# MODELLING THE HEIGHT DEPENDENCE OF THE WET PATH DELAY USING ERA5 MODEL-LEVEL FIELDS


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## INTRODUCTION & OBJECTIVE

- ✓ Accurate determination of sea surface height from satellite altimetry depends on the Wet Path Delay (WPD) accuracy.
- ✓ WPD from on-board Microwave Radiometers (MWR) measurements (at sea level) become invalid over coastal and inland waters [1].
- ✓ Global Navigation Satellite Systems (GNSS) and atmospheric models, e.g. from European Centre for Medium-Range Weather Forecasts (ECMWF) are alternative WPD sources (at station height and at the level of their orography, respectively) [2].
- ✓ An expression to reduce the WPD from GNSS station height and orography level to sea level (over coastal zones) and to water body height (over inland waters) is required [3]. There is an expression for the altitude modelling of the WPD [4], however it has some limitations.
- ✓ The **objective** of this study is the modelling of the height dependence of the WPD, aiming to derive improved expressions to account for its complex 4D variation.

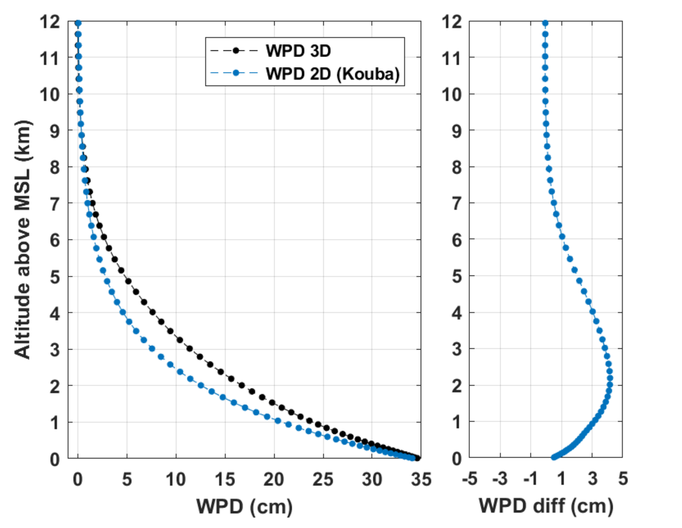
## DATA & METHODOLOGY

- ✓ The reanalysis model **ERA5** from ECMWF (1h, 0.3°x0.3°, 137 vertical levels) is used. Two types of WPD are derived from ERA5:
  1. From single-layer parameters and then reduced to the level of interest with the Kouba or the UP expression (2D approach) [4];
  2. From numerical integration of model-level parameters and then interpolated to the level of interest (3D approach).
- ✓ This study is performed in two main steps:
  1. The errors introduced when using the Kouba expression are assessed, providing a quantification of their magnitude and spatial distribution.
     - ✓ WPD vertical profiles computed using the 2D approach are compared with the corresponding profiles computed from the 3D approach;
     - ✓ An independent assessment is performed at GNSS sites by comparing GNSS-derived WPD at station height and those derived from ERA5 using different methodologies (2D and 3D).
  2. An improved expression for the altitude dependence of the WPD is developed, considering expressions with regional dependence terms.

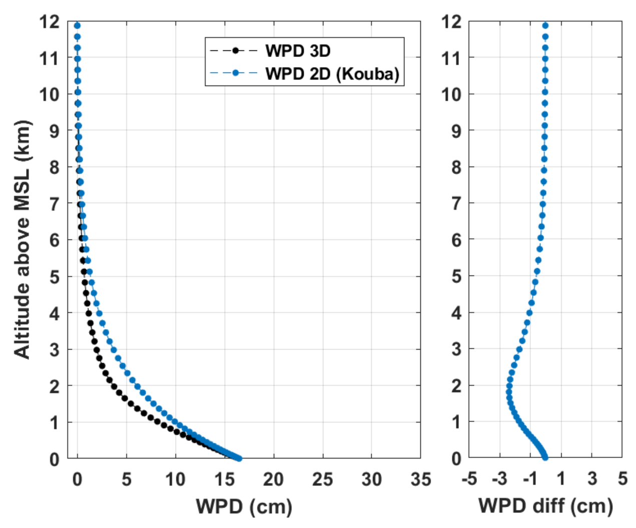
## ASSESSMENT OF THE KOUBA EXPRESSION

Fig. 1-4 show some examples of the WPD vertical profiles. **Black points** represent WPD derived from vertical integration of model-level parameters from ERA5, while **blue points** represent those derived from single-layer parameters, at orography level, and then reduced with the Kouba expression [4], at each vertical level. Both profiles are annual means (2010) at each point. Right panels represent the difference between them.

