HYDROCOASTAL

SAR/SARin Radar Altimetry for Coastal Zone and Inland Water Level

Technical Note

DTC and WTC for Case Studies

CCN2 Deliverable D4

Sentinel-3 and Cryosat SAR/SARin Radar Altimetry for Coastal Zone and Inland Water

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1 Introduction

1.1 The HYDROCOASTAL Project

The HYDROCOASTAL project is a project funded under the ESA EO Science for Society Programme, and aims to maximise the exploitation of SAR and SARin altimeter measurements in the coastal zone and inland waters, by evaluating and implementing new approaches to process SAR and SARin data from CryoSat-2, and SAR altimeter data from Sentinel-3A and Sentinel-3B.

One of the key objectives is to link together and better understand the interactions processes between river discharge and coastal sea level. Key outputs are global coastal zone and river discharge data sets, and assessments of these products in terms of their scientific impact.

1.2 Scope of this Report

This document is a Technical Note (TN), in complement to the Product Validation Report (PVR) and it corresponds to the deliverable D4 of CCN2 of the HYDROCOASTAL project. The scope of this report is to gather the main results obtained by UPorto for the Dry Tropospheric Correction (DTC) and the Wet Tropospheric Correction (WTC) over Coastal Zones and Inland Water regions developed in WP3000 of the main project and in WP2000 of CCN2 of the HYDROCOASTAL project. This includes the computations for 16 Case Study areas and for 9 Additional Areas.

1.3 Document Organisation

This document is organised in two main sections:

- Section 1: A short introduction defining the scope of this report.
- Section 2: The results of the validation activities for the Wet and Dry Troposphere corrections for the Case Studies and Additional Areas.

1.4 Reference documents

HYDROCOASTAL Proposal: SAR/SARin Radar Altimetry for Coastal Zone and Inland Water Level. Proposal, January 2020.

HYDROCOASTAL Product Validation Plan (PVP – D2.4)

HYDROCOASTAL Product Validation Report (PVR – D2.5)

2 Validation of new DTC and WTC over CZ and IW regions (UPorto)

This section describes the assessment results obtained by UPorto for the Dry Tropospheric Correction (DTC) and the Wet Tropospheric Correction (WTC) over Coastal Zones (CZ) and Inland Water (IW) regions developed in WP3000 and in WP2000 of CCN2 of the HYDROCOASTAL project.

In the PVR the methods used in the computation of the corrections for the project test areas have been described in detail, as well as the corresponding assessment and main results.

In this TN the main differences between the methods previously used to generate the corrections for the text areas and those now used to compute the corrections for the Case Studies and Additional Areas are described. In addition, the main results are highlighted for some representative areas.

Subsection 2.1 provides background on the computation of these corrections, while subsections 2.2 and 2.3 present the validation results for the WTC and DTC, respectively, for some representative areas. Finally, subsection 2.4 summarises the main conclusions on the validation of the WTC and DTC.

2.1 Computation of DTC and WTC over CZ and IW regions

2.1.1 Introduction

In this part of the project, tropospheric corrections have been computed for 16 regions of interest (ROI), selected for the Case Studies and for 9 Additional Areas. These have been grouped into three different region categories: **Coastal**, **Lake** and **River** as presented in Table 1 (case studies as represented in Figure 1) and Table 2 (additional areas as illustrated in Figure 2).

Table 1 - Regions of Interest for the project Case Studies. The regions coloured in blue have been computed both for S3 and CS2 and those in black only for S3.

Coastal	Lake/Land	River
bight	ireland	amazon
severn	yakutian	amur
thailand		ebro
venice		kolyma
wadden		mackenzie
		nadym
		po
		rhine
		watson

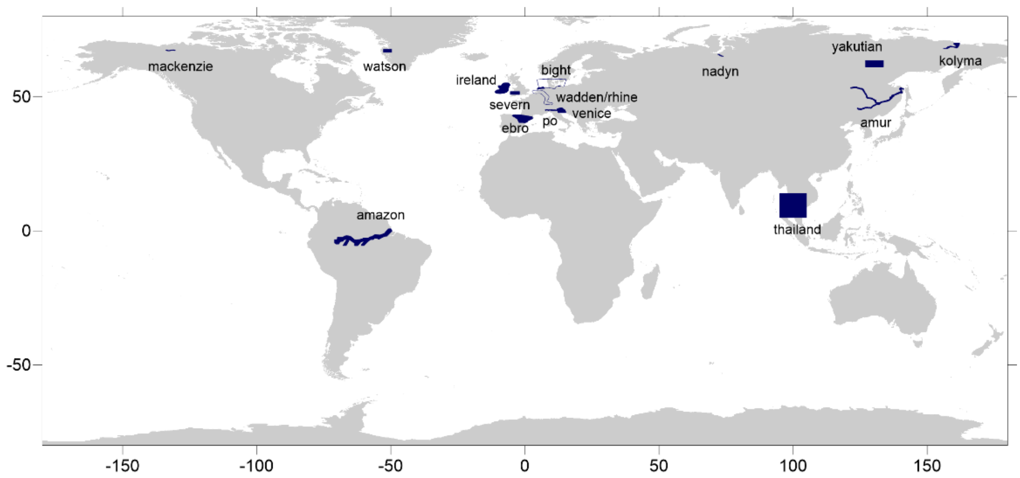

Figure 1 - Location of the 16 regions of interest for the project Case Studies.

Table 2 – Additional Areas, computed only for S3

Coastal	**River**
australia	ganges
	garonne
	murray
	niger
	orange
	parana
	whitenile
	yenisey

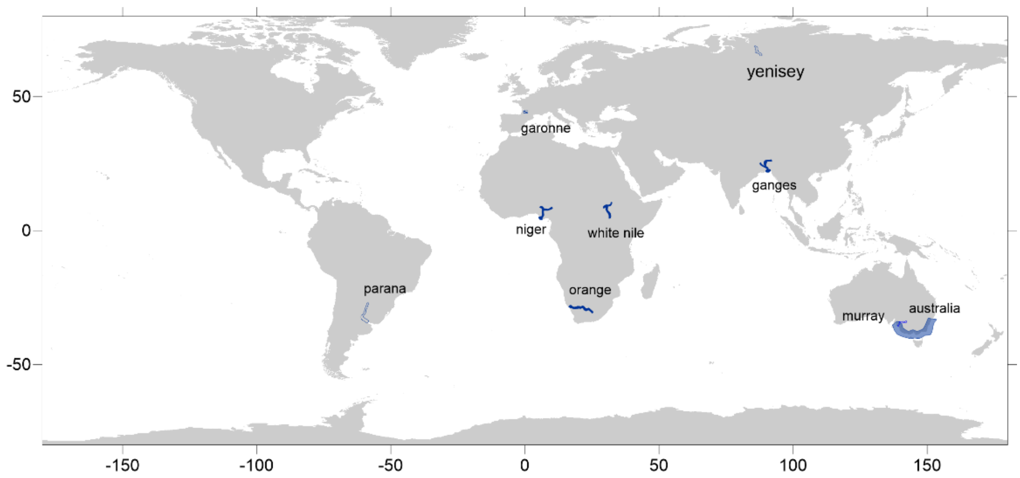

Figure 2 - Location of the 9 Additional Areas, only computed for S3.

Altimeter 20 Hz data from S3A, S3B and CS2 have been made available by IsardSAT in the project ftp site for all ROI. Depending on the satellite and ROI, these data cover the period from mission start until end of September 2022.

In these computations two approaches have been used:

- **ROI approach**: the method previously used in the test cases and described in the PVR. This was used in all rivers common to the test cases (Amazon, Amur, Po, Rhine): i) for points inside a buffer around the river, corrections are computed at the height of the river profile; ii) for all remaining points, they are computed at surface height, given by ACE2 DEM (3”).

- **Global approach:** used in all other ROI: i) corrections are computed at sea level, for points over ocean (surface type=0); ii) at surface height given by ACE2 DEM (3”) for all remaining points.

Global approach in the computation of the DTC and WTC.

Due to the height dependence of the tropospheric corrections, an important aspect in the computation of the DTC and WTC is to ensure that these are computed using the most accurate surface elevations and that these elevations are provided in the products, to allow the application of future corrective terms.

