 km. This is very comparable to ERS-1 and Jason-1 geodetic mission as also illustrated in Figure 2. Accuracy will partly be determined by the number of data used to defined the residual geoid height so it is expected that the accuracy with which bathymetry can be derived *will reflect this.*

In table 1 the data retracked using the ESA SAMOSA3 implementation. All range corrections have been applied In the table the standard deviation on all data are given and the standard deviation within 1 Hz. The latter "noise" parameter is the one important for sea floor prediction.

The standard deviation of all data will reflect the standard deviation of the geophysical signal as well.

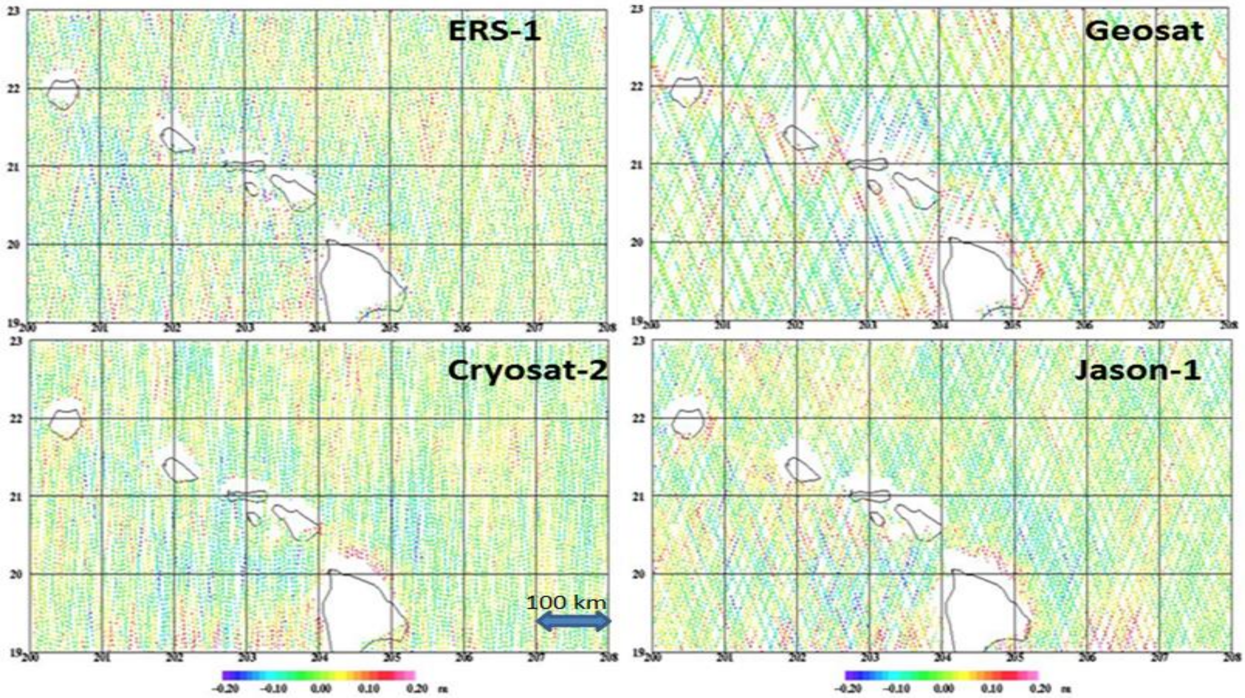

Figure2. Residual geoid height relative to EGM2008 (in meters) derived from 1 year of various geodetic missions around the Hawaiian island chain in the Pacific Ocean. Upper left: ERS-1 (11 month); Upper right: Geosat; Lower left: Cryosat-2; Lower right: Jason-1. One degree in longitude on the x-axis corresponds to roughly 100 km at the given latitudes, as illustrated in the lower left figure. An old version of the NGDC coastline is shown to outline the Hawaiian island chain.

3. Independent dataset.

In the following a set of marine gravity and bathymetry observations provided to DTU as unclassified marine observations by the National Geospatial Agency was used for the comparison and validation. The survey data contains 150345 points that were measured during the 1990's and consequently the accuracy is expected to be around 3-5 mGal and 30-60 meters depth. The data and the region of SAR altimetry is shown in Figure 4.