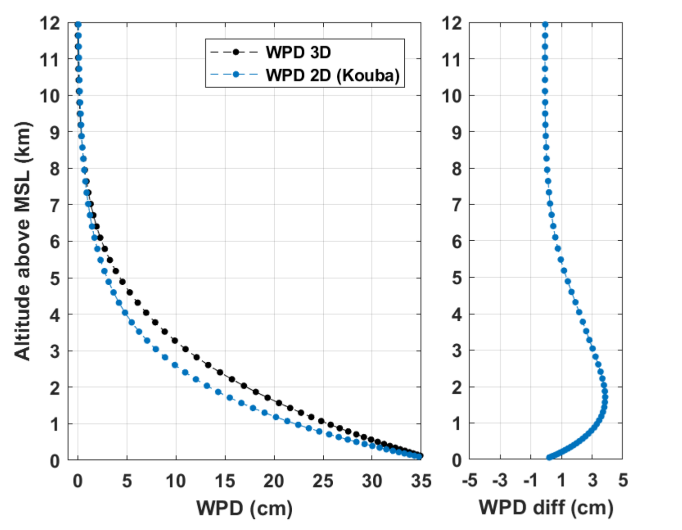
Fig. 1 shows the point with the largest difference (at location as observed in Fig. 5), where the Kouba expression is not clearly a good modelling, while Fig. 4 shows an example where WPD vertical variation is well modelled by the Kouba expression.



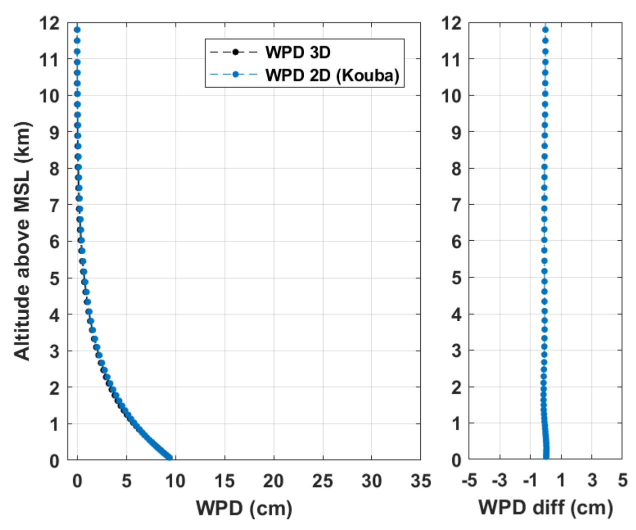

↑**Fig. 1** – Vertical profiles of WPD at 0°,108°E with maximum difference of 4.2 cm.




↑**Fig. 2** – Vertical profiles of WPD at 18N°,156°W.

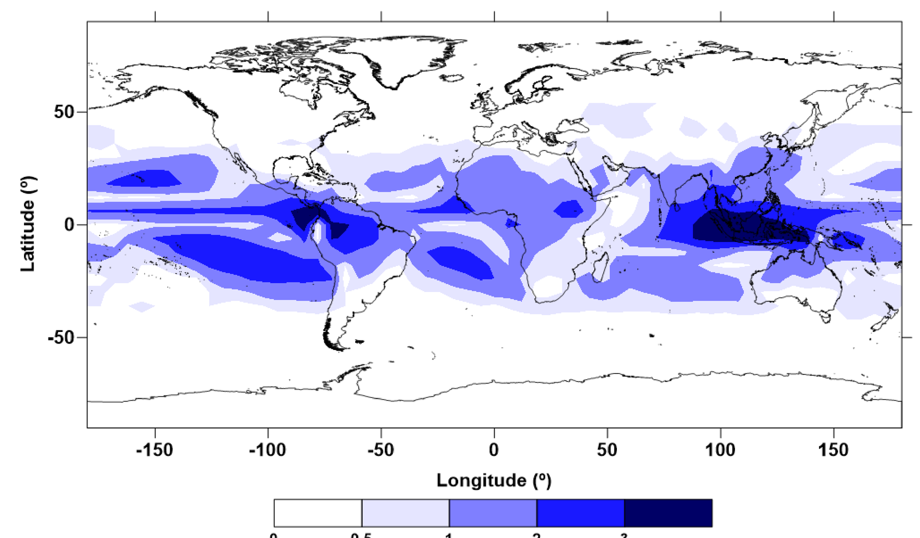



↑**Fig. 3** – Vertical profiles of WPD at 6°N,78°W.

