February 22, 2019
Dear editor,
We now provide point-to-point reactions also to your own comments as well as an updated version of the manuscript.

Yours Sincerely,
Authors.

January 16, 2019
Dear editor,
We provide point-to-point reactions to your comments within the two Referee's comments. Our text is written in green italics. We updated the manuscript accordingly and provide its new version (and also a version with tracked changes).

Yours Sincerely,
Authors.

Dear Authors,

I have read your answers to the two Referee's comments. In general, they are satisfying and revisions should be implemented accordingly in the manuscript. However, some of the referee comments are not or are incompletely answered, and some answers call for further argumentation and/or additional details. Below you will find my specific remarks on the referees' comments and your answers. You will also find my own comments on the manuscript in the last section. Please provide a line-by-line response to all remarks and comments and submit a revised version of the manuscript.

Best regards,

Olivier BOCK

Co-editor ANGEO for the GNSS4WEC Special Issue

Remarks on answers to Referee No. 1.

Referee comments in blue, your answers in red, my remarks and comments in black.

As a preliminary general comments, I would like to draw your attention to the fact that this Referee raised 5 comments on page 3 (section 2.2 / Figure 1) and 7 comments on page 13 (Section 4 and Figs. 4 and 5), and that Referee No. 2 was also concerned about Figure 1 and its related comments. Please provide a careful revision of these sections of the manuscript. Some suggestions are given below.

p03/l13: is it not hazardous to include post-fit residuals into STD formulation? PFRs represent mis-modeling of troposphere, but also for antenna mis calibration, multipath, liquid water, unmodeled solid earth displacements, etc.

We agree and we removed post-fit residuals term from the formula and from the text.

Please answer the issue raised by the referee regarding the information contained in the post-fit residuals, especially as post-fit residuals are shown in Fig. 6.

We fully agree with the referee about the content of post-fit residuals and we excluded the term from the equation 1 in previous revision. Anyway, the equation is included purely for the definition of tropospheric model used for estimating ZTD and horizontal gradient parameters, not for retrieving slant tropospheric delays.
We also slightly edited the paragraph describing Figure 7 (previously Figure 6) where the constitution of the post-fit residuals was also mentioned. However, the figure is again used purely for showing differences of applied GNSS models when looking at elevation dependence of post-fit residuals, and not considered for reconstructing slant delays.

p03/l33: in my opinion "Gn*cos(a)+Ge*sin(a)" is not "the projection of the horizontal gradient vector in the direction of the individual satellites": it has to be multiplied by mfg(e), otherwise it is the projection onto zenith of horizontal gradient magnitude.

The projection is just in the horizontal plane, thus not using the gradient mapping function. We substituted the word 'direction' with 'azimuth' as it was used in the figure caption.

I think the misunderstanding here comes from what you call "gradients" in Fig. 1 which is actually the component of STD due to azimuthal asymmetry of the atmosphere (Chen and Herring, 1997). The term "gradient" should be restricted to the vector **G** (Gn, Ge). It would be much more clear if you define the quantity plotted in Fig. 1 by an equation as I already suggested in the preliminary review.

*The visualized quantities are Gn*cos(a)+Ge*sin(a) where a is the azimuth of the satellite. We returned the equation in the description text and removed the term 'gradient values' and if necessary we use 'gradient contributions'. We hope it is clear now.*

p03/l31-p04/l08: I wonder if figure 1 is really useful. A simple comparison of mapping functions plotted according elevation will highlight the maximum values of each mf. The right part is shortly described in text, but it is not used to support any statements. Moreover, the black dots (for a single epoch, 20:30UTC) do not help to support any statements either. Maybe you could just replace this figure by a mfg comparison.

We decided to remove the dependence on elevation angle and black dots for a single epoch. We then kept the original left figures when directly comparing mapping factors (range in x-axis) and ranges of gradients (scatters in y-axis) for three gradient mapping functions. Based on this figure, we could focus on the two extreme mfg in the following part.

I agree that Fig. 1 is useful here to illustrate the variation of the delay due to the horizontal gradients and the size of the mapping factors, given that it is clarified as suggested above.

We kept the figure after clarifying values showed in the figure.

p06/l5-p06/l10: as you mention, gradients retrieved from NWP depends on mfg (BS or CH). Why do not use your ray-tracing algorithm to compute gradient with their closed form expression depending on NS and EW horizontal gradient of refractivity? (See Davis et al., 1993, RS)

We calculate the tropospheric gradients from ray-traced delays by least square adjustment to be as close as possible to the method applied in the GNSS analyses for parameters estimation.

You justify what you did but you don't really answer the referee's question. I think the referee suggested computing Gn and Ge from the integrals defined e.g. in Davis et al., 1993. This is another approach. Did you compare both approaches? Is there a reason why your approach is preferred?

We calculated the gradients from ray-traced delays by least square adjustment because

(1) we can assume that this is the most rigorous approach, that is, this approach is as close as possible to the method applied in the GNSS parameters estimation and (2) at the time writing the manuscript we did not have the routines to calculate gradients with their closed form expression depending on NS and EW horizontal gradient of refractivity (see Davis et al., 1993, RS). We now implemented the routines to calculate gradients with their closed form expression depending on NS and EW horizontal gradient of refractivity (see Davis et al., 1993, RS). We compared NWM (ERA5) tropospheric gradients derived with the two different methods with GNSS tropospheric gradients. We find that for the considered stations (over the entire benchmark period) the root-mean square deviation between NWM and GNSS tropospheric gradients is 10 % smaller if we apply the first instead of the second method. This is in line with our expectation. Our approach is well justified. We added a short paragraph with these results to section 2.3.

p06-p07: Did the gradient modeling affect the estimation of positions? Maybe you could complete Table2 with comparisons of position (height?) repeatability?

There were already published some studies which dealt with positioning changes related to tropospheric gradients estimation which we cite in our paper. Since our focus is only the quality of tropospheric gradients, we would rather not provide results for positioning.

I think the referee's question and suggestion are relevant. Inspecting the station repeatability is a standard approach to evaluating the quality of the processing, overall, and might thus help assess the relevance of the different gradient models tested. It would certainly be useful and interesting to check the station height repeatability. This is an additional validation to the NWP comparisons.

We analyzed station position repeatability both in horizontal and vertical direction and we provide results on this in section 3.3 (Table 5) of updated manuscript and discuss them. As expected, the station coordinates repeatability was improved when using combined GPS+GLONASS solutions compared to GPS-only solutions, namely by a factor of 2 and 1.2 in horizontal components and the height, respectively. This corresponds to Zhou et al. (2017) who suggested 7° for the height repeatability too (solutions ranged from 3° to 15°). It should be noted that GPT+GMF models and the PPP method were used in both these studies. Contrary, Douša et al. (2017) observed a small improvement in the height even when using the elevation angle cut-off 3° (compared to 7° and 10°), however, exploiting double-difference observation, VMF1 and the Bernese Software. This discrepancy might be attributed to a slightly worse modelling of low-elevation observations, in particular due to using GPT+GMF and PPP strongly depending on all aspects of undifferenced observation modelling.

Concerning the impact of elevation angle cut-off on actually estimated gradients, these achieved with the 3° cut-off agreed better with NWMs, which corresponds to results reported in Douša et al. (2017).

Douša, J., Václavovic, P. and Eliaš, M.: Tropospheric products of the second European GNSS reprocessing (1996-2014), Atmospheric Measurement Techniques, 10, 3589–3607, doi:10.5194/amt-10-3589-2017, 2017.

p07/Table2: I think it is important to have an overview of gradient time series in order to understand the comparisons. Especially, unlike for ZTD we do not have many ideas about gradients magnitude (maybe some ideas from figure 1): is a 0.01 mm bias significant? and a 0.76 mm stdev? These values may be put into perspectives with gradient magnitude.

We do not provide gradient time series in this paper, the reader can find them i.e. in the cited publication Li et al. (2015). However, we added a paragraph into the section 3.1 to describe typical values of gradient components under standard and severe weather conditions and we provide information on ZTD rate of change due to tropospheric gradient with an increasing distance from the receiver. The bias of 0.01 mm is not significant in respect to typical values of gradient components and also according to estimated standard deviation of comparisons.

The publication by Li et al. (2015) that you are citing here and in the manuscript only shows time series for Onsala station (not included in your study) and for a different period. They are not directly linked with the results of you study. By the way, the second referee also asked for time series. I agree with their comments that it would be useful to give some insight into the temporal variability and size of variations, rather than just giving values for means or extreme conditions.

We now provide a time series of tropospheric gradients for a station LDB2 (Brandenburg, Germany) for a period from May 15, 2013 till June 15, 2013 in figure 2. It shows values from two GNSS variants of solution and from NWM ERA5 solution.

I'm not sure that the rate of change of ZTD with distance is a very relevant information as it is not directly related with a measurable quantity. Instead, you could quantify the contribution of gradient to the STD given by the 2nd part in Eq. (1).

We removed the information about the rate of change of ZTD with distance, as it was not useful.

I agree with the both referees that some indication of the significance of the numbers should be given especially since the gradient values (Gn, Ge) are very small (e.g. 0.3 mm quoted in the Abstract). Significance statements should be supported by a statistical test.

The value of 0.3 mm in the abstract does not correspond to any mean value of gradients, but to a systematic effect observed in the manuscript solely due to different applied mfg. The value of 0.3 mm used originally indicated a maximum difference on a global scale (i.e. prevailing hydrostatic N-S gradient). We added also the value of 0.9 mm corresponding to a systematic error observed in individual gradient components observed in a local scope.

In Section 3.1 and Table 2, we could observe only very small biases as these are overall statistics. In Section 4 we then demonstrate actual differences which are already significant with respect to achieved SDEV. We added a discussion on a significance of impacts of applied models, cite: By using common data, period, processing strategy and software in our analysis, a significance of the impact of different models can be assessed by confronting our SDEV with those obtained when comparing gradients from different software, processing methods and even observing techniques. Generally, the SDEV values in Table 2 reach 30-50% of those obtained from comparing two different GNSS software and processing methods with two different NWM sources, and still using the same data set from the benchmark campaign (Douša et al. 2016).

We also realized statistical significance tests and provide their results in sections 3.1 and 3.2.

p07/Table2: I wonder if the computation of correlation will be helpful to investigate the comparisons. A linear fit?

We now provide linear correlation coefficients in table 2 to and table 3 and we updated the text in this regards

Please answer the questions. Does the provision of correlations/linear fit help in the interpretation of the results? If it doesn't, you just have to mention it and not include the (unnecessary) results.

Computation of correlation coefficients was helpful to investigate the comparisons, e.g. demonstrated a perfect correlation for ZTD and progressively reduced correlation for impacts of different models. The correlation was also high when using different mfg which underlined a comparatively larger biases in this case though still strongly averaged over all stations and period. They also clearly showed a penalty of the current RT processing and gradient estimates. The correlation coefficients are therefore included in the manuscript.

p07/Table3: same comments as for table2. Maybe the computation of correlation or linear fit will be more relevant here.

See answer for the previous comment.

Please answer the question.

Computation of correlation coefficients was also helpful to investigate the comparisons and these results are therefore included in the manuscript.

I recommend the authors to improve legibility of figures (by using a better resolution)? I also recommend the use of an equation editor for mathematical expressions.

In the updated manuscript version all the equations are created using an equation editor.

What about the legibility of Figures?

For the final revised paper, I recommend that you provide the maps in uniform format.

We updated Figure 1 and 7 to increase their legibility (numbering corresponds to new updated version of the manuscript). We kept Figure 5 in its previous form (therefore different from Figures 3 and 4), because we found that it better emphasizes differences in tropospheric gradients delivered by different observation elevation weightings. We also kept Figure 6 in its previous form, i.e. different from Fig 5 due to displaying different characteristics (gradient differences in North & East separately).

Remarks on answers to Referee No. 2.

Referee comments in blue, your answers in red, my remarks and comments in black.

… My interpretation is that the present version has the form of a summary of the results, rather then what is your message to the community on how to handle tropospheric gradients. My conclusion is that it does not really matter which of the different processing option that are chosen given the data that you have studied (excluding the near real time and real time solutions, as expected). Also the small impact of adding GLONASS data may be an issue to raise for further investigations, possibly related to a higher temporal resolution of the estimated gradients.

From our point of view, we provide a recommendation to the user everywhere we think it can be given based on our own results: 1, we recommend using observations from very low elevation angles to get better gradients (this was already shown also in paper by Meindl et al. (2004) which we cite). 2, we find a small positive impact coming from adding GLONASS in our processing (it can be however different when using other products with satellite ephemerides and clock error corrections, different weighting of observations from various GNSS, etc., and some other investigations related to multi-GNSS data processing in general will follow). 3, we present the penalty in quality of tropospheric gradients from real-time processing and we show that this penalty is mainly related to the quality of used products. 4, we show that selection of gradient mapping function does not affect general quality of estimated tropospheric gradients but their magnitudes (one has to be careful then with comparing gradients from various sources due to existing systematic differences).

Please revise the Conclusion section according to the referee's comments and highlight clearly the four points you mention in your answer. Additionally, I would like to see a more insightful discussion of your results, including a comparison to other past and recent studies.

1. Revise the statements regarding the study by Meindl et al. (2004). The improvement in precision at lower elevation angles they noticed is only based on rms errors (formal errors) of the gradient parameters. This is a well-known result, explained by the use of more observations and better decorrelation of gradients from other parameters. It does not say whether they are more accurate. Accuracy of the gradient estimates can only be tested by comparison with independent data (e.g. from VLBI, MWR, NWP). Accuracy of the processing can also be tested by inspecting the coordinate repeatability, which e.g. Meindl et al. (2004) did when they compared two processing variants, with and without estimation of gradients, but not for different cutoff angles. This conclusion is actually not consistent with Zhou et al. (2017) who observed better results at 7° and 10° compared to 3°. Can you comment on this?

You are right with Meindl et al. (2004) and we thank you for this comment. We removed the sentence with our statement from the Conclusion section and now we compare our results with this paper only in section 3.3 while analyzing station position repeatability. In the same section, we also newly discuss similarities of our results with Zhou et al. (2017) and differences with Douša et al. (2017) when it concerns a utilization of different elevation angle cut-off. We attribute differences to the GPT+GMF used in PPP for the two former while using VMF1 and double-difference solution for the latter and thus most likely a worse modelling of low-elevation observations in the two former. As better agreement between GNSS and NWM tropospheric horizontal gradients were achieved for the 3° elevation angle cut-off, and optimal modelling in Douša et al. (2017) showed even better results for height repeatability when using the VMF1, we could recommend to use the 3° cut-off for an optimal estimation of tropospheric gradients from GNSS data.

2. Discuss the sensitivity of results to addition of GLONASS data, and compare to other recent studies (e.g. Zhou et al., 2017).

Please see updated version of the manuscript. In the Conclusion section we now discuss our results in respect to study presented by Li et al. (2015) and Lu et al. (2016). And in the section 3.3 we now discuss the addition of GLONASS data regarding the station position repeatability and compare our results with Zhou et al. (2017).

3. RT1 solution is slightly more accurate than the RT3 solution. Can you elaborate a bit more your comments on the quality of the used RT clock and orbit products?