We recall that, as described in the PVR, in the first part of the project the so-called *ROI approach* has been adopted. This means that the computations were tuned for each ROI, requiring the a priori knowledge of the corresponding river profile or mean lake level. Considering the large number of ROI, the methodology evolved to the so-called *global approach*, based on the adoption of what is still consider to be one of the best global digital elevation models for use over inland waters, the ACE2 DEM.

For this purpose, the global set of tiles at the ACE2 DEM at its highest spatial resolution (3”) has been downloaded from SEDAC (Socioeconomic Data and Applications Center), a data centre in NASA's Earth Observing System Data and Information System (EOSDIS) hosted by Columbia University. This DEM is organised in tiles, each covering 18000x18000 points at 3” intervals, thus covering a region of 15ºx15º. A few tiles, covering oceanic regions without significant islands, do not exist in this data base. To allow the use of a single grid each time and be able to perform bilinear interpolation, a modified version of the model has been created, of **18002x18002 3”** tiles, by adding an additional row/column copied from the neighbouring tiles. In this way, all neighbouring tiles have one duplicated row/column, allowing continuous bilinear interpolation without discontinuities in the tile transitions zones.

In this global implementation, for each 20Hz along track altimeter point, the computation procedure searches for the tile inside which the point is located and, in case this tile ifs different from the tile used in the previous point, it opens the new tile for interpolation and closes the previous one. In case the tile does not exist (which only happens for open ocean areas) the height is interpolated from a single file containing the whole ACE DEM at 1’ spatial resolution.

As previously described in the PVR, the procedure adopted in the computation of DTC and WTC over CZ and IW regions is implemented in two steps:

- Step 1: Compute DTC and WTC from the ECMWF ERA5 Numerical Weather Model (NWM) (Fernandes et al, 2021).

- Step 2: Compute WTC from the GNSS-derived Path Delay Plus (GPD+) algorithm (Fernandes and Lázaro, 2016, Lázaro et al., 2020).

Step 1: Computation of DTC and WTC from NWM

Step 1 inputs:

- Altimeter 20 Hz data from S3A, S3B and CS2 from the L2e reduced products made available in the project ftp site. The following fields have been used: time, lat, lon, WTC from the onboard Microwave Radiometer (MWR) and various flags (radiometer flags and surface type).
- ERA5 model:
  - single layer fields at 0.25ºx0.25º spatial resolution and 3h intervals: Sea Level Pressure (SLP), Total Column Water Vapour (TCWV) and 2m-Temperature (2T).
  - Wet Path Delay (WPD) vertical profiles at 2ºx2º spatial resolution and 6h intervals, previously computed from 3D pressure level fields (temperature and specific humidity), for use in the modelling of the WPD vertical variability.
  - Model orography at 0.25ºx0.25º spatial resolution.
- Geoid model: EIGEN-6C4 (Förste et al., 2014). For use in this project, a file generated in the scope of the SHAPE project has been shared. It is a global grid at 0.05ºx0.05º spatial resolution, containing the EIGEN-6C4 geoid heights with respect to WGS84 and using the tide-free system. To be in line with EGM2008 global grids, a constant zero-degree term of -41 cm has been applied (Fernandes and Vieira, 2019).
- Mean Sea Surface (MSS): DTU21 at 1'x1' spatial resolution, available from ftp.space.dtu.dk/pub/DTU21/1_MIN.
- Water "occurrence" product based on Landsat imagery, from the Global Surface Water Explorer (GSW), https://global-surface-water.appspot.com/download (Pekel et al., 2016). Original resolution (1") has been resampled to 57.6".
- Digital Elevation Model (DEM):
  - Altimeter Corrected Elevations 2 (ACE2) (3") (Berry et al., 2008).
- Distance from coast: global grids computed from a global netCDF grid (2'), with distances to the nearest GSHHG (Global Self-consistent, Hierarchical, High-resolution Geography Database) shoreline (Wessel and Smith WH,1996).
- River profiles:
  - From Karina Nielsen (DTU): Rhine, Amur, Po.
  - From the SWOT a priori River Database (SWORD) version v2, https://zenodo.org/record/5643392, (Altenau et al., 2021) for all the Amazon ROI

Step 2: Computation of WTC from the GNSS-derived Path Delay Plus (GPD+) algorithm

Step 2 inputs:

- WTC from on-board MWR (only for S3) and corresponding MWR validity flag (previously computed in Step 1), specifying if a given MWR observation is valid or not.
- WTC from ERA5, from step 1, to be used as first guess in the Objective Analysis (OA) procedure implemented in GPD+.
- WTC from Global Navigation Satellite Systems (GNSS).
- WTC from scanning Imaging MWR (SI-MWR).

- ERA5 model:
  - WPD vertical profiles at 2ºx2º spatial resolution and 6h intervals, previously computed from 3D pressure level fields, for use in the modelling of the WPD vertical variability.
  - Model orography at 0.25ºx0.25º spatial resolution.
- ACE2 (3") (Berry et al., 2008).
- Altimeter data: time, lat, lon, MWR WTC, various flags (20 Hz).

2.1.2 Provided corrections and instructions of use

Corrections are computed for all points of the HYDROCOASTAL L2E files. Therefore, there is a one-to-one point correspondence between input and UPT correction files. The corrections are provided in netCDF files with the following fields

- **time_20_ku, lat_20_ku, lon_20_ku** – as in input files
- **upt_dry_tropo** – DTC_UPT, DTC from the ERA5 model, at surface height (h_surf), in metres.
- **gpd_wet_tropo** - WTC_GPD, WTC from the GPD+, at surface height (h_surf), in metres.
- **gpd_wet_tropo_flag** – Flag specifying the data sources used in the estimation of the GPD+ WTC. (0) – Valid on-board MWR value, eventually scaled; (1) – Estimate from on board MWR observations only; (2) – Estimate from SI-MWR observations only; (3) – Estimate from MWR and SI-MWR observations; (4) – Estimate from GNSS observations only; (5) – Estimate from MWR and GNSS observations; (6) – Estimate from SI-MWR and GNSS observations; (7) – Estimate from on-board MWR, SI-MWR and GNSS observations; (8) – No observations exist, estimate is from the NWM used as first guess (ERA5).
- **h_surf** – height at which the DTC and WTC have been computed, in meters.
- **geoid_EIGEN_6C4** - in meters.

All corrections are referred to the surface elevation given by the h_surf field.

- For the 4 River ROI for which the ROI approach has been used (amazon, amur, rhine, po), the corrections are referred to the height of the closest point in the river profile (h_surf=river profile height) for all points up to distance from river profile $D \leq \Delta$, Δ = max(2.0, river_width*1.5) km. For the remaining points, h_rurf is the height of the adopted DEM (ACE2. 3").
- For the remaining ROI the global approach has been adopted. In this case, for ocean points, with surface type=0, corrections are referred to mean sea level (h_surf=0). For the remaining points, they are referred to surface elevation, h_surf, the height of the adopted DEM (ACE2, 3").

Instructions of use of the DTC and WTC UPT corrections:

- Both DTC and WTC are computed at the provided surface altitude, h_surf.
- To convert the DTC to another height (H), the following formula (1) can be used, with all variables in metres:

$$DTC(H) = DTC(h\_surf) + 0.0002563(H - h\_surf) \qquad (1)$$

- To convert the WTC to another height (H), the following formula (2) can be used, with all variables in metres and k=3000:

$$WTC(H) = WTC(h\_surf)e^{\frac{h\_surf - H}{k}} \quad (2)$$

When retracked and more accurate heights are available, it is recommended that these altitude conversions are applied, in particular for the DTC, for which the impact is more pronounced. However, it is important to note that these corrective terms should only be applied for small altitude differences, otherwise significant errors will be introduced, mainly in the DTC.

Figure **3**, already presented in the PVR, illustrates the errors introduced when the DTC is reduced from surface elevation using the values at sea level followed by the linear correction (Eq. 1) instead of being directly computed at surface elevation.