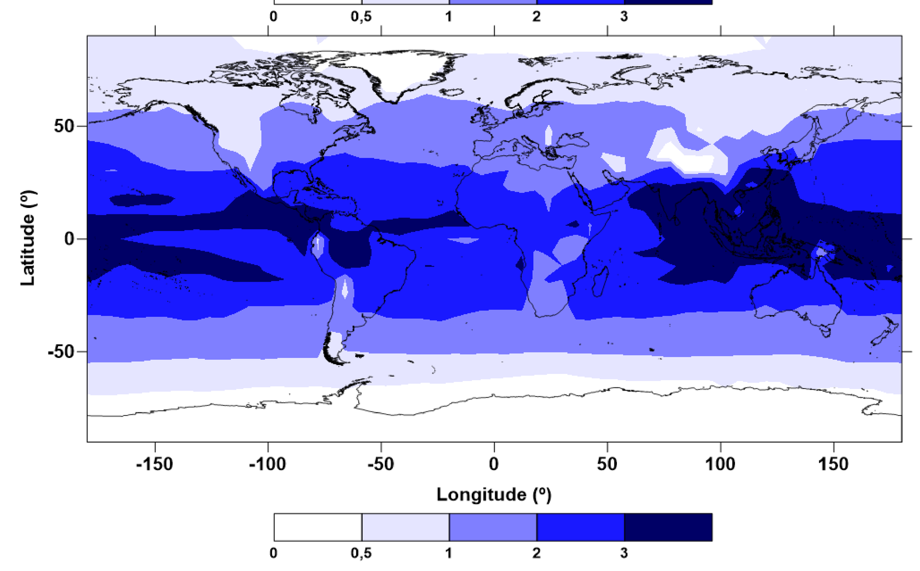



↑**Fig. 4** – Vertical profiles of WPD at 54°N,6°W.

The mean vertical profiles as represented in Fig. 1-4 were computed globally at 6°x6°. At each point of this grid, absolute differences between the two WPD are computed and the maximum differences (cm) observed at a certain altitude are represented in Fig. 5.



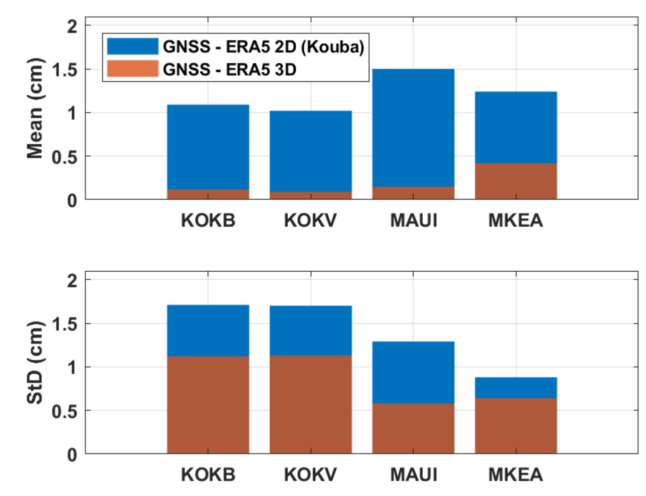

←**Fig. 5** – Maximum absolute WPD differences (cm) between 3D and 2D (Kouba expression), when using annual mean profiles.
Maximum absolute differences larger than 0.5 cm are observed at altitudes above MSL smaller than 3000 m.




←**Fig. 6** – RMS (cm) of the maximum absolute WPD differences between 3D and 2D (Kouba expression), using profiles at 6-h intervals during one full year (2010).

Fig. 5 represents the errors introduced when using the Kouba expression, providing a global quantification of their magnitude and spatial distribution, in terms of annual mean profiles. Fig. 6 provides the same with RMS values, but in terms of instantaneous profiles. Due to the WPD spatial variation, Fig. 5-6 show that Kouba expression is suitable for high latitudes, however close to the equator differences of several centimeters exist.

