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Atmospheric Measurement Techniques Discussions

Interactive comment on "Inter-technique validation of tropospheric slant total delays" *by* Michal Kačmařík et al.

Anonymous Referee #1

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In the last decade the assimilation of zenith total delays into numerical weather models became operational at many weather services. At the same time the focus of research shifted to the processing and utilization of slant total delays (STDs). The manuscript presented by Kačmařík et al. describes a comprehensive STD validation study which covers 7 different STD processing strategies and their validation with independent observations. The focus of the manuscript is on the identification of the optimal processing strategy and on the impact of post-fit residuals on the quality of STDs.

This is the most extensive and detailed study in this field which has been presented up to now and it provides a wealth of information. The results are in general well justified and of high significance for GNSS processing and for potential applications as well.

The manuscript is well written and organized. However, some points need clarifica-

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tion and additional information which is important for the reader to better understand different aspects of the validation study. This would require a minor revision.

General Comments

Errors
The manuscript compares STD data from different sources: GNSS STDs processed in different ways, raytraced STDs from numerical weather models and STDs obtained from water vapor radiometers. As there is no reliable reference for STD observations, such comparisons provide the difference between two erroneous quantities but not the STD error, i.e. the error with respect to the truth.

At some points of the discussion the authors highlight this aspect but in some cases the standard deviation is regarded as the error of a certain STD product without proper justification. Especially when comparing GNSS STDs with and without residuals the increasing standard deviation due to the residuals is very often regarded as an increasing error. While this might be true in many cases it is not always justified by the analysis.

The manuscript might be improved if this issue is discussed in a paragraph somewhere at the beginning of the analysis and by addressing the corresponding specific comments.

Residuals
The application of residuals is presumably the most important topic in GNSS STD processing. The simple model used in equ. 1 is not sufficient to describe local atmospheric variations in case of severe weather events. Residuals could provide the directional information necessary to locate meteorological phenomena if the GNSS specific errors were below a certain threshold.

In the manuscript the application of residuals is discussed in detail but the analysis does not lead to a clear recommendation. Regarding the analysis presented in the manuscript the results are well justified. However, the analysis is focused on two month mean values/standard deviations and presumably not the best way to analyze the impact of residuals. Most of the time atmospheric variations are rather smooth and can be described by equ. 1. Under such conditions residuals will probably add some noise to the solution and provide little extra information. In case of severe weather events rather large residuals would be necessary to complement equ. 1 and to locate e.g. convective cells. Under such conditions much larger errors of the residuals could be tolerated. This cannot be analyzed using two month means.

At some points in the manuscript it is mentioned that further studies are required to address this problem but the recommendations how to use residuals remain somewhat indefinite. The presented results could be understood much better if an assessment of the statistical analysis with respect to the application of residuals would be added.

Statistics
The manuscript describes basically a statistical analysis. However, almost nothing is said about the statistical procedures used to analyze the data. At some points bias and standard deviation are used, median, median RMS, median values of biases and standard deviations, mean standard deviations, ... at others. To understand the results it is necessary to describe the statistical analysis and to explain why certain statistical methods are used for a specific analysis.

Specific Comments

Abstract, line 18
Results show generally a very good mutual agreement among all solutions from all the techniques.
This sentence contradicts the results of the study in some way as the reader gets the impression that all solutions/techniques have almost the same high quality and it

makes no difference which one is used. At the same time it would not be possible to answer the questions raised in the manuscript, i.e. which processing strategy leads to the best STD quality.

The abstract should focus more on the questions which will be answered in the manuscript and on the difficulties to come to a definite conclusion.

Page 3, equ. 1, 2
Equation 1 is essential for the discussion of residuals. Therefore it would be important to discuss the downsides of this approach. Equ. 1 is a rather simple model where all information on elevation is shifted to the mapping functions and variations with the azimuth are described by only two numbers (G_N and G_E). Equ. 2 describes a very smooth azimuthal variation which cannot represent the atmospheric state in case of severe weather events. Furthermore, the gradients are temporal means, usually over 1 h. In case of fast moving fronts or convective events the temporal mean can become rather misleading and can lead to an unrealistic azimuth distribution of the STDs.

Using this approach all information provided by GNSS observations is reduced to 3 numbers (ZWD, G_N and G_E, assuming that the Saastamoinen ZHD is used) and no directional information survives this process. If it turned out that this is the best way to model atmospheric variations the processing of STDs would be almost meaningless. It would be sufficient to provide these quantities and the user could compute any number of STDs in any direction.