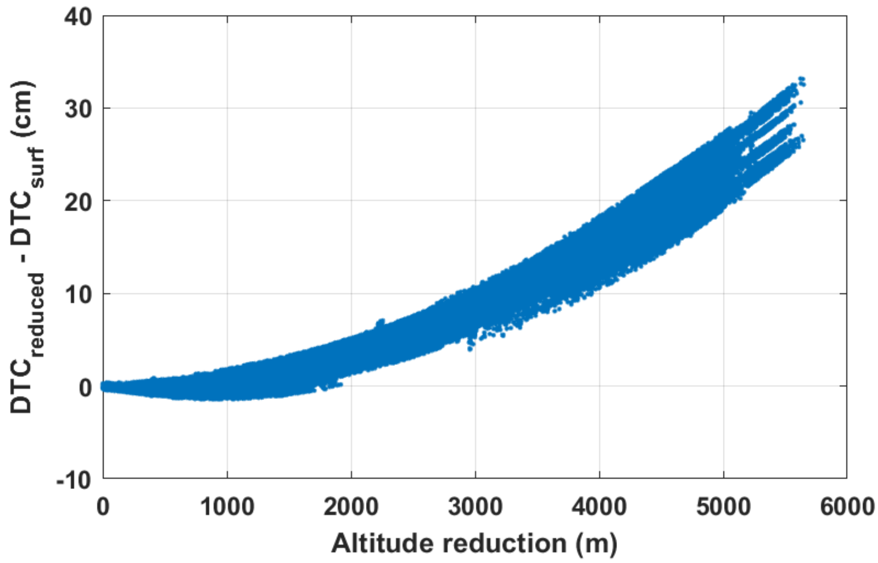

Figure 3 - Differences between DTC reduced from zero level to the height of each S3A point, using a linear height reduction, and the DTC_UPT (DTC_{surf} in the Y axis label), originally computed at this.

These errors increase with the magnitude of the altitude reduction. For an altitude reduction of 1000m the errors are about 1 cm. For an altitude difference of 3000m, the errors are larger than 5 cm (see Figure **3**). These figures are a clear indication of the importance of having corrections properly computed at the correct surface elevation.

2.2 Validation of the WTC

In this task, methodologies for the assessment of WTC datasets (Fernandes and Lázaro, 2016, 2018, Lázaro et al., 2020), already described in the PVR, are adopted in the validation of the new WTC, namely:

a) Comparison with the MWR-derived WTC present in products (only for S3) – for coastal regions (e.g. Australia and Venice).

b) Comparison with the WTC from the ECMWF operational model – for all regions.

For a better illustration of the results, data have been grouped into 27-day cycles (S3) or 27&29-day sub-cycles (CS2, using the RADS convention for sub-cycle numbering).

In the current S3 products, two types of model-derived WTC are provided, both from the ECMWF Op. model: one computed at zero level, **WTC_ECM_{zero}** (mod_wet_tropo_cor_zero_altitude field) and another at the altimeter measurement level, **WTC_ECM_{meas}** (mod_wet_tropo_cor_meas_altitude field).

For S3, over all regions, **WTC_GPD** is compared with the corresponding WTC provided in the S3 products at measurement level (**WTC_ECM_{meas}**) and with the MWR-derived WTC, **WTC_MWR** (rad_wet_tropo_cor field).

For CS2, in all cases, the **WTC_GPD** is compared with the only model-derived WTC present in the products, referred to the model orography (**WTC_ECM_{oro}**).

In the validation of the WTC and the DTC, statistics have been computed for "water" points. The criteria used to select these "water" points are:

- Ocean points (surface_type=0) up to distances from coast of 150km or
- inland water points (surface type=1) or
- land points (surface type=3) and GSW occurrence value larger than 20%.

The reason for excluding from the analysis ocean points with distances from coast larger than 150 km aims to remove some passes that are in the database but are not inside the predefined ROI as, for example, a few passes over open ocean in the Southern part of the Australia ROI.

2.2.1 Australia

Figure **4** illustrates the location of S3A tracks for cycle 80 and the interleaved S3B tracks for cycle 61 (S3B cycle starts 10 days later than S3A cycle) for the Australia region.

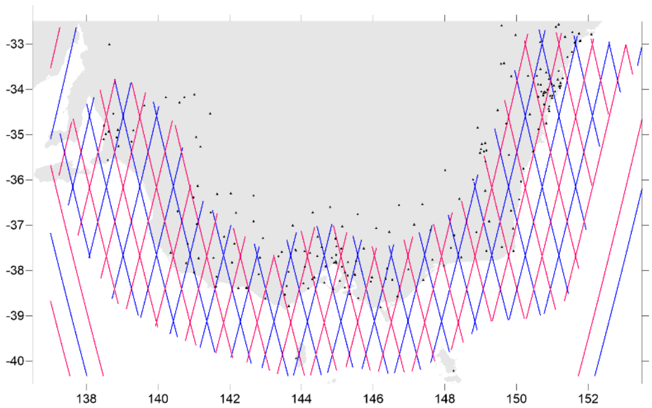

Figure 4 - Location of S3A points for cycle 80 (blue) and S3B cycle 61 (red). The black triangles show the location of GNSS stations with available data for use in the estimation of the GPD+ WTC for these cycles.

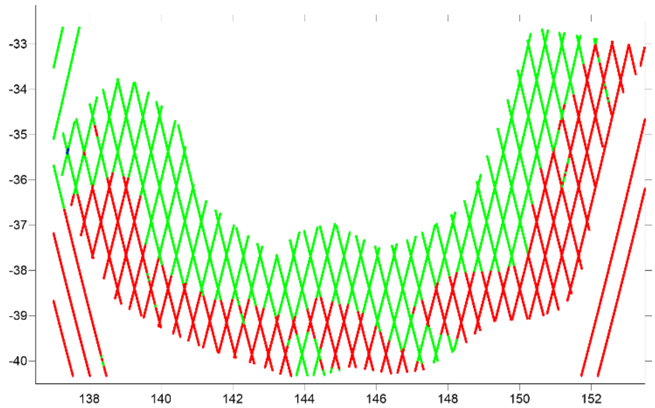

Figure 5 - GPD source flag for S3A cycle 80 and S3B cycle 61: 0 (red) – valid on-board MWR values; 1-7 (green) – estimated from observations; 8 (blue) – from ERA5 model.

We recall that a major step in the estimation of the GPD+ WTC is the establishment of the MWR validity flag, specifying if a given WTC from the on-board MWR is considered valid or not. For S3, all land points and coastal points at distances from coast less than 25 km are considered invalid. Additional points are also rejected based on product flags and statistical criteria.

Figure **5** depicts the GPD source flag (gpd_wet_tropo_flag) for S3A cycle 80 and S3B cycle 61, providing information on the data sources used in the estimation of each GPD+ WTC. For each 20Hz S3A/B ground-track point the WTC_GPD is:

- The S3A/B MWR-derived WTC (eventually scaled after calibration) for all S3 points with valid MWR values - gpd_wet_tropo_flag = 0 (red points);
- A new estimate obtained from data combination of all available observations for all S3 points with invalid MWR - gpd_wet_tropo_flag with values from 1 to 7 (green points);
- The ERA5 model-derived WTC in the absence of observations - gpd_wet_tropo_flag = 8 (blue points, zero points in this figure).

For the S3 cycles illustrated in Figure **5**, the large majority of the points have been estimated from observations, i.e., only on a few points the WTC is equal to the ERA5 model. This happens for almost the entire data set of the Australia ROI. This is not only due to the availability of valid on-board MWR data and external imaging radiometers, but also mainly to the availability of a large number of GNSS stations, as illustrated in Figure **4**.

Figure **6**, Figure **7** and Figure **8** depict WTC_ECM_{meas}, WTC_MWR and WTC_GPD for S3A cycle 80 and S3B cycle 61, approximately 10-days apart, over an austral summer period. The major feature is the invalid WTC_MWR values around the coastal regions and over land, which are not present in WTC_GPD.

Considering the whole S3A "water" points over S3A cycle 80 (26698 points) the statistics of the differences between WTC_GPD and WTC_MWR are: RMS=5.5 cm and max abs diff=41.3cm. The corresponding values for the differences between WTC_GPD and WTC_ECM_{zero} are: RMS =1.2 cm and max abs diff=8.1 cm.

Considering the whole S3B "water" points over S3B cycle 61 (25624 points) the statistics of the differences between WTC_GPD and WTC_MWR are: RMS=5.0 cm and max abs diff=37.7cm. The corresponding values for the differences between WTC_GPD and WTC_ECM_{zero} are: RMS =2.5 cm and max abs diff=19.0 cm.

After an overall assessment of the WTC over the Australia ROI, a finer analysis is performed individually for each pass, in order to identify specific behaviours of the corrections.

