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CryoSat Plus for Oceans (CP4O) – CCN2 Improvement of the Arctic Ocean Bathymetry and Regional Tidal Atlas

ESA Contract 4000106169/12/I-NB

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Final Report

	Name	Signature	Date
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SUMMARY OF MODIFICATIONS

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1 INTRODUCTION

Cryosat Plus for oceans (CP4O) is a project under the European Space Agency's "Support To Science Element" programme which aims to develop and evaluate new ocean products from the CryoSat cryosphere earth observation mission.

Under CCN2 to CP4O, DTU Space and Noveltis have carried out activities to develop an improved arctic bathymetry and a regional tidal atlas. SatOC has provided project management.

The work started in January 2017, and was completed in December 2018.

There were 5 Work Packages, listed below:

- WP 1000 Project Management
- WP 2000 Evaluation Of R-Topo Bathmetry
- WP 3000 Generation Of A New Combined Cryosat-2 Arctic Bathymetry
- WP 4000 Evaluation Of A New Combined Arctic Bathymetry
- WP 5000 Altimetry Tidal Analysis, Generation And Evaluation Of Improved Tidal Atlas
- WP 6000 Final Report And Outreach

We provide more details of the major results from each of the technical Work Packages in later sections of the report

This is the final report for this CCN2 activity, forming Deliverables D6.1 and D6.2

2 PROJECT DELIVERABLES

In the table below we list the project deliverables:

	Title	Format	Who	Status
D1.1	Project Management Plan	Internal Document	SatOC	Last version 2.4 -07/06/18
D1.2	Quarterly Reports	Public Document	SatOC	Provided by email
D3.1	Cryosat-2 Bathymetry	Data Set	DTU Space	Delivered 05/18
D4.1	Combined Arctic Bathymetry	Data Set	DTU Space	Delivered 11/18
D5.1	Revised Tidal Atlas	Data Set	Noveltis	Delivered 12/18
D6.1	Final Project Report	Public Document	SatOC	Delivered 11/18
D6.2	Publication List	Public Document	SatOC	Delivered 11/18

3 TECHNICAL INTRODUCTION

Cryosat Plus for Oceans (CP4O) is a project under the European Space Agency's "Support to Science Element" programme which aims to develop and evaluate new ocean products from the Cryosat cryosphere earth observation mission. The main focus of CP4O has been on the additional measurement capabilities that are offered by the Synthetic Aperture Radar mode offered by the innovative SIRAL altimeter, with further work in developing improved geophysical corrections.

Under a CCN to CP4O a further activity has been supported to address the important issue of improving the bathymetry for the Arctic Ocean, and developing a regional tidal atlas.

The Arctic Ocean is a challenging region, because of its complex and not well-documented bathymetry, together combined with the intermittent presence of sea ice and the fact that the in situ tidal observations are scarce at such high latitudes. This initiative addresses the bathymetry in the Arctic in attempting to improve altimetric bathymetry using the near 7 years of Cryosat-2 high quality and high resolution "geodetic" SAR altimetry all the way up to 88°N. Subsequently the project progresses to use Cryosat-2 in TWO ways for improved ocean tide modelling in the Arctic Ocean. One is to use Cryosat-2 improved bathymetry, the second is to use Cryosat-2 derived harmonic tidal constituents for assimilation into a regional tide model.

The project includes the following activities:

- Evaluate existing bathymetries available for the Arctic (R-TOPO2, IBCAO etc).
- Generate an improved Arctic bathymetry by inverting the high resolution DTU15 gravity field derived from Cryosat-2 data, and combining with the bathymetry selected in the previous task.
- Evaluate this new bathymetry through comparisons against available reference data, and assessments with the TUGO hydrodynamic model.
- Using tidal constituents (with associated error estimates) derived from Cryosat-2 data, together with the TUGO hydrodynamic model, develop and evaluate a new regional Arctic Tidal model for the Arctic Ocean.

4 WP2000 EVALUATION OF R-TOPO 2 BATHYMETRY

In this section we briefly review the major results and recommendations from WP2000, which was carried out by Noveltis.

An accurate bathymetry is a key parameter in tidal modelling, and crucial for high resolution models. However, access to accurate bathymetry is a major problem for the Arctic Region, partly due to the difficulty in making accurate in-situ measurements, and also partly due to political sensitivities.

The RTopo-2 bathymetry, released by (Schaffer et al, 2015), towards the end of 2016 was identified as potentially the most interesting and so was carefully evaluated.

