HYDROCOASTAL

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

Dry and Wet Tropospheric Corrections for Coastal Zones and Inland Waters

Deliverable D1.3

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

ESA Contract 4000129872/20/I-DT

Project reference: HYDROCOASTAL_ESA_UPORTO_TN_D1.3

Issue: 1.0

This page has been intentionally left blank

Change Record

Date	Issue	Section	Page	Comment
21/06/20	1.0			

Control Document

Process	Name	Date
Written by:	UPorto	21/06/2020
Checked by	SatOC	22/07/20
22/07/20		

Subject	Radar Altimetry for Coastal Zone and Inland Water Level	Project	HYDROCOASTAL
Author	**Organisation**	**Internal references**	
M.J. Fernandes, C Lazaro	U Porto	HYDROCOASTAL_ESA_UPORTO_TN_D1.3	

	Signature	Date
For HYDROCOASTAL team		22/07/20
For ESA		

Table of Contents

List of Acronyms

ACE2	Altimeter Corrected Elevations 2
CP4O	CryoSat Plus for Oceans
CS2	CryoSat-2
CZ	Coastal Zone
DEM	Digital Elevation Model
DTC	Dry Tropospheric Correction
ECMWF	European Centre for Medium-Range Weather Forecasts
ECMWF Op	European Centre for Medium-Range Weather Forecasts Operational Model
ERA	ECMWF ReAnalysis
ESA	European Space Agency
GNSS	Global Navigation Satellite System
GPD+	GNSS-derived path delay Plus
GPT2	Global Pressure and Temperature 2
GSHHG	Global Self-consistent, Hierarchical, High-resolution Geography Database
IW	Inland Water
MWR	MicroWave Radiometer
NWM	Numerical Weather Models
RD	Reference Document
SCOOP	SAR Altimetry Coastal & Open Ocean
S3	Sentinel-3
SHAPE	Sentinel-3 Hydrologic Altimetry PrototypE
SI-MWR	Scanning Imaging MWR
SL_cci	Sea Level Climate Change Initiative
SLP	Sea Level Pressure
SSM/I	Special Sensor Microwave Imager
SSM/IS	Special Sensor Microwave Imager Sounder
STD	Slant Total Delay

SurfP	Surface Pressure
TCWV	Total Column Water Vapour
WTC	Wet Tropospheric Correction
UPorto	University of Porto
ZHD	Zenith Hydrostatic Delay
ZTD	Zenith Tropospheric Delay
ZWD	Zenith Wet Delay

1 Introduction

1.1 Scope of this Technical Note

The scope of this technical note is to describe the processing algorithms that will be used by the University of Porto (UPorto) in the course of WP2300 for the computation of enhanced and adequate dry and wet tropospheric corrections in the coastal zone and inland water regions, for CryoSat-2 (CS2) and Sentinel-3 (S3). The mathematical description, processing steps, the development choices and trade-offs of the algorithms are described. The input/output data and their requirements are also presented. The computed corrections are evaluated at the CryoSat-2 and Sentinel-3 orbit space-time sampling. The generated products are global Dry Tropospheric Corrections (DTC) and Wet Tropospheric Corrections (WTC) datasets, valid over all surface types, with particular focus on coastal and inland water zones.

1.2 Reference Documents

RD-01 HYDROCOASTAL Technical Note 1, SatOC and HYDROCOASTAL team, 2020.

1.3 Document Organisation

After this introductory section, section 2 provides an overview of the processing approach. Sub-sections 2.1 and 2.2 provide the description of the individual algorithms for the DTC and WTC, respectively. Section 3 provides a summary of the UPorto recommendations and conclusions.

2 Altimeter range corrections for coastal and inland waters

This section describes the algorithms used to calculate the tropospheric corrections that need to be applied to satellite altimeter measurements over the coastal zone (CZ) and inland water (IW) regions, in the framework of the HYDROCOASTAL project. Since most radar altimeter products have been designed for oceanographic purposes, they generally fail to provide the adequate tropospheric corrections (Dry Tropospheric Correction, DTC, and Wet Tropospheric Correction, WTC) over coastal and continental water regions. In fact, several issues arise over inland waters, mostly due to the fact that altimeter measurements refer to land surface and not to sea level, opposite to the case of oceanic data points. Most of these issues are due to an inadequate modelling of the height dependence of the tropospheric corrections, which must be computed considering the actual height of the surface. However, the tropospheric corrections computed from Numerical Weather Models (NWM) are usually referred to the height of the model orography, which is known to depart considerably from the actual surface height. This is particularly true for the DTC, which shows a strong height dependence. Therefore, in contrast to what happens over ocean, inland studies require the modelling of the height dependence of the tropospheric corrections. Over oceanic coastal regions, on the opposite, corrections should be provided at sea level instead of at the level of the model orography. Moreover, the retrieval algorithms for the wet tropospheric correction, based on collocated observations acquired by the on-board microwave radiometer (MWR) have been adjusted for open-ocean conditions, therefore providing invalid MWR-derived WTC over-non ocean surfaces, among which coastal and inland water zones are included. UPorto has been developing specific methodologies to retrieve valid DTC and WTC for these regions and their description is provided in sub-sections 2.1 and 2.2, respectively. Another main source of error is the inappropriate rate at which the tropospheric corrections are provided in the altimeter products. Consequently, this issue is also addressed for both CZ and IW regions.
The aim of this task is to generate and validate enhanced dry and wet tropospheric corrections for CryoSat-2 and Sentinel-3A/B in the coastal zone and inland water domains, using the best available data sources (observations, including third-party data, and models). The know-how acquired in the scope of previous projects funded by the European Space Agency (ESA) (CP4O, SL_cci, SCOOP and SHAPE) shall be used, with several enhancements as specified below. The corrections shall be evaluated at the Cryosat-2 and Sentinel-3 orbit space-time sampling and appropriate data rate.
The outputs will be continuous and consistent sets of DTC and WTC, valid over all surface types.