For all examples of S3 or CS2 passes shown in this report, the very light blue and grey areas represent water and land, respectively, which can be confirmed in the spatial representation of each track, in the small bottom left panel in each figure.

Figure 9 and Figure 10 illustrate examples of the same S3A passes (630) for different epochs, over cycles 71 and 54, respectively. In these figures and in the most of the following pass examples, the WTC from the ERA5 model computed at surface height (WTC_ERA) is also shown for comparison with the model-derived WTC present in the HYDROCOASTAL products (WTC_ECM_{meas}).

These examples show that the model WTC and GPD can be significantly different, with differences of several centimetres. For cycle 54 pass 630 (Figure 10), the RMS of the differences between WTC_ECM_{meas} (blue) and WTC_GPD (black) over water points is 3.33 cm (see the differences between the blue and black lines). The corresponding value for cycle 71 pass 630 (Figure 9) is 5.94 cm. In both cases, the maximum absolute differences exceed 10 cm.

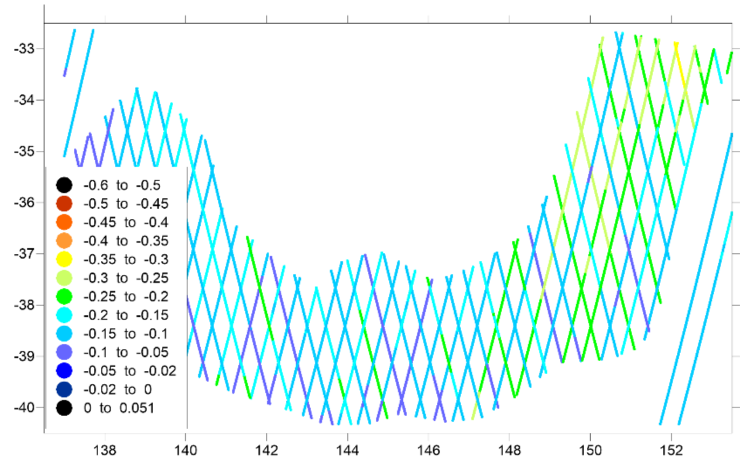

Figure 6 - WTC_ECM$_{meas}$ over the Australia ROI, for S3A cycle 80. and S3B cycle 61

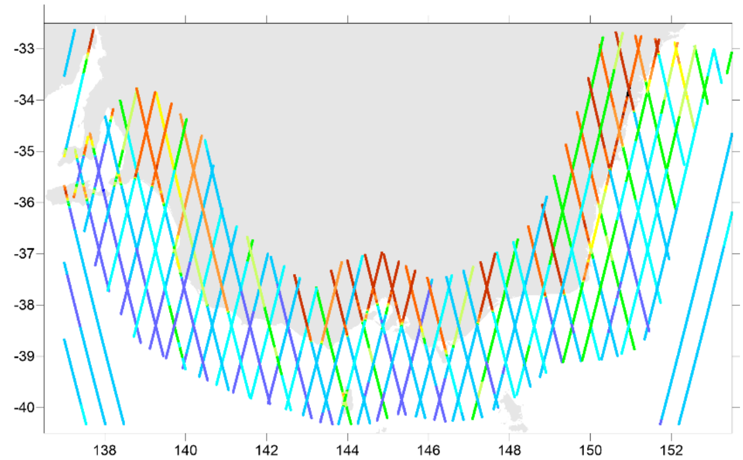

Figure 7 - WTC_MWR over the Australia ROI, for S3A cycle 80 and S3B cycle 61.

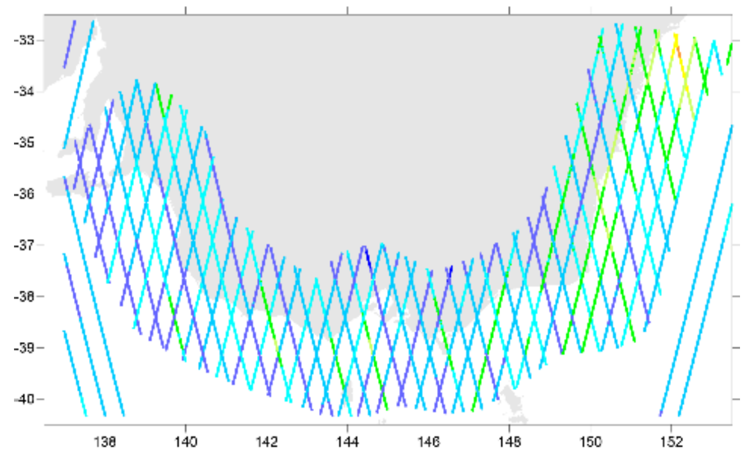

Figure 8 - WTC_GPD over the Australia ROI, for S3A cycle 80 and S3B cycle 61

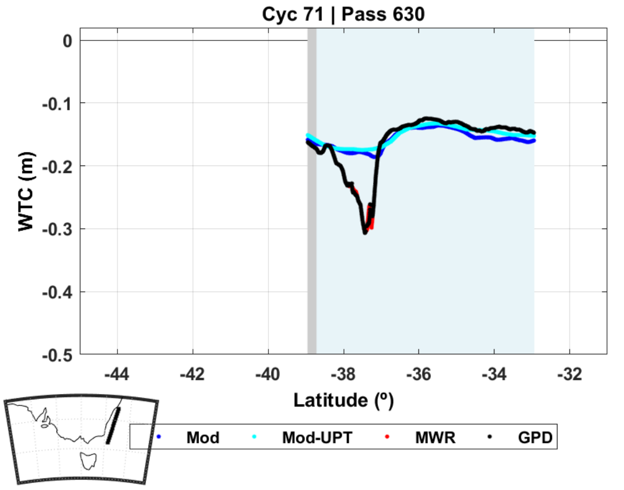

Figure 9 - Various WTC for S3A cycle 71 pass 630: WTC_ECM_{meas} (blue), WTC_ERA (cyan), WTC_MWR (red) and WTC_GPD (black).

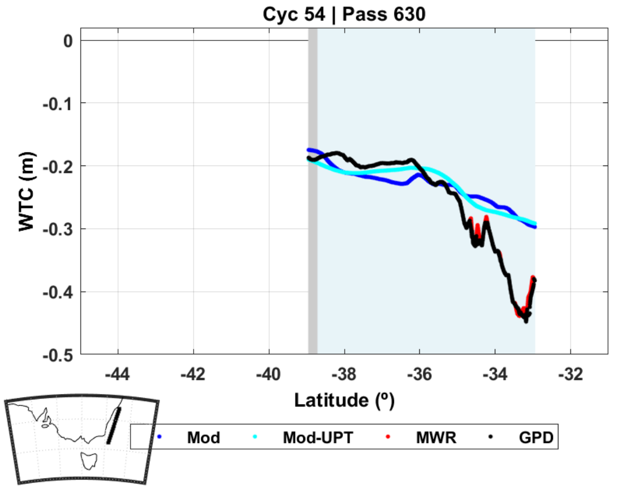

Figure 10 - Various WTC for S3A cycle 54 pass 630: WTC_ECM_{meas} (blue), WTC_ERA (cyan), WTC_MWR (red) and WTC_GPD (black).

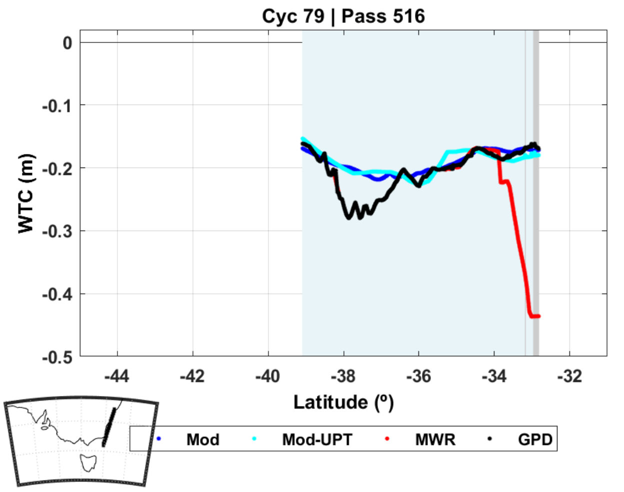

Figure 11 - Various WTC for S3A cycle 79 pass 516: WTC_ECM_{meas} (blue), WTC_ERA (cyan), WTC_MWR (red) and WTC_GPD (black).