It is a global composite bathymetry and, in the Arctic Region, it is composed of the source bathymetries listed below:

- GEBCO World Ocean Bathymetry GEBCO_2014 (Weatherall et al., 2015)
- Arctic Ocean Bathymetry IBCAOv3 (Jakobsson et al., 2012)

- Greenland ice sheet / glacier surface height and thickness and bedrock topography (Morlighem et al., 2014)
- Fjord and shelf bathymetry close to the Greenland Continental Shelf (Bamber et al., 2013)
- Bathymetry on Northeast Greenland Continental Shelf (Arndt et al., 2015)
- Bathymetry in several narrow Greenland fjords and on parts of the Greenland continental shelf
- Ice thickness for Nioghalvfjerdsfjorden Glacier and Zhachariae Isstrom (Various sources)

For the evaluation, R-Top02 was compared to RTopo1.05 and to the LEGOS composite bathymetry, which was used to implement the FES2014 global tidal atlas and the regional tidal atlas Arctide2017 (Cancet et al, 2018), as listed below:

- LEGOS composite bathymetry (F. Lyard, personal communication)
  - Nucleus: etopo-1
  - 38 modifications worldwide (FES2014 bathymetry)
  - In the Arctic Ocean: IBCAO v2, Smith and Sandwell (SW-16) patches, RTopo-1.0.5 patches and some other very local improvements

- Rtopo-1.0.5 bathymetry (Timmermann et al, 2010)
  - S-2004 1-minute digital terrain model (Marks and Smith, 2006)
  - GEBCO poleward of 72° latitude or shallower than 200 m depth (and on land)
  - Smith and Sandwell (1997) equatorward of 70°and deeper than 1000 m
  - Smooth blending for areas in between
  - Other data sources in the Antarctica region only

The evaluation consisted of visual examination and by tidal hydrodynamic modelling. The visual inspection looks for clear discontinuities that can sometimes be seen at the junction of different component data sets (Figure 1).

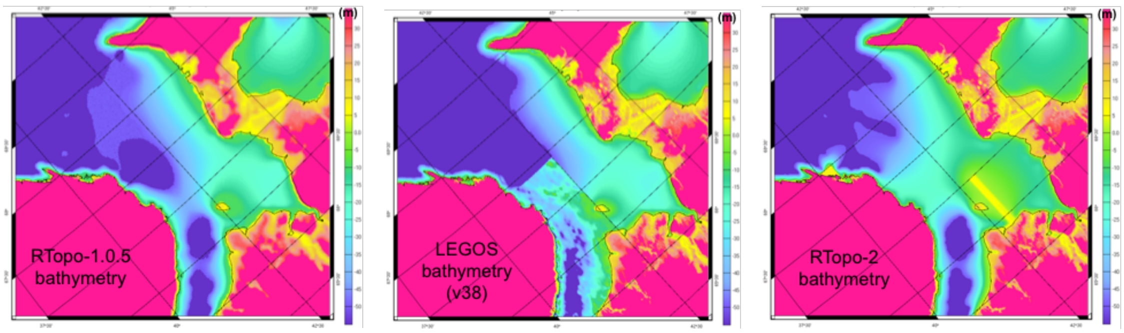


Figure 1: Bathymetry Evaluation. Comparison between bathymetry detail in Mezen Bay, White Sea. RTopo1.0.5 (left), LEGOS (Centre), R-Topo 2 (right) . R-Topo 2 and LEGOS show some clear discontinuities.

For tidal hydrodynamic modelling, the different bathymetries were input to the T-UGOm barotropic model and the outputs compared to Tide Gauge and altimeter data (Figure 2Figure 2).

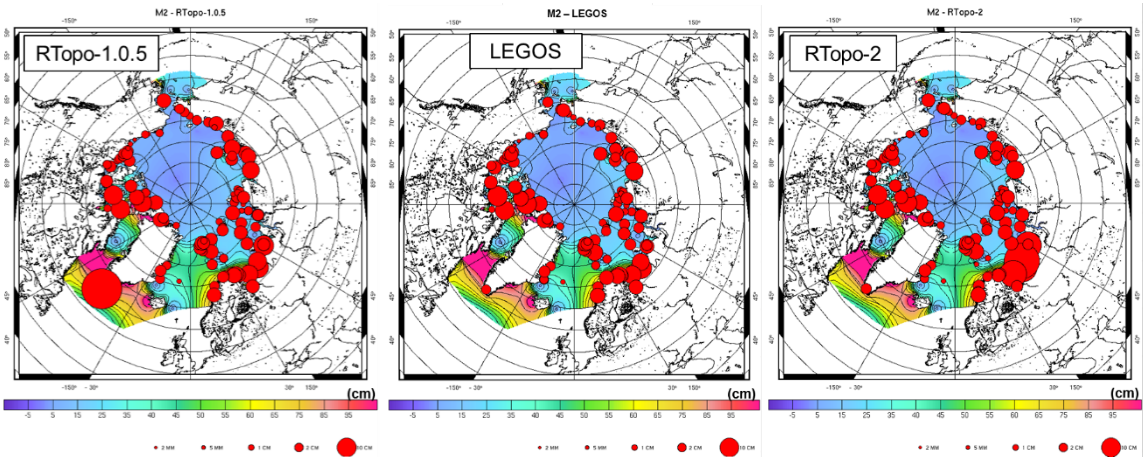


Figure 2: Bathymetry Evaluation. Comparison between TUGOm model output and Tide Gauges. Vector differences for the M2 Tidal Component. RTopo 1.0.5 (left), LEGOS (Centre), R-Topo 2 (right). LEGOS shows the best agreement with Tide Gauges