The worse result of the RT3 solution can be attributed to the worse quality and stability of the new RT2+RT3 (IGS02, IGS03) products compared to RT1 (IGS01) within the first half of 2013. Douša et al. (2018b) performed a long-term quality evaluation of all IGS RT products for the period of 2013-2017. Eventually, the RT1 and RT3 products are based on different software, combination strategy and constellations, which has been described in Section 2.2..

Douša, J., Václavovic, P., Zhao, L. and Kačmařík, M.: New Adaptable All-in-One Strategy for Estimating Advanced Tropospheric Parameters and Using Real-Time Orbits and Clocks, Remote Sensing, 10, 232, doi:10.3390/rs10020232, 2018b.

4. I don't understand what you mean by the 'quality' of the estimated gradients. I would suppose you mean their accuracy, but if their magnitude is affected this means their accuracy is impacted as well. Please clarify.

We use the general term quality of gradients to speak about their accuracy and robustness (stability in time and space). Could you please specify where exactly in the manuscript you struggle to understand the meaning of the 'quality' of the estimated gradients term?

The conclusion that the magnitude of gradient parameter estimates is changing depending on the used mapping function is important and should be better highlighted. Given the topic of this paper, it is expected that this point is thoroughly discussed and that strong conclusions and recommendations are given and not a final remark such as "it is hard to assess which *mfg* is more suitable for the troposphere modelling in GNSS analyses".

Our main conclusion was the assessing the impact of gradient mapping functions, which resulted mainly in systematic effects what are not critical for the estimation of other parameters (e.g. minor difference in the quality of coordinates), but mainly for the use of gradients and their evaluation or inter-comparisons between different solutions and techniques (so far the impact was usually neglected). It is really hard to guess about correct systematic effect (absolute magnitude) of gradients without a possibility to compare with independent data of the same quality at least. It seems that neither NWM, nor WVR, nor VLBI can provide comparable gradients, in particular when multi-GNSS is used. From our point of view, we sufficiently inform the reader what happens with gradient estimates if Chen and Herring or Bar-Sever gradient mapping function is applied. We show the results and discuss them in section 2.2, 3, 4 and in Appendix A and summarize them in Abstract and in Conclusion.

The issue of time sampling of the gradient parameters should be discussed as well. Though it is not a limitation with the software you used, this question is of concern to many other scientists who use different software packages (e.g. Bernese, GAMIT) where it is more common to use a 24-h sampling.

We agree the question is important, but also strongly related to applied troposphere modelling (deterministic vs stochastic, constraining vs. random-walk). A detail study of gradients temporal resolution for one software/strategy was presented by Zhou et al. (2017) which we mentioned in the Introduction. We consider this aspect out of the scope of this study and most likely relevant to a dedicated study consider additionally a random-walk settings. In our case, both were pre-selected and fixed (based on the prior optimizing for this purpose by using many testing variants and visual inspections of the full benchmark data set).

Another important question is to what extent your conclusions holds during more general circumstances, because it seems as you have selected the two most extreme months for the benchmark data set. It is of course a lot of work to address this question and give a reliable answer, but it does not prevent you from an initiated discussion in the present manuscript.

We based our analyses on a data set from wet spring/summer season when the gradients could provide a valuable information for meteorological applications. Although the time period covers some severe weather events, it also contains a lot of days with standard weather conditions with tropospheric gradients close to zero. So, the results should provide a good overview on the situation in Europe during the warmer part of the year. On the other hand, we agree that new studies based on different GNSS software a data sets should be done to strengthen and confirm our results.

Please add these comments in the revised manuscript. But I don't understand your point about the necessity of new studies based on different software. Can elaborate it? Maybe it is worth discussing this point in the paper.

We added the comment regarding selection of the Benchmark data set into introduction part of the Conclusion section. Regarding the necessity to realize other studies using different software please see our reaction on your previous comment about the time sampling of tropospheric gradients estimates.

An overall question is that I would like to see a more critical discussion related to the numerical weather prediction models. First of all their resolution is poor, given that probably most of the large gradients occur in the atmospheric boundary layer. For example, for an elevation angle of

3° the propagation path at the height of 500 m will be approximately 10 km horizontally from the ground-based reference station. That corresponds to the resolution of the limited area model (WRF). One possibility to investigate the scale (temporal as well as spatial) of the gradients is to use the WVR data mentioned in Section 2.1. Since you mention that these data exist the reader will wonder why you do not use them for an assessment, even if the WVR data only exist at a couple of sites.

We split our reaction into two parts:

1, we would be very careful about the statement that large gradients occur in the atmospheric boundary layer. Please see i.e. a paper from Elosegui et al. (1999). According to his findings GNSS tropospheric gradients are more sensitive to tropospheric features at larger heights, in different words – i.e. the same type of tropospheric feature at the height of 3 km would cause a larger gradient value than while occurring at the height of 0.5 km. And also sometimes (even during not winter season) a hydrostatic gradient can prevail in total tropospheric gradient estimated by GNSS. And these hydrostatic gradients are related to large scale (up to several hundreds of km) features, not to local station asymmetry. Of course, we are aware of limitations of NWMs we use in this study and we also state them in the paper. On the other hand, this is the first time when a NWM with a 10 km horizontal resolution was used for comparisons with GNSS results and there is a visible increase of its gradient magnitudes compared to outputs of global NWMs with 1° horizontal resolution used in Douša et al. (2016).

2, the usage of WVR for this study is problematic from several reasons: a) it is available only for a single station (POTS, Germany) for the benchmark campaign; b) WVR measures IWV therefore it can deliver only wet delay gradient, a hydrostatic gradient would need to be added from an external source (NWM) to get a total gradient which is delivered by GNSS; c) data quality of WVR observations at elevation angles below approximately 20-25° is generally poor (see i.e. Kačmařík et al., 2017, AMT).

Please provide full detail of the references you are citing (Elosegui, Dousa, Kacmarik).

Douša, J., Dick, G., Kačmařík, M., Brožková, R., Zus, F., Brenot, H., Stoycheva, A., Möller, G. and Kaplon, J.: Benchmark campaign and case study episode in central Europe for development and assessment of advanced GNSS tropospheric models and products, Atmospheric Measurement Techniques, 9, 2989–3008, doi:10.5194/amt-9-2989-2016, 2016.

Elosegui, P. Davis, J. L. Gradinarsky, L. P. Elgered, G. Johansson, J. M. Tahmoush and D. A. Rius, A.: Sensing atmospheric structure using small-scale space geodetic networks, Geophysical Research Letters 26, 2445-2448. doi:10.1029/1999GL900585, 1999.

Kačmařík, M., Douša, J., Dick, G., Zus, F., Brenot, H., Möller, G., Pottiaux, E., Kapłon, J., Hordyniec, P., Václavovic, P., and Morel, L.: Inter-technique validation of tropospheric slant total delays*, Atmospheric Measurement Techniques, 10, 2183-2208, doi:10.5194/amt-10-2183-2017, 2017*

It seems that there is an interesting point of debate here on which atmospheric layer is impacting most the estimated gradient parameters. Please add some elements of this discussion in the manuscript regarding the sensitivity of tropospheric delay gradient parameters to hydrostatic and wet gradients in the atmospheric refractivity. I think this was also discussed in early papers by Davis et al., Radio Science (1993) or Chen and Herring, JGRB (1997).

Reconcile also your position with your statement in a previous publication “The first-order horizontally asymmetric delay … reflects local changes in temperature and particularly in water vapour.” (*Kacmarik et al., AMT, 2017).*

We added a short sentence into section 2.2 which notifies the reader that GNSS gradient represents a gradient of total delay, therefore a sum of dry and wet gradient. We are going to elaborate the problematics of dry/wet gradients and the relation between GNSS gradients and real weather conditions (together with NWM data quality evaluation) in our upcoming separated study.

Regarding your 1st point, I know at least one study which compared GPS gradients and gradients from a NWP with a resolution of 0.1°x0.1°, and it is from 2002:

Walpersdorf, A., E. Calais, J. Haase, L. Eymard, M. Desbois and H. Vedel, Atmospheric gradients estimated by GPS compared to a high resolution numerical weather prediction (NWP) model. Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy, Vol. 26 (3), pp. 147-152, 2002.

Thank You for this input, we apologize for neglecting this study. Now we briefly mention it in the Introduction section.

Regarding your 2nd point, I am surprised of your answer because: a) A single station was used in your previous publication (Kacmarik et al., AMT, 2017) as well as in Lu et al., JGR, 2016, and Li et al. GRL, 2015; b) You solved the problem of hydrostatic gradient in Kacmarik et al., AMT, 2017, for the same COST Benchmark dataset, so it would be a strong argument to re-use these WVR data to compute gradient parameters and use them in this study as an additional source of validation; c) you suspect the quality of WVR data is poor below an elevation of angle 20-25° (even 40° is the quoted in Kacmarik et al., 2017) but according to the numerous publications which used such data, one would rather suspect that there was an issue with the data or the comparisons used in your previous study. This last point merits probably further investigation and should be commented.

Lu, C., X. Li, Z. Li, R. Heinkelmann, T. Nilsson, G. Dick, M. Ge, and H. Schuh (2016), GNSS tropospheric gradients with high temporal resolution and their effect on precise positioning, *J. Geophys. Res. Atmos.*, 121, 912–930, doi: 10.1002/2015JD024255.

The overall lower quality of WVR measurements at low elevation angles is a generally known fact (see example i.e. in Shangguan et al., 2015). Many studies therefore avoid using low elevation data from WVR in their evaluations – apart from both mentioned Li et al. (2015) and Lu et al. (2016) for example also Pottiaux and Wamant (2002) or Davis et al. (1993). The WVR used in Li et al. (2015) and Lu et al. (2016) at the Onsala station is operated in a so-called “sky-mapping” mode therefore making observations at regular azimuth and elevation angles in repeated cycles. However, the available WVR operated at GFZ Potsdam only tracks directly GPS satellites – since only one satellite is being tracked at one moment the WVR provides much less observations than GNSS receiver. We are therefore not in favor of evaluating differences between GNSS gradients estimated at 3° or 7° or with GPS or GPS+GLONASS observations while we would have to use WVR observations at elevations above i.e. 20 ° made only in direction of GPS satellites.

Pottiaux, E. and Warnant, R.: First comparisons of precipitable water vapor estimation using GPS and water vapor radiometers at the Royal Observatory of Belgium, GPS Solutions, 6, 11–17, doi: 10.1007/s10291-002-0007-5, 2002.

Davis, J., Elgered, G., Niell, A. and Kuehn, K.: Ground-based measurement of gradients in the “wet” radio refractivity of air, Radio Science, 28, 1003-1018, 1993.

Shangguan, M., Heise, S., Bender, M., Dick, G., Ramatschi, M., and Wickert, J.: Validation of GPS atmospheric water vapor with WVR data in satellite tracking mode, Ann. Geophys., 33, 55–61, doi: 10.5194/angeo-33-55-2015, 2015.

Additional Editor comments.

The additional comments below should help to strengthen the relevance of the manuscript for the final publication.

General comments

One of your strong conclusions is that changing the gradient mapping function impacts the magnitude of the estimated gradient parameters. I would surmise that this impacts also the ZTD estimates and possibly the STD estimates. Can you comment on this point? Some quantitative results would be useful (e.g. correlation analysis of ZTD/gradient/STD differences).
Results for ZTD differences due to a change of gradient mapping function are already incorporated into the manuscript, please see section 3.1 and mainly table 2, where values of bias, SDEV and correlation coefficient are given. It is evident that the impact on ZTD values is close to zero. When STD is reconstructed, the difference in magnitude of gradient values will be compensated by difference of gradient mapping function values (mapping factors) as is apparent from figure 1 and we shortly comment on this at the end of the conclusion section.

Compare and discuss the results from this study to similar recent studies such as Li et al., 2015; Lu et al., 2015, 2016; Zhou et al., 2017; etc. who also evaluated GPS and GNSS gradient estimates, namely in against NWP data and WVR data.
Please see an updated version of the manuscript – section 3.3 and mainly the Conclusion section.

Provide more insight into the significance of the gradient magnitudes and differences as the numbers reported in the manuscript are very small (< 1 mm) and may seem negligible to many readers. This should be done by using a statistical significance test when comparing two results. For instance, a 0.01 mm difference when adding GLONASS data (change of SDEV from 0.48 to 0.49 mm, quoted as 2% in the conclusions) is probably not significant but a 0.06 mm difference when changing the mapping function (from 0.48 to 0.42 mm) probably is. This would also help you to clearly (objectively) state and conclude about the results.
We realized statistical significance tests and provide found results in sections 3.1 and 3.2 in the updated version of the manuscript. We also added a discussion on a significance of impacts of applied models based on comparing the results of this study with results reached in our previous study (Douša et al., 2016), please see section 3.1.

Better insight into the results would be brought by changing slightly the order of presentation. Starting with present subsection 3.3 and Tables 4 and 5 would help introducing the magnitudes, directions and formal errors of gradients (answering some comments by the referees), and provide a first discussion of the sensitivity of different processing options based on statistics for GNSS results only. Time series could be included here. Then, the variants could be inter-compared (present subsection 3.1) and finally the validation using NWP data and maybe the WVR data.
We decided not to change the order of presentation and keep it in the current format as it would significantly impact the whole manuscript at this stage.

Finally, a major revision is required in Section 4 and in the discussion/conclusions as also asked by the referees. In its present form Section 4 appears as an additional piece of work on the impact of the observation elevation-dependent weighting, but for a single day. Instead, it should be included in the main study, as a dedicated sub-section if you wish, and treated with the same methodology (243 stations, 55 days). It is an important aspect of the sensitivity study, as you mention in the

Introduction, which merits a proper treatment. The particular day discussed could be used as a case study, in a similar way as done with Fig. 2 and 3.

Whole section 4 went through a significant update according to comments of reviewers. However, it is still based on the results from one specific day. From our point of view, it sufficiently represents an indication of influence of the selected observation elevation-weighting scheme (and gradient mapping function) on estimated tropospheric gradients and these will not dramatically change from day to day, we believe. Applying the same methodology as you mention would require another major calculation as well as the intervention into the paper which we do not find worthy for this case.

Specific comments

P1L13: include "observation elevation-dependent weighting" as one of the processing aspects that are investigated

Corrected.

P1L16: "a clear relation to real weather conditions" appeals for two comments: 1) such as statement would imply that you studied the results with more information and description on the weather situations (instead, I only found in the manuscript indication that "a weather front was passing over the studied area" P9L6); 2) Isn't it obvious that there is a relation with the gradient maps and weather conditions? (otherwise it would be really problematic using GNSS data for meteorology). Please be more specific. You can write that you illustrated gradient maps in the case of two weather fronts, etc.

We agree that in the manuscript we do not provide clear evidences for our statement cited above in your comment. Therefore, we reformulated the sentence in the abstract. Regarding your point 2), from a theoretical point of view you are completely right, however based on our experience the estimation of good quality GNSS tropospheric gradients (especially in high temporal resolution) requires an optimization of the processing options and only after this optimization the gradients really shows a clear relation to weather condition. Gradients are generally more sensitive than ZTDs and they can much easier absorb other errors or modelling/adjustment problems.

P1L18: "systematic effects…" assumes that the results are based on some average (not just one day).

Please see abstract in the updated version of the manuscript. This part was reformulated.