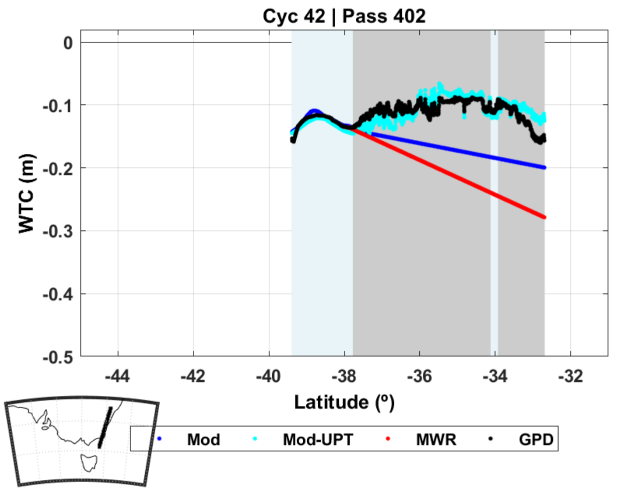

Figure 12 - Various WTC for S3A cycle 42 pass 402: WTC_ECM_{meas} (blue), WTC_ERA (cyan), WTC_MWR (red) and WTC_GPD (black).

Figure 11 illustrates a coastal pass where typically strong land contamination can be observed on WTC_MWR in the points close to the sea borders (latitude around 33°S). Again, in this example, large differences can be observed between WTC_GPD and WTC_ECM_{meas}, reaching 8 cm.

Similar large differences between WTC_GPD and WTC_ECM_{meas}, associated to signals and magnitudes similar to those shown in Figure 9, Figure 10 and Figure 11 have been found in the Venice region.

Figure 12 illustrates erroneous behaviour of both model and radiometer corrections present in the HYDROCOASTAL S3 products, most probably due to interpolation or extrapolation of the fields.

Considering the whole S3A “water” points over Australia (2039061 points) the statistics of the differences between WTC_GPD and WTC_MWR are: RMS=5.4 cm and max abs diff=44.7cm. The corresponding values for the differences between WTC_GPD and WTC_ECM_{zero} are: RMS =1.3 cm and max abs diff=15.9 cm. For the whole S3B “water” points over Australia (1328232 points) the statistics of the differences between WTC_GPD and WTC_MWR are: RMS=5.4 cm and max abs diff=44.4cm. The corresponding values for the differences between WTC_GPD and WTC_ECM_{zero} are: RMS =1.3 cm and max abs diff=19.0 cm. When considering the various S3 cycles, the RMS of the differences between WTC_GPD and WTC_MWR ranges from 3.7 cm to 6.2 cm while the RMS of the differences between WTC_GPD and WTC_ECM_{zero} ranges from 0.7 to 2.5 cm.

The large differences between WTC_GPD and WTC_MWR mainly reflect the differences in the points near the coast, since over the points where the MWR has been considered valid, the two corrections are equal.

These results for S3 in this region of South Australia are a clear indication that using model-derived WTC in open ocean and coastal regions causes a significant degradation in the quality of the corresponding derived sea surface heights. Additionally, WTC retrieved from MWR in coastal regions is invalid and cannot be used.

2.2.2 Ganges

Regarding the Ganges region, Figure 13 illustrates the location of S3A points for cycle 73 (blue) and S3B cycle 54 (red), while Figure 14 represents the GPD source flag (gpd_wet_tropo_flag) for the same cycles. It can be observed that for this period there are no GNSS observations and, apart from the southern part of the region, where some MWR observations are available, most GPD+ estimations are based only on ERA5 model values (blue points in Figure 14).

Figure 15, Figure 16 and Figure 17 illustrate WTC_ECM_{meas}, WTC_MWR and WTC_GPD for S3A cycle 73 and S3B cycle 54 over the Ganges region. The major features are the large magnitude of the WTC over this region and the expected invalid WTC_MWR values over land and over the river, which are not present in WTC_GPD.

Considering the whole S3A “water” points (2026) fore S3A cycle 73 over the Ganges ROI, the statistics of the differences between WTC_GPD and WTC_ECM_{meas} are: RMS=2.7 cm and max abs diff=5.4 cm. The corresponding values for S3B cycle 54 (1977 points) are: RMS=1.4 cm and max abs diff=3.6 cm.

Figure 18 and Figure 19 represent examples of various WTC for two S3A passes (cycle 10 pass 636 and cycle 84 pass 735) over the Ganges region. In the first pass, the track crosses the Ganges River at around latitude 23.5º, where the WTC_GPD differs from WTC_ECM_{meas} by about 5 cm. In the second case, the track crosses the river at about latitude 24º, where the differences between the two WTC can reach 6 cm.

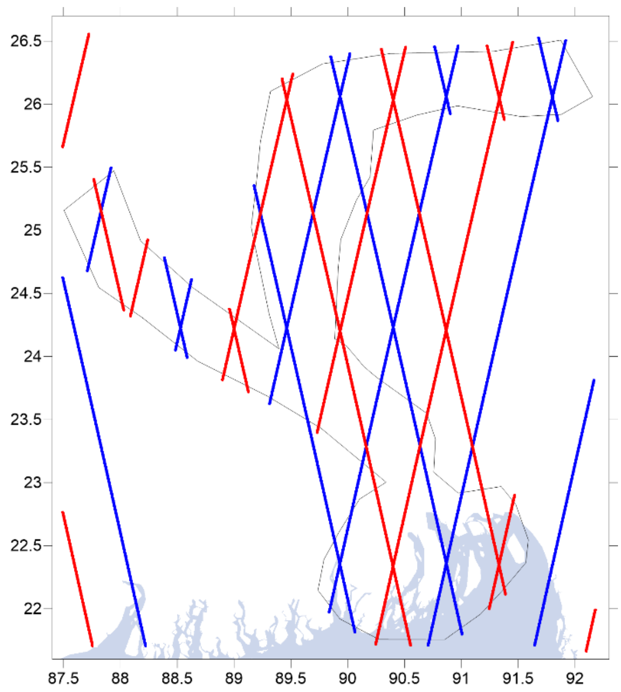

Figure 13 - Location of S3A points for cycle 73 (blue) and S3B cycle 54 (red) over the Ganges ROI.

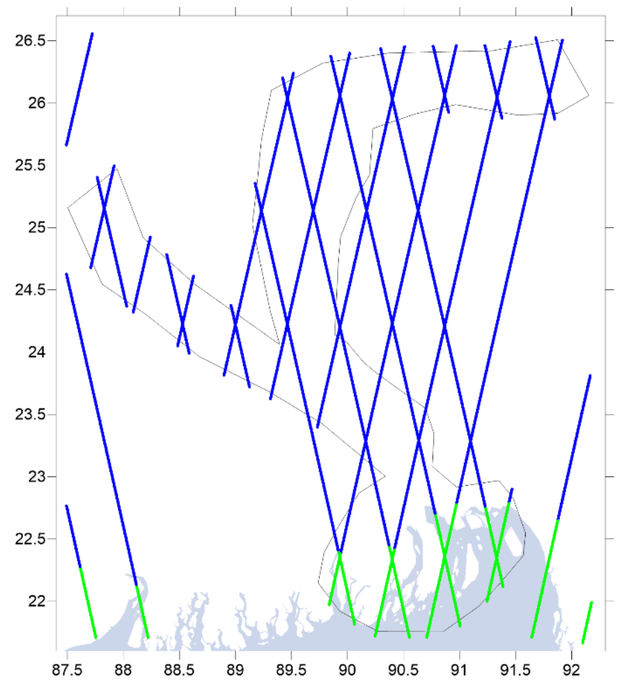

Figure 14 - GPD Source flag for S3A cycle 73 and S3B cycle 54: 0 (red) – valid on-board MWR values; 1-7 (green) – estimated from observations; 8 (blue) – from ERA5 model.