The conclusions of the evaluation were as follows:

- The bathymetry choice has a clear impact on the tidal solution, even if the links are not always direct.
- A problem identified in RTopo-1.5 South of Greenland was corrected in RTopo-2
- A patch issue was identified in the Barents Sea in the LEGOS bathymetry and was corrected. This only had a small impact on the hydrodynamic tidal simulation
- RTopo-2 shows more realistic details in some regions, but also some very unrealistic patterns in other regions
- The current mesh resolution is probably too coarse to manage some of these details in the hydrodynamic simulations
- The "parental" links between all the bathymetry datasets make it difficult to find a single good basis
- The LEGOS approach (composite bathymetry) is preferred as it tries to take the best from each dataset.

Following this evaluation Noveltis passed a modified version of the LEGOS composite bathymetry to DTU Space as the recommended basis for developing a bathymetry from Cryosat-2 data. The intention is that this bathymetry will become available online, connected to the acceptance for publication of the scientific paper describing the bathymetry model (currently under review).

It was noted that there were some recent releases of regional bathymetries that could be used to further improve the available combined bathymetry.

Two recommendations from the project follow from the experience of this analysis:

REC-01: It should be an international priority to collaborate to improve Polar Ocean Bathymetry, by allowing access to recent bathymetric surveys and in commissioning new surveys, as the lack of a good bathymetry is now one of the major limitations in polar ocean science.

REC-02: It is recommended to improve the bathymetry by including new patches where available (e.g. from J Bamber around Greenland) and to increase the resolution of the hydrodynamic model mesh in order to better manage the bathymetry details at coast.

5 WP3000 GENERATION OF A NEW COMBINED CRYOSAT-2 ARCTIC BATHYMETRY

For WP3000 DTU Space had the task to generate a new Arctic Bathymetry, derived from CryoSat-2 data, using the combined LEGOS 2017 bathymetry (passed from WP2000) as a starting model.

The predicted bathymetry $\mathrm{H_p(x)}$ can be written as the sum of the long wavelength component of the source bathymetry $\mathrm{B_{long}(x)}$ and the inverted topography from band-pass filtered gravity $\mathrm{G_{BP}(x)}$:

$$\mathrm{H_p(x) = B_{long}(x) + S(x) \cdot G_{BP}(x)}$$

where $\mathrm{S(x)}$ is the scaling factor to invert gravity to topography, in m/mGal.

CryoSat-2 altimeter data from the long repeat (369 day), finely spaced CryoSat were processed and combined with the SARAL geodetic mission data to derive the DTU2017 gravity field. The downward continued gravity field and bathymetry may show linear correlation at wavelength between 20-70 km (Abulaitijiang et al., 2018, under review). At shorter wavelengths, the gravity field is insensitive to sea floor topography due to upward continuation. At longer wavelengths, isostatic compensation cancels out most of the gravity field due to the sea floor topography. Therefore, a band-pass filtering of the gravity field and downward continuation to the local sea floor depth is necessary before the application of the correlation operator. The bathymetry is also band-pass filtered to match with the gravity signal in the spectrum (Smith and Sandwell, 1994).

After filtering, an inverse Fourier transform was applied to the gravity and bathymetry grids and the procedure developed by Smith and Sandwell (1994) applied to derive scaling factor and coherence parameter. The scaling factor $\mathrm{S(x)}$ is estimated on 30 km spacing grid nodes, which will invert the bandpass filtered gravity to topography. The coherence parameter is the linear correlation between the bandpass filtered bathymetry and gravity, which implies the correlation between topography and gravity. In Figure 3, the grid nodes where the coherence is greater than 0.5 are shown. When the coherence is low (defined by correlation < 0.5), the gravity field is not used to derive bathymetry and the original bathymetry value is used (Figure 3).

Analysis of the regions of low coherence suggests that the technique of gravity field inversion (to retrieve bathymetry) is less effective in shallow water close to the coasts, and in regions where there are thick sediment layers.

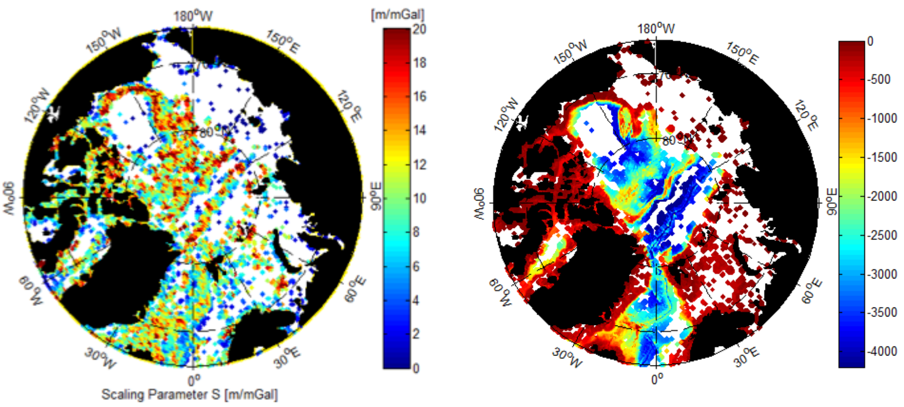


Figure 3: Demonstrating where a bathymetry value was derived from the inverted gravity field. Scaling Parameter S (left) and derived bathymetry (right).