P1L20-22: the global scale results are out of scope for the paper; and the last part of the sentence is not clear (are the large local gradients the cause of differences? Difference wrt to what?)

The global scale results are presented in the appendix A, they are part of the paper, so we do not see a problem to mention them in the abstract. Please see the abstract in the updated version of the manuscript.

P2L7: "Dousa et al. (2018a) demonstrated the advantage of similar pseudo-observations in the 2-stage troposphere model combining optimally NWM and GNSS data". What are pseudo-observations? What do you mean by combining optimally NWM and GNSS data? Be more specific on objectives, methods and results/conclusions of the cited study like you did for Brenot et al., Morel, etc.

Thought in the paper we used term of pseudo-ZTD observations (i.e. those calculated at a virtual station by exploiting estimated ZTD and gradients at actual station). We now simplify the sentence by writing: "… Dousa et al. (2018a) demonstrated the advantage of using tropospheric gradients in the 2-stage tropospheric model combining NWM and GNSS data". By optimally we meant (in a simplified version) combining hydrostatic and wet components from NWM and GNSS, respectively, but it can be further specified in details what is used from NWM and GNSS (ZHD, ZWD, MF, parameters for vertical corrections etc.) and including a possible weighting in a combination.

P2L20: “systematic errors”: Gradient estimates from NWP models used in this study are computed using the CH gradient mapping function (P6L8-10). This choice implies a systematic difference compared to e.g. BS gradient mapping function. For this reason, it is not possible to assess the bias, or systematic, or absolute errors of the GNSS gradient estimates. Please be careful here and throughout the manuscript about using the term “bias” and prefer systematic or mean difference instead.

We now do not use the term bias in the manuscript at all, we replaced it with proposed terms mean difference and systematic difference.

P3 Eq. (2) and (3), and in other equations, use ‘e’ for denoting the elevation angle rather than ‘ele’.

Corrected.

P4L4: “inversely proportional” implies a 1/x variation but this is not the case (and the demonstration would require fitting a function in the data). Please reformulate.

Whole paragraph describing the Figure 1 was reformulated in the updated version of the manuscript.

P6L1-2: “under the assumption of a spherically layered atmosphere” from the local vertical profile?

Yes. We now write: ”Second, we compute azimuth independent STDs from the local vertical refractivity profile.”

P6L3: say here that this fitting is done using the CH mapping function in this study.

This information is given in the following paragraph, where the question of gradient mapping function selection is being discussed. Therefore we keep the sentence in its previous form.

P6L6: what is the “standard elevation angle dependent weighting”? Be more specific.

For clarification we now write: ”(equal versus the elevation dependent weighting of $1/sin^2(e)$)”

P6L8-10: “comparison with GNSS gradients estimated with BS mfg should be treated cautiously” This sounds like a warning to the readers or to the users of your results. I think it is your work to interpret your results properly given this limitation. Please reformulate and add comments on the BS results where presented.

The sentence was reformulated, we now just inform the reader in it that NWM derived tropospheric gradients were estimated using CH mfg. We now comment on this limitation in Section 3.2 where we discuss results of GNSS versus NWM comparisons.

P6L15: is there a reason/explanation why you chose 5% as the limit?

The number of 5% comes from a very simple calculation: a range between 3 and 7 degrees equals to 4.44 % of total range between 0 and 90 degrees. This number was rounded up to 5% to strengthen the selection of stations with a reasonable number of low elevation observations.

P7L3: explain why you expect “negative biases”

See the updated manuscript, whole paragraph was rewritten. Previously it was a mistake in the text, the word “negative” should not be there.

P7L9: “The two RT solutions can be still considered of good quality if we take into consideration results found in Ahmed et al. (2016) or Kačmařík (2018).” Be more specific.

We provide more details on this topic in the updated version of the manuscript.

Table 2: reverse the differences in the RT results: RT1GxCH3 - GxCH3 (etc.) instead of GxCH3 - RT1GxCH3, as it is standard to use the reference data to the right.

Corrected.

Indicate the number of data points used in the computation of statistics.

The number of data points entering the computation of statistics is given in the text, see sentence where Table 2 is mention in the text for the first time.

Could the increase in standard deviation for RT3 be due to unrealistic cases such as illustrated in Fig. 3? Some data screening should be applied before computing the statistics.

*A standard screening was applied for statistics computation when values exceeding MEAN±2.5*SDEV were excluded as outliers. However, a manual exclusion of values computed under epochs of unrealistic cases was not applied and therefore these cases could partly influence the statistics for RT3 solution.*

P8L12: "Obviously, NWMs cannot be regarded as a ground truth" Should be reformulated.

Sentence was slightly reformulated.

P9L6: "when a weather front was passing" use plural as they were different events

Corrected.

P9L11: "A detailed evaluation of tropospheric gradient maps with meteorological observations will be a subject of an upcoming study." This sentence suggests that the present study is not complete. I suggest removing it. But I suggest also to include more meteorological information on the cases illustrated in the present study, otherwise it is difficult to conclude on the relevance of GNSS gradients regarding the meteorological situations.

The mentioned sentence was removed from the manuscript. We do not provide more information on meteorological situation on the illustrated cases in the manuscript, since both of them were already described in Douša et al. (2016) – we added information on this into the manuscript.

P11L21: "a developed area in south-west Germany" sound awkward, please reformulate.

Word "developed" was replaced with "urban".

P12L3: "It suggests to reflect only the impact of differences in mapping factors on calculating formal errors." I don't understand how the mapping factors influence the formal errors.

The mfg coefficients contribute to the design matrix and thus affects parameter variances. However, the sentence was modified in significantly rewritten paragraph.

P13L12: "all the OEW schemes demonstrate a strong impact of low-elevation observations reflecting an actual local tropospheric asymmetry in the water vapour distribution" this sentence is a bit surprising for two reasons: 1) the OEW schemes are expected to reduce the impact of noisy low-elevation observations and 2) their impact is expected to be quite different. And second remark: how can you be sure the local tropospheric asymmetry is in the water vapour distribution?

There is no surprise Ad 1 – the reduction of impact of more noise low-elevation estimates also affects a possibility to estimate tropospheric gradients. It is due to a significantly reduced signal (most frequently due to the non-isotropic water vapour distribution in a horizontal space) as well as due to an increased correlation of estimated gradients with other parameters. The meaning of Ad 2 is not clear to us. The sentence was reworded and shortened: "The SINEL4 weighting then shows highly reduced gradient values indicating a strong impact of the low-elevation observations on their estimates."

P14L6-10: the description of figure 6 is not clear. To me the results in the right panel (EQUAL) look more homogeneous whereas in the left panel (SINEL2) there is a steep variation with elevation (even above 30° where it becomes more difficult to see but I guess the shape more or less varies as 1/sin(e)). Please correct.

The main point is that the homogeneous distribution of post-fit residuals is not what we are expecting, and it seems to be unrealistic (see text below). And mainly considering any degradation close to the zenith which we noticed in other figures (stations, days). We generally consider more important the behavior of the post-fit residuals roughly above 30 degrees. At lower degrees, the behavior could be more strongly affected by various other aspects (see text below). It is difficult to show all this in a single figure, but mainly looking at different cases.

P14L10-12: what is "a more realistic view"? This sentence is not clear and too long. Please reformulate.
The text was modified: "The SINEL2 resulted in a distribution of the post-fit residual reflecting the expectation due to contributing errors in both GNSS observations and models. The errors generally increase with a decrease of the elevation angle, and the lowest contribution is expected at the zenith. The effects include contributions from atmospheric models, multipath, uncertainty of receiver antenna phase centre variations, lower signal-to-noise ratio and cycle slips".

The following part of the sentence (with corrections) could be introduced at the start of the paragraph to explain what is expected. "errors in GNSS observations which are expected to increase with a decrease of elevation angle, ~~besides atmospheric ones we mean e.g.~~ due to multipath effects, uncertainty of receiver antenna phase centre variations, lower signal-to-noise ratio, ~~obstructions~~ or cycle slips." Obstructions do not produce errors, they simply cut off the observations.
The modification was applied as proposed.

P15L8: "all post-processing solutions can be regarded as robust and their gradient estimates are clearly related to real weather conditions" I didn't get how you checked the robustness of the solutions, maybe use another term or specify based on which diagnostics you can conclude that. And the relation to real weather conditions was not demonstrated, only two cases were illustrated (and not based on meteorological diagnostics).
We removed the sentence from the manuscript.

P15L9: "which are fully independent of meteorological input data" please clarify what you mean here. I think the GNSS processing is not completely independent of NWP data since mapping functions are derived from NWP data (even GMF).
We reformulated the sentence for its better clarification.

P15L10: "tropospheric gradients thus provide additional interesting information in support of NWM forecasts" forecasting is not the only application, and in the Introduction you wrote that gradients are not assimilated. Please correct.
The word "forecasts" was removed.

P15L11-13: Need be reformulated e.g. "Better agreement was found between GNSS gradients and NWM when the cut-off elevation angle was decreased from 7° to 3° (the standard deviation of differences decrease by 10 %), for both the single- and dual- constellation results."
Whole paragraph was rewritten, see the updated version of the manuscript.

P15L27-32: needs be reformulated and integrated into the main discussion.
The paragraph was partly rewritten in the updated version of the manuscript. Unfortunately, we do not understand what do you mean that the content needs to be integrated in the main discussion – the paragraph represents a summary of individual Section 4 and forms a logical part of the Conclusion section.

P15L32-33: the long-term mean gradient results in the Appendix are not part of the main study.

Yes, you are right. However, we do not see a reason why we should not mention it in the Conclusion section and invite the reader to read the Appendix itself.

P16L1-5: needs be reformulated (see comments above).
Whole paragraph was reformulated, see the updated version of the manuscript.

Appendix A: the discussion should be stand-alone. Instead of citing Meindl et al. (2004), I suggest that you add maps of mean GN and GE from ERA5, or maybe only GN but for CH and BS *mfg*. The figure should be labelled A1.

As suggested we added maps of mean GN and GE from ERA5 using CH mfg. We modified the text in the Appendix accordingly.

Technical corrections: see the annotated manuscript
All proposed technical corrections were applied except cases where the manuscript undergone rewriting and therefore corrections could not be applied

Sensitivity of GNSS tropospheric gradients to processing options

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Abstract. An analysis of processing settings impact on estimated tropospheric gradients is presented. The study is based on the benchmark data set collected within the COST GNSS4SWEC action with observations from 430 GNSS reference stations in central Europe for May and June 2013. Tropospheric gradients were estimated in eight different variants of GNSS data processing using Precise Point Positioning (PPP) with the G-Nut/Tefnut software. The impact of the gradient mapping function, elevation cut-off angle, GNSS constellation, observation elevation-dependent weighting and real-time versus post-processing mode were assessed by comparing the variants by each to other and by evaluating them with respect to tropospheric gradients derived from two numerical weather prediction models (NWM). ~~Generally, all~~ All ~~the~~ solutions using final orbit and clock products provided tropospheric gradients with a ~~visible~~clear relation to ~~real weather conditions~~ NWM outputs. However, the quality of high-resolution gradients estimated in (near) real-time PPP analysis still remains challenging task due to the quality of the real-time orbit and clock corrections. Although using simplified models, the comparison of GNSS and NWM gradients suggests the 3° elevation angle cut-off and GPS+GLONASS constellation for obtaining optimal gradient estimates. The state-of-the-art models should be then applied for low-elevation observations for obtaining the best repeatability of the station coordinates. Finally, systematic errors can affect the gradient components solely due to the use of different gradient mapping functions, and still depending on the applied observation elevation-dependent weighting. A latitudinal tilting of the troposphere in a global scale causes a systematic difference up to 0.3 mm in the north gradient component, while large local gradients, usually pointing to a direction of increasing humidity, can cause differences up to 0.9 mm in any component depending on the actual direction of the gradient.~~in the post-processing mode provided a robust tropospheric gradient estimation with a clear relation to real weather conditions. The quality of tropospheric gradient estimates in real-time mode mainly depends on the actual quality of the real-time orbits and clocks. Best results were achieved using the 3° elevation angle cut-off and a combined GPS+GLONASS constellation. Systematic effects of up to 0.3 mm were observed in estimated tropospheric gradients when using different gradient mapping functions which depend~~ also ~~on the applied observation elevation-dependent weighting. While the latitudinal troposphere tilting causes a systematic difference in the north gradient component on a global scale, large local wet gradients pointing to a direction of increased humidity cause systematic differences in both gradient components depending on the gradient direction.~~

1 Introduction

When processing data from Global Navigation Satellite Systems (GNSS), a total signal delay due to the troposphere is modelled by epoch- and station-wise Zenith Total Delay (ZTD) parameters, and, optimally, together with tropospheric gradients representing the first order asymmetry of the total delay. ZTDs, which are closely related to Integrated Water Vapour (IWV), are operationally assimilated into ~~numerical~~ Numerical ~~weather~~ Weather ~~prediction~~ Prediction models (NWM) and have been proven to improve precipitation forecasts (Vedel and Huang, 2004, Guerova et al., 2006, Shoji et al., 2009). Previous studies demonstrated that the estimation of tropospheric gradients improves GNSS data processing mainly in terms of receiver position and ZTDs (Chen and Herring, 1997, Bar-Sever et al., 1998, Rothacher and Beutler, 1998, Iwabuchi et al., 2003, Meindl et al., 2004). Nowadays, ~~Tropospheric~~ tropospheric gradients are not assimilated into NWMs, however, they could be assimilated in future (see Zus et al., 2019) and they are essential for ~~the reconstruction~~ reconstructing ~~of~~ slant total delays (STD). The STDs represent the signal travel time delay between the satellite and the station due to neutral atmosphere and they are considered useful in numerical weather prediction (Järvinen et al., 2007, Kawabata et al., 2013, Bender et al., 2016) and reconstruction of 3D water vapor fields using the GNSS tomography method (Flores et al., 2000, Bender et al., 2011).

Brenot et al. (2013) showed a significant improvement of IWV interpolated 2D fields when tropospheric gradients are taken into account. With the improved IWV fields, the authors studied small scale tropospheric features related to thunderstorms. Douša et al. (2018a) demonstrated the advantage of ~~similar pseudo-observations~~using tropospheric gradients in the 2-stage troposphere model combining ~~optimally~~ NWM and GNSS data. Morel et al. (2015) presented a comparison study on zenith delays and tropospheric gradients from 13 stations at Corsica Island in the year 2011. Despite a good agreement in the ZTD, they found notable discrepancies in tropospheric gradients when estimated by using two different GNSS processing software~~.~~, ~~Besides~~ two different gradient mapping functions, and two different processing methods: ~~(~~1) double-differenced network solution, and 2) ~~versus~~ Precise Point Positioning, PPP (Zumberge et al., 1997) solution~~), the two software used different gradient mapping functions~~. Douša et al. (2017) indicated a problem with systematic errors in tropospheric gradients due to absorbing instrumentation errors. ~~Minimum~~ Few attempts were made to compare the tropospheric gradients with independent estimates, i.e., those derived from Water Vapor Radiometer (WVR) or NWM data. For a selected number of stations such a comparison was made in Walpersdorf et al. (2001) where ZTDs and tropospheric gradients from GPS were compared with those derived from a high-resolution NWM ALADIN. A good correlation between GPS and NWM gradients was found for inland stations, but not for coastal ones. More recently Li et al. (2015) and Lu et al. (2016) ~~to~~ showed that with the upcoming finalization of new systems such as Galileo and BeiDou the improved observation geometry yields more robust tropospheric gradient estimates. Li et al. (2015) found an improvement of about 20~35% for the multi-GNSS processing when compared with NWM and 21~28% when compared to WVR. Another multi-GNSS study on tropospheric gradients (Zhou et al., 2017) used data from a global network of 134 GNSS stations processed in six different constellation combinations in July 2016. An impact of gradients estimation interval (from 1 to 24 h) and cut-off elevation angle (between 3° and 20°) on a repeatability of receiver coordinates was examined. Better results were found for solutions where a shorter time interval of tropospheric gradient estimation was used and where the elevation cut-off angle of 7° or 10° was applied. However, strategies were not compared from the point of view of actually obtained gradient values. Finally, systematic ~~errors~~ differences and impacts of a gradient mapping function or observation elevation weighting on estimated gradients have not been studied yet.