2.1 Dry Tropospheric Correction

The DTC is one of the most precise range corrections for open-ocean regions, being calculated from Sea Level Pressure (SLP) grids from any of the ECMWF atmospheric models with an accuracy better than 1 cm. However, it should be emphasized that the DTC presents, in some of the present-day altimeter products, the largest errors for IW studies, which can reach several centimetres [RD-01]. Over the oceanic CZ, the DTC is generally provided at the level of the model orography instead of at sea level. As a consequence, errors up to several centimetres may also arise in these regions [RD-01]. It has been shown that using the appropriate computation procedures, the DTC can be accurately computed from SLP grids and appropriate surface elevations, both for CZ and IW regions (Vieira et al., 2018, Fernandes et al., 2018, Fernandes et al., 2020). In the following sub-sections, the algorithm, the main processing steps for the computation of the DTC within the HYDROCOASTAL project, the development choices, and data flow are presented.

2.1.1 Algorithm Definition: Mathematical Description

The algorithm used to estimate the DTC is addressed in this section. Equation 1 is used to compute the DTC in metres (Davis et al., 1985):

$$DTC = -\frac{0.0022768\, P_s}{1 - 0.00266\, cos\, 2\varphi - 0.28\, \cdot 10^{-6}\, h_s} \quad \text{Eq. 1}$$

where P_s is the total surface pressure (in hPa) at surface height h_s above the geoid (in metres) and φ is the geodetic latitude. Considering that P_s is the sum of the partial pressures due to dry air and water vapour, Equation 1 gives the zenith path delay caused by the hydrostatic component of air, instead of that due to the dry component, the so called "dry delay". However, being the difference between the hydrostatic and dry components of the tropospheric path delay small, and since the hydrostatic term can be calculated from the total atmospheric pressure data, which are routinely made publicly available, the term "dry tropospheric delay" is usually used within the altimetry community to refer to the hydrostatic tropospheric path delay. Combined with the corresponding expression for the wet path delay (sub-section 2.2.1), Equation 1 is accurate to better than 0.2%, i.e., for a total tropospheric delay (dry + wet) of 2.5 m, the error is < 5 mm (Chelton et al., 2001).
Equation 1 shows that the dependence of the DTC with height is governed by the height variation of atmospheric pressure, P_s, which can be computed from sea level pressure, P_0, using Equation 2 (Hopfield, 1969):

$$P_s = P_0\, exp\left[-\frac{g_m(h_s - h_0)}{R_d T_m}\right] \quad \text{Eq. 2}$$

In Equation 2, R_d is the specific constant for dry air (R_d =287.058 J·K^{-1}·kg^{-1}), T_m is the mean temperature (in K) of the layer between heights h_0 (sea level) and h_s (surface height), and g_m is the mean gravity given by Equation 3 (Saastamoinen, 1972):

$$g_m = 9.784\,(1 - 0.00266\, cos\, 2\varphi - 0.28 \cdot 10^{-6}\, h_s) \quad \text{Eq. 3}$$

Given the values of T_0 at mean sea level e.g. from the Global Pressure and Temperature 2 (GPT2) model (Boehm et al., 2007), T_m can be estimated from Equation 4 considering the normal lapse rate of temperature with height:

$$T_m = T_0 - 0.0065 h_s \quad \text{Eq. 4}$$

In the computation of the DTC using equations 1 and 2, global grids of sea level pressure (SLP) and surface pressure (SurfP), from Numerical Weather Models (NWM) may be used as input data. Currently, the best models are those from the European Centre for Medium-Range Weather Forecasts (ECMWF) and two types are of particular interest, typically provided every six hours at different spatial samplings, depending on the selected model: the operational (Op.) model (Miller et al., 2010) at a spatial resolution of 0.125° × 0.125° (regular grid) or about 16 km (Gaussian grid), available with a latency of a few hours, and reanalysis models, with a latency of 1-2 months. The operational model is usually used from 2004 onwards, since several changes have been implemented over the course of several years, while the reanalyses are uniform and should be adopted for older missions (Fernandes et al., 2013b; Fernandes et al., 2014; Legeais et al., 2014). In this project, the most recent reanalysis model from ECMWF, ERA5 (ECMWF ReAnalysis 5), will be used.