Finally the full bathymetry was recompiled by combining the newly derived band passed bathymetry with the short and long wavelength components of the source bathymetry.

This new bathymetry has been provided to ESA as a Deliverable 4.1. The predicted Arctic bathymetry is available via https://ftp.space.dtu.dk/pub/ArcticBATH/.

6 WP4000 EVALUATION OF A NEW COMBINED ARCTIC BATHYMETRY

DTU space then evaluated the new combined bathymetry by comparing against available in-situ data sets. Available data are very limited but DTU identified a multi-beam survey from the Chukchi cap which is part of the Healy cruise from 2016, denoted as HE1603 (Mayer et al., 2016), and the results from the combined bathymetry are compared to the survey results, and to IBCAOv3 in Figure 4. In the top row the new bathymetry can be seen (at along track distance 200 km) to correct an error in the original IBCAOv3 bathymetry that incorrectly shows a valley not seen in the survey.

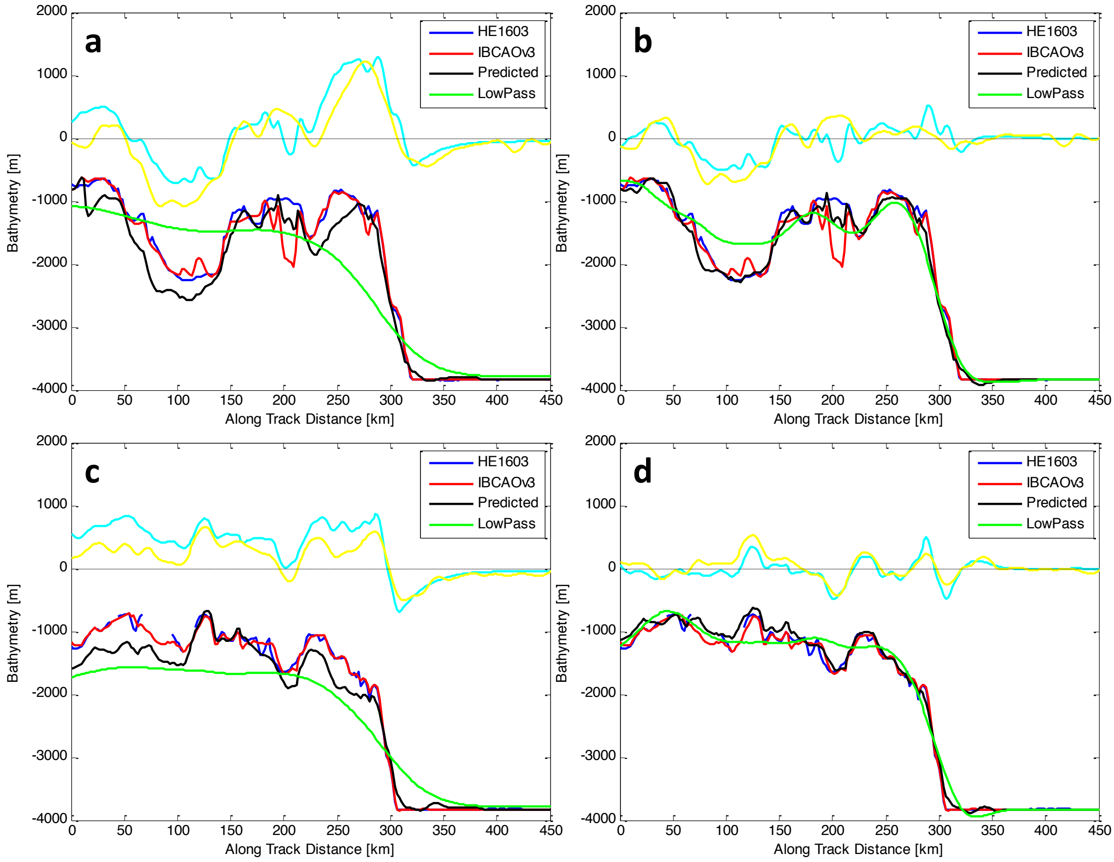


Figure 4: The along track profiles of Healy cruise path 1 (top row, subfigures a & b) and path 2 (bottom row, subfigures c & d) are shown; subfigure a and c : using the Smith and Sandwell (1994) filter; subfigure b and d : using the modified filter in this project. Blue curve for the HE1603, red curve for the IBCAOv3, black curve for the predicted bathymetry in this project, green curve for the low-pass filtered bathymetry $B_{long}(x)$, cyan for band-pass filtered bathymetry and yellow for the band-pass filtered gravity which is scaled by $S(x)$.