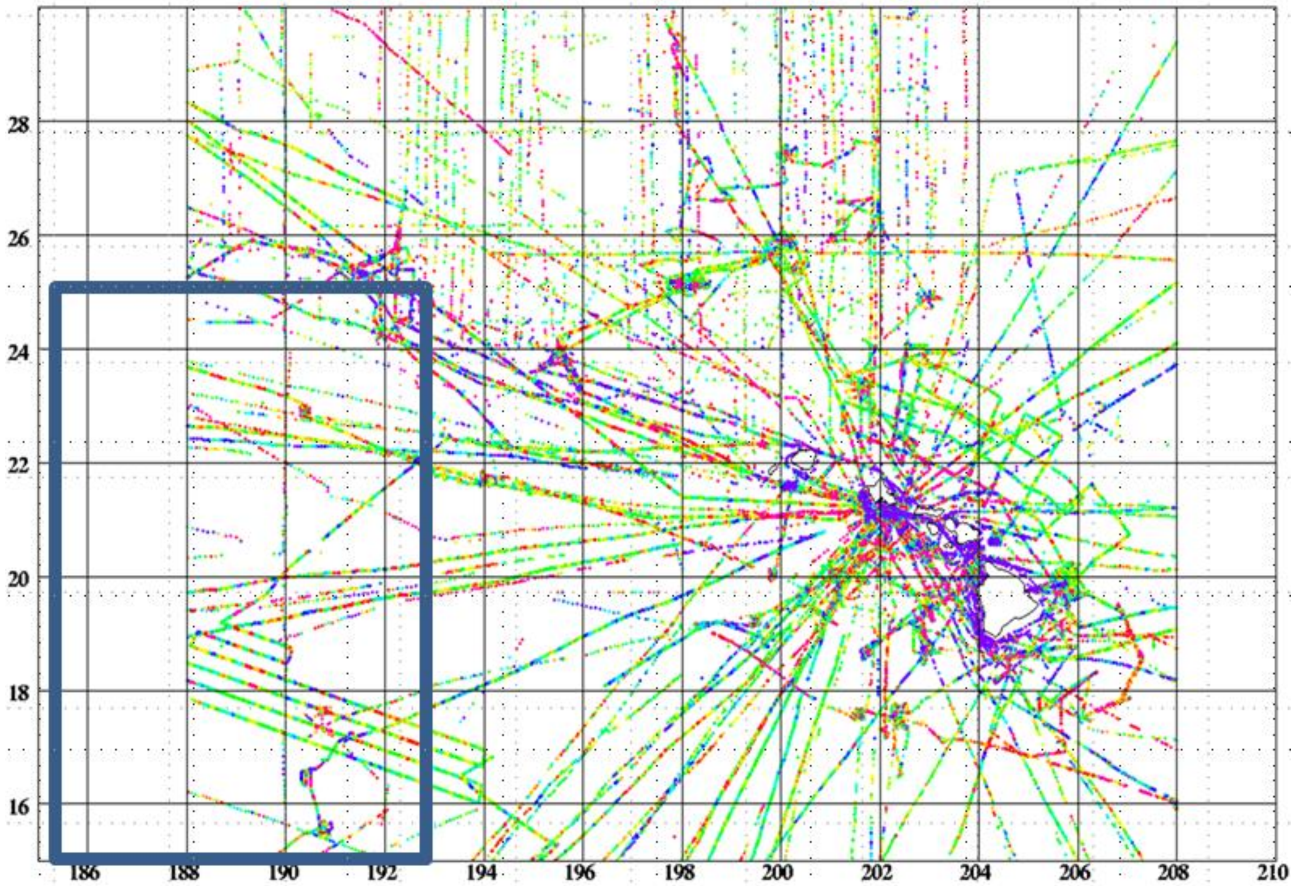

Figure 4. The survey data provided to DTU as unclassified marine observations by the National Geospatial Agency contains 150345 points that were measured during the 1990's. The Blue box marks the joint region containing the Cryosat-2 SAR processed data.

4. Validation region and validation sub-dataset.

Notice that the majority of the data for validation were are taken around the island of Hawaii, where as the region of investigation only contains a total of 13400 marine observations for validation. In order to evaluate the performance of the use of Cryosat-2 SAR data for sea floor predictions under various conditions we operated with several sub-regions for the comparison. These sub-regions are illustrated in Figure 4 and the boundaries and number of observations is shown in Table 2.

Besides the entire region containing a total of more than 14000 marine observations of gravity and bathymetry, three sub-regions bounded by latitude was chosen. These are a northern, a southern and a central region.

The northern region contains a number of very large named seamount and also includes a lot of observations very close to the coast of the western most islands in the Hawaii'an inland chain like the Midway Island. The average depth of this region is close to 5 km. The standard deviation of the observed gravity observations is very high which is due to the fact that many of these are observed very close to the coast.

The southern region is a region of a very high number of seamounts. A few of these are named, but this region is selected for validation as it has potential for containing unmapped sea mounts. Unfortunately the average depth of this region is again close to 5 km, which due to upward continuation hampers the mapping of sea floor signal.

The central region is a plateau region with somewhat shallower depth with an average depth of less than 4 km but with a central plateau area at 2800 meters average depth. This, in principle, should enhance the change of detecting smaller bathymetric features and this is the reason why this region is chosen for a close inspection.