The DTC should be computed for the height of each satellite measurement. Therefore, for oceanic and coastal applications, the DTC should be provided at sea level, whereas for inland water studies it should be referred to the height of the surface. However, since it has been proven (Fernandes et al., 2014; Vieira et al., 2018) that it is preferable to use SLP instead of SurfP, as the latter usually leads to Gibbs effects in the corrections, the computation of the DTC for continental surfaces is usually performed in two steps.

In the first step, surface pressure P_s is computed from SLP and appropriate surface elevations using Equation 2. In the second step, the DTC is estimated from the values of P_s using Equation 1.

A dataset of Global Navigation Satellite System (GNSS) coastal stations with heights up to 1000 m were used by Fernandes et al. (2013a) to assess the accuracy with which the DTC can be computed from SLP global grids (ECMWF Op. model or ECMWF reanalysis) using Equations 1 and 2. Results have shown that the accuracy is within the range of 1 to 3 mm at the global scale. Simplified expressions are obtained when the temperature dependence is neglected. However, such expressions induce seasonal signals with amplitudes of several millimetres, owing to the seasonal variation of pressure with temperature. The same studies show that larger effects can be expected for higher altitudes.

The best value for h_s should be the height of the mean river profile or the height of the mean lake level, for measurements over rivers and lakes, respectively. Usually the value of h_s is known from previous local studies or can be calculated from altimeter measurements averaged over time to obtain e.g. mean lake levels. For global applications or in the absence of an accurate altimeter-derived value for h_s, an accurate Digital Elevation Model (DEM), like e.g. Altimeter Corrected Elevations 2 (ACE2) should be used (Berry et al., 2008).

2.1.2 Algorithm Definition: Processing Steps

The DTC should be computed at sea level for ocean and (ocean) coastal points. However, in many altimeter products, the DTC is given at the model orography instead, which is a smoothed topography that varies from model to model. While over open ocean the model orography generally coincides with sea level, and therefore the DTC can be computed with an accuracy better than 1 cm, in coastal and continental areas the orography can depart considerably from sea level and actual surface height, respectively. Considering that the absolute value of the DTC decreases 2.5 cm for each 100 metres height change, errors of several centimetres exist in the DTC referred to model orography, in these regions. Thus, for coastal and inland water studies, the handling of the height dependence of the DTC is of crucial importance.

Therefore, to compute the DTC, the following steps should be followed:

1. Read data from the altimeter data file: latitude, longitude and instant of measurement.
2. For ocean and coastal regions, compute the DTC at sea level using the following steps:
    - Interpolate SLP (P_0) from ECMWF SLP grids for each altimeter measurement location and instant of measurement.
    - Estimate the DTC using Equation 1, taking $P_s = P_0$ and $h_s = 0\ m$.
    - Jump to step 4.
3. For inland water bodies, the DTC should be computed at the height of the water body. This step can be divided into the following:

- Interpolate SLP (P_0) from ECMWF SLP grids for each altimeter measurement location and instant of measurement.
- Read ACE2 DEM and use a bilinear interpolation to extract the field for the geodetic position of each record (h_s or output variable h_surf).
- Replace the ACE2 DEM surface height associated with each point by the height of the closest point from the mean river profile, in case the point is over a river, or by a pre-computed mean lake level, if the point is over lake, and update h_s value; if a better estimate for the surface height is not available, skip this step.
- Compute g_m using Equation 3, the temperature at mean sea level given by the GPT2 model and T_m using Equation 4.
- Compute surface pressure P_s at the surface height h_s obtained in the previous step, using Equation 2 and setting h_0 to zero.
- Use Equation 1 to compute the DTC at surface height h_s using P_s from previous step.

4. Write the output file. For each altimeter data record the following variables are output in this order: Time (as provided in the input L1 file), latitude, longitude, h_surf, DTC from UPorto (upt_dry_tropo).

2.1.3 Development Choices and Trade Offs

The modelling of the DTC is well established and no further developments in the mathematical description and/or processing steps are expected during the project implementation.

2.1.4 Data Flow

INPUT DATA

For the computation of the DTC, the following input is needed:
- Altimeter data files generated within the project (merged L1BS-L1B-L2 product);
- Sea Level Pressure (SLP) grids from ECMWF;
- Global Pressure and Temperature 2 (GPT2) Model;
- Altimeter Corrected Elevations 2 (ACE2) Digital Elevation Model (DEM) at highest resolution (3″);
- Mean river profiles and mean lake levels, if available.

OUTPUT DATA

The output product will be a NetCDF/ASCII file containing the L2 DTC at the same rate as provided in the input altimeter data files. As summarised in Section 3, L2 DTC may be provided at 1 Hz for ocean and coastal points but at a higher rate (20 Hz) for points over land. The provision of a single file with a continuous DTC over all surface types is supported, in this case, at high rate (20 Hz). The output product should also contain the height at which the DTC has been computed, allowing in this case the update of the correction in case new retracked altimeter ranges are computed. Moreover, the DTC should be provided at sea level for ocean and coastal points and at surface height given by ACE2 DEM or local reference surface for points over inland water bodies.