The conclusions were:

- Improved Arctic gravity maps that include input from satellite altimeter data (e.g., DTU17GRA) can enhance and resolve detailed features that are not available in other bathymetries
- The band pass filtering cut-off frequency should be adapted for the Arctic to avoid the long wavelength error from gravity
- The results in the Chukchi cap show good agreement with the high resolution multi-beam ship sounding (HE1603), and also resolve a valley (1000 m deep) that is incorrectly mapped in the IBCAOv3
- Still lack of external validation data after the release of IBCAOv3
- Predicted bathymetry could be underestimated due to unknown sediment thickness or isostatic compensation; this needs further investigation

Further recommendations from the project follow from this analysis:

REC-03: It is recommended to re-process CryoSat-2 SAR mode data with a suitable configuration optimised for accurate range retrieval in sea ice covered seas. Surface backscatter could be included in the process to discriminate ocean echoes.

REC-04: It is recommended to also include Sentinel-3 and Altika data in subsequent development

7 WP5000 ARCTIC TIDAL ATLAS

The regional tidal atlas Arctide2017 was implemented in the Arctic Region by NOVELTIS and DTU Space in the framework of a previous CCN to the CP4O project (Cancet and Andersen, 2016; Cancet et al, 2017). This atlas is based on a reference hydrodynamic simulation with the T-UGO model and ensemble assimilation of altimetry and tide gauge tidal observations.

In the framework of the current CCN, the aim was to improve the tidal atlas in two ways:

- By improving the processing of the altimeter data to generate the tidal constituents (DTU Space) and by proceeding to the assimilation of this new altimetry dataset in the Arctide configuration (NOVELTIS) ;
- By enriching the spectrum of the atlas with a hydrodynamic time-stepping run of the T-UGO model that provided the non-linear tidal components (NOVELTIS).

7.1 New altimeter tidal constituents processing and new assimilation in the tidal model

The altimeter tidal constituents were computed by DTU Space. To improve the efficiency of the remove/restore process, the FES2014 global model was used on its native unstructured grid. The predictions of FES2014 geocentric tides (ocean tides + loading tides) were computed and provided by NOVELTIS to DTU Space along the CryoSat-2 tracks (CCN3).

Three datasets are considered separately due to possible biases between the datasets

1) The C2 PLRM dataset.
2) The C2 SAR lead dataset.

3) The C2 SARin lead dataset.

The three datasets were initially extracted and the FES2014 ocean tide correction is applied. The C2 PLRM dataset is extracted from the RADS data archive as 1 Hz data. Using normal corrections for range and geophysical corrections (Andersen and Scharroo, 2011).

The C2 SAR and C2 SARin datasets is extracted as 20 Hz original L1 Baseline C data and retracked using the Narrow peak retracker (Jain et al., 2015). Only data with Pulse peakiness exceeding a threshold and the stack standard Deviation being lower than a secondary threshold estimated by experience (Stenseng and Andersen, 2012). The data were finally binned in 1° latitude by 3 ° longitude bins and the harmonic tidal constituents where estimated using the response formalism by Andersen including simultaneous estimation of the annual signal as a sinusoidal wave with a period of 1 year.

These reprocessed altimeter tidal constituents were used by NOVELTIS to perform a new assimilation in the Arctide atlas configuration.

Contrary to the altimetry dataset used to compute the Arctide2017 atlas, this new dataset is only based on CryoSat data and does not contain any ENVISAT observations. This decision was made because the Envisat ALES+ data did not have a consistent tide model with the Cryosat data. In retrospect RADS data could have been used to address this problem.

The density of altimetry points highly increases close to the North Pole. However, the tidal amplitudes are very low in this region (Figure 2) and there is thus no need to strongly constrain the model with a lot of observations there. More generally, given that the errors in the prior hydrodynamic solution are small and that the altimetry data are not perfect, the choice was made to maintain a balance between the weight of the observations and the weight of the model. This is why the altimetry dataset was decimated in the open ocean before the data assimilation, following the same process as for the Arctide2017: a maximum distance of 200 km between two points in the open ocean, 100 km for points on the shelves. In the end, the altimetry dataset has a higher density on the Siberian shelf and in the Bering Strait (Figure 5). The new altimetry dataset (left plot) contains more points on the Siberian shelf than the previous dataset (right plot) due to the fact that the former is composed of three different datasets (ocean, leads and SARin data) that were processed and decimated separately.

