Review of the paper

MS No.: angeo-2018-49

Title: An empirical zenith wet delay correction model using piecewise height functions

General comment

The paper presents a climatology of the ZWD field by modelling the spatial, temporal and vertical variations of this field. With respect to state-of the art models such as GPT2w, the novelty of the paper is the modelling of the vertical variation of the ZWD by dividing the troposphere into three different regions (0-2 km; 2-5km and 5-10km) and adjusting different functions for each region (quadratic polynomials in the first case and exponentials in the last two cases).

The topic is of interest as the wet path delay is a major error source in various remote sensing techniques such as satellite altimetry, as well as in satellite positioning and navigation.

The paper is scientifically sound and well structured. Although the paper is generally well written, some parts, particularly those concerning the discussion of the results, need some language improvement and polishing.

The less strong points of the paper are the need for some more details and clarification in some parts and the fact that the proposed model is only a marginal improvement with respect to GPT2w and that, considering the large variability of the ZWD field, improvements of millimetre level are insignificant. Nevertheless, the proposed methodology is overall correct and interesting.

Below I point out some suggestions for improvement.

Detailed comments

General comment to all figure captions: add to captions the necessary information to understand what each figure represents, e.g. the location of the represented point, etc. Each figure should be self-explanatory.

The plots of ZWD against height are more intuitive if ZWD is given in x-axis and height in the y-axis. Although not mandatory, please consider changing the plots accordingly.

1. Introduction

The authors should distinguish between the various types of ZWD models, namely:

(1) Models that make use of observations (e.g. radiosonde profiles) or 3D fields from atmospheric models (e.g. ECMWF) such as the Davis et al, 1995, Eq. (1). These provide the best accuracy as they model the spatial, temporal and vertical variations of the field.

(2) Models that make use of single layer parameters such as total column water vapour (TCWV) and temperature, such as those by Bevis et al. 1992, 1994. See for example, Fernandes et al., 2013 for a reference to the use of this model and that of Stum et al., 2011 which only uses TCWV. These provide similar results to those in (1) but only at the level of the model orography to which the meteorological parameters refer to. Note that TCWV includes the modelling of the amount of water vapour along the vertical profile up to the reference orography, so the result is not very different from case (1). As this orography may depart significantly from the actual surface and the vertical variation of the ZWD is not well known, at a different surface elevation they possess errors associated with the uncertainty in the modelling of the ZWD height variation (see for example Fernandes et al, 2014, Vieira et al,. 2017).

(3) Models such as Saastamoinen or Hopfield, that make use only of surface observations, these lack information about the vertical distribution of the water vapour, so they are considerably less accurate than (1) and (2)

(4) Climatologist which, unlike the other mentioned approaches, do not use observations nor meteorological parameters from atmospheric models; they attempt to model the space-time and sometimes also the vertical variation of the ZWD field, such as the GPT2w type of models.

Clearly, the paper proposes a model that belongs to the last type. The paper would benefit from a clarification of this nature, putting this study into the right context. Moreover, the accuracy of each of the two climatology models used in the paper for comparison with the new model (GPT2w, and UNB3m)) should be clearly indicated as quoted by the respective authors (e.g. 3.6 cm for GPT2w)

The paper should include a brief description of the space-time variability of the ZWD field as well as of its vertical variation, as published in the literature, including proper references. The vertical variation is mentioned in section 2, but the space-time variations are missing. About the vertical variation, the work by Kouba, 2008 is worth mentioning.

The use of the words “obvious” and “obviously” is not recommend in scientific writing. I suggest to replace them throughout the text by “clear” or similar synonyms.

2. Vertical variations of ZWD

In Eq. (1) the authors quote the values for the refractivity constants as given by Bevis et al, 1992. However, Bevis et al, 1994 revisited these constants. I recommend the addition of this reference (see list of some suggested references at the end of this review) and of the updated values for the constants (k_3=3.739 x10^5 K^{2}mbar^{-1}; k_2' =22.1 Kmbar^{-1}).

Authors should justify the use of “pressure levels” instead of “model levels” as, according to ECMWF, for wet path delay computations the second should be adopted as they lead to better accuracy.

Although ECMWF allows the extraction of ERA Interim with various spatial resolutions, the actual spatial resolution of the model is 0.75°× 0.75° (regular grid) or about 80 km (Gaussian grid), Dee et al., 2011. Please rephrase the sentence describing the model accordingly.

Equation (2): a reference should be provided for the first line of Eq. (2).

Caption of Figure 1 – Please add time and place to which profiles correspond.

Caption of Figure 2 – Please explain how these figures were made. Points represent mean values of ZWD gradients for which period and location?