A comparison between GNSS-derived WPD and those derived from ERA5 (2D and 3D) was performed at each station height. Fig. 7 shows the statistics for some stations.



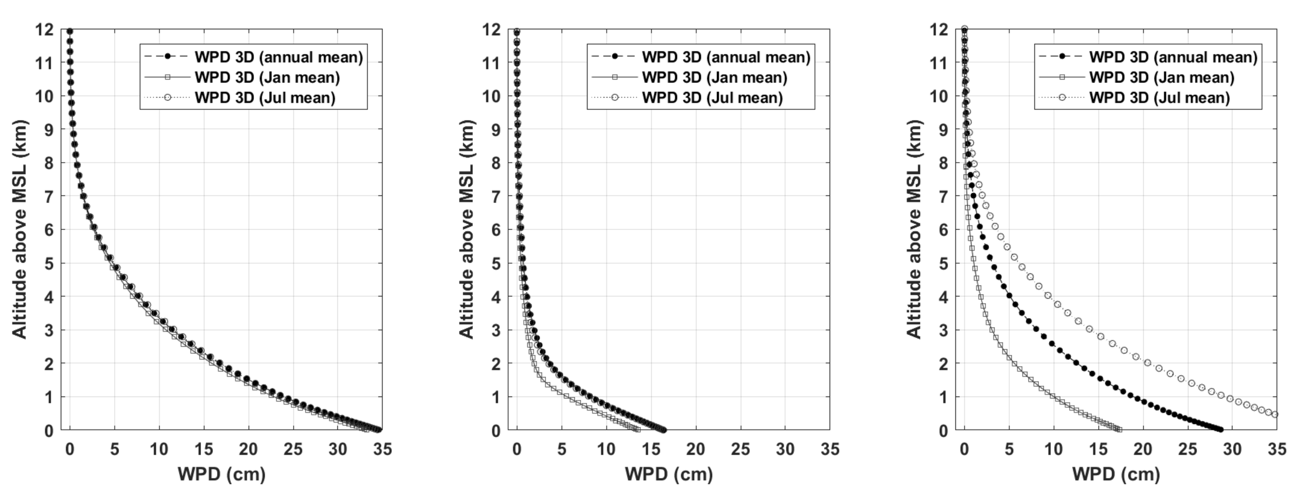

↑**Fig. 7** – Absolute mean and standard deviation (cm) of the differences between GNSS-derived WPD and 2D approach (with Kouba expression) and between GNSS and 3D approach, at the altitude of the corresponding GNSS station. A time span of three years (2010-2012) was used to perform this comparison.

When compared with the 2D approach using the Kouba expression, the 3D approach can reduce the differences between GNSS and ERA5, both in terms of mean and standard deviation (Fig. 7).

This comparison allows to assess the Kouba expression and also the 3D computation of the WPD vertical profiles, showing that the Kouba expression needs to be improved.

**Fig. 5-6 show the requirement of modelling the height dependence of the WPD, aiming to derive improved expressions to account for its complex 4D variation, mainly for latitudes in the range [-50 50]°.**

## DEVELOPMENT OF AN IMPROVED EXPRESSION



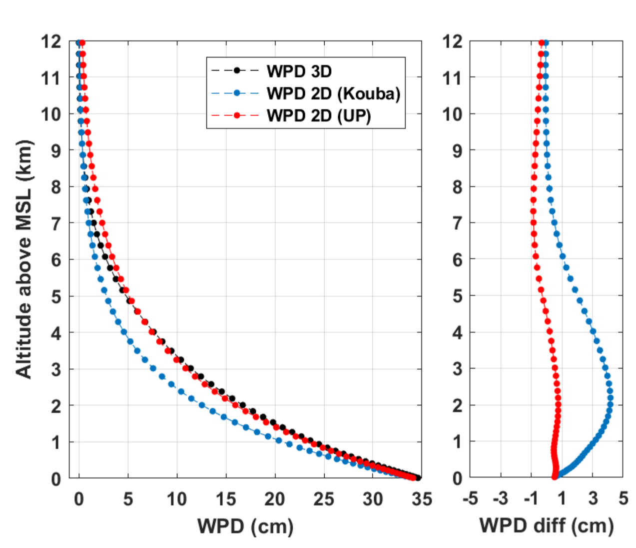

↑**Fig. 8** – Mean vertical profiles of WPD at 0°,108°E (left panel), 18°N,156°W (middle panel) and 18°N,84°E (right panel). Points represent annual (2010) means, while squares and circles represent monthly means (January and July 2010, respectively).