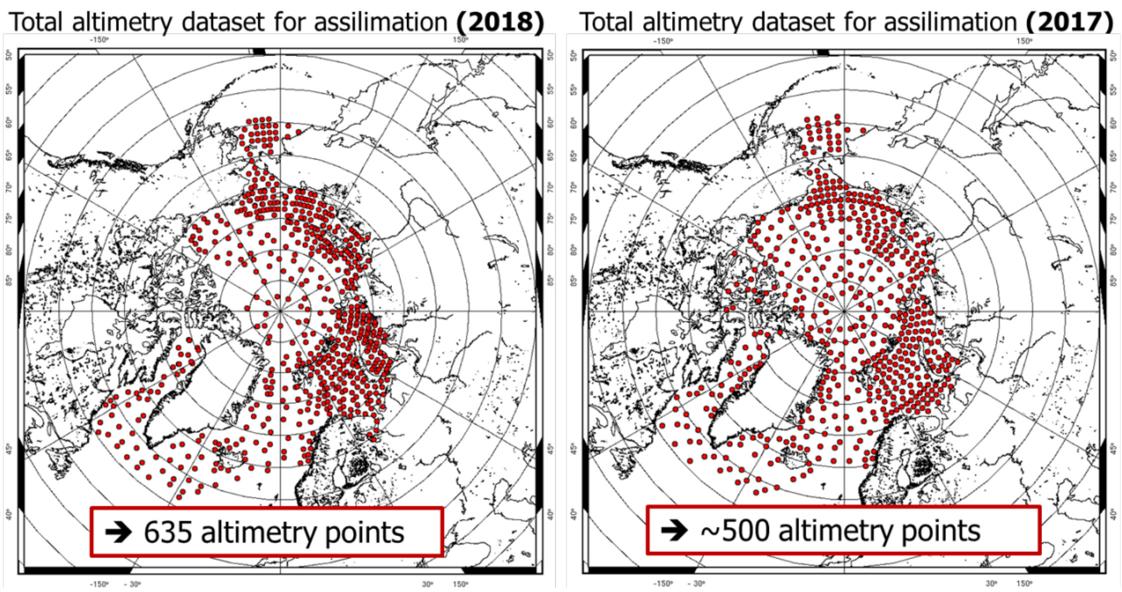


Figure 5: Altimetry points used for the assimilation process after geographical decimation. New dataset (left), Arctide2017 dataset (right).

First, assimilation experiments were done with datasets containing only altimetry observations, in order to keep the tide gauges for totally independent validation.

The analysis of these assimilation experiments showed:

- A slight improvement on the M2 tidal component in the Barents Sea and in the Baffin Bay, where the largest differences were observed between the altimetry data and the FES2014 solution.
- Some degradation in other parts of the basin (Laptev Sea in particular).
- The altimetry data appeared to be rather noisy but a stricter editing process did not enable to obtain better results.
- The decorrelation radius (i.e. the influence distance of each observation) used in the assimilation process was set to 5 000 km for the computation of the Arctide2017 solution, which is more adapted to a global solution than to a basin region like the Arctic Ocean. Reducing this decorrelation radius to 500 km improved the new solution, but not to the level of the Arctide2017 atlas still.
- This means that the observations in the new altimetry dataset are less coherent with their neighbours than in the Arctide2017 dataset. This could potentially be due to the fact that the Arctide2017 dataset contains Envisat and CryoSat observations, while the new dataset is based on CryoSat only. It is probable that the CryoSat data have a higher level of error in the region than the Envisat data.

As a consequence, the new altimetry dataset did not enable to produce a better assimilated solution than the Arctide2017 tidal atlas.

7.2. Time-stepping hydrodynamic simulation

The T-UGO model is a hydrodynamic model developed at LEGOS. The 2D equations of the model are based on the classical shallow-water equations of continuity and movement. The model can be run using the finite elements discretization, with unstructured grids of triangular elements. The unstructured grid enables to easily increase the resolution in the most demanding parts of the model, in terms of coastal geometry and/or hydrodynamic constraints.

For tidal simulations, two modes are available to solve the equations:

- The spectral mode solves the quasi-linearized Navier-Stokes equations in the spectral domain, in a wave by wave, iterative process. This mode is very well adapted to compute the waves resulting of the astronomical forcing, whereas it is less accurate for the non-linear components, which are better resolved with the time-stepping mode. The run duration is drastically reduced with the spectral mode (a few minutes to a few hours depending on the size of the domain and the resolution of the mesh), compared to the time-stepping mode that would require several days.
- The time-stepping mode consists in running the model over a given period, long enough (generally one year) to be able to discriminate the various tide waves with good accuracy. The equations of the ocean dynamics are integrated over the time with a time step adapted to the grid resolution and to the tide propagation. Once the simulation is achieved, a harmonic analysis is performed on the sea surface elevations generated by the model, in order to compute the harmonic constituents of the tide components. This method enables to model the non-linear tide components following the natural process of dynamical interactions between the various components of the spectrum.