For for the sake of completeness it should be defined how residuals are applied, i.e. equ. 1 + residual.

Page 11, section 4.4
The results presented in this section have presumably be obtained using a numerical weather model. This should be mentioned as the real situation might differ from the model state. Which model was used?

Page 13, line 6,7

... and corresponding delays in the zenith direction have been computed and mapped using mapping functions presented in Eq. 1 ...
Why do we need ZTDs to understand fig. 3? It seems that STDs are computed using the weather model and that the differences are mapped to zenith and shown in fig.3.

Page 13, line 12-15

The sentence *Figure 3 confirms ...* sounds somewhat strange and should be rephrased.

Page 14, line 18, 19

What is the *hydrostatic mapping function derived from the NCEP-GFS*?

Page 14, line 19-22

SIWV to STD: Why are hydrostatic horizontal gradients required to convert SIWV to STD? Both observations have been taken in (almost) the same direction and the SHD in this direction should be sufficient. Li, 2015b, describes a way to estimate gradients from different SIWV observations for GNSS gradient validation. Has this also been done?

Page 16 - 21, section 7.1

Section 7.1 is quite large and it would be very beneficial for the reader to divide it into some subsections, e.g. comparison with GFZ, comparison with/without residuals, differences of software parameters, differences depending on elevation.

Page 15, line 18, 19

Hence the smaller values for these settings, the smaller number of pairs found and the higher standard deviations resulted between GNSS and WVR STDs.
Shouldn't it be ... **smaller** standard deviations ... ?

Page 16, line 14

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These were observed mainly as systematic errors ranging from -3.6 mm to 0.6 mm.
Fig. 4 shows differences between the GFZ solution and all other solutions. As long as the error of the GFZ solution is unknown it's not possible to attribute the differences as systematic errors.

Page 17, line 8, 9, discussion of pages 17 - 19
Both comparisons demonstrate systematic errors at a sub-millimetre level over all stations and solutions.
Adding residuals to the nonRES solution should lead to a somewhat different bias and a larger standard deviation, even in case of true, error free residuals. This is due to the spatial and temporal variability of the atmosphere and not necessarily an error. However, reading the discussion one gets the impression that smaller biases and standard deviations are better. This section could be improved by an evaluation of the information and potential errors provided by different solutions.

Page 19, line 18, 19
Surprisingly, the impact of the elevation angle cut-off (3° versus 7°) resulted in a minimum mean standard deviation below 1 mm, see TUW-3 and TUW-7.
The impact of low elevation STDs below 7° depends considerably on the amount of data below 7°. The small impact on bias and SDEV could be due to the small amount of data or due to the high quality of the data.

Page 21, section 7.2
It would be very beneficial for the reader to start section 7.2 with a short summary of section 4.1 – 4.3. A short paragraph and a table giving the main parameters of the weather models and raytracers would be helpful.

Page 26, line 12, 13
... and it should be noted that the stability on a daily time scale was much better for GNSS STDs than for NWM ray-traced STDs.

This is presumably not a problem of the model stability but indicates that the model state deviates from the real atmospheric state for some time/region. This is the usual behavior of weather models which cannot be avoided even if STDs are assimilated.

Page 30, line 2
Two sets of STDs from the same solution, but ... Which solution was used in this section?

Page 34, line 7, 8
... that we are currently not able to remove completely all other effects due to the local troposphere.
Isn't that misleading? The ideal residual should describe the effect of the local troposphere while all GNSS specific errors should be removed.

Technical Corrections

Page 1, line 30
... part, caused by the atmospheric constituents, and the wet ...
Shouldn't it be ... the **dry** atmospheric constituents ... ?

Page 10, line 14
$R_d = 287.058$ J/(kg K) = 287.058 J kg^{-1} K^{-1}

Page 11, line 5
Contribution to hydrometeors: 17 mm to ZTD or STD?

Page 11, fig. 1
Fig. 1 needs some improvement: It should be clearly indicated which subplot shows which quantity. The text and the color bars inside the subplots cannot be read.

Page 12, fig. 2
It's rather unusual to provide polar plots with a x and y axis. The angles (azimuth) and the radial axis (ΔSTD) should be given.

Page 16, line 8, 9
Figure 4: Comparison ... It seems that parts of the figure's caption have accidentally been copied.

Page 16, line 15
It is particularly ... What does "It" mean?

Page 22, line 8, p. 25, l. 21, ...
side => site

Fig. 4, 6, 7, 9, 11
These plots show a large number of symbols/lines and could be improved by scaling the y axes according to the min/max values in the plots.

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