Fig. 8 represents means of the WPD derived from ERA5 using the 3D approach, at three different locations. Points represent annual means (2010), while squares and circles represent monthly means. The way how the WPD varies with the altitude can be different for different epochs, at the same point, however the curves seem similar.

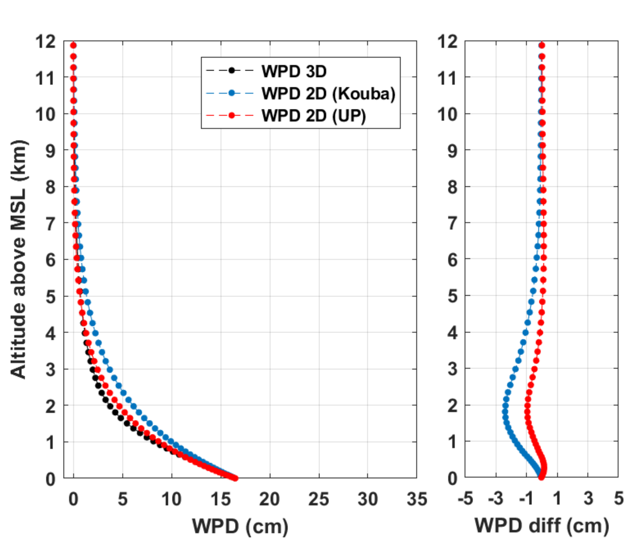
From the annual mean profiles, the decay coefficient (α) of the following equation was determined for each point in a grid 6°x6°.

$$WPD_h = WPD_{surf} \cdot e^{\alpha(h-h_{surf})}$$

Using this equation with regional dependence coefficients (UP expression) the profiles represented by red points in Fig. 9-10 are obtained.




↑**Fig. 9** – Vertical profiles of WPD at 0°,108°E.

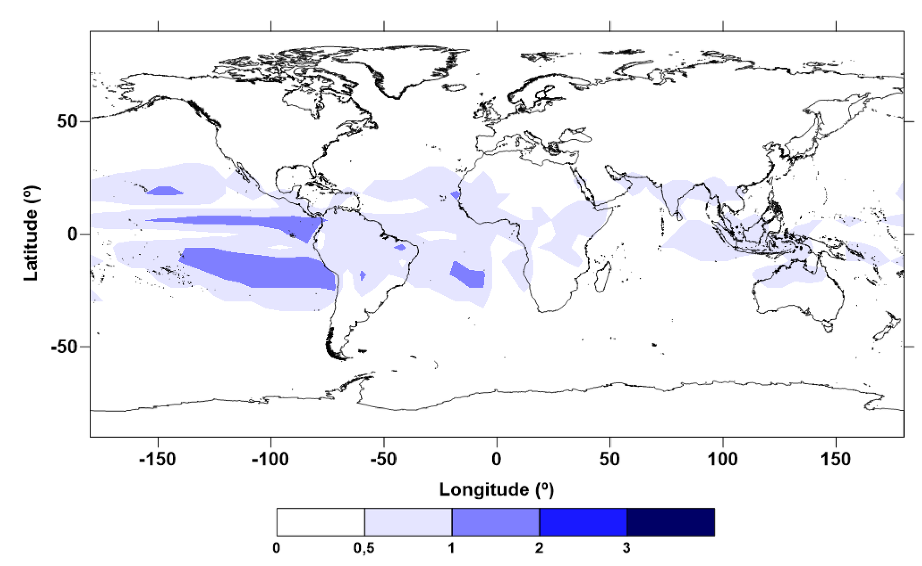



↑**Fig. 10** – Vertical profiles of WPD at 18N°,156°W.