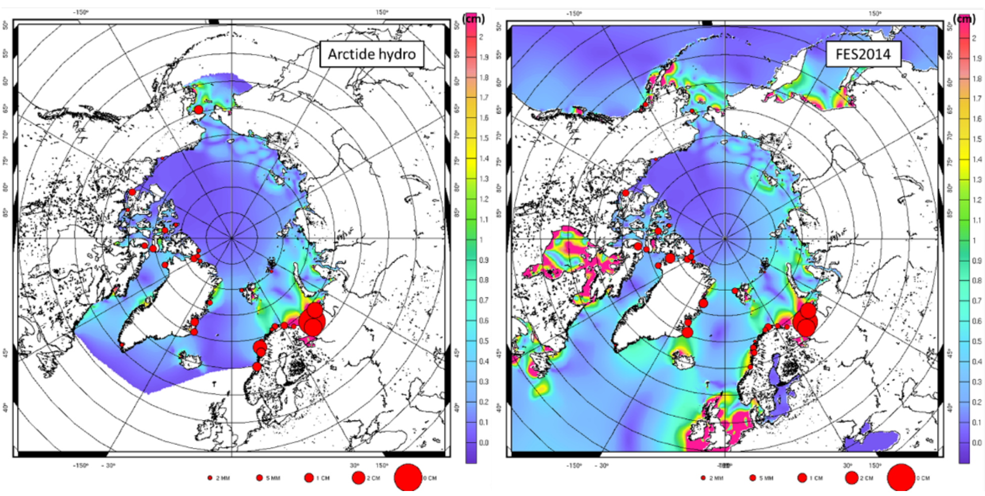
The tidal components already available in the Arctide2017 tidal atlas were computed with the spectral mode and the spectrum was thus limited to the 8 main linear waves (M2, K1, K2, N2, O1, P1, Q1 and S2).

To enrich the spectrum of the atlas, NOVELTIS ran the T-UGO model over a one-year period in time-stepping mode in order to compute non-linear tidal components. The configuration was chosen as follows:

- Same unstructured mesh as the Arctide2017 solution;
- LEGOS bathymetry with correction in the Barents Sea as mentioned in section 4;
- Same bottom friction and wave drag coefficients as for the Arctide2017 solution.

The additional tidal components computed in time-stepping are: M3, M4, M6, M8, MKS2, MN4, MS4, N4 and S4.

It should be noticed that for most of the tide gauge stations in the validation dataset, these non-linear tidal components are not available and it was not possible to thoroughly validate the time-stepping solution. However, the comparison for the M4 tidal component shows (Figure 6) that the Arctide regional hydrodynamic time-stepping simulation gives results close to the assimilated FES2014 global solution. Figure 6 also shows that the global solutions (FES2014, GOT4.8 and TPXO7.2) are quite different from one another for the M4 tidal component and the truth is probably somewhere in-between.



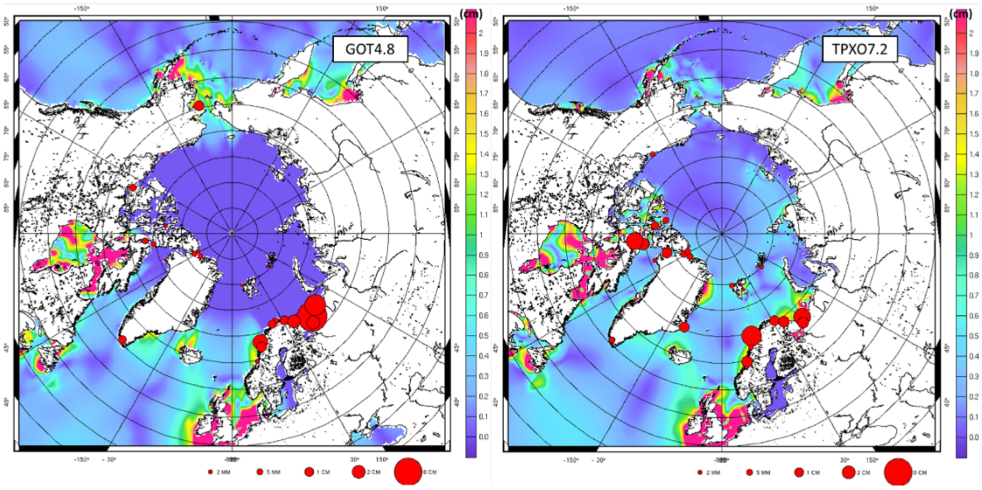


Figure 6: Comparison between tidal models and Tide Gauges. Vector differences for the M4 Tidal Component. Arctide regional time-stepping hydrodynamic run (up left), FES2014 (up right), GOT4.8 (bottom left), TPXO7.2 (bottom right).

Some additional recommendations from the project follow from the experience of this Work Package:

REC-05: Recognising that the assimilation process of the altimeter derived tidal constituents decimates the input data significantly, tidal constituents should be calculated for larger areas, thus also reducing the errors in the derived constituents.

REC-06: It is recommended to also include Envisat, Sentinel-3 and AltikA data in subsequent development

8 CONCLUSIONS AND RECOMMENDATIONS

A new Arctic Bathymetry and Tidal Atlas have been generated, and made available (Deliverables 4.1 and 5.1).

The predicted Arctic bathymetry is available via https://ftp.space.dtu.dk/pub/ArcticBATH/.

However, analysis has shown that the new altimetry dataset did not result in a better assimilated solution than the Arctide2017 tidal atlas.