2.2 Wet Tropospheric Correction

The WTC derived from altimeter-collocated measurements acquired by on-board MWR is the most accurate correction to account for the wet path delay, accurate at the centimetre level (1-1.5 cm). However, the retrieval algorithms for the WTC are tuned to compute the WTC for open-ocean domains, where surface emissivity values representative of water conditions only are assumed. Moreover, the large footprint of present MWR (10-40 km) makes the direct measurements of these instruments unusable for a band of 10-40 km width around the coastline. This is particularly critical for applications over coastal and large lakes/closed seas, where a large amount of absent or invalid measurements exists. In addition, MWR measurements are also strongly contaminated by ice and heavy rain. Therefore, methodologies for the calculation of valid WTC over these regions are necessary.

The GNSS-derived path delay Plus (GPD+) algorithm was primary developed by U.Porto (Fernandes et al., 2010; Fernandes et al., 2015) to estimate the WTC for measurements over coastal regions with an MWR-derived WTC flagged as invalid or inexistent and has been applied to all altimeter missions (Fernandes and Lázaro, 2016; Fernandes and Lázaro, 2018). The methodology was later improved to cover the open ocean, extending the validity of the correction up to the coast, as well as high latitudes, and to correct for invalid observations due to the presence of land, ice and rain contamination and instrument malfunction (Fernandes et al., 2015). In the scope of ESA's project SHAPE, the algorithm has been further ameliorated to provide the WTC over inland water regions using the best available models (Fernandes et al., 2014; Vieira et al., 2018). The proper handling of the WTC variability with height is a key issue over IW regions. A simple expression for the variation of the WTC with height has been given by Kouba (2008) and has been revisited by UPorto (Vieira et al., 2019a), which has led to new developments in the methodology. GPD+ are WTC which preserve the valid MWR over open-ocean and extend the correction to all surface types, providing inter-calibrated, continuous and consistent WTC. For Sentinel-3 (S3), GPD+ WTC will be based on the best S3 baseline MWR-derived WTC while for CryoSat-2, it will be based on the best available third-party data and models.

In the following sub-sections, the algorithm, the main processing steps for the computation of the WTC within the HYDROCOASTAL project, the development choices, and data flow are presented.

2.2.1 Algorithm Definition: Mathematical Description

The GPD+ Algorithm

The GPD+ methodology provides the WTC estimates using space-time objective analysis, by combining all available wet path delay observations, the symmetric of WTC, in the vicinity of the point of interest. The methodology takes into account the variability of the WTC field, as well as the accuracy of each set of observations.

The GPD+ inputs are wet path delays from: i) the on-board MWR measurements whenever they exist and are valid; ii) new WTC values estimated by data combination, through space-time objective analysis of all available data sources, whenever the previous are considered invalid. In the estimation of new WTC values, the following data sets are used: valid measurements from the on-board MWR, from water vapour products derived from a set of scanning imaging radiometers (SI-MWR) on board various remote sensing satellites, and wet path delays derived from GNSS coastal and island stations. In the estimation process, WTC derived from the best NWM are used as first guess and are the output values in the absence of measurements. Over coastal and large IW regions, such as lakes and enclosed seas, where valid MWR data can be found, improved WTC datasets can be obtained using the GPD+ methodology. In regions

possessing GNSS permanent stations, GNSS-derived WTC can be a very valuable and accurate data source, particularly for small lakes where data from a single station can be considered representative of the local wet path delay conditions. For missions that do not possess an on-board MWR like CryoSat-2, only third-party data will be used.
In the absence of observations, e.g. over small lakes and rivers, the WTC from the adopted NWM, ERA5, will be used.
To ensure the consistency and the long term stability of the WTC, datasets from the different radiometers used by the GPD+ are previously inter-calibrated with respect to the Special Sensor Microwave Imager (SSM/I) and SSMI/I Sounder (SSM/IS) instruments on board the Defense Meteorological Satellite Program satellite series, due to their well-known stability and independent calibration (Fernandes et al., 2013b; Fernandes et al., 2018).
The details concerning the WTC computation from the available datasets of observations and models are presented in the paragraphs that follow.

WTC from NWM
The WTC can be computed from global grids of NWM single-layer parameters, namely the Total Column Water Vapour (TCWV) and near-surface air temperature (2-metres temperature, T_0) using Equation 5 (Bevis et al., 1994):

$$WTC = -\left(0.101995 + \frac{1725.55}{T_m}\right)\frac{TCWV}{1000} \qquad \text{Eq. 5}$$

where T_m is the weighted mean temperature of the atmosphere that can be computed from Equation 6, provided that T_0 is known (Mendes, 1999):

$$T_m = 50.40 + 0.789\, T_0 \qquad \text{Eq. 6}$$

Equations 5 and 6 can be used to calculate WTC whenever TCWV and T_0 fields are available, namely when estimating the WTC from NWM single layer fields.
In the estimation of WTC from TCWV data solely, i.e., when using data from SI-MWR, Equation 7 from Stum et al. (2011) can be used (or a similar expression by Keihm et al. (2000)):

$$WTC = -(a_0 + a_1 TCWV + a_2 TCWV^2 + a_3 TCWV^3)\, TCWV \,.\, 10^{-2} \qquad \text{Eq. 7}$$

where the coefficients a_0 to a_3 take the values 6.8544, −0.4377, 0.0714 and −0.0038, respectively. Using TCWV expressed in centimetres, the resulting WTC values are expressed in metres. WTC from SI-MWR TCWV values can also be computed using Equation 5, however in this case the temperature must be computed from Equation 6 using near-surface air temperature data from an NWM. At present, SI-MWR data are available only over ocean.