In this work, we systematically evaluate the quality of tropospheric gradients estimated from a regional GNSS dense network under different atmospheric conditions. Using a unique data set, we study the impact of several approaches. ZTDs and tropospheric gradients are then compared with the ones estimated from two NWMs – ERA5, which is a global atmospheric reanalysis, and a limited area short range forecast utilizing the Weather Research and Forecasting (WRF) model. Finally, we quantified systematic differences in tropospheric gradients coming from the gradient mapping function and the method of observation weighting during a local event with strong wet gradients.

2 Data and Methods

2.1 Benchmark data set

The benchmark campaign was realized within the European COST Action ES1206 GNSS4SWEC to support development and validation of a variety of GNSS tropospheric products. An area in central Europe covering Germany, the Czech Republic and part of Poland and Austria was selected as a domain while May and June 2013 as a suitable time period due to occurrence of severe weather events including extensive floods. Data from 430 GNSS stations were collected together with meteorological observations from various instruments (synoptic, radiosonde, WVR, meteorological radar, etc.). In addition, tropospheric parameters from two global and one regional NWMs were generated. Detailed information about the benchmark campaign can be found in Douša et al. (2016). Although the presented study is based on the GNSS data collected within the benchmark campaign, all the presented GNSS and NWM solutions were newly prepared for this study.

2.2 Estimation of tropospheric gradients from GNSS

The STD as a function of the azimuth (a) and elevation (e) angle can be written as follows:

$$STD(a,e) = mfh(e) * ZHD + mfw(e) * ZWD + mfg(e) * (Gn * cos(a) + Ge * sin(a)) ~~+ R~~ \quad (1)$$

where ZHD denotes the Zenith Hydrostatic Delay and ZWD denotes the Zenith Wet Delay. The elevation angle dependency is given by mapping functions, which are different for the hydrostatic (*mfh*), wet (*mfw*) and gradient (*mfg*) part. The tropospheric horizontal gradient vector is defined in the local horizontal plane with two components, one for the north-south direction (*Gn*) and one for the east-west direction (*Ge*). From the formula (1) is evident that GNSS gradient represents a gradient of both hydrostatic and wet part of the delay, therefore a total delay gradient. ~~The post-fit residual R represents any un-modelled effects (Shoji et al., 2004).~~

During GNSS data processing, the ZHD is commonly taken from an a priori model, e.g. Saastamoinen (1972) or Global Pressure and Temperature (GPT, Boehm et al., 2007) based on climatological data, or it can be derived from NWM data. The

ZWD, or a correction to the modelled ZHD, and tropospheric gradients are estimated as unknown parameters using a deterministic or stochastic model.

Current mapping functions for hydrostatic (*mfh*) and wet (*mfw*) delay components are based either on climatological data, e.g. Global Mapping Function, GMF (Boehm et al., 2006a) or NWM data, e.g. Vienna Mapping Function, VMF (Boehm et al., 2006b). An advantage of the first approach is its independence of external data. Several mapping functions for tropospheric gradients have also been developed in the past, e.g. by Bar-Sever et al. (1998), by Chen and Herring (1997), or the tilting mapping function introduced by Meindl et al. (2004). The gradient mapping function (*mfg*) by Bar-Sever (BS) is given as

$$mfg = mfw * cot(ele) \quad (2)$$

and from the formula is apparent that it depends on the selected *mfw*. The Chen and Herring (CH) *mfg* reads as

$$mfg = 1 / (sin(ele) * tan(ele) + c) \quad (3)$$

where $c = 0.0032$. Since c is related to the scale height, it experiences spatiotemporal variations. Nevertheless, based on Balidakis et al. (2018) a variable c does not yield a statistically significant improvement in describing the atmospheric state over a constant c. Finally, the tilting mapping function is defined in a generic way as a tilting of the *mfw* by using the so-called tropospheric zenith z and can be expressed as.

$$mfg = \partial mfw / \partial z \quad (4)$$

Figure 1 illustrates the variability of the term $(Gn * cos(a) + Ge * sin(a))$ in Eq. (1) and the size of the mapping factors represented by actual values of the three *mfg*. We included gradient contributions corresponding to all GNSS observations in the benchmark campaign andduring a single day (May 31, 2013). While the BS *mfg* generates the highest mapping factors and smaller gradient contributions (scatters in y-axis), the CH *mfg* provides the lowest mapping factors and, consequently, higher gradient values. The tilting *mfg* gives then factors in between BS and CH *mfg* and results in gradient contributions in between the two. We can thus further focus on BS and CH *mfg* only as these can be considered as two extreme cases.

Figure 1 shows the fractional contribution of the tropospheric gradients to the slant total delay expressed in Eq. (1) as $(Gn * cos(a) + Ge * sin(a))$, i.e. the projection of the horizontal gradient vector in the direction of the individual satellites, as a function of a) the mapping factor represented by actual values of the *mfg* (left plot), and b) the observation elevation angle (right plot). The figure includes all GNSS observations in the benchmark campaign on one specific day (May 31, 2013). The x-range of gradient mapping factors clearly shows the difference in the three *mfg*. The tilting one gives the factors in between BS and CH *mfg* and, consequently, results in values in between them – the figure clearly shows the maximum values are inversely proportional to the maximum *mfg* factors. The black dots indicate values from a single epoch of the day (20:30 UTC).

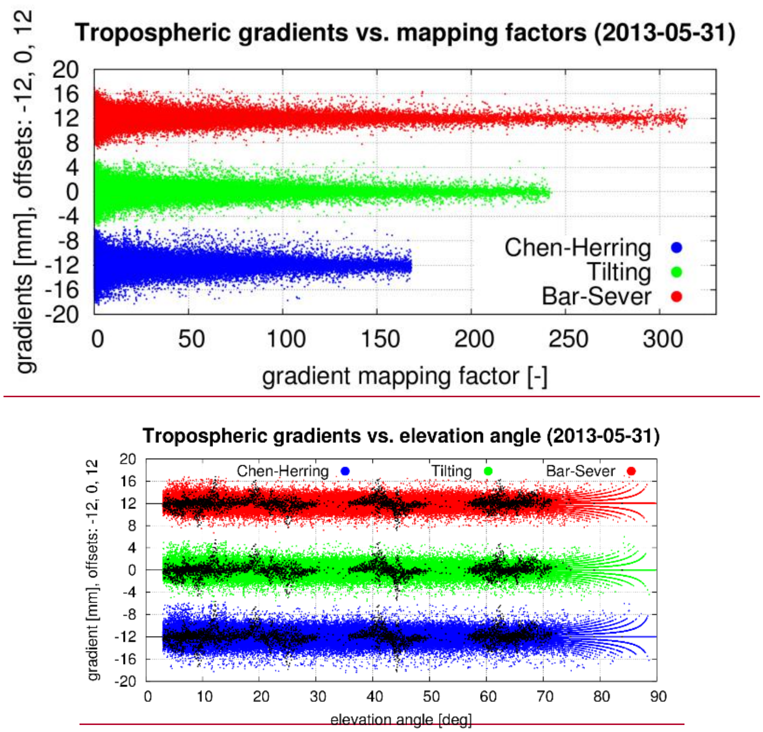


Figure 1. Variability of gradient mapping factors and tropospheric gradient contributions expressed in azimuths of individual satellites. Three *mfg* were studied on May 31, 2013: Chen and Herring *mfg* (blue), Bar-Sever *mfg* (red) and tilting *mfg* (green).~~Dependence of tropospheric gradients expressed in satellites azimuth on gradient mapping factors (left) and elevation angles of actually contributing observations (right). Three *mfg* were studied on May 31, 2013: Chen and Herring *mfg* (blue), Bar-Sever *mfg* (red) and tilting *mfg* (green). Black dots show only values from 20:30 UTC.~~

We use the G-Nut/Tefnut software (Václavovic et al., 2014) for GNSS data processing of the benchmark campaign. This software utilizes the PPP method and is capable of multi-GNSS processing in real-time (RT), near-real time (NRT) and post-processing (PP) mode with a focus on all the tropospheric parameters estimation: ZTDs, tropospheric gradients and slant delays (Douša et al., 2018b). Stochastic modelling of the troposphere allows an epoch-wise parameter estimation by extended Kalman filter in RT solutions (FLT) or its combination with a backward smoother which is used for NRT and PP solutions (FLT+SMT), see Václavovic and Douša (2015).

Table 1 describes all eight variants of solution for the benchmark campaign produced using the G-Nut/Tefnut which differ in (a) elevation cut-off angle (3° or 7°), (b) gradient mapping function (Chen and Herring = CH or Bar-Sever = BS), (c) constellations (GPS only = Gx or GPS+GLONASS = GR) and (d) processing mode (post-processing using the FLT+SMT processing or simulated real-time using the FLT processing only). ~~All the variants except the three were~~Five variants based on the post-processing mode ~~using~~ used the backward smoother and the ESA final orbit and clock products (http://navigation-office.esa.int/GNSS_based_products.html). Three ~~additional solutions~~variants, abbreviated as RT1GxCH3, RT3GxCH3 and RTEGxCH3, were ~~included~~ used to test the performance of the Kalman filter and RT orbit and clock corrections ~~instead of a post-processed solution supported with final precise products. The solutions RT1GxCH3 and RT3GxCH3 simulate a real-time~~

~~capability of estimates when~~ using the IGS01 (RT1GxCH3) and IGS03 (RT3GxCH3) corrections from the IGS Real-Time Service (RTS, http://rts.igs.org). ~~While~~ The IGS01 RTS product is a GPS only single-epoch solution produced using software developed by ESA/ESOC~~,~~. ~~the~~ The IGS03 product is a GPS+GLONASS solution based on ~~a~~ the Kalman filter and the BKG's BNC software. The last solution, RTEGxCH3, applying the ESA final product is used to test a benefit of the backward smoothing on the one hand, and, an impact of the quality of RT corrections on the other hand. Unfortunately, the solution based on the processing of GPS+GLONASS data in the simulated RT mode had to be rejected due to a highly variable quality of RT corrections in 2013 affecting mainly the GLONASS contribution (and we noted temporal problems in GPS solutions too, see Figure 4).

The GPT model was used for calculating a priori ZHDs and the GMF was used for mapping hydrostatic and wet delays to the zenith. Estimated tropospheric parameters are thus independent from any meteorological information. GNSS observations were processed using 30-hour data batches when starting six hours before the midnight of a given day in order to eliminate the PPP convergence. In all variants, the observation sampling of 300 s was used with ZTDs and tropospheric gradients estimated for every epoch. The station coordinates were estimated on a daily basis. The random walk of 6 mm/sqrt(hour) was applied for the ZTD and 1.5 mm/sqrt(hour) for the gradients. Absolute IGS model IGS08.ATX was used for the antenna phase centre offsets and variations. All variants used the elevation observation weighting of $1/sin^2(e)$ ~~$1/sin^2(ele)$~~.

Table 1. Processing parameters of individual variants from the G-Nut/Tefnut software. Mode FLT denotes to simulated real-time solution using Kalman filter only, FLT+SMT to post-processing solution using the Kalman filter and the backward smoother.

Solution name	Elevation cut-off	Constellation	Gradient mapping function	Products	Mode
GxCH3	3	GPS	Chen and Herring	ESA final	FLT+SMT
GRCH3	3	GPS+GLONASS	Chen and Herring	ESA final	FLT+SMT
GRBS3	3	GPS+GLONASS	Bar-Sever	ESA final	FLT+SMT
GxCH7	7	GPS	Chen and Herring	ESA final	FLT+SMT
GRCH7	7	GPS+GLONASS	Chen and Herring	ESA final	FLT+SMT
RT1GxCH3	3	GPS	Chen and Herring	IGS01 RT	FLT
RT3GxCH3	3	GPS	Chen and Herring	IGS03 RT	FLT
RTEGxCH3	3	GPS	Chen and Herring	ESA final	FLT

2.3 Estimation of tropospheric gradients from NWM

Tropospheric gradients and zenith delays were derived from the output of two different numerical weather models; the ERA5 (https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-datasets/era5) and a simulation utilizing the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008). The ERA5 is a reanalysis produced at the European Centre for Medium-Range Weather Forecasts (ECMWF). The pressure, temperature and specific humidity fields are provided with a horizontal resolution of approximately 31 km (T639 spectral triangular truncation) on 137 vertical model levels (up to 0.01 hPa) every hour. ~~Although the ERA5 output is available every hour, we derived tropospheric parameters from it in 3-hour~~

~~interval to avoid an extensive data handling.~~ The WRF simulations are performed at GFZ Potsdam. The initial and boundary conditions for the limited area 24-hour free forecasts (starting every day at 0 UTC) stem from the analysis of the Global Forecast System (GFS) of the National Centers for Environmental Prediction (NCEP). The pressure, temperature and specific humidity fields are available every hour with a horizontal resolution of 10 km on 49 vertical model levels (up to 50 hPa). The ray-trace algorithm by Zus et al. (2012) is used to compute STDs. The tropospheric gradients are derived from STDs as follows. At first, 120 STDs are computed at elevation angles 3°, 5°, 7°, 10°, 15°, 20°, 30°, 50°, 70°, 90° and all azimuths between 0° and 360° with an interval of 30°). Second, we compute azimuth-independent STDs from the local vertical refractivity profile.~~under the assumption of a spherically layered troposphere.~~ Third, the differences between the azimuth-dependent STDs and the azimuth-independent STDs are computed. Finally, the gradient components are determined by a least-square fitting. For details the reader is referred to the Appendix in Zus et al. (2015).

Using ERA5 long-term global data, we ~~experimented with~~tested different observation elevation weighting schemes (equal versus the elevation dependent weighting of $1/sin^2(e)$~~standard elevation angle dependent weighting~~) and two *mfg*s (BS and CH). While using different observation elevation weighting schemes led to negligible differences in the tropospheric gradients, we found a significant systematic difference in the north gradient component between tropospheric gradients derived with BS and CH *mfg* (see Appendix A). ~~Since~~ In this regard it is important to note that NWM derived tropospheric gradients presented in this study were computed using CH *mfg*~~, in principal their comparison with GNSS gradients estimated with BS *mfg* should be treated cautiously~~.