	Latitude	Longitude	Std Gravity	Number of observations	Std / mean Bathymetry
Entire Region	15 N – 25 N	180 W – 192 W	34.10	14101	891 /4620
Northern region (large Sea Mounts	21 N – 25 N	188 W – 192 W	37.09	5408	814/4701
Southern region (small sea Mounts)	15 N – 18 N	188 W – 192 W	32.09	4607	588/5007
Central shallow region Depth (2 - 3 km)	18 N – 21 N	188 W – 192 W	28.35	3996	1008/4097

Table 2. Description and statistics of the various test sub-regions. Geographical boundaries as well as the standard gravity within each region and the number of marine gravity and bathymetric observations in the regions are shown in the table.

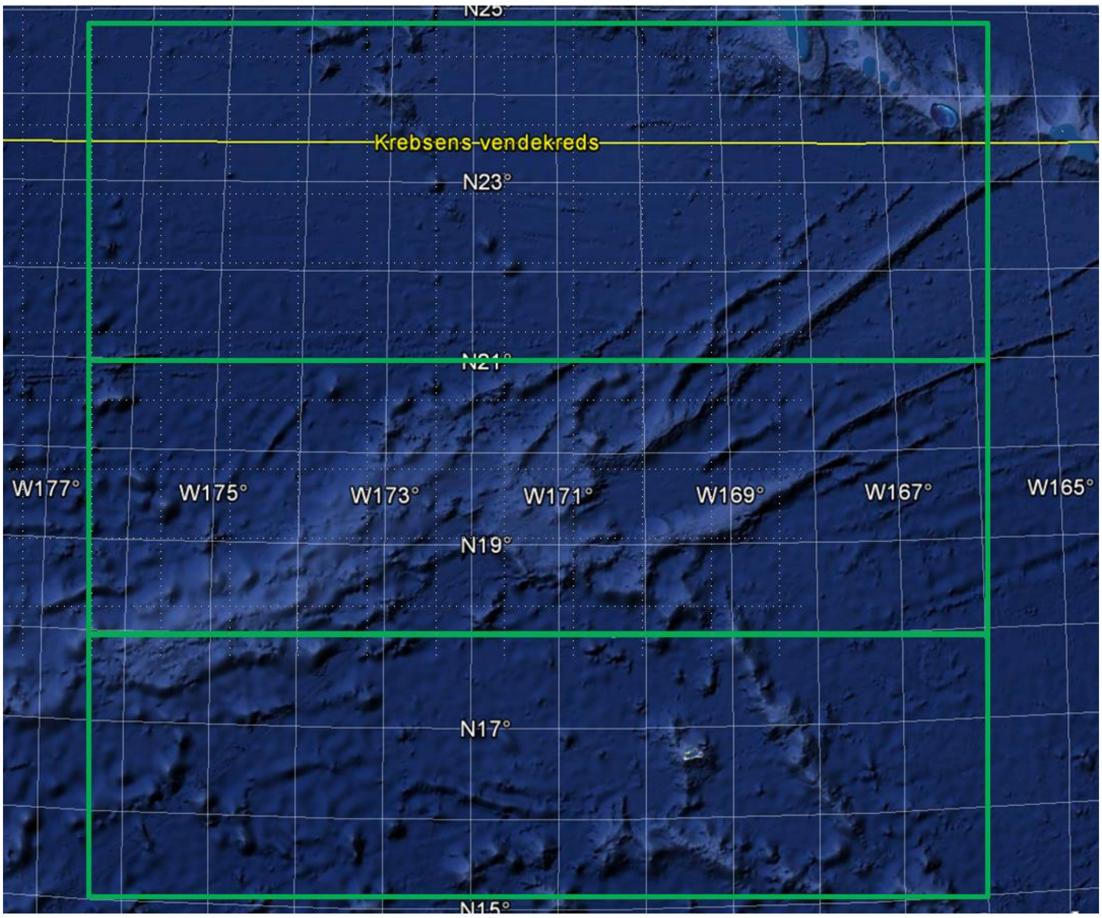

Figure 4. Geographical boundaries as well as the standard gravity for each sub-region investigated.

	Entire Region	Northern	Southern	Central
Gebco-1 (reference)	432 m	275 m	435 m	559 m
Sandwell V 17.1 (2014)	412 m	278 m	411 m	539 m
DTU10BAT (reference)	408 m	261 m	398 m	540 m

Table 3. Reference bathymetric information comparing measured bathymetry with interpolated bathymetry from Gebco-1 (2008 version), Sandwell v 17.1 (2014) and DTU10BAT bathymetry for the four test regions.

Besides the sub regions, two compilations of profiles were used for the validation. These are shown below in Figure 5 and Figure 6.