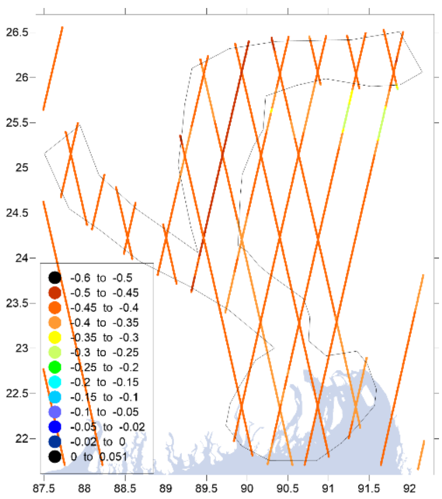

Figure 15 - WTC_ECM$_{meas}$ over the Ganges ROI, for S3A cycle 73 and S3B cycle 54

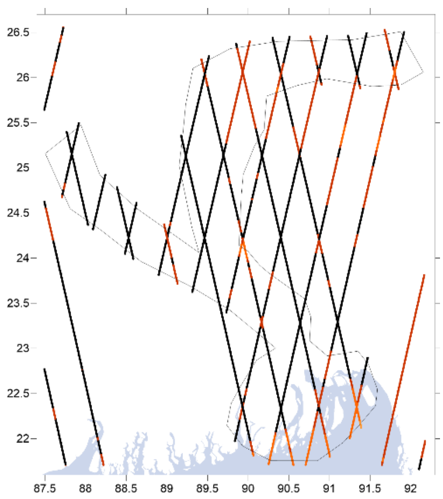

Figure 16 - WTC_MWR over the Ganges ROI, for S3A cycle 73 and S3B cycle 54.

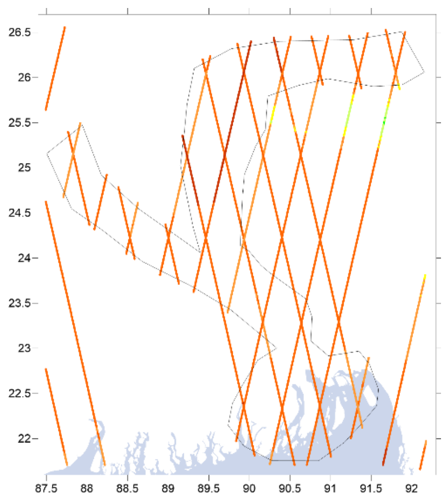

Figure 17 - WTC_GPD over the Ganges ROI, for S3A cycle 73 and S3B cycle 54.

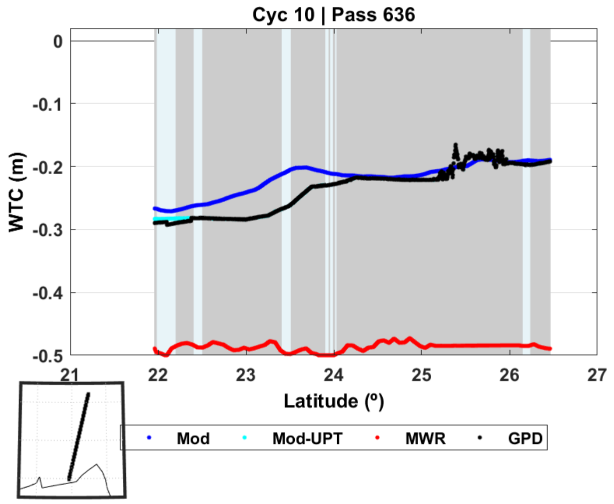

Figure 18 - Various WTC for S3A cycle 10 pass 636: WTC_ECM$_{meas}$ (blue), WTC_ERA (cyan), WTC_MWR (red) and WTC_GPD (black).

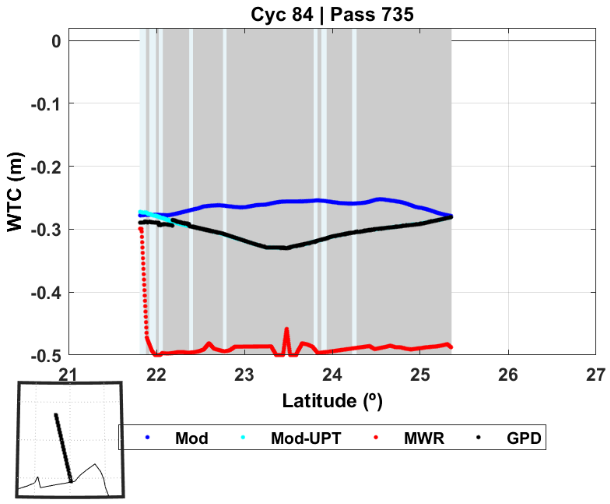

Figure 19 - Various WTC for S3A cycle 84 pass 735: WTC_ECM$_{meas}$ (blue), WTC_ERA (cyan), WTC_MWR (red) and WTC_GPD (black).

Considering the whole S3A "water" points (177287) dataset over the Ganges ROI, the statistics of the differences between WTC_GPD and WTC_ECM$_{meas}$ are: RMS=1.2 cm and max abs diff=6.9 cm. The corresponding values for S3B (104483 points) are: RMS=1.2 cm and max abs diff=6.6 cm.

Overall, the differences are small, however they can be very significant over some passes. Again, over this region, on one hand, the WTC from MWR is always invalid and, on the other hand, WTC_GPD and WTC_ECM$_{meas}$ can have very significant differences over water.

2.3 Validation of the DTC

In the validation of the DTC the following analyses are performed:

1. Comparison with DTC present in products.
2. Along-track analysis of DTC and water level profiles, inspecting unexpected behaviour of the corrections, present in some current products.

In the current S3 products, two types of DTC are provided, both from the ECMWF Op. model: one computed at zero level, **DTC_Zero** (mod_dry_tropo_cor_zero_altitude field) and another at the altimeter measurement level, **DTC_meas** (mod_dry_tropo_cor_meas_altitude field).

For CS2, the **DTC_UPT** is compared with the only model-derived DTC present in the products, referred to the model orography (**DT C_oro**).

2.3.1 Australia

Figure 20 shows the ACE2 DEM over the region of South Australia. Figure 21 and Figure 22 illustrate, for S3A cycle 80 and S3B cycle 61, the DTC_meas, and DTC_UPT respectively, over the Australia region.

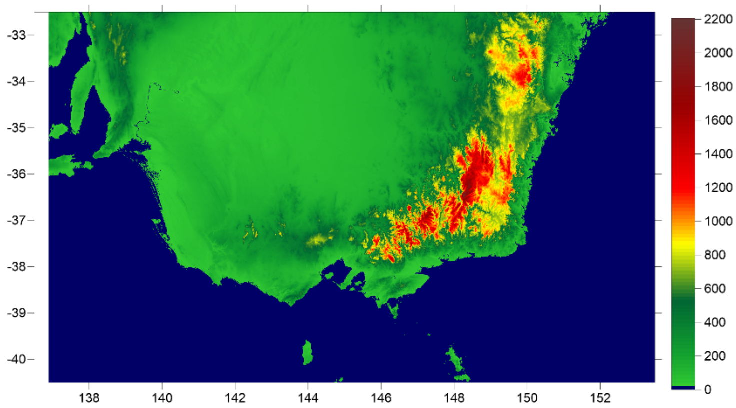

Figure 20 – Digital Elevation model over the Australia ROI.

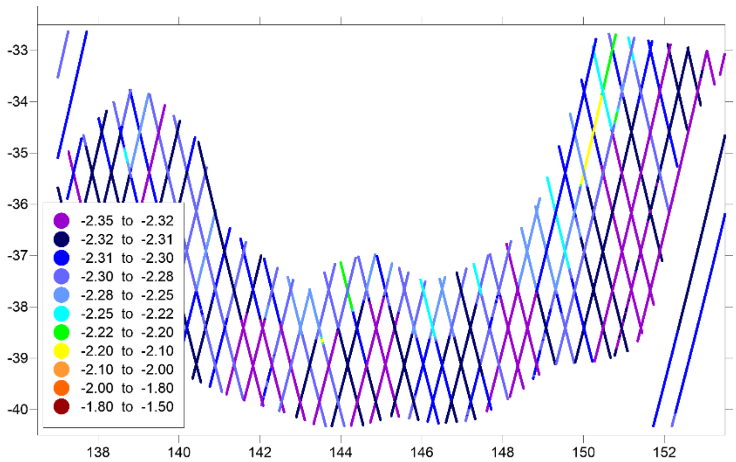

Figure 21 - DTC_meas over the Australia region, for S3A cycle 80 and S3B cycle 61.