We also note that tropospheric gradients can be derived (approximated) with the closed form expression depending on the north-south and east-west horizontal gradient of refractivity (Davis et al., 1993). We compared the tropospheric gradients derived with the two different methods with GNSS tropospheric gradients. We utilized the ERA5 and GNSS GRCH3 data. We find that for the considered stations (over the entire benchmark period) the root-mean square deviation between NWM and GNSS tropospheric gradients is 10 % smaller if we apply the first instead of the second method. This can be explained by the fact that the first approach, that is, calculating tropospheric gradients from ray-traced delays by least square adjustment, is the approach which is closer to the method applied in the GNSS analysis (parameter estimation).

3 Impact of applied processing settings on GNSS tropospheric gradients estimation

ZTDs and tropospheric gradients from all eight variants were compared to each other and to the tropospheric parameters from ERA5 and WRF to evaluate the impact of various settings in GNSS data processing. Although about 430 GNSS stations are available in the benchmark data set, statistical results given in this section 3 are based on a subset of 243 stations. Firstly, 84 stations without the capability of receiving GLONASS signals were excluded. Secondly, stations which did not have at least 5 % of all the observations in the range of elevation angles between 3° and 7° were excluded as well. This rule was applied to allow a systematic evaluation of elevation cut-off angle impact on tropospheric parameters. The majority of the stations (103) had to be excluded because of inability to provide a sufficient number of observations at very low elevation angles.

Tropospheric parameters from the G-Nut/Tefnut software were provided every 5 minutes while the output from ~~the WRF~~both NWM models was available every hour~~ and the output from the ERA5 model was computed every three hours~~. Therefore, comparisons between GNSS solutions are based on a 5-minute interval while comparisons between GNSS and NWM solutions are based on a ~~3~~1-hour interval.

3.1 Comparison of individual GNSS variants with each other

Absolute values of tropospheric gradient components stay typically below 1-2 mm under standard atmospheric conditions and can reach 4-6 mm during severe weather conditions. The gradient of 1 (6) mm corresponds to about 55 (330) mm slant delay correction when projected to 7° elevation angle. For an illustration an example time series of tropospheric gradients at station LDB2 (Brandenburg, Germany) for a period between May 15 and June 15, 2013 is given in Figure 2.

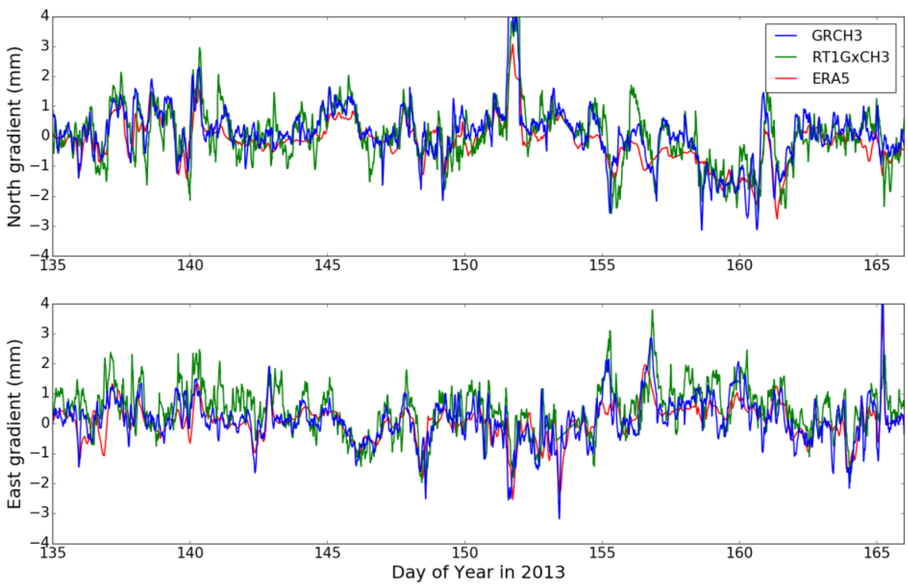


Figure 2. Tropospheric gradients retrieved from GNSS data processing (GRCH3, RT1GxCH3) and from NWM ERA5 at station LDB2 (52.209°N, 14.121°E, Germany) for a period from May 15, 2013 till June 15, 2013.

Results for individual GNSS variants comparison based on 3.6 million of pairs of values over 55 days and 243 GNSS stations are presented in Table 2. We notice a good agreement among all the post-processing (PP) variants from the statistics. The standard deviation (SDEV) indicates a negligible~~the smallest~~ impact due to the change of *mfg* for both ZTD estimates (0.2 mm) and the smallest impact on tropospheric gradients (~0.14 mm). The impact increases then ~~slightly~~ for both ZTD and gradients when comparing results of ~~a~~ single ~~-/~~and dual-constellation (1.2 mm for ZTD, ~0.18 mm for gradients). It -should be noted that ~~In dual-constellation,~~ GLONASS observations were down-weighted by a factor of 1.5 in dual-constellation variants of solution. The gradients estimated with improved geometry and using more observations are expected to provide more accurate and reliable estimates. ~~which~~It is notable in the comparisons of single-/dual-constellation at different elevation cut-off angles (the impact is larger for a higher cut-off). Generally, tThe largest impact is eventually observed due to the elevation cut-off angle, i.e. 2.2 mm and ~0.21 mm for ZTD and tropospheric gradients, respectively. By using common data, period, processing strategy and software in our analysis, a significance of the impact of different models can be assessed by confronting achieved SDEV with those obtained when comparing gradients from different software, processing methods and even observing techniques. Generally, the SDEV values in Table 2 reach 30-50% of those obtained from comparing two different GNSS software and processing methods with two different NWM sources, and still using the same data set from the benchmark campaign (Douša et al. 2016). Differences between ZTDs and tropospheric gradients from all compared variants of solution were also statistically tested. And in all cases, the differences were found to be statistically significant at the 5% significance level while using the Wilcoxon signed-rank test. This non-parametric test was used since none of the processed variant of solution evinced a normal distribution of their ZTDs and tropospheric gradients.

Linear correlation coefficients (CorCoef) reach value of 1.0 in all cases for the ZTD comparisons with an exception of 0.999 in case of standalone GPS solution and 7-deg elevation cut-off. The ZTDs were thus practically unaffected by different models. The correlation coefficients are then progressively decreasing from 0.99 to 0.95 for gradient comparisons when following trends described for results of SDEV. –Generally, we then observed very small biasesmean differences in all the cases. Interestingly, comparing results with CH and BS *mfg*s provided the largest biasesmean differences of -0.05 mm and 0.03 mm for north and east gradient component, respectively, although they fit the best in terms of SDEV and correlation coefficients compared to all other cases. These small systematic effects can be attributed to the average difference between tropospheric gradients computed with BS *mfg* compared to CH *mfg*. However, they are averaged over all stations and the period while they still strongly depend on both size and orientation of gradients as will be discussed in Section 4.There were no significant negative biases observed, but smallFor tropospheric gradients biases of -0.05 mm and 0.03 mm for north and east gradient component, respectively, were observed when comparing solutions using CH and BS mapping functions. These small systematic effects are attributed to the smaller tropospheric gradients computed with BS *mfg* compared to CH *mfg* (see Section 4). The larger effect can be found in the north-south direction reflecting the mean gradient (see Table 4) pointing towards the equator.

An increased scatter penalty of RT processing versus PP ones is visible on the standard deviation values for of ZTD and tropospheric gradients increased by a factor of 3 and on significant biasesmean differences. These are also emphasised by the reduction of correlation coefficients mainly for tropospheric gradients. The two RT solutions can be still considered of good quality if we take into consideration results found in Ahmed et al. (2016) or Kačmařík (2018), where mean biases and SDEV values up to 12 mm were reported for comparisons between RT ZTD solutions based on IGS01 and IGS03 streams and post-processing solutions based on final products. Since no significant virtually zero biases mean differences for both ZTD and tropospheric gradients were present in the RTEGxCH3 variant, when using the Kalman filter too, the quality of RT tropospheric parameters is mainly a consequence of a lower the quality of IGS01 and IGS03 RT products (Douša et al., 2018b).

Table 2. Comparison of individual variants of GNSS data processing run in post-processing mode (top) and in simulated real-time mode (bottom), units: BIAS Mean and SDEV in mm, CorCoef represents a linear correlation coefficient.

Compared solutions	PP	ZTD ~~BIAS~~Mean	SDEV	CorCoef	N-S gradient MeanBIAS	SDEV	CorCoef	E-W gradient Mean~~BIAS~~	SDEV	CorCoef
GRCH3 – GRBS3		0.0	0.2	1.000	-0.05	0.15	0.991	0.03	0.13	0.995
GRCH3 – GxCH3		0.1	1.1	1.000	0.00	0.17	0.970	-0.02	0.16	0.973
GRCH7 – GxCH7		0.1	1.2	1.000	-0.01	0.20	0.961	-0.02	0.18	0.961
GRCH3 – GRCH7		0.1	2.1	1.000	0.01	0.20	0.958	0.00	0.18	0.964
GxCH3 – GxCH7		0.2	2.2	0.999	0.01	0.23	0.947	-0.01	0.21	0.954

Compared solutions	RT	ZTD Mean~~BIAS~~	SDEV	CorCoef	N-S gradient Mean~~BIAS~~	SDEV	CorCoef	E-W gradient Mean~~BIAS~~	SDEV	CorCoef
~~GxCH3 –~~ RT1GxCH3-GxCH3		~~-~~3.5	5.9	0.996	0.10	0.55	0.698	-0.18	0.57	0.648
~~GxCH3 –~~ RT3GxCH3 - GxCH3		~~-~~2.7	6.4	0.996	0.05	0.76	0.649	-0.08	0.80	0.584
~~GxCH3 –~~ RTEGxCH3 - GxCH3		~~-~~0.1	4.4	0.998	0.00	0.39	0.827	0.02	0.44	0.763
RT1GxCH3 – RT3GxCH3		0.8	5.0	0.997	-0.05	0.75	0.664	0.11	0.75	0.638

3.2 Comparison of individual GNSS variants with NWM

The statistics for the GNSS and NWM comparisons are summarized in Table 3. A ~~bias~~ mean difference of about 1 (4) mm is visible for ZTDs between GNSS and ERA5 with standard deviations around 9 (11) mm for individual PP (RT) GNSS solutions. The standard deviations are about 2 mm larger when GNSS and WRF are compared. This is probably due to the fact that the solution from WRF is based on a 24-hour free forecast (errors are supposed to grow with increasing forecast length) whereas the solution from ERA5 is based on a reanalysis. ~~We attribute a~~The negative ~~bias~~ mean difference of -3 mm in ZTD between GNSS and WRF might be due to the global NCEP GFS analysis which is used for the initial and boundary conditions for the WRF solution. A negative ~~bias~~ mean difference of -5 mm in ZTD between two GNSS reference solutions and a solution based on the NCEP GFS was already reported in the past (Douša et al., 2016).

Table 3. Comparison of individual variants of GNSS data processing run in post-processing mode (top) and in simulated real-time mode (bottom) with NWM solutions, units: ~~BIAS~~Mean and SDEV in mm, CorCoef represents a linear correlation coefficient~~mm~~.

Compared solutions	PP	ZTD Mean~~BIAS~~	SDEV	CorCoef	N-S gradient Mean~~BIAS~~	SDEV	CorCoef	E-W gradient Mean~~BIAS~~	SDEV	CorCoef
GRCH3 – ERA5		1.0	8.8	0.992	-0.02	0.47~~8~~	0.725	-0.01	0.~~48~~47	0.721
GRBS3 – ERA5		1.0	8.9	0.992	0.04~~3~~	0.42	0.714	-0.03	0.43	0.708

GxCH3 – ERA5	1.00.9	9.1	0.991	-0.01	0.49	0.703	0.01	0.48	0.709
GxCH7 – ERA5	0.78	10.2	0.989	-0.02	0.56	0.624	0.0102	0.53	0.652
GRCH7 – ERA5	0.9	9.8	0.990	-0.03	0.54	0.655	-0.0100	0.5251	0.672
GRCH3 – WRF	-2.83.0	11.23	0.987	-0.04	0.54	0.654	-0.000.01	0.56	0.630
GRBS3 – WRF	-2.98	11.23	0.986	0.01	0.49	0.643	-0.02	0.52	0.618
GxCH3 – WRF	-2.83.0	11.45	0.986	-0.04	0.5556	0.633	0.02	0.5657	0.621
GxCH7 – WRF	-3.02	12.23	0.984	-0.0405	0.6162	0.564	0.03	0.61	0.573
GRCH7 – WRF	-2.93.1	11.912.0	0.985	-0.05	0.59	0.592	0.01	0.6059	0.589

Compared RT solutions	ZTD			N-S gradient			E-W gradient		
	MeanBIAS	SDEV	CorCoef	MeanBIAS	SDEV	CorCoef	MeanBIAS	SDEV	CorCoef
RT1GxCH3 – ERA5	4.54	10.35	0.988	-0.12	0.5859	0.606	0.2019	0.58	0.578
RT3GxCH3 – ERA5	3.6	10.79	0.988	-0.0607	0.8385	0.504	0.08	0.9087	0.456
RTEGxCH3 – ERA5	1.0	9.67	0.990	-0.01	0.47	0.692	-0.01	0.46	0.680
RT1GxCH3 – WRF	0.57	12.6	0.983	-0.14	0.6365	0.544	0.21	0.65	0.504
RT3GxCH3 – WRF	-0.23	12.89	0.982	-0.0809	0.879	0.451	0.0910	0.9592	0.391
RTEGxCH3 – WRF	-2.89	1112.90	0.985	-0.04	0.5354	0.627	0.01	0.5554	0.597
ERA5 - WRF	-3.89	11.01	0.987	-0.02	0.40	0.771	0.01	0.4544	0.722

With regards to the tropospheric gradients, the biases mean differences between GNSS and NWM stayed within a range from -0.05 to 0.03 04 mm .(with Tthe exception was of the GNSS RT solutions RT1GxCH3 with a bias of -0.1 mm for the north component and 0.2 mm for the east component). Here the existing differences between two GNSS variants solution based on different *mfg*s can be attributed to usage of CH *mfg* for derivation of NWM tropospheric gradients and to the existing systematic difference between tropospheric gradients estimated using these two *mfg*s (see Section 2.2 and Appendix A). The standard deviations between GNSS and NWM were approximately doubled or tripled when compared to standard deviations between individual variants of GNSS solutions. They were also found to be higher for the WRF than for ERA5. Again, this can be probably explained by the fact that the solution from WRF is based on a 24-hour free forecast whereas ERA5 is based on a reanalysis.

In order to evaluate the statistical significance of differences between ZTDs and tropospheric gradients from all variants of GNSS solution and both NWMs we realized the same statistical tests as mentioned in the previous section. Again, the differences were found to be statistically significant at the 5% significance level in all cases.