The project team would like to make the following recommendations to the scientific community:

- *It should be an international priority to collaborate to improve Polar Ocean Bathymetry, by allowing access to recent bathymetric surveys and in commissioning new surveys, as the lack of a good bathymetry is now one of the major limitations in polar ocean science*.
- *There should be a full reprocessing of CryoSat-2 data in a configuration suitable for Polar Ocean Bathymetry / tide applications*

The team has also identified the following recommendations for follow on work to improve the accuracy of the bathymetry and tidal atlas:

To improve the bathymetry and hence the hydrodynamic modelling:

- *It is recommended to improve the bathymetry by including new patches where available (e.g. from J Bamber around Greenland) and to increase the resolution of the hydrodynamic model mesh in order to better manage the bathymetry details at coast.*
- *We recommend to take advantage of the extended CryoSat-2 mission to improve bathymetry predictions using stacked CryoSat-2 geodetic mission tracks, which will improve the signal to noise ratio.*
- *There has been a recent reprocessing of CryoSat-2 data in a configuration suitable for Polar Ocean Bathymetry / tide applications (using GPOD), this should be analysed and considered for inclusion in a future improvement to the atlas.*

To improve the data for assimilation and tidal modelling:

- *Taking the above into account, further improvements to CryoSat-2 processing could be considered, and CryoSat-2 SAR mode data should be re-processed (including the latest available data) with a suitable configuration optimised for accurate range retrieval in sea ice covered seas. Surface backscatter could be included in the process to discriminate ocean echoes.*
- *It is recommended to also include Envisat, Sentinel-3 and Altika data in subsequent development.*
- *The areas over which altimeter Tidal Constituents are calculated should be optimised to better match the assimilation process.*

The team also suggest that improvements to processing that are recommended from the SCOOP project should be considered for application. Although the final report is not yet available, we understand that inclusion of zero padding, and application of Hamming windowing along track has been shown to improve range retrieval in the FBR to L1 processing of SAR mode. Also it is recommended that specific coastal re-trackers should be considered: e.g. Samosa+ for SAR mode (Dinardo et al., 2018) , and ALES Passaro et al. 2014for RDSAR mode (Passaro et al., 2014).

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ANNEX – PUBLICATIONS

Conference and Meeting Publications

1. Cotton, P.D. Nilo-Garcia, M. Cancet, O. B. Andersen, P. Cipollini, F. Martin, M. Passaro, M. Naeije, M. Restano, A. Ambrosio, J. Benveniste, 2017, Improved Oceanographic Measurements with CryoSat SAR Altimetry. North American Cryosat Science Meeting, 20-24 March 2017, Banff, Canada.
2. O. Andersen, M. Cancet, 2017, Improvement of the Arctic Ocean Bathymetry and Regional Tide Atlas – a CP4O initiative, EGU General Assembly, Vienna, Austria, 23-28 April 2017
3. O. Andersen, M. Cancet, D. Cotton, J. Benveniste, 2017, Improvement of the Arctic Ocean Bathymetry and Regional Tide Atlas – First Results from the CP4O initiative. OSTST, 23-27 October 2016. Miami, FL, USA
4. M. Cancet, O. Andersen, D. Cotton, J. Benveniste, 2018, Improvement of the Arctic Ocean Bathymetry and Regional Tide Atlas – a CP4O initiative. Poster, 11th Coastal Altimetry Workshop, 12-15 June 2018, ESA-ESRIN, Frascati, Italy
5. Andersen, O., M. Cancet, P. D. Cotton, J. Benveniste, Improved Arctic Ocean Bathymetry and Regional Tide Atlas. 25 Years Progress in Radar Altimetry Symposium, Punta Delgada, Sao Miguel Island, Azores Archipelago, Portugal, 24-29 September 2018
6. Abulaitijiang, A., Andersen, O., M. Cancet, P. D. Cotton, J. Benveniste, The Contribution of DTU17 Marine Gravity for the Arctic Bathymetry Prediction. 25 Years Progress in Radar Altimetry Symposium, Punta Delgada, Sao Miguel Island, Azores Archipelago, Portugal, 24-29 September 2018

Refereed Journals

1. Cancet M., O. B. Andersen, F. Lyard, D. Cotton, J. Benveniste, 2018, Arctide2017, A high-resolution regional tidal model in the Arctic Ocean, Advances in Space Research, Vol 62, Issue 6, 15 September 2018 pp 1324-1343. https://doi.org/10.1016/j.asr.2018.01.007
2. Abulaitijiang, A., Andersen, O. B., Sandwell, D. 2018 Improved Arctic Ocean Bathymetry derived from DTU17 Gravity model, Earth and Space Science, submitted
3. Cancet, M., Andersen, O., Abulaitijiang, A., Cotton, D., Benveniste, J. (2018) Improvement of the Arctic Ocean bathymetry and regional tide atlas – First result on evaluating existing Arctic Ocean bathymetric models. International Association of Geodesy Symposia. submitted.