The sentence “*the ZWD gradients at high latitudes are much larger and water vapour is more variable than at low latitudes, resulting from the fact that the water vapour at high latitudes are more variable*” is not true and needs rephrasing. Please see for example figures 1 and 2 in Fernandes et al, 2013 for the mean and standard deviation of the ZWD. You can see that the

ZWD variability is largest in the tropics and minimum at high latitudes. In the paper you probably refer to the variation of ZWD with height. Even in this case the sentence is also not true as the scales in the various plots in figures 3 and 4 are different. Please use the same scale in all figures, so that they can be compared. Some additional background information about the ZWD variability (in space, time and vertically) by citing references such as the one mentioned above should be given at the introduction.

In "and semi-annual, cycles" please remove the ",".

Table1 – I don't understand what is represented in the first line of the table. According to the text, the piecewise height functions statistics should be the same to those for the quadratic functions for the layer 0-2km and to the exponential functions in the other two cases. Please explain.

3 The HZWD model

Figure 6 – for comparison of the various plots the sane colour scale should be used. In this way the decrease of ZWD with height would be clearer.

"For each grid point, there are 27 parameters" – please indicate explicitly the 27 parameters, e.g. 5 for Z_1, etc.

Please avoid using the same symbol for different variables in different equations, e.g. β.

4 Validation and analysis of the HZWD model

In my view, the sub-section on the validation using ECMWF ERA Interim data for the year 2015 does not add any information to the validation performed with radiosondes. Indeed, the comparison with ECMWF data from a different period is not a true validation. Since the HZWD model only uses periodic functions (annual and semi-annual), examining the differences between model predictions and ECMWF-derived ZWD for a year inside or outside the 10-year period used in model fitting should give very similar results. This would not be the case if e.g. the HZWD model included inter-annual signals. Please try to explain the utility of including this analysis or consider removing it from the paper.

Please define RMS.

In the sentence "In equation (5) and (6), ZWD_i^M is the value estimated by the model and ZWD_i^0 is the reference value.", clarify the sentence by writing "In equation (5) and (6), ZWD_i^M is the value estimated by the HZWD model developed in this study and ZWD_i^0 is the reference value."

In Eq. (7) please specify full expressions and how each term is computed: T_m, g_m, etc.

In Eq. (8) please define all terms and describe how they are computed.

The equivalent to Figure 10 but for the RMS instead of the bias should be added. This would give a better indicator of each model accuracy. The same should be done for the comparison with radiosondes (Figure 14)

Replace “precusion” by ”precision”

The sentences “Taking the uncertainty of radiosonde ZWD into account, the improvement of HZWD model over GPT2w model below 2 km seem to be insignificant. However, the validation is based on the same radiosonde ZWD values and the RMS error of ZWD of HZWD is smaller, thus we can reasonably expect that the ZWD of HZWD is closer to true ZWD value than the ZWD of GPT2w in spite of the uncertainty of radiosonde ZWD.” are confusing and repetitive. Please rephrase the second sentence and try to split into shorter sentences.

5. Conclusions

Mentioning the percentage of improvement for the various layers may be misleading as e.g. 33% of the signal for the top layer is only 2-3 mm, which is insignificant. Authors should put their results into perspective of the magnitude of the ZWD field in each layer.

The last paragraph of the paper is an example of the need for language improvement:

“The HZWD model offers good precision stability in the vertical direction and can meet the requirements of ZWD correction at different heights within the troposphere; however, it can be seen that neither the HZWD, nor the GPT2w, models, i.e., those non- meteorological parameter-based models, performed well in the lower region of the troposphere. In addition, compared with the GPT2w model, HZWD model is a closed model with a limitation to facilitate on-site meteorological observations. Further research is required to assess the variation in and factors influencing of the wet delay and explore the possibility of incorporation of on-site meteorological data.”

Suggestions:

Remove “,” in “GPT2w, models

Replace “lower” by “lowest”

Replace “compared with the GPT2w model, HZWD model is a closed model with” by “compared with GPT2w, HZWD is a closed model with”, this way avoiding the repetition of the word “model”.

Remove “and” in “in and factors”

List of suggested references:

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.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. Q. J. R. Meteorol. Soc., 137, 553–597.

Fernandes, M. J., Nunes, A. N., & Lázaro, C. (2013). 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., Lázaro, C., Nunes, A. N., & Scharroo, R. (2014). Atmospheric Corrections for Altimetry Studies over Inland Water. Remote Sensing, 6(6), 4952-4997. doi:10.3390/rs6064952

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

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. (2017). Analysis and retrieval of tropospheric corrections for CryoSat-2 over inland waters. Advances in Space Research. doi:10.1016/j.asr.2017.09.002

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