Obviously, NWMs obviously cannot be regarded as representing a ground truth atmospheric conditions. However, a similar pattern is present in results for both of them: standard deviations are smaller and correlation coefficients higher for GNSS solutions using a lower cut-off elevation angle (3° instead of 7°) and when using more observations (GPS+GLONASS). For example, the SDEV for north gradient component between GNSS and ERA5 is 0.56 mm for the GxCH7 variant while 0.48 47 mm for the GRCH3 variant. This represents a decrease of 14 16 %. In this regards we also derived tropospheric parameters from both NWMs using a 7° cut-off elevation angle and repeated the comparisons to test if GNSS variants of solution with a 7° cut-off would not be closer to NWM solutions based also on the 7° cut-off angle. And we always found a better agreement between any evaluated GNSS variant of solution and the NWM solution based on the 3° cut-off angle – in terms of biasmean difference, standard deviation and correlation coefficient. It indicates that the settings of cut-off elevation angle in NWM ray-tracing does not influence the described pattern in GNSS results. From two GNSS variants differing only in the *mfg*, the solution applying the BS mapping function is closer to the NWMs in terms of standard deviation. Since the solution based on CH *mfg* reaches slightly higher values of correlation coefficient than the solution based on BS *mfg*, t. The lower values of standard deviation can This can be partly understood as the magnitudes (modulus of the gradient vectorcomputed as $\sqrt{Gn^2 + Ge^2}$) of GNSS tropospheric gradients using the BS *mfg* are smaller compared to the ones from the CH *mfg* (see next Section 2.2) and the magnitudes of NWM tropospheric gradients are in general smaller and more smoothed compared to the GNSS tropospheric gradients.

Maps showing tropospheric gradients were generated for all the variants of GNSS solutions and both NWM solutions and visually evaluated for the whole benchmark period. For better visualization we included all the GNSS stations of the benchmark campaign, i.e. not just the subset of 243 stations used for the presented statistics. Generally, GNSS provided homogenous fields of tropospheric gradients without a noisy behaviour at the level of individual stations and a very good agreement in gradient directions and usually also in gradient magnitudes was found between GNSS and NWM gradient maps. In Figure 23, two examples are shown for different events when a weather fronts was were passing over the studied area. For a description of meteorological conditions prevailing during these events the reader is referred to Douša et al. (2016). Tropospheric gradients derived from NWM provided more smoothed gradient fields, but somehow limited to render local structures mainly due to the spatial resolution of both NWMs. As the ERA5 model has coarser spatial resolution than the WRF model, such behaviour was a little bit more apparent in its outputs. On the other hand, when compared to results of the 1° × 1° resolution global models ERA-Interim and NCEP GFS (Douša et al., 2016), the presented NWMs tropospheric gradients have larger magnitudes. A detailed evaluation of tropospheric gradient maps with meteorological observations will be a subject of an upcoming study.

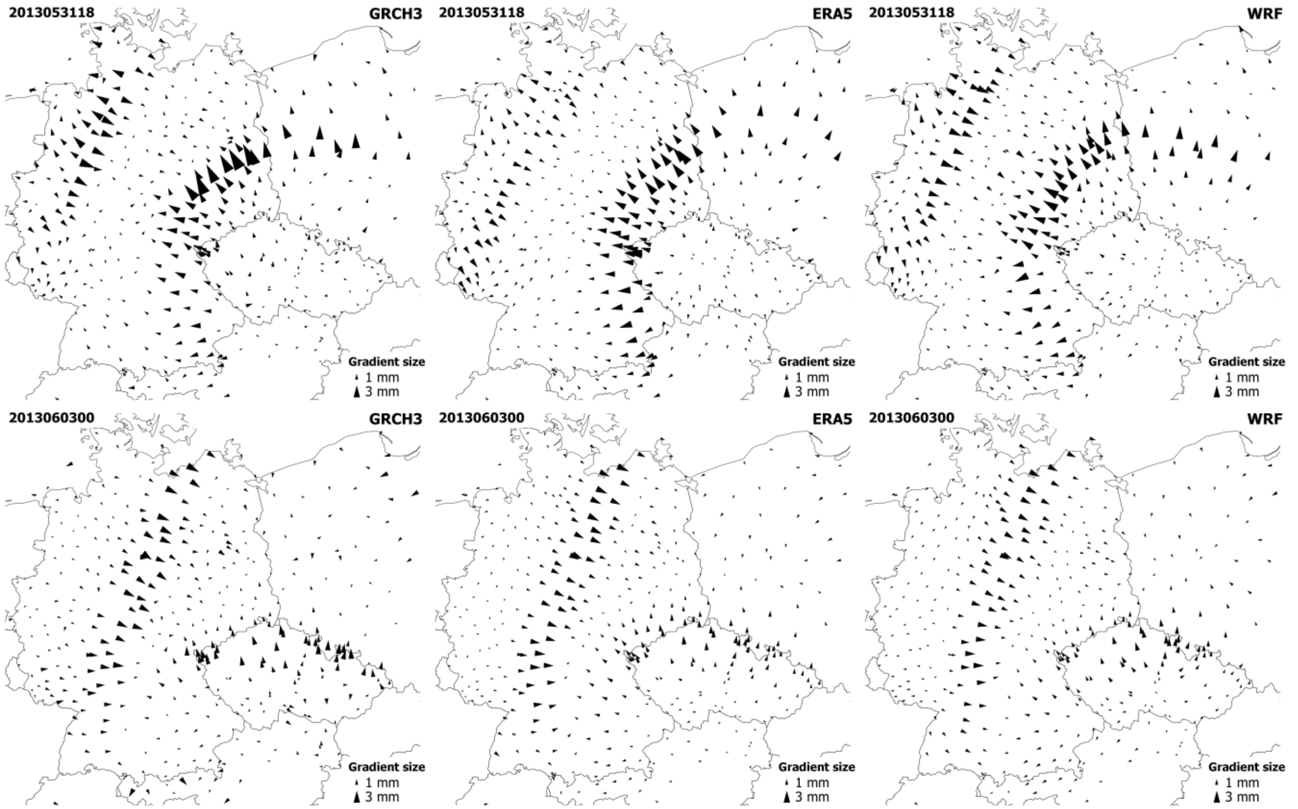


Figure 23. Tropospheric gradient maps from GNSS GRCH3 solution (left), NWM ERA5 solution (middle) and NWM WRF solution (right) on 31 May 2013, 18:00 UTC (top) and on 03 June 2013 00:00, UTC (bottom).

Comparing GNSS to NWM products in Table 3 indicated that the RTEGxCH3 solution driven by the Kalman filter and the ESA final product shows a comparable performance to the GxCH3 solution driven by the Kalman filter and the backward smoother. An increase of bias mean difference and standard deviation values for other solutions based on RT mode indicates that the quality of the RT tropospheric product solution is dominated by an actual quality of RT orbit and clock corrections. In this regard, we examined systematically all tropospheric gradient maps and found that gradients from the RTEGxCH3 solution are always in a very good agreement with PP solutions. Although there were imperfections in matching RT1GxCH3 gradients and PP solutions, the performance can be still considered as generally good and stable. This was however not the case of the RT3GxCH3 solution where we observed a varying quality of estimated tropospheric gradients. For the majority of epochs, in particular during the periods with strong gradients, the tropospheric gradients could be evaluated as acceptable. However, situations when gradients from all the stations point to the same direction occurred from time to time, obviously without a physical relation to the actual weather situation. An example of this behaviour is presented in Figure 3 4 where tropospheric gradients from the RT3GxCH3 solution behave normally on 31 May 2013, 18:00 UTC, and became unrealistic on 6 May 2013, 18:00 UTC where all the stations point to the south-west direction and reveal high gradient magnitudes. These Such issues occurred occasionally and for a limited period of time and in the RT3GxCH3 solution only. The reason is an instability of the

RT3 stream during the initial period (the first half of 2013) affected by many interruptions and data gaps thus caused frequent parameter re-initialization in PPP.~~It happened most probably due to many interruptions (mainly in GLONASS RT corrections) which affected the quality of RT products and caused frequent PPP re-initialization.~~

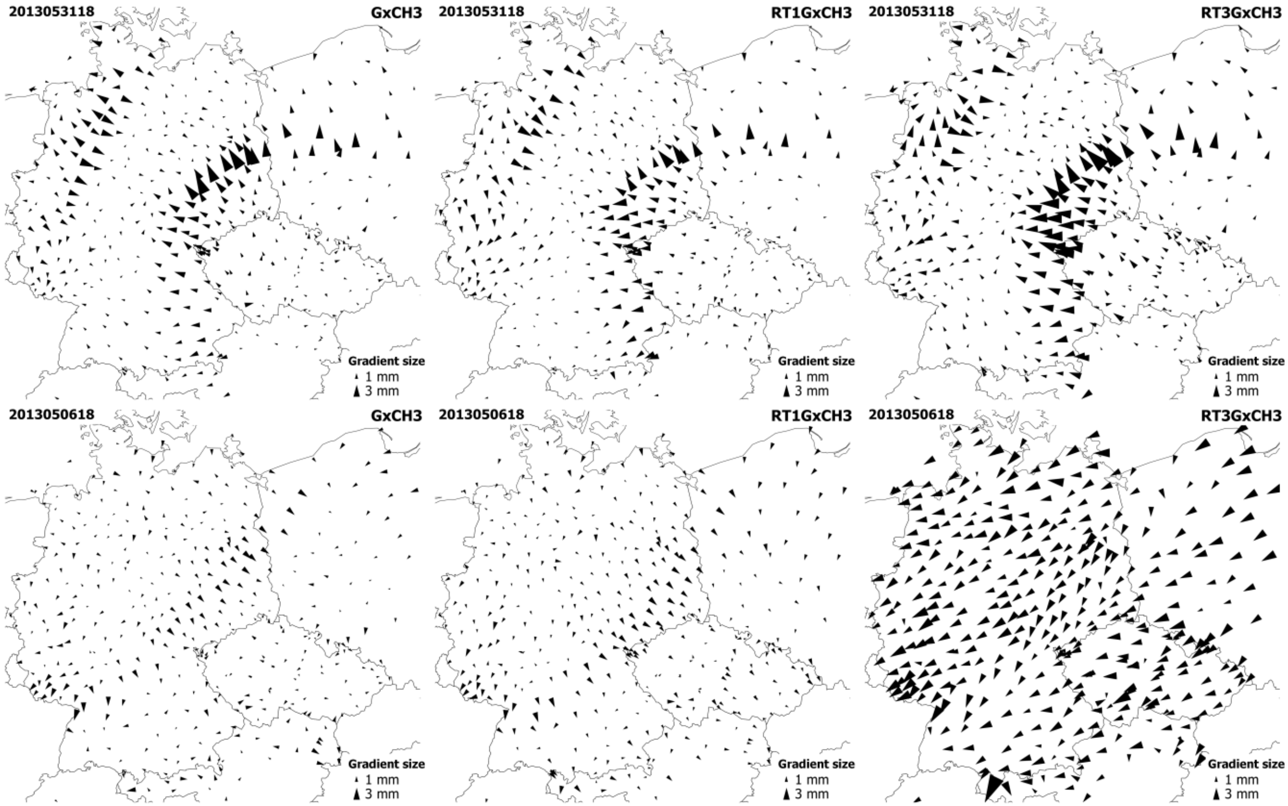


Figure ~~3~~4. Tropospheric gradient maps from GNSS GxCH3 solution (left), GNSS RT1GxCH3 solution (middle) and GNSS RT3GxCH3 solution (right) on 31 May 2013, 18:00 UTC (top) and on 06 May 2013, 18:00 UTC (bottom).

3.3 Additional assessment of processing settings on GNSS tropospheric gradients

Mean gradient magnitudes and azimuth angles (direction of gradient) over the whole benchmark period were computed for 243 GNSS stations and are presented in Table 4. Mean magnitudes of tropospheric gradients from all PP GNSS variants oscillated around 0.85 mm and 0.67 mm when using the CH *mfg* and the BS *mfg*, respectively. Gradients computed using the latter show about 17 % smaller gradients compared to the former if all the processing aspects remained identical. Both RT solutions also resulted with higher gradient magnitudes, namely +14 % for RT1GxCH3 and +47 % for RT3GxCH3 when compared to the corresponding GxCH3 PP variant. A mean gradient magnitude of about 0.7 mm was found for both NWM solutions, i.e. of about 0.1 mm smaller than for the GRCH3 solution. This can be mainly explained by the limited horizontal resolution of the NWMs.

Table 4 shows that mean tropospheric gradients point towards the equator~~, see also~~ what is in an agreement with Meindl et al. (2004). Such a mean gradient direction does not depend on the gradient mapping function. By adding GLONASS observations the mean gradient direction was changed by +2°, however, actual effects were found to be highly station-dependent with a typical range of ±5° for individual stations. The direction of mean gradient in both NWM solutions was in a very good agreement with ~~that in~~ all GNSS post-processing variants. ~~GNSS. solutions using GPS+GLONASS constellation.~~

Directions of mean gradient over individual stations were mostly within ±15° when compared to the total mean gradient estimated for the stations and the solution variant. On the other hand, the performance was not identical for the individual solutions. A change of cut-off elevation angle from 7° to 3° led to an ~~significantly~~ increased number of stations with the mean gradient direction within ±15° of the total mean direction and to a decreased number of stations with a mean gradient direction differing for more than 30° (regarded as outlier stations in Table 4). Two GNSS stations were marked as outliers by all processed variants with their mean gradient direction differing by more than 50° from the total variant mean. Both of them are located in an urban~~a developed~~ area in south-west Germany and are using the same receiver and antenna type from Leica, which is however used by many other stations in the same region where no issues with gradient mean angle were identified. Still, the reason of their different behaving can be of instrumental or environmental origin.

Table 4. Mean magnitudes and azimuth angles of tropospheric gradients from all individual GNSS variants of processing and NWMs ERA5 and WRF.

Solution	Mean magnitude (mm)	Mean azimuth (°)	Percentage of stations with mean azimuth = total_mean ± 15°	Percentage of stations with mean azimuth = total_mean ± 30°	Number of outlier stations
GRCH3	0.81	170.3	88.9	99.2	2
GRBS3	0.67	170.4	91.8	98.8	3
GxCH3	0.83	168.4	88.1	97.5	6
GxCH7	0.86	168.2	74.1	95.1	12
GRCH7	0.84	170.5	79.8	97.1	7
RT1GxCH3	0.95	152.4	92.6	97.9	5
RT3GxCH3	1.22	162.7	96.3	98.8	3
RTEGxCH3	0.75	168.7	86.0	97.5	6
ERA5	0.68~~9~~	169.4~~171.8~~	9~~7.1~~6.3	100.0	0
WRF	0.73	171.0	100.0	100.0	0

Table 5 summarizes mean repeatability of daily coordinates as well as statistical comparison of formal errors of estimated ZTDs and tropospheric gradients from different GNSS processing variants. The station coordinates repeatability is improved when using combined GPS+GLONASS solutions compared to GPS-only solutions, namely by a factor of 2 and 1.2 in horizontal components and the height, respectively. The number of available satellites and their geometry plays a significant role in this context. An increase of the elevation angle cut-off (from 3° to 7°) resulted in improved height repeatability, which corresponds to Zhou et al. (2017) suggesting optimal 7° cut-off for the height repeatability when comparing results of different elevation angle cut-off (3° - 15°). However, it should be noted that GPT+GMF models and the PPP method were used in both cases. Contrary, Douša et al. (2017) observed an improvement in the height repeatability even when using the elevation angle cut-off 3° (compared to 7° and 10°) when exploiting double-difference observations, the VMF1 mapping function (Boehm et al., 2006b) and the Bernese GNSS Software (Dach et al. 2015). This discrepancy might be attributed to a slightly worse modelling of low-elevation observations when using the GPT+GMF, in particular when the PPP strongly depends on all modelling aspects of undifferenced observations. We also notice a slightly better performance in case of the BS *mfg* when compared to the CH *mfg*. The results of the forward filter processing didn't show any degradation when using the ESA final products (RTEGxCH3). When using the IGS real-time product, the repeatability of all coordinates got worse by a factor of 2-3 and 4-5 for RT1GxCH3 and RT3GxCH3 variant respectively. The latter is attributed to a lower quality of the IGS03 RT3 products during some periods, see Figure 4. In Table 5, mean formal errors of ZTDs and both horizontal gradient components from GNSS data processing are examined for all the processed variants.