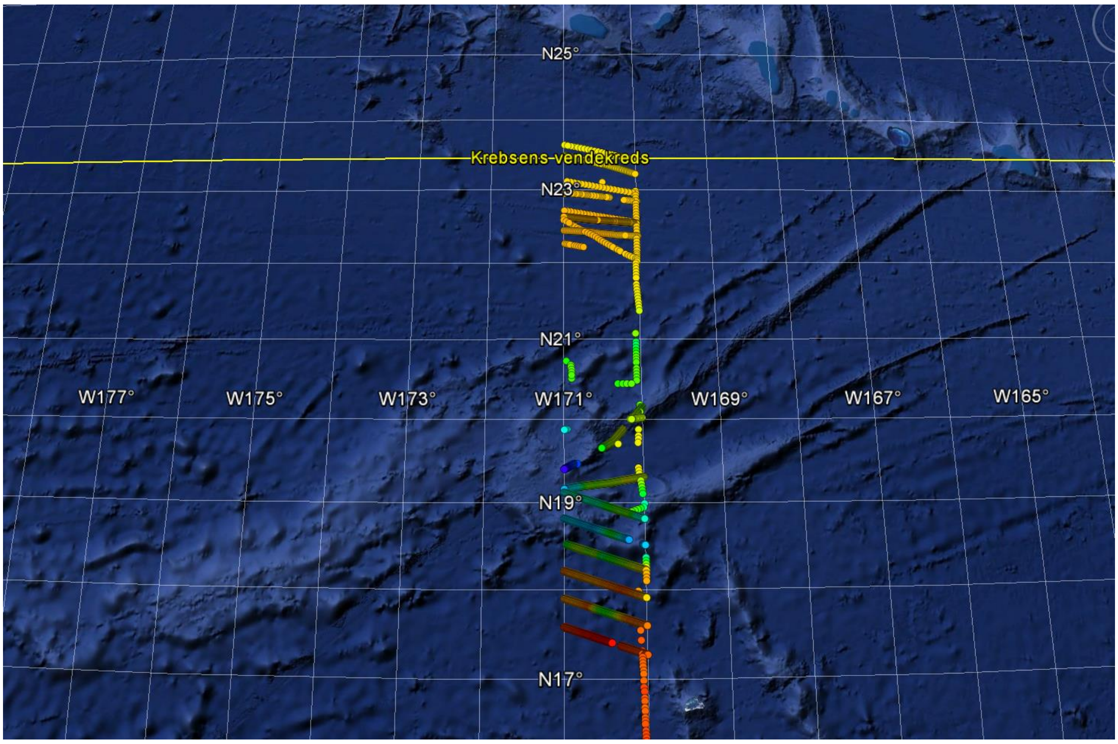

Figure 5. Compilation of profiles across the entire test region. Measured depths are colour coded in the figure.

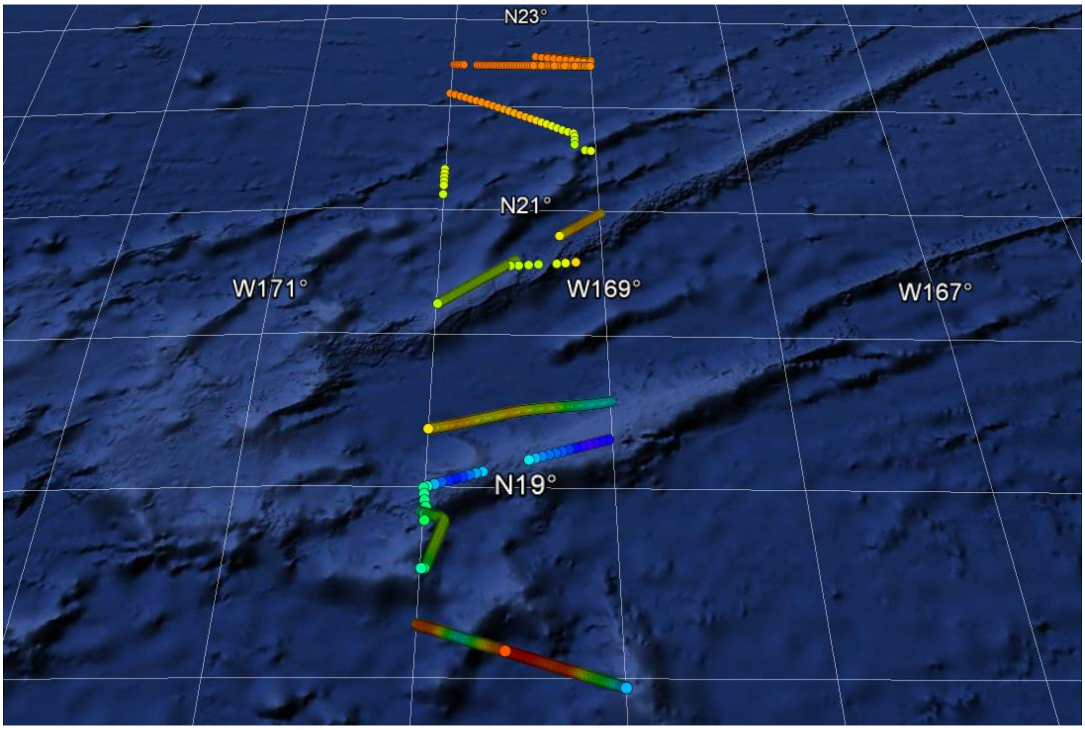

Figure 6. Compilation of profiles covering the central and southern sub-regions. Measured depths are colour coded in the figure.