The computation of the WTC can also be performed using 3D NWM fields. In these case, Equation 8 is used with parameters pressure P, temperature, T, and specific humidity, q, along vertical profiles, from the surface up to above 200 hPa (Fernandes et al., 2020):

$$WTC = -\left[1.034\times10^{-3}\int_{P_{sat}}^{P_s} q\,dP + 17.43\int_{\infty}^{P_s}\frac{q}{T}dP\right](1 + 0.0026\,cos2\varphi) \quad \text{Eq. 8}$$

In Equation 8, the pressure values are given in hPa, the temperature in K, the specific humidity in kg/kg, resulting WTC in metres. The integrals are evaluated from the surface pressure P_s up to the model vertical level pressure P_{sat} for which humidity is negligible (typically 200 hPa).
This equation provides the highest accuracy for WTC estimation from NWM. However, since the WTC computation using 3D fields makes these computations very demanding, the determination from single-layer surface parameters, i.e., using Equations 5 and 6, is often preferred.
Since all NWM parameters refer to the model orography, the WTC estimated from NWM fields using Equations 5 and 7 also refer to the level of the atmospheric model orography. As already stated, this reference may depart substantially from the actual surface height by hundreds of metres. Whenever accurate surface heights are available, the WTC value at the level of the model orography must be corrected to refer the correction to the height of the surface at which the altimeter measurement is referred to. For ocean points located in the CZ, the WTC must be referred to sea level, while for points over IW regions, the WTC must be referred to the height of the mean river profile or mean lake level, depending on the case. To perform this step, the variability of the WTC with height must be accurately known.

WTC height dependence
The height dependence of the WTC is of difficult modelling due to the large variability of the water vapour content in the atmosphere. Equation 9 has been proposed by Kouba (2008) to account for this height dependence of the WTC:

$$WTC(h_s) = WTC(h_o)e^{\frac{h_o-h_s}{k}} \quad \text{Eq. 9}$$

where h_O and h_S are the heights of the model orography and surface above sea level, respectively, and k is a constant, which, according to Kouba (2008), attains the value 2000. Equation 9 shows that errors in the surface height of, e.g., 100 and 500 m, induce errors of 5% and 28%, respectively, which can translate into errors in the WTC of 1 cm and 5.6 cm for a WTC value of 20 cm (Fernandes et al., 2020). The WTC provided in most current altimetric products are, therefore, subject to errors of this magnitude since the model-derived WTC are commonly referred to the model orography (or given at sea level).
Since Equation 9 should be used to perform WTC height reductions for surface heights up to 1000 m (Kouba, 2008), UPorto has been investigating its improvement. Some progress has been made by using k coefficients dependent on geographic location and time (Vieira et al., 2019a), herein called UP coefficients. Results show that the use of UP coefficients, instead of Kouba's, has led to an improvement in the RMS error of the WPD better than 1 cm.

WTC from GNSS
WTC can also be estimated at GNSS stations with an accuracy of a few millimetres. (e.g. Niell et al., 2001; Pacione et al., 2011; Fernandes et al., 2010; Fernandes et al., 2013a; Vieira et al., 2019b). From GNSS data processing, knowing the slant total delay (STD) along the elevation angle of the GNSS satellites, E, and the mapping functions $mf_h(E)$ and $mf_w(E)$, also function of the same angle, and using a zenith hydrostatic delay (ZHD or, equivalently, the dry tropospheric path delay, the symmetric of DTC) calculated *a priori*, the zenith wet delay (ZWD or, equivalently,

WPD) is solved from Equation 10. Therefore, the zenith tropospheric delay (ZTD) is obtained as the sum of the ZHD (*a priori* value) and the ZWD, at each GNSS station, being the quantity that is publicly provided by the GNSS processing centres. Computing a more accurate ZHD value, as described in Section 2.1, an updated value of ZWD is obtained subtracting this latter ZHD from ZTD. This value of ZWD (or WPD) is used as input in the GPD+. In IW regions, GNSS may be the best source for WPD retrieval (Fernandes et al., 2014; Vieira et al., 2018). GNSS-derived WPD from coastal GNSS stations are also crucial for the estimation of WTC in the CZ and are valuable for assessing the accuracy and stability of MWR-derived WTC (Sibthorpe et al., 2011; Fernandes and Lázaro, 2018; Vieira et al., 2019b).

$$STD(E) = ZHD\ mf_h(E) + ZWD\ mf_w(E) \qquad \text{Eq. 10}$$

2.2.2 Algorithm Definition: Processing Steps

GNSS-derived WPD (or WTC) refer to the altitude of the station for which they are calculated, which can be significantly different from sea level. WTC from SI-MWR refer to sea level, while those from NWM are referred to the height of the model orography. To be used in the CZ, these WTC observations and model values must be reduced to sea level, while for IW regions, they should be provided at the height of the surface. Therefore, a crucial step in the preparation of the WTC dataset that will be used as input in the GPD+ is the height reduction.
To compute the WTC, the following steps should be followed:
Preprocessing steps:

1. For the period of the computations, read GNSS ZTD data from all available stations. From ERA5 SLP grids, estimate ZHD at station height using Equations 1 and 2. For validation purposes, ZWD from ERA5 (ZWD_mod) is also estimated using Equation 5. Then, compute ZWD from GNSS at station height from Equation 10 and ZWD =ZTD – ZHD. Store fields Time, ZHD, ZWD and ZWD_mod. Station coordinates are stored on a separate file.
2. For each new GNSS station, interpolate geoid height from EIGEN-6C4, ERA5 model orography, distance from coast or lake border from GSHHG (Global Self-consistent, Hierarchical, High-resolution Geography Database) (Wessel and Smith, 1996) and Natural Earth (NACIS, 2020), and store fields on station coordinates file.
3. For the period of the computations, read TCWV data from all available SI-MWR (TCWV_SI). Interpolate TCWV (TCWV_mod) and T_0 from ERA5 for each measurement point. Compute T_m from Equation 4 and store fields Time, Latitude, Longitude, TCWV_SI, TCWV_mod and T_m, in NetCDF files. All fields refer to sea level.

Processing steps:

1. Read data from the altimeter data file: latitude, longitude and instant of measurement.
2. Read WTC datasets previously computed from SI-MWR TCWV data at sea level.
3. Read WTC datasets previously computed from GNSS precise tropospheric data, at station height.
4. Read model orography and ACE2 DEM.
5. For each along-track measurement point:
   - Check the validity of the MWR-derived WTC. This step is performed using the flags provided in the altimeter products and a set of criteria established by UPorto, which are usually tuned for each mission. Then, proceed as follows:

- If the MWR-derived WTC is valid, this is the value that will be output and jump to step 6; in case of CryoSat-2, skip this step.
- Interpolate the model orography and ACE2 DEM to the geodetic location of the point.
- Compute the WTC from ECMWF to use as first guess in GPD+, using Equations 5 and 6 and the TCWV and T_0 fields from the ECMWF model. The WTC are computed at the orography level for the instant and location of each altimeter file data record.
- Compute WTC from TCWV_SI using Equation 7.
- Reduce the WTC from ERA5 and the WTC values derived from GNSS to sea level (for CZ points) or to surface elevation (for IW points), using Equation 9. For IW points, reduce the WTC from SI-MWR to surface elevation.
- Select all observations within the spatial and temporal influence regions centred on the point for which an estimate is required (valid WTC from MWR, WTC from GNSS and SI-MWR).
- Compute a GPD+ WTC, using ECMWF as first guess, updating this value if observations, previously reduced to sea level or surface height, are available; this is the WTC estimated that will be output (gpd_wet_tropo), so jump to step 6.

6. Write the output file. For each altimeter data record, the following variables are output in this order: Time (as provided in the input L1 file), latitude, longitude, h_surf, WTC from UPorto (gpd_wet_tropo), data source flag for the Wet Tropospheric Correction from UPorto (gpd_wet_tropo_flag).

For each S3 and CS2 ground-track point the WTC shall be:

- The ERA5 model-derived WTC in the absence of observations.
- The S3 MWR-derived WTC (eventually scaled after calibration), for all S3 points with valid MWR values.
- A new estimation obtained from data combination of all available observations for all S3 points with invalid MWR values and for all CS2 points.

All WTC values will be provided at surface level: i) sea level (h=0) over open ocean and CZ; ii) surface level (h given by ACE2 or local reference surface) over IW regions.

2.2.3 Development Choices and Trade Offs

The computation of the WTC will incorporate a set of new developments:

- An improved modelling of the height dependence of the WTC. As explained before, the WTC has a height dependence that, due to its variability, is difficult to model. The use of improved expressions for this vertical variation (Vieira et al., 2019a) will have an effect in the GPD estimates, which are combined WTC values often obtained at different heights and different from the height of point at which an estimate is required. The largest impacts are expected to be in the coastal regions and inland waters, the focus of this project.
- The use of the most recent reanalysis model from ECMWF (ERA5), for the first time providing global hourly WTC grids, in the absence of observations.
- An integrated approach for open-ocean, CZ and IW regions, by generating a single product, valid for all surface types, despite different specificities in terms of the WTC retrieval that CZ and IW regions have. This way, the WTC datasets shall be continuous, valid over all surface types and provided at 20 Hz. However, depending on project decisions, differences may exist between CZ and IW products, e.g., CZ WTC may be provided at 1 Hz instead of 20 Hz.

For S3, using tuned validity criteria and the inter-calibrated MWR datasets, new WTC will be estimated for all points which have been considered to have an invalid MWR-based WTC. In case of CryoSat-2 estimations will be performed for all points.

2.2.4 Data Flow

INPUT DATA

For the computation of the WTC, the following input is needed:
- Altimeter data files generated within the project (merged L1BS-L1B-L2 product);
- TCWV grids from SI-MWR;
- ZTD from GNSS stations;
- ECMWF TCWV and 2-metres temperature fields;
- ECMWF model orography;
- GSHHG and Natural Earth databases;
- Altimeter Corrected Elevations 2 (ACE2) Digital Elevation Model (DEM) at highest resolution (3″);
- Mean river profiles and mean lake levels, if available.