Formal error of the parameter can be generally regarded as an estimation uncertainty. Typically, high formal errors for tropospheric parameters occur at situations when they were estimated under not unfavourable conditions, it means i.e.e.g. low number of observations and/or their poor geometry and/or their poor quality. Naturally, smaller formal errors correspond to the lower elevation angle cut-off, which can be observed for both Both for ZTDs and horizontal tropospheric gradients in Table 5. Formal errors are about 17% and 11% smaller when using the 3° cut-off (GRCH3) compared to the 7° cut-off (GRCH7) for horizontal gradients and ZTDs, respectively, thus indicating a higher impact on the former. a decrease of a mean formal error was occurring when more observations were used in the processing. This behaviour is logical and expectable since a higher number of observations is being used to estimate the same number of unknown parameters. A decrease of formal errors of tropospheric gradients estimated with a 3° cut-off compared to 10° cut-off was previously reported also by Meindl et al. (2004). On the other hand,In our results, when the solution GRCH7 using GPS+GLONASS observations and an elevation cut-off of 7 degrees was compared to the GRCH3 solution using the same constellation but a cut-off of 3 degrees, a decrease of formal error in horizontal gradients was approximately 16.5 % but the increase in number of observations between these two solutions was only 8 %. Since the decrease of formal error for ZTD in the same case was only 11 %, observations from very low elevation angles affect here more the horizontal tropospheric gradients estimation than ZTDs. Interestingly, using the BS *mfg* resulted in smaller formal errors of tropospheric gradients, but we haven't observed any change in formal errors of other estimated parameters. The smaller errors may suggest an improvement in estimated parameters, i.e. see coordinates repeatability, but it can be also partly attributed to the effect of different size of *mfg* coefficients.Using the BS *mfg* gives gave generally smaller formal errors for tropospheric gradient estimates, but these do did not differ significantly substantially for any other estimated parameters when compared to any other *mfg*. It suggests to reflect only the impact of differences in mapping factors on calculating formal errors.

Table 5. Mean position repeatability and formal errors and their standard deviation for tropospheric parameters from individual GNSS processing variants.

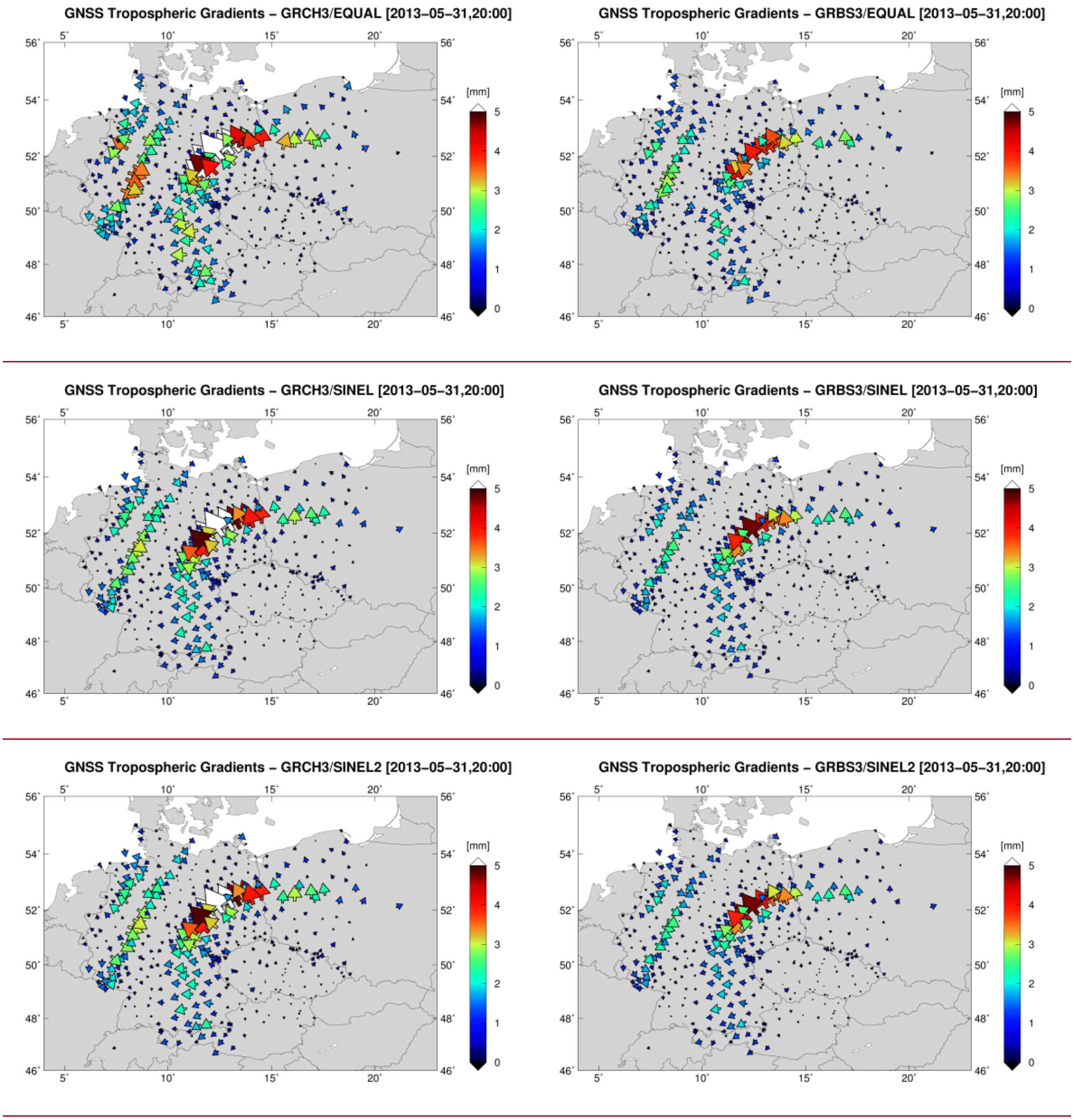
GNSS solution	Position repeatability			ZTD formal error		N gradient formal error		E gradient formal error	
	North (mm)	East (mm)	Height (mm)	Mean (mm)	SDEV (mm)	Mean (mm)	SDEV (mm)	Mean (mm)	SDEV (mm)
GRCH3	1.71	4.13	5.60	3.81	0.37	0.81	0.10	0.81	0.09
GRBS3	1.69	4.13	5.53	3.82	0.37	0.74	0.09	0.75	0.09
GxCH3	3.62	8.68	5.91	4.28	0.46	0.93	0.13	0.90	0.13
GxCH7	3.46	9.26	5.43	4.84	0.44	1.14	0.14	1.05	0.14
GRCH7	1.71	4.09	4.96	4.28	0.36	0.99	0.10	0.95	0.11
RT1GxCH3	3.97	10.71	7.57	6.71	1.72	0.91	0.08	0.92	0.09
RT3GxCH3	9.13	19.69	8.51	7.09	1.76	1.50	0.22	1.53	0.22
RTEGxCH3	1.68	3.91	5.74	6.60	0.67	0.91	0.08	0.92	0.08

4 Systematic effects of GNSS tropospheric gradients estimation

In this section, we focus on systematic differences induced by utilizing different *mfg* and observation elevation-dependent weighting (OEW). For two solutions defined in Section 2.2 and utilizing CH *mfg* (GRCH3) and BS *mfg* (GRBS3), we additionally generated four variants using various OEW schemes: 1) EQUAL, equal weighting, 2) SINEL1, $1/sin(e)$ ~~1/sin(ele)~~, 3) SINEL2, $1/sin^2(e)$ ~~$1/sin^2(ele)$~~, and 4) SINEL4, $1/sin^4(e)$ ~~$1/sin^4(ele)$~~. The contribution of low-elevation observations to all estimated parameters decreases with increasing power y in $1/sin^y(e)$~~$1/sin^y(ele)$~~. As a consequence, the magnitude of tropospheric gradients is reduced due to the strong dependence on such observations. The impact of the *mfg* on the estimated tropospheric gradients is then reduced too. These variants were provided for May 31, 2013 which is an interesting day due to an occlusion front present over Germany~~,~~ and captured by strong tropospheric gradients both from GNSS and NWM.

Figure 5 displays maps of tropospheric gradients on May 31, 2013 (18:00 UTC) from both GRCH3 (left panels) and GRBS3 (right panels) solutions when applying EQUAL, SINEL, SINEL2 and SINEL4 OEW schemes (panel rows from top to bottom). We can observe that OEW impacts magnitudes of gradients, but not much their directions. Magnitudes of individually estimated gradients from nearby stations show better consistency when using any real weighting compared to the EQUAL weighting suggesting a better quality of such product. This is also in agreement with our previous findings when studying the distribution of post-fit carrier-phase residuals with respect to the elevation angle (not showed). We achieved better performance when using SINEL2 scheme and worse when using EQUAL elevation-dependent weighting, see below in this section. The impact of *mfg* on estimated gradients clearly shows then systematic differences in magnitudes of gradients when considering different OEW schemes, compare panels from top to bottom. The gradients estimated with CH *mfg* (left panels) are then always larger than with BS *mfg* (right panels), independently of OEW used. We can also notice the gradient maps from SINEL and SINEL2 are very similar. The SINEL4 weighting then shows highly reduced gradient values indicating a strong impact of the low-elevation observations on their estimates.~~The comparison of OEW schemes also demonstrated a strong impact of low-elevation observations reflecting a local tropospheric asymmetry in the water vapour distribution where SINEL4 weighting shows highly reduced gradients.Figure 4 displays maps of tropospheric gradients on May 31, 2013 (18:00 UTC) from both~~

~~GRBS3 and GRCH3 solutions when applying two selected schemes of OEW (EQUAL and SINEL2). This particular epoch shows a significant difference in magnitudes of estimated gradients.~~



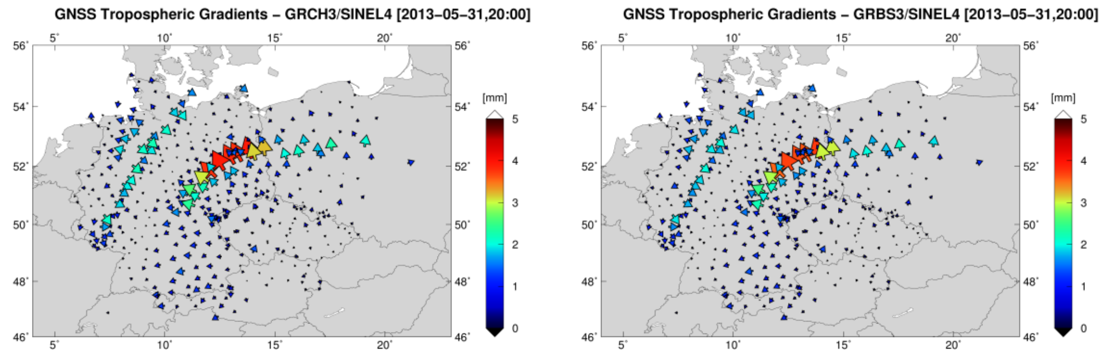
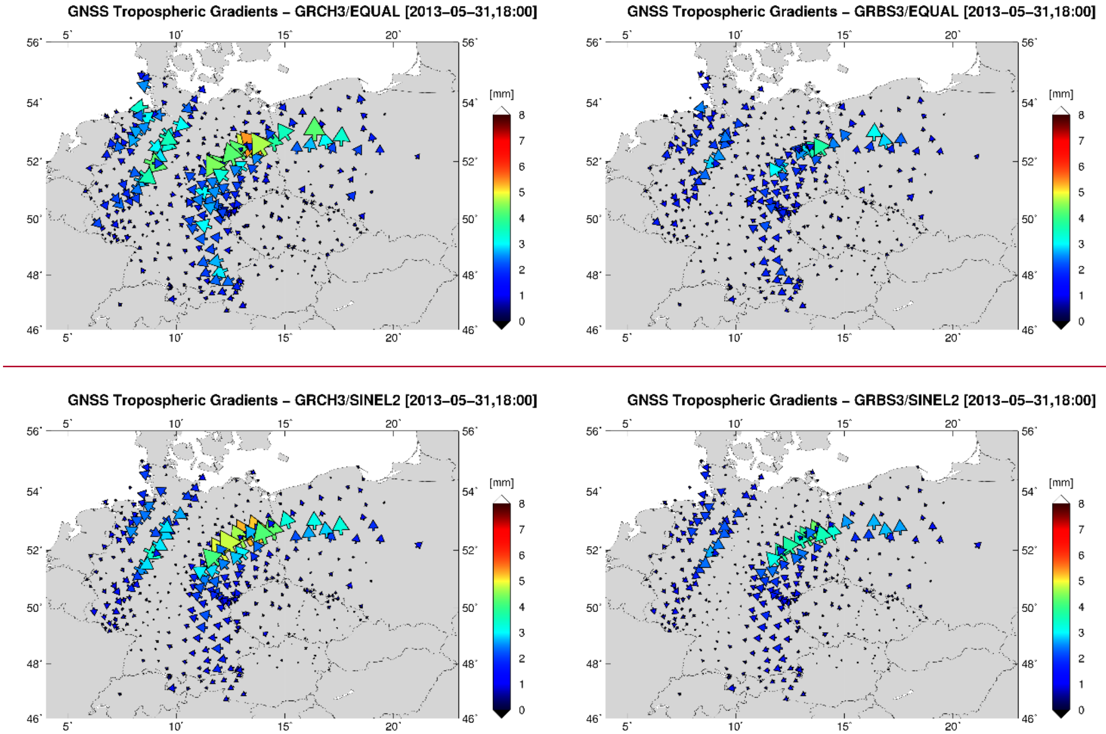


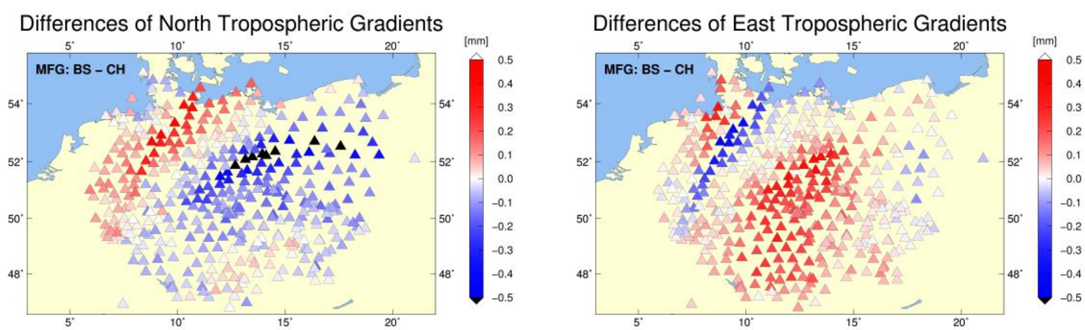
Figure ~~4~~5. Tropospheric gradient maps on May 31, 2013 (18:00 UTC) from GNSS solutions using: Chen and Herring *mfg* (left panels), Bar-Sever *mfg* (right panels) and EQUAL, SINEL,- SINEL ~~(top)~~ and SINEL~~2~~4 (from top to bottom panels) observation weighting schemes.