Both in Figure 5 and 6 the problem of points with mis-placed longitudinal coordinates (set equal to 170W) can be seen. It is very clear in particularly Figure 6 just north of latitude 21N. Such mis-placement will decrease the agreement between measured and predicted bathymetry which can be achieved using this dataset.

For identification in the following plots of profile comparison, the first points in the profile are the southernmost data and shot numbers increasing northwards.

5. Validation activities

Bathymetry was derived in the region using Cryosat-2 data for the 472 tracks processed and delivered by ESA. When interpreting the results it must be stated very carefully that it is not possible to compare the numbers directly with the statistics in Table 2 for general bathymetric models as these are derived from multiyear and multi-satellite compilations of data.

The numbers should be compared internally in the Tables below for bathymetric estimation using 1 year of the following data sets.

1) 1 Hz cryostat SAR data (during 2013).
2) 1 HZ LRM Cryosat data (during 2011) – from RADS.
3) 1 Hz RD-SAR Cryosat-2 data (during 2013) – from RADS.
4) 2 Hz Cryosat-2 SAR data (during 2013) - using setting as for 1 Hz data.
5) 2 Hz Cryosat-2 SAR data (during 2013) - with re-optimized setting to the use of 2 Hz (less filtering).
6) 4 Hz Cryosat-2 SAR data (during 2013) –using setting as for 1 Hz data.

The comparison between estimated and interpolated bathymetry from Cryosat-2 using the 4 various datasets and measured bathymetry from the marine vessels are displayed in Table 4.

	Entire Region	Northern	Southern	Central
1 Hz SAR (provided)	484 m	398 m	410 m	523 m
1 Hz LRM	482 m	397 m	411 m	521 m
1 Hz RD-SAR	486 m	401 m	411 m	522 m
1 Hz SAR (computed)	467 m	372 m	411 m	489 m
2 Hz SAR (1 Hz setting)	467 m	372 m	412 m	489 m
2 Hz SAR (optimized)	465 m	371 m	410 m	487 m
4 Hz SAR (1 Hz setting)	467 m	367 m	409 m	488 m

Table 4. Standard deviation between estimated and interpolated bathymetry from Cryosat-2 using the 5 various datasets and measured bathymetry from the marine vessel. All are are given in meters.

Table four clearly demonstrate the high potential of the SAR data in comparison with existing LRM and RD-SAR data. Particularly the enhanced short wavelength content is particularly important in mapping sea mounts

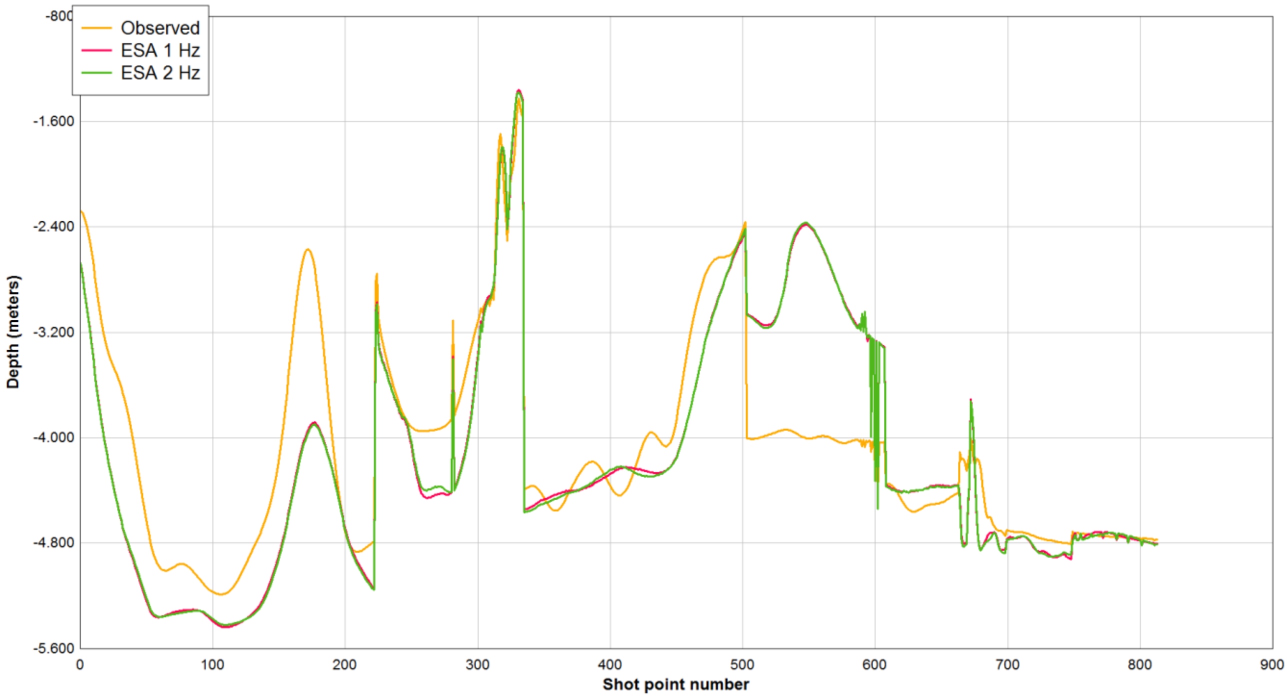

Figure 7. Depth along the compiled set of profiles shown in Figure 5.