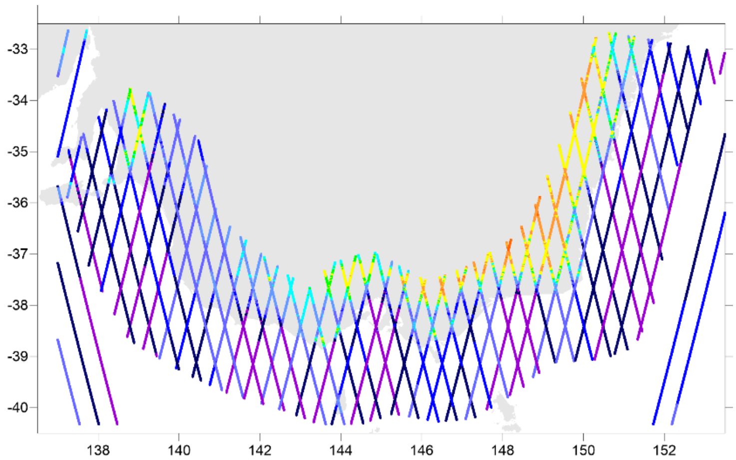

Figure 22 - DTC_UPT over the Australia region, for S3A cycle 80 and S3B cycle 61.

For this S3A cycle the statistics of the differences between these DTC over “water” points are: RMS =0.7 cm; max abs diff = 16.2 cm. For S3B cycle 61 the statistics of the differences between these DTC over “water” points are: RMS =0.2 cm; max abs diff=6.1 cm.

As previously reported in the PVR, results show that, over ocean, the DTC differences are very small and negligible.

However, the DTC present in the S3 HYDROCOASTAL products for the Australia ROI, extracted from the S3 Marine products, over land and inland water regions reveal an unexpected behaviour. When the DTC present in the products shown in Figure 21 is compared with DTC_UPT shown in Figure 22, it can be observed that, while the second has a clear and expected variation with height, in most coastal land regions the first correction seems to be too negative to be referred to the surface elevation.

This unexpected behaviour of DTC_meas is further illustrated in Figure 23 and Figure 24, where two example passes are given. In the first case, the DTC over land seems to be given at sea level, while in the second case it shows an unrealistic variation expressed by various linear segments.

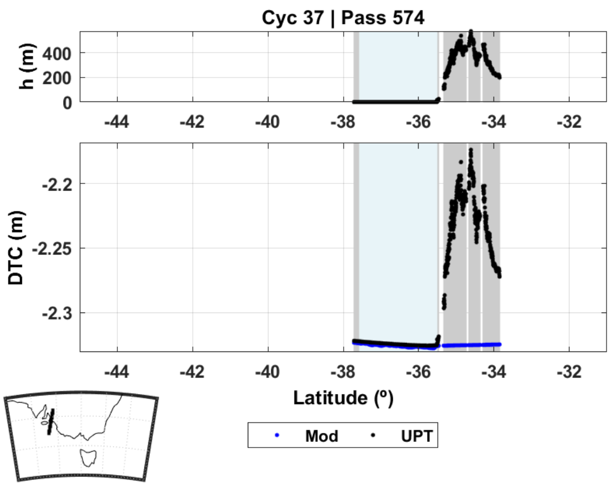

Figure 23 - Various DTC for S3A cycle 37 pass 574: DTC_meas (blue) and DTC_UPT (black) over the Australia region.

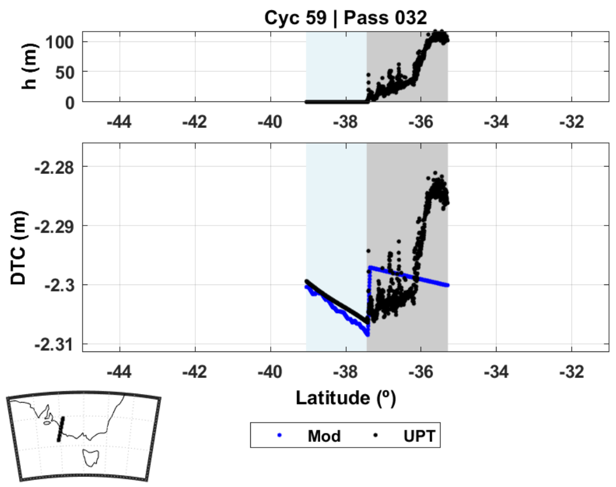

Figure 24 - Various DTC for S3A cycle 59 pass 32: DTC_meas (blue) and DTC_UPT (black) over the Australia region.

Due to the unexpected behaviour of **DTC_meas** present in the products, the statistics of the differences between the two DTC are not significant nor representative of the results. Overall, over ocean the corrections seem to be correctly provided at sea level and without any significant errors. On the contrary, in these products, the corrections present over land and inland water points reveal erroneous behaviour that should be investigated.

2.3.2 Mackenzie

Figure 25 shows the ACE2 DEM over the region of the Makenzie River. Figure 26 and Figure 27 illustrate, for S3A cycle 43 and S3B cycle 24, the DTC_meas, and DTC_UPT respectively, over the same region.

For this S3A cycle, the statistics of the differences between these DTC over “water” points are: RMS =2.2 cm; max abs diff=6.9 cm. For S3B cycle 24 the statistics of the differences between these DTC over “water” points are: RMS =1.5 cm; max abs diff=3.3 cm.

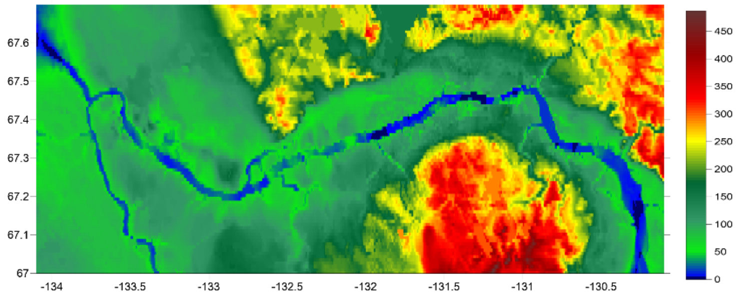

Figure 25 – Digital Elevation model over the Mackenzie ROI.

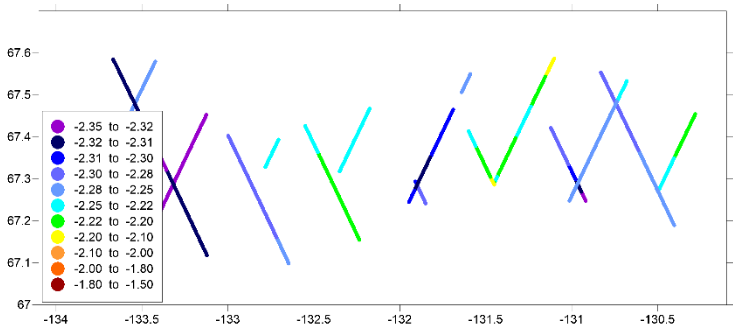

Figure 26 - DTC_meas over the Mackenzie region, for S3A cycle 43 and S3B cycle 24.

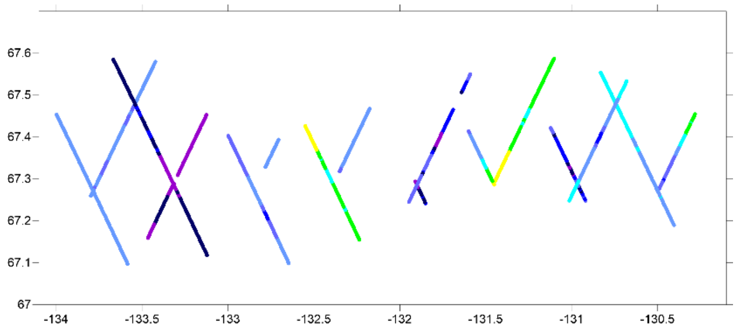

Figure 27 - DTC_UPT over the Mackenzie region, for S3A cycle 43 and S3B cycle 24.

Results are further illustrated in Figure 28 and Figure 29, where two example passes are given. In the first case, the track crosses the river at about latitude 67.5º, where a DTC differences of about 3 cm is found. In the second case, the track crosses the river at about latitude 67.3º, where a DTC difference of the order of 6 cm is detected.