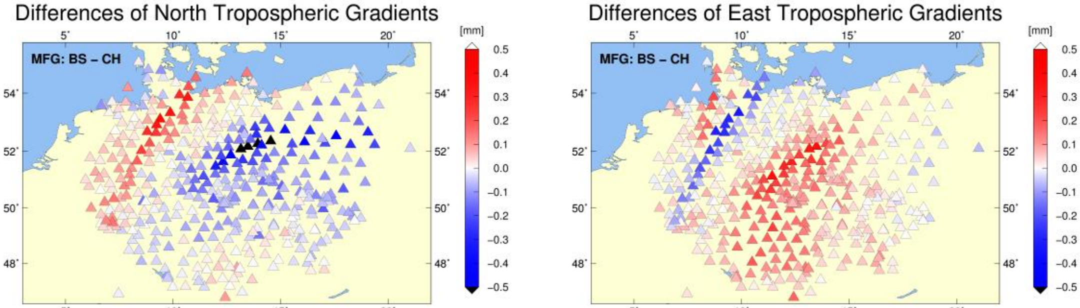
Figure ~~5~~6 shows mean differences (over all epochs in May 31, 2013) in north (left panels) and east (right panels) gradient components between the two *mfg* (BS *mfg* minus CH *mfg*) when using all OEW schemes. Such differences depend on both the magnitude and direction of estimated gradients when these are decomposed into two components. In our ~~example~~case, positive differences in north and east component appear when the estimated gradients point to south and west, respectively, and negative differences occur when the gradients point to opposite directions. Largest differences were observed for EQUAL weighting (top panels), which gradually decreased for SINEL, SINEL2 (next panel rows) and almost disappeared for SINEL4 (bottom panels).

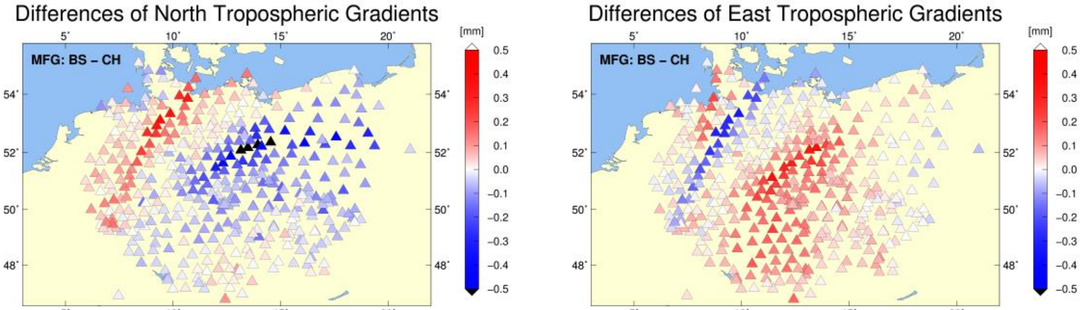
~~Figure 5 then shows a cumulative systematic difference (over all epochs in May 31, 2013) in north and east gradient components between two *mfg* and OEWs. In this case, the systematic difference clearly depends on both magnitudes and direction of gradients. A positive difference can be seen for the north gradient component when the actual gradient points to north and east component when the actual gradient points to east. Negative differences occurred when gradients were pointing to the opposite directions. A maximum systematic difference was observed for the EQUAL OEW, while it has been reduced for the SINEL1 weighting (not shown) and further for the SINEL2 weighting. A systematic difference has been almost eliminated when using the SINEL4 weighting (not shown). Generally, all the OEW schemes demonstrate a strong impact of low-elevation observations reflecting an actual local tropospheric asymmetry in the water vapour distribution.~~

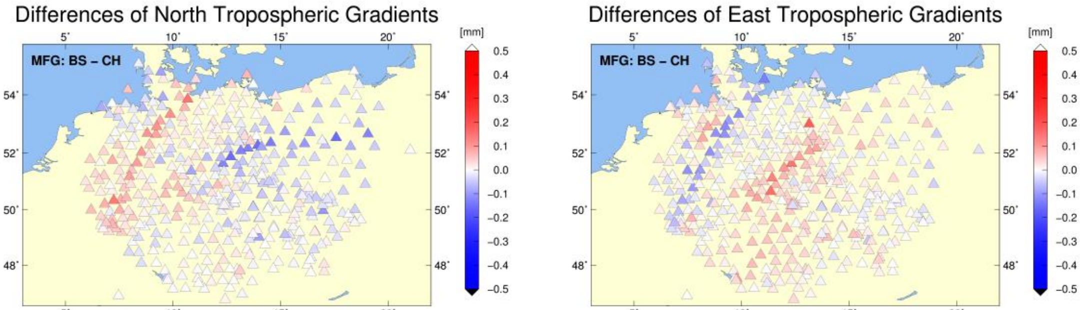


~~**Figure 4.** Tropospheric gradient maps on May 31, 2013 (18:00 UTC) from GNSS solutions using: Chen and Herring *mfg* (left), Bar-Sever *mfg* (right) and EQUAL (top) and SINEL2 (bottom) observation weighting schemes.~~




Differences of North Tropospheric Gradients
MFG: BS – CH
Differences of East Tropospheric Gradients
MFG: BS – CH
[mm]


Differences of North Tropospheric Gradients
MFG: BS – CH
Differences of East Tropospheric Gradients
MFG: BS – CH
[mm]


Differences of North Tropospheric Gradients
MFG: BS – CH
Differences of East Tropospheric Gradients
MFG: BS – CH
[mm]

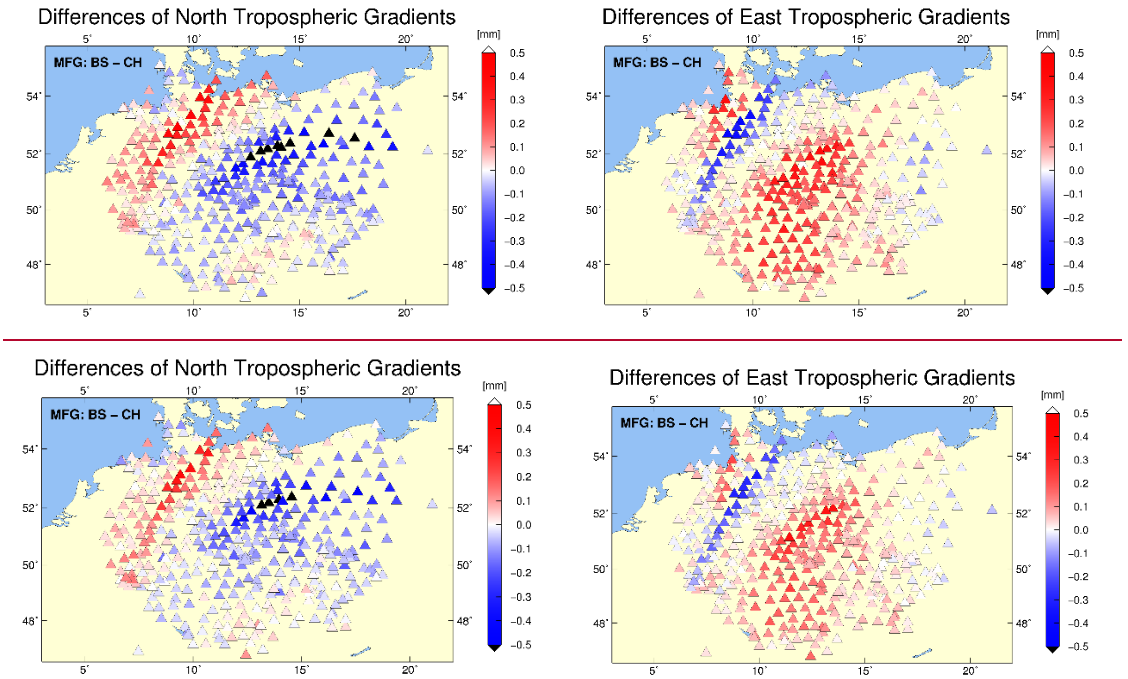


Figure ~~5~~6. Mean differences of tropospheric gradient north component (left panels) and east component (right panels) due to different *mfg*: Chen and Herring (CH), Bar-Sever (BS) when using the EQUAL, SINEL, SINEL2 ~~(top)~~ and ~~SINEL2~~ SINEL4 (from top to bottom panels) observation weighting schemes. ~~The~~ Mean differences are ~~cumulated~~ calculated over full day May 31, 2013.

Figure ~~6~~ 7 finally displays carrier-phase post-fit residuals with respect to the elevation for selected solutions. The SINEL2 OEW scheme in the left panel shows more homogenous distribution of carrier-phase post-fit residuals above the elevation angle of 30° when compared to the EQUAL scheme (right panel). While the *mfg* selection impacts SINEL2 residuals on a few millimetre-level below 15°, the EQUAL residuals could be affected at any elevation angles even up to the zenith direction. The SINEL2 resulted in a distribution of the post-fit residual reflecting the expectation due to contributing errors in both GNSS observations and models. ~~Generally, the SINEL2 results in a more realistic view considering the errors in GNSS observations which are expected to~~ The errors generally increase with a decrease of the elevation angle, and the lowest contribution is expected at the zenith ~~which,~~ . ~~besides~~ The effects of errors include contributions from the atmosphere~~atmospheric ones we mean e.g.~~ , multipath ~~effects~~, uncertainty of receiver antenna phase centre variations, lower signal-to-noise ratio~~, obstructions~~ or cycle slips.

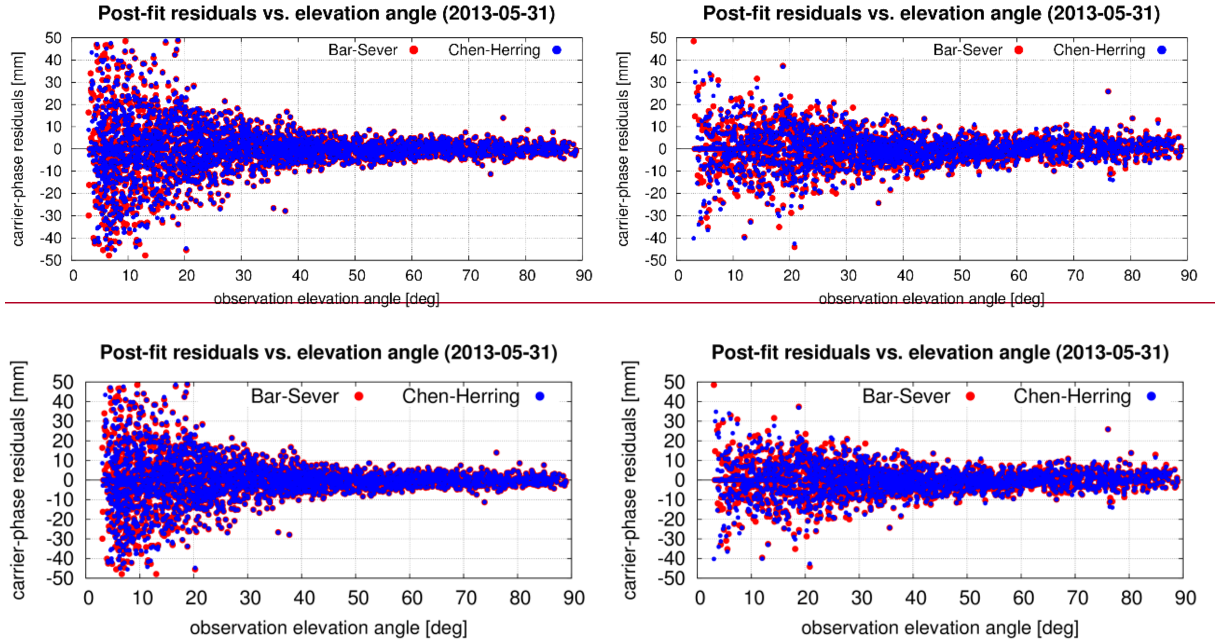


Figure ~~6~~7. Post-fit phase residuals distribution when using different gradient mapping functions, Bar-Sever (red) and Chen and Herring (blue), and observation weighting: SINEL2 (left) and EQUAL (right).

5. Conclusions

We presented an impact assessment of selected GNSS processing settings on estimated tropospheric gradients together with an evaluation of systematic differences resulting from gradient mapping function and observation elevation weighting. ~~Primarily, w~~ We exploited the GNSS4SWEC benchmark campaign ~~of 430 GNSS reference stations and~~with ~~two months of data~~covering May and June in 2013 with prevailing wet weather when the GNSS tropospheric gradients could provide a valuable information for meteorological applications. ~~during including severe weather event occurrences~~. Although the time period covered some severe weather events, it also contained a lot of days with standard weather conditions with tropospheric gradients close to zero. Presented results ~~sh~~could be therefore considered representative for European conditions during the warmer~~and more humid~~ part of the year.

ZTD values and tropospheric gradients were estimated in eight variants of GNSS data processing and derived from two NWMs (a global reanalysis and a limited area short range forecast).

~~Statistical comparisons and a systematic visual inspection of tropospheric gradient maps demonstrated that all post-processing solutions can be regarded as robust and their gradient estimates are clearly related to real weather conditions.~~ All ~~S~~solutions ~~provided~~ gave tropospheric parameters in high temporal resolution (5 minutes). ~~which are~~Since no meteorological data providing any information about prevailing atmospheric conditions during the evaluated time period entered the GNSS data processing, estimated tropospheric gradients can be regarded as fully independent, ~~of meteorological input data, and besides~~

~~the ZTD,~~ ~~tropospheric gradients thus~~ and therefore can provide additional interesting information, along with the ZTD, in support of NWMs ~~forecasts~~.

A positive impact of a lower ~~cut-off~~ elevation angle cut-off (from 7° to 3°) suggested more robust tropospheric gradient estimates. A 10% reduction in standard deviation was obtained when comparing GNSS gradients to NWM gradients, and also by analysing formal errors of tropospheric gradients and station-wise mean gradient directions. On the other hand, the usage of lower cut-off angle led to a slightly worse station height repeatability (10 %), which is partly in contradiction to the achievements from Douša et al. (2017). However, our results agree with Zhou et al. (2017) and the discrepancy is attributed to the use of PPP method with simplified modelling (GPT+GMF) for low-elevation observations. The 3° elevation angle cut-off can be thus recommended for an optimal gradient estimatione~~s~~ from GNSS data.

~~Better agreements were observed between single- and dual- constellation products, when comparing to NWM gradients (a decrease of standard deviation of 10 %) and when analysing station-wise mean gradient directions.~~ ~~This finding is in a full agreement with Meindl et al. (2004) where a positive impact of