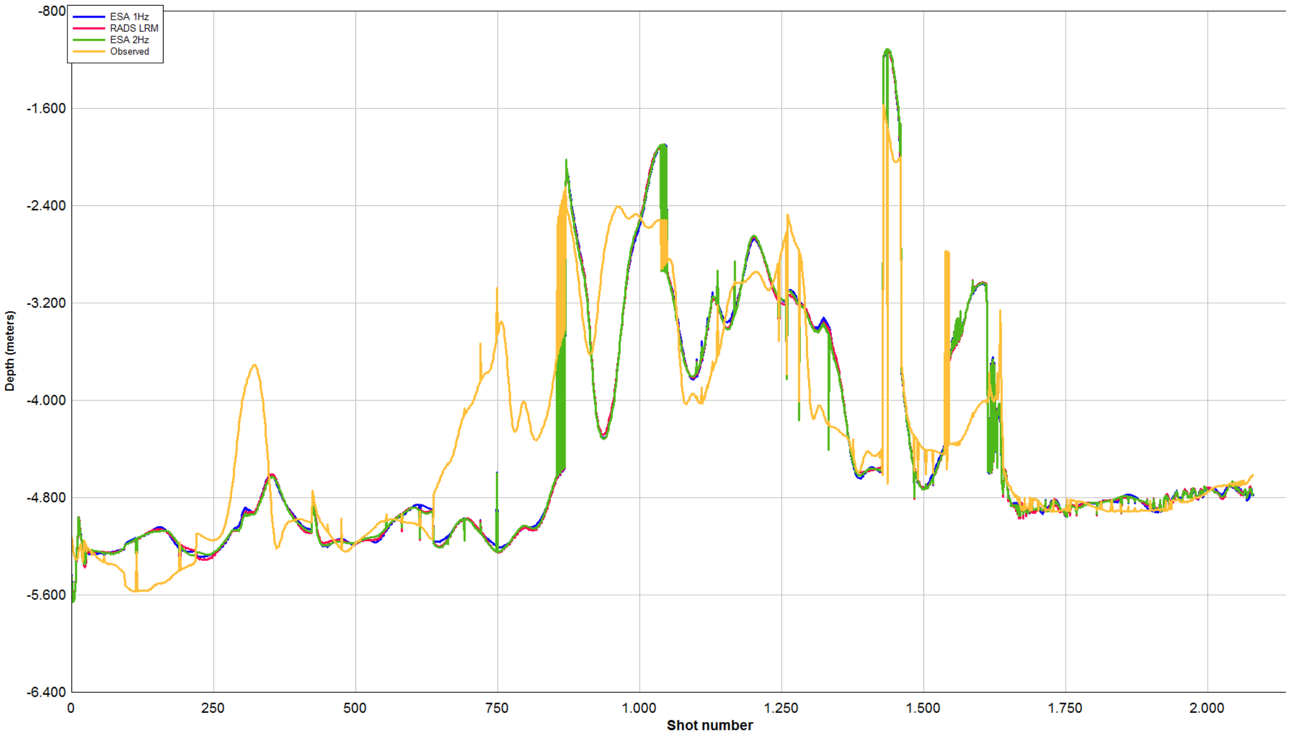

Figure 8 Depth along the compiled set of profiles shown in Figure 6.

In Figure 7 and 8 the comparison between observed and predicted bathymetry Is clearly displayed. The result points towards the presence of large long wavelength differences in the measured and predicted bathymetry. A lot of this difference is inherent in the GEBCO-1 bathymetric model used to predict the long wavelength which cannot be predicted by satellite altimetry.