OUTPUT DATA

The output product will be a NetCDF/ASCII file containing the L2 WTC at the same rate as provided in the input altimeter data files. As summarised in Section 3, L2 WTC may be provided at 1 Hz for ocean and coastal points but at a higher rate (20 Hz) for points over land. The provision of a single file with a continuous WTC over all surface types is supported, in this case, at high rate (20 Hz). The output product should also contain the height at which the WTC has been computed, allowing in this case the update of the correction in case new retracked altimeter ranges are computed. Moreover, the WTC should be provided at sea level for ocean and coastal points and at surface height given by ACE2 DEM or local reference surface for points over inland water bodies.

3 Summary

Despite the increasing awareness about the requirements for accurate retrieval of tropospheric path delays over the coastal zone and over inland waters, there is still no agreement on the best way to provide these corrections over these regions.
Although the methodologies used in DTC retrieval are well established, over coastal and inland water zones some altimeter products still contain significant errors, of several centimetres. Therefore, errors on DTC may be larger than those of the wet tropospheric correction (Vieira et al., 2018; Fernandes et al., 2000; Fernandes et al., 2018).
Currently, in CryoSat-2, both the DTC and WTC are given at 1 Hz, at the level of the ECMWF model orography, while in Sentinel-3 two products are provided, both at 1 Hz: one at sea level and another at the level of the altimeter measurement. Therefore, as explained in RD-01 and in this technical note, while in CS2 the errors are essentially due to the fact that the corrections are given at 1 Hz, at the level of model orography, instead of at sea level or surface height, in S3 the errors, besides these, are also due to the fact that the corrections are given at measurement height.
Considering the specificities of coastal and inland water regions and the height dependence of both tropospheric corrections, the following conclusions can be withdrawn:
i) Coastal zone
To avoid interpolation errors, over open and coastal ocean, the corrections should be provided at sea level. Although high rate (20 Hz) corrections are preferable for use with high rate products, considering the smoothness of both corrections over ocean, 1 Hz rate give enough detail (i.e. the corrections can be interpolated to 20 Hz without introducing any significant error).
ii) Inland waters
Over inland waters the corrections should be computed, not just interpolated, at 20 Hz. Therefore, the reduction of the corrections to the adequate height must be taken into account. To perform the height reduction over IW regions, the height of the surface must be known. For global studies, the best reference is an accurate digital elevation model such as ACE2, while for local applications, the most appropriate reference surface is mean surface level (river profile or lake level).
UPorto supports the generation of global datasets, valid over all surface types. Consequently, it is our intention to provide both corrections at the highest rate of the altimeter measurements (20 Hz), independently of being CZ or IW domains.

4 References

Berry, P. A. M., Smith, R. G., Benveniste, J. (2008). ACE2: The New Global Digital Elevation Model, in Gravity, Geoid and Earth Observation, vol. 135, edited by S. P. Mertikas, Springer., 2008, Chania, Greece, 231–238.

Bevis, M., Businger, S., Chiswell, S., Herring, T. A., Anthes, R. A., Rocken, C., Ware, R. H. (1994). GPS meteorology—Mapping zenith wet delays onto precipitable water. J. Appl. Meteorol., 33, 379–386.

Boehm, J., Heinkelmann, R., Schuh, H. (2007). Short note: a global model of pressure and temperature for geodetic applications. J. Geod. doi:10.1007/s00190-007-0135-3.

Chelton, D. B., Ries, J. C., Haines, B. J., Fu, L. L., Callahan, P. S. (2001). Satellite Altimetry. In Satellite Altimetry and Earth Sciences: A Handbook of Techniques and Applications; Fu, L. L., Cazenave, A., Eds.; Academic: San Diego, CA, USA, 2001; Volume 69, pp. 1–131.

Davis, J. L., Herring, T. A., Shapiro, I. I., Rogers, A. E. E., Elgered, G. (1985). Geodesy by Radio Interferometry—Effects of atmospheric modeling errors on estimates of baseline length. Radio Sci., 20, 1593–1607.

Fernandes, M.J., and Lázaro, C. (2016). GPD+ Wet Tropospheric Corrections for CryoSat-2 and GFO Altimetry Missions. Remote Sensing, 8(10), 851. doi:10.3390/rs8100851

Fernandes, M.J., and Lázaro, C. (2018). Independent assessment of Sentinel-3A wet tropospheric correction over the open and coastal ocean. (2018) Remote Sensing, 10(3), 484. doi:10.3390/rs10030484

Fernandes, M.J., Lazaro, C., Nunes, A.L., Pires, N., Bastos, L., Mendes, V.B. (2010). GNSS-Derived Path Delay: An Approach to Compute the Wet Tropospheric Correction for Coastal Altimetry. IEEE Geoscience and Remote Sensing Letters, 7(3), 596-600. doi:10.1109/lgrs.2010.2042425

Fernandes, M.J., Nunes, A.L., & Lázaro, C. (2013a). Analysis and Inter-Calibration of Wet Path Delay Datasets to Compute the Wet Tropospheric Correction for CryoSat-2 over Ocean. Remote Sensing, 5(10), 4977-5005. doi:10.3390/rs5104977