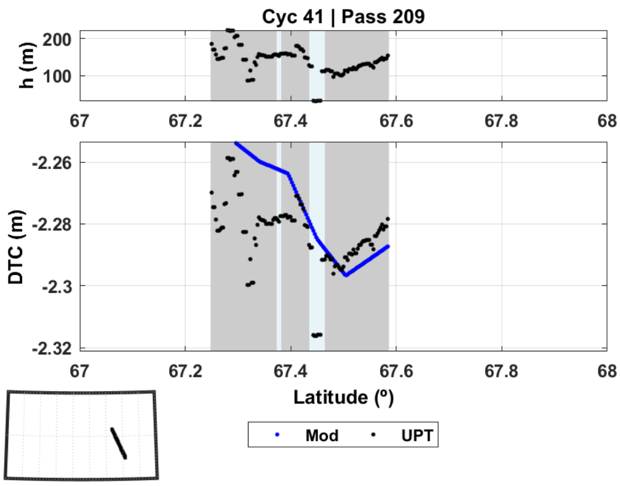

Figure 28 - Various DTC for S3A cycle 41 pass 209: DTC_meas (blue) and DTC_UPT (black) over the Mackenzie region.

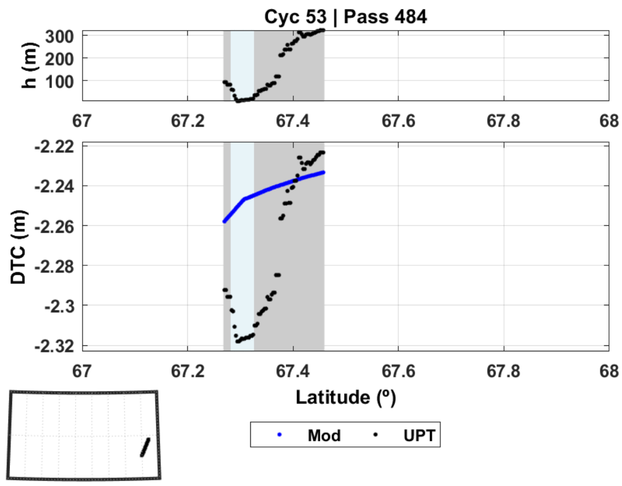

Figure 29 - Various DTC for S3A cycle 53 pass 484: DTC_meas (blue) and DTC_UPT (black) over the Mackenzie region.

2.4 Main conclusions on the validation of the WTC and DTC

As described in section 2.1, in this part of the project, improved DTC and WTC have been computed for a total number of 25 ROI. Although a global assessment of the corrections has been performed for all regions, a more detailed analysis has been carried out for the following set of 7 ROI: Australia and Venice (coastal regions), Amur, Ganges, Mackenzie, Niger and Watson (rivers). From these, in the above two subsections, the results have been illustrated for 3 of these regions: Australia, Ganges and Mackenzie.

The results obtained for the Case studies and additional areas confirm those found for the test areas, already reported in the PVR and recalled here.

2.4.1 Main conclusions for the WTC

Concerning the WTC from MWR, over rivers and small lakes the WTC differences between GPD and MWR are not analysed, since the WTC retrieved from MWR over narrow rivers and small water bodies is always invalid.

For the Australia coastal region, the RMS of the WTC differences between GPD and MWR is 5.3 cm for both S3A and S3B. For the Venice coastal region, the corresponding RMS of WTC differences is 11.4 and 9.3 cm for S3A and S3B, respectively. For coastal regions and large lakes, these very significant differences mainly reflect the differences in the points near the coast, since over the points where the MWR has been considered valid, the two corrections (WTC_GPD and WTC_MWR) are equal. Overall, these results confirm that the MWR observations cannot be used near the coast, due to the land contamination. The independent comparison with GNSS previously performed in the California test area reinforces this conclusion.

Erroneous behaviour of both model and radiometer corrections present in the HYDROCOASTAL S3 products has been detected, most probably due to interpolation or extrapolation of the fields.

Regarding the differences between GPD and model (WTC_ECM$_{meas}$ for S3 and WTC_ECM$_{oro}$ for CS2), although the overall statistics of the global differences for the entire ROI dataset indicate small RMS values in the range of 0.3-1.9 cm, there are passes where the RMS values can reach 6 cm and maximum absolute differences exceeding 10 cm (over Australia and Venice). Small differences with RMS values less than 1 cm correspond to ROIs for which no observations are available and the WTC_GPD is mostly equal to ERA5.

Examples of S3 passes where the magnitude of these differences is of several centimetres were shown. These examples indicate that, although the differences between the model-derived WTC and those based on observations are statistically small, at small scales these two corrections can still be significantly different. These results are a clear indication that the adoption of model WTC present in the S3 and CS2 products may lead to a significant increase in the altimeter derived sea/water surface heights errors over these regions.

Thus, in these regions, neither the MWR nor the model should be adopted. The adopted WTC should be an improved and continuous WTC such as GPD+, based on observations when they exist. Moreover, studies carried out by Ablain et al. (2022) indicate that the WTC accounts for ~40% of the current errors in the SSH, therefore, improvements in the WTC are still required.

2.4.2 Main conclusions for the DTC

The global differences between DTC_UPT and DTC_meas (or DTC_oro for CS2) for the “water points” dataset of the various analysed ROI are small, with RMS values at sub-centimetre level, except for Mackenzie, Amur and Watson, with RMS values of 1.6 cm, 2.2 cm and 8.2 cm, respectively.

A detailed analysis of the Watson ROI is not presented, in order to understand the large differences found there, since we were not able to identify the position of the river. Without this identification, it is not possible to determine if the large differences correspond to water bodies or to land points.

Overall, it can be concluded that over clean water points DTC_UPT and the DTC present in the S3 and CS2 products are very close, at sub-centimetre level. In particular, this is the case of coastal regions. However, for high and narrow inland water bodies, the differences between these two DTC can be of several centimetres.

In addition, unexpected behaviour of the DTC_meas correction was found over Australia.

Over the Amur River, the overall statistics of the differences between DTC_UPT and DTC_ECM$_{oro}$ (CS2) indicate an RMS value of 2.2 cm and in some passes these differences can be larger than 5 cm. In the case of CS2, the largest errors found may be due to “wrong” model orography.

In the case of the S3 products these very significant errors still present in the DTC may be due to the use of “wrong” altimeter-derived water heights, caused e.g., by poor retracker performance, mainly in narrow regions of the water body. A step shape of the S3 DTC observed in some regions, previously reported in the PVR, is not well understood.

Therefore, the adoption of the DTC present in products may lead to a significant increase in the altimeter derived water surface heights errors, in particular over regions at high altitudes. Over these regions the DTC should be correctly referred to the actual surface height, using the best available topographic information.

Moreover, the provision of the height at which the corrections have been computed allows for the application of corrective terms, in case more accurate retracked heights become available and these differ from the reference heights by more than 40m.

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List of Acronyms

ACE2 Altimeter Corrected Elevations (vers. 2)
AD Applicable Documents
CCN Contract Change Notice
CS2 CryoSat-2
CZ Coastal Zone
DEM Digital Elevation Model
DTC Dry Tropospheric Correction
DTU Danmarks Tekniske Universitet (Technical University of Denmark)
ECMWF European Centre for Medium-Range Weather Forecasts
EGM Earth Gravitational Model
ESA European Space Agency
FTP File Transfer Protocol
FCUP (from portuguese) *"Faculdade de Ciências da Universidade"*, Science faculty of the University of Porto
GFZ Deutsche GeoForschungsZentrum (German Research Centre for Geosciences)
GNSS Global Navigation Satellite System
GPD GNSS-derived Path Delay
GSW Global Surface Water
GSHHS Global Self-consistent, Hierarchical, High-resolution Shorelines
IW Inland Water
L2 Level-2
MSS Mean Sea Surface
MWR Microwave Radiometer
netCDF Network Common Data Form
NWM Numerical Weather Model
PVR Product Validation Report
RADS Radar Altimeter Database System
RMS Root Mean Square
ROI Region(s) Of Interest
SARIn SAR Interferometric (CryoSat-2/SIRAL mode)
SAR Synthetic Aperture Radar
SHAPE Sentinel-3 Hydrologic Altimetry PrototypE
SI-MWR Scanning Imaging MWR
SLA Sea Level Anomaly
SRAL SAR Radar Altimeter
SRTM Shuttle Radar Topography Mission
SSH Sea Surface Height
TCWV Total Column Water Vapour
TN Technical Note
WPD Wet Path Delay
WTC Wet Tropospheric Correction