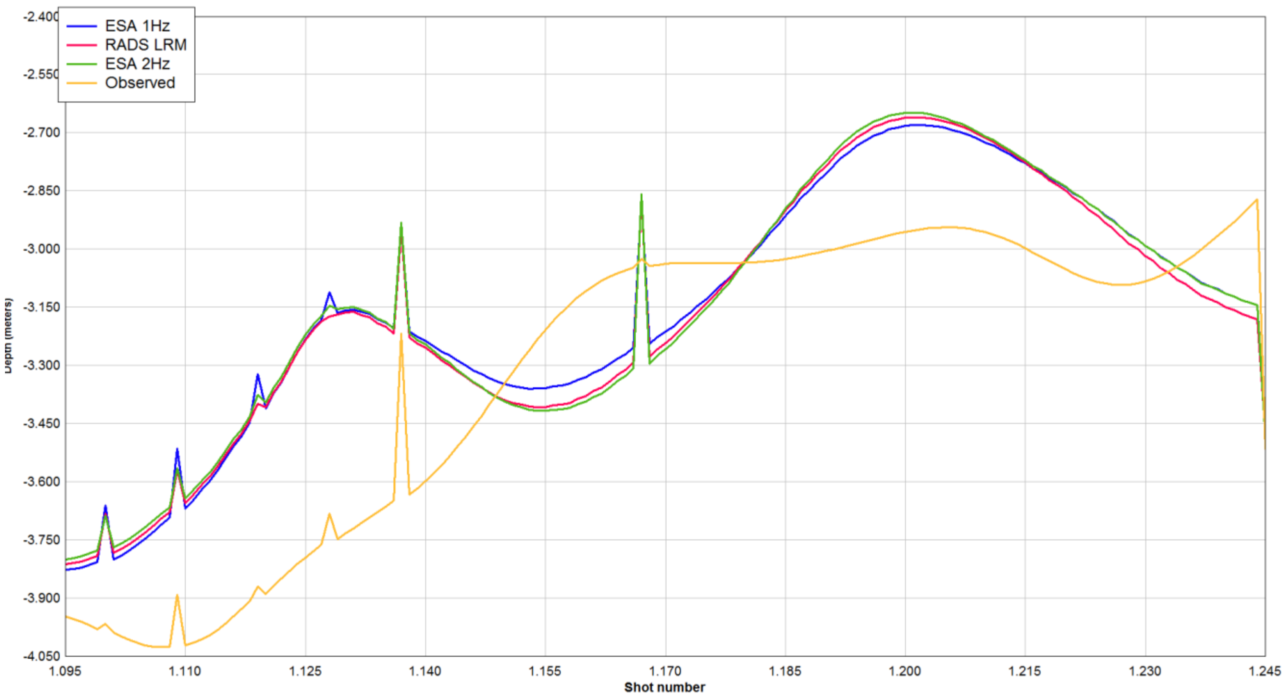

Figure 9 Zoom in on the southern profile in Figure 6 just north of 20N. The shot numbers relates to Figure 8 and figure 6.

In Figure 9 a zoom in on the southern profile in Figure 6 just north of 20N is seen. The altimetric derived bathymetry clearly captures several of the misplaced profile points but generally sees larger bathymetric variation that what is observed by ship sounding in the region. What is interesting is that 2 Hz retracked Cryosat-2 here gives the best comparison with observed bathymetry.