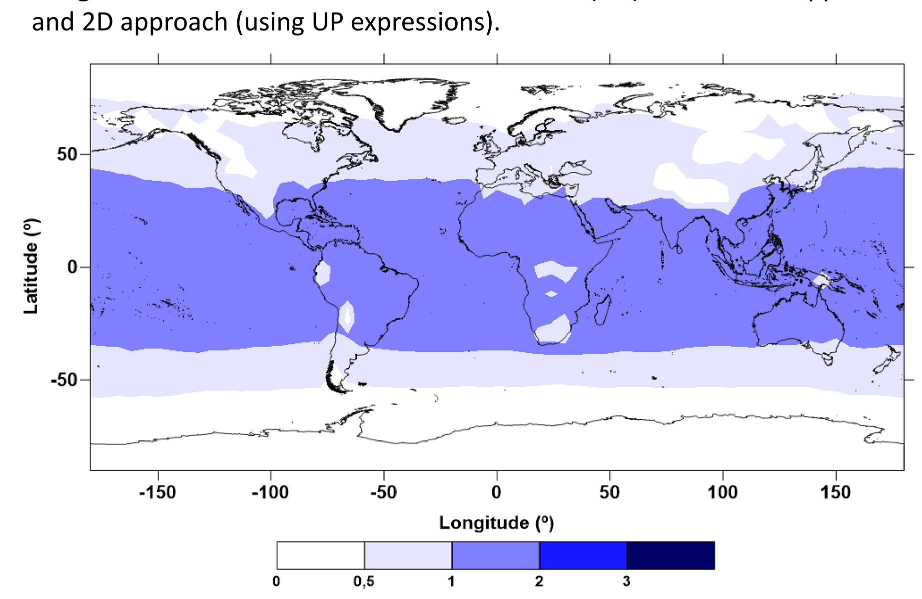
Fig. 9-10 show that **UP expression** reduces the differences between 3D and 2D WPD, when compared with the **Kouba expression**. The mean vertical profiles as represented in Fig. 9-10 were computed globally. At each point, the differences between 3D and 2D (UP expression) are computed and the absolute maximum differences (cm) observed at a certain altitude are represented in Fig. 11.

Fig. 12 represents the RMS of the maximum absolute differences between 3D approach and 2D using UP expressions, using profiles at 6-h intervals during 2010.

**Fig. 12 shows RMS values smaller than 2 cm (UP expressions), while Fig. 6 shows RMS values up to 4.4 cm (Kouba expression).**




↑**Fig. 11** – Maximum absolute WPD differences (cm) between 3D approach and 2D approach (using UP expressions).




↑**Fig. 12** – RMS of the maximum absolute WPD differences (cm) between 3D and 2D (UP expressions), using profiles at 6-h intervals during one full year (2010).

## CONCLUSIONS & FUTURE WORK

- ✓ The only expression available in the literature for the modelling of the height dependence of the WPD [4] assumes that the altitude dependence of the WPD is the same over the whole globe.
- ✓ The first results show that this expression has limitations due to the complex 4D variation of the WPD, with errors up to several cm in some regions.
- ✓ From WPD at several vertical levels (model-levels from ERA5), an improved expression was developed in this study (UP expression), considering regional dependence coefficients.
- ✓ This new expression has errors smaller than the Kouba expression. The maximum RMS for the Kouba expression is 4.4 cm (Fig. 6), while for the UP expression is 1.8 cm (Fig. 12).
- ✓ In order to establish the best modelling, future work will consider temporal dependence of the modelled coefficients and piecewise functions at different altitude intervals.
- ✓ The last step of this study will be the validation (using e.g. radiosondes and GNSS data) and application of the new expressions in cases of interest (coastal zones and inland waters).
- ✓ These expressions are crucial for the retrieval of accurate WPD measurements over coastal regions and inland waters, such as rivers and lakes, in order to obtain accurate absolute water levels.

## References


[1] Vieira, T.; Fernandes, M.J.; Lázaro, C. Independent assessment of on-board Microwave Radiometer measurements in coastal zones using tropospheric delays from GNSS. IEEE Trans. Geosci. Remote Sens. 2018, accepted.

[2] Fernandes, M.J.; Lazaro, C.; Nunes, A.L.; Scharroo, R. Atmospheric corrections for altimetry studies over inland water. Remote Sens. 2014,6, 4952–4997

[3] Vieira, T.; Fernandes, M.J.; Lázaro, C. Analysis and retrieval of tropospheric corrections for CryoSat-2 over inland waters. Advances in Space Research 62 (2018) 1479–1496

[4] Kouba, J. Implementation and testing of the gridded vienna mapping function 1 (VMF1). J. Geod.2008,82,193–205.