Fernandes, M.J., Pires, N., Lázaro, C., Nunes, A.L. (2013b). Tropospheric delays from GNSS for application in coastal altimetry. Advances in Space Research, 51(8), 1352-1368. doi:10.1016/j.asr.2012.04.025

Fernandes, M.J., Lázaro, C., Nunes, A.L., Scharroo, R. (2014). Atmospheric Corrections for Altimetry Studies over Inland Water. Remote Sensing, 6(6), 4952-4997. doi:10.3390/rs6064952

Fernandes, M.J., Lázaro, C., Ablain, M., Pires, N. (2015). Improved wet path delays for all ESA and reference altimetric missions. Remote Sensing of Environment, 169, 50-74. doi:10.1016/j.rse.2015.07.023

Fernandes, M.J., Lázaro, C., Pires, N., Vieira, T., Vieira, E. (2018). On the need for high-rate range corrections for satellite altimetry studies over coastal and inland water regions. Presented at the 11th Coastal Altimetry Workshop. ESA-ESRIN, Frascati, Italy, 12-15 June 2018.

Fernandes, M. J., Lázaro, C., Vieira, T. (2020). On the Role of the Troposphere in Satellite Altimetry. Submitted to Remote Sensing of Environment in June 2020.

Hopfield H. S. (1969). Two-quartic tropospheric refractivity profile for correcting satellite data. J. Geophys. Res. 74, 4487-4499.

Keihm, S.J., Zlotnicki, V., Ruf, C. S. (2000). TOPEX Microwave radiometer performance evaluation, 1992–1998. IEEE Trans. Geosci. Remote Sens., 38, 1379–1386.

Kouba, J. (2008). Implementation and testing of the gridded Vienna Mapping Function 1 (VMF1). J. Geodesy, 82, 193–205.

Legeais, J. F., Ablain, M., Thao, S. (2014). Evaluation of wet troposphere path delays from atmospheric reanalyses and radiometers and their impact on the altimeter sea level, Ocean Sci., 10, 893-905, doi:10.5194/osd-11-1613-2014.

Mendes, V.B. (1999). Modeling the Neutral-Atmosphere Propagation Delay in Radiometric Space Techniques. PhD. Thesis, University of New Brunswick, Fredericton, New Brunswick, Canada.

Miller, M., Buizza, R., Haseler, J., Hortal., M., Janssen, P., Untch, A. (2010). Increased resolution in the ECMWF deterministic and ensemble prediction systems. ECMWF Newsletter 124: 10-16.

North American Cartographic Information Society (NACIS) (2000), Natural Earth, https://www.naturalearthdata.com/, accessed in June, 2020.

Niell, A.E., Coster, A.J., Solheim, F.S., Mendes, V.B., Toor, P. C., Langley, R.B., Upham, A. (2001). Comparison of measurements of atmospheric wet delay by radiosonde, water vapor radiometer, GPS, and VLBI. J. Atmos. Oceanic Technol. 18, 830-850.

Pacione, E., Pace, B., Vedel, H., de Haan, S., Lanotte, R., Vespe, F. (2011). Combination methods of tropospheric time series, Adv. Space Res. 47, 323–335.

Saastamoinen, J. (1972). Atmospheric correction for troposphere and stratosphere in radio ranging of satellites. In Henriksen, S., Mancini, A., Chovitz, B. (Eds.) The use of artificial satellites for geodesy 15, 247-251, Geophysics Monograph Series, AGU, Washington D.C.

Sibthorpe, A., Brown, S., Desai, S.D., Haines, B.J. (2011). Calibration and Validation of the Jason-2/OSTM Advanced Microwave Radiometer Using Terrestrial GPS Stations, Marine Geodesy, 34:3-4, 420-430, DOI:10.1080/01490419.2011.584839.

Stum, J., Sicard, P., Carrere, L., Lambin, J. (2011). Using objective analysis of scanning radiometer measurements to compute the water vapor path delay for altimetry. IEEE Trans. Geosci. Remote Sens., 49, 3211–3224.

Vieira, T., Fernandes, M.J., Lázaro, C. (2018). Analysis and retrieval of tropospheric corrections for CryoSat-2 over inland waters. Advances in Space Research, 62 (6), 1479-1496. doi:10.1016/j.asr.2017.09.002

Vieira, T., Fernandes, M.J., Lázaro, C. (2019a). Modelling the altitude dependence of the Wet Path Delay for coastal altimetry using 3D parameters from ERA5. (in preparation, to be submitted to Remote Sensing).

Vieira, T., Fernandes, M.J., Lázaro, C. (2019b). Independent Assessment of On-Board Microwave Radiometer Measurements in Coastal Zones Using Tropospheric Delays From GNSS, IEEE Trans. Geosci. Remote Sens, vol. 57, no. 3, pp. 1804-1816, March 2019, doi: 10.1109/TGRS.2018.2869258.

Wessel, P. and Smith, W. H. F. (1996). A global, self-consistent, hierarchical, high-resolution shoreline database, Journal of Geophysical Research, Solid Earth, vol. 101, no. B4, pp. 8741–8743, doi: 10.1029/96JB00104.