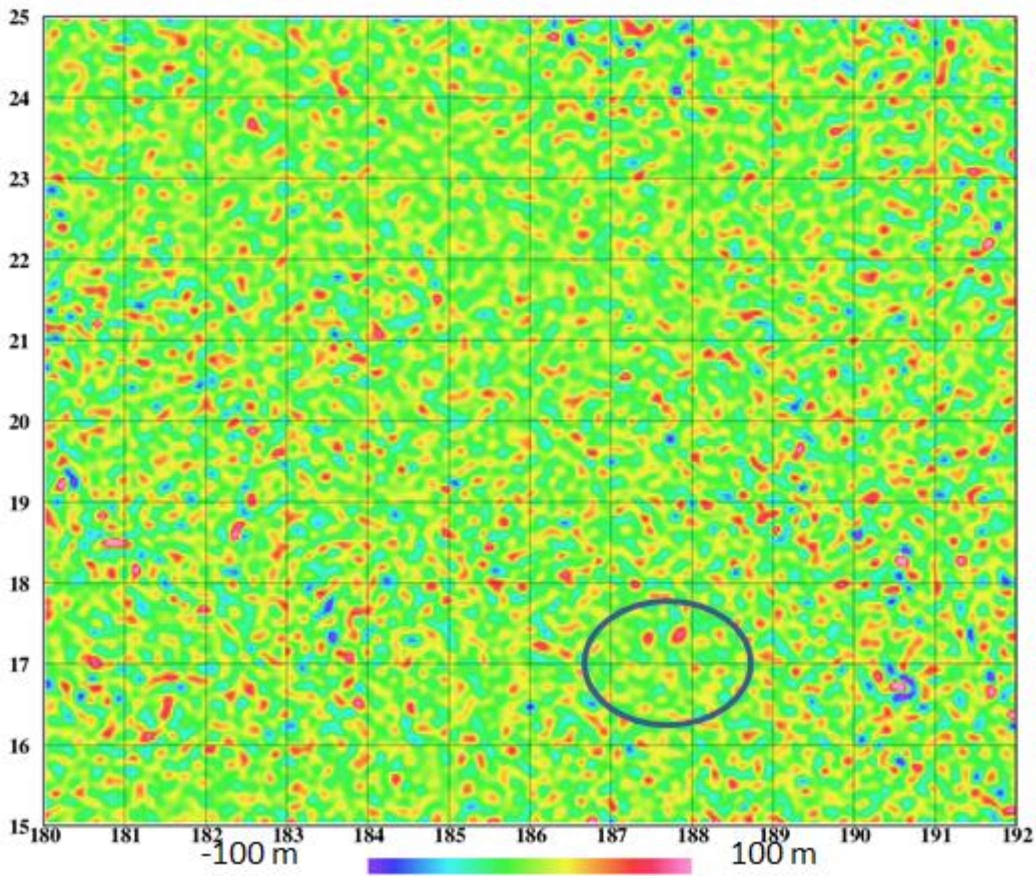

Figure 10 The retrieved residual bathymetry signal relative to a "pre" Cryosat-2 era bathymetry (DTU10 Bathymetry). There are some clear indications in the marked circle of a bathymetric/tectonic feature that could be an improved mapping of an existing seamount or a mapping of an unknown sea mount.

6. Summary

The validation performed here demonstrates that the potential of SAR altimetry derived within the ESA CP40 project to derive sea floor bathymetry and the ability to predict bathymetric features using Cryosat-2 SAR altimetry.

Table four clearly demonstrate the high potential of the SAR data in comparison with existing LRM and RD-SAR data. Particularly the enhanced short wavelength content is particularly important in mapping sea mounts

In this limited PVR analysis a well surveyed region was used for validation of the ability to predict improved bathymetry using Cryosat-2 SAR altimetry. The result was generally relatively good. The input retracked data delivered by ESA (see Table 1) seemed to include a remaining unknown correlated signal. However, this had no effect on the result at such long wavelength are removed in the processing. Hence very nice results could be obtained using the various sub-hertz products.

The conclusions highlighted that we actually were able to clearly predict sea floor bathymetry better than with both one year of conventional LRM data an one year of RDSAR data from the RADS database .

We were also able to predict bathymetry in the central (shallow most) part of the region more accurate than with LRM and RD SAR data in this analysis. We were even able to predict bathymetry more accurate that with the DTU10 and Sandwell and Smith V17.1 (2014) bathymetry model.

The results also points toward the used bathymetry for the long wavelength are in-adequate in our investigation. We used GEBCO-1 (version 2008) which does not include altimetry. However we have recently been alerted to a new 30 minutes NGDC bathymetry (Becker et al., 2009) which should also use the bathymetric observations presented here and hence should give considerably better agreement. However this bathymetry has already been fitted to altimetry by Sandwell and Smith in the development and hence errors in old altimetric data (ERS-1 and GEOSAT) might have affected this bathymetry" and as such we chose to use a bathymetry which did not use altimetric observations to be on the safe side. Unfortunately this bathymetry had considerable short wavelength errors due to few marine data. This can be seen from the fact that the standard deviation between this and observed are in most places larger than 400 meters.

7. Conclusions and recommendations.

The conclusions of this work of the CryoSat+ for Ocean (CP4O) contract dealing with the use of Cryosat-2 SAR data to detect ocean bathymetry features are the following,

- We were able to predict sea floor bathymetry better than one year data from both conventional LRM data and RDSAR data from the RADS database.
- We were also able to predict bathymetry in the central (shallow most) part of the region more accurate than with LRM and RD SAR data in this analysis. We were even able to predict bathymetry more accurate that with the DTU10 and Sandwell and Smith V17.1 (2014) bathymetry model.
- The validation performed here demonstrates that the potential of SAR altimetry derived within the ESA CP40 project to derive sea floor bathymetry and the ability to predict bathymetric features using Cryosat-2 SAR altimetry.
- We did not yet se the full potential of using Cryosat-2 for sea mapping. However we highlighted the potential of using 1,2 and even 4 hz for sea floor mapping to resolve finer scale structures.
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Recommendations are:

- The full potential of using SAR for sea floor bathymetry should be further investigated as bathymetry is a fundamental important parameter for i.e. climate and ship safety and Cryosat-2 SAR can provide very valuable new information which is to be investigated further.
- We recommend a revisit of the investigation area using multiple years of altimetry to retrieve the full potential at these medium water depth (3-5 km).
- We recommend a careful analysis is performed in more coastal / shallow water region to explore the limitations of the data as we expect that there is also a huge potential here with the very positive results obtained.

- The results also point toward performing a study with the use of a better prior bathymetry for the long wavelength signal which proved inadequate in our investigation. We used GEBCO-1 (version 2008) which does not include altimetry. However we have recently been alerted to a new 30 minutes NGDC bathymetry (Becker et al., 2009) which should also use the bathymetric observations presented here and hence should give considerably better agreement.

8. References

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9. Acronyms and Abbreviations

ATBD	Algorithm Theoretical Baseline Document
CP40	Cryosat Plus for Ocean
GEBCO	General Bathymetric Charts of the Ocean (www.gebco.net)
NGA	National geospatial-intelligence Acency
DTU Space	National Space Institute, Technical University of Denmark
ESA	European Space Agency
PVR	Product Validation Report
RADS	Radar Altimetry database System (rads.tudelft.nl)
SAR	Synthetic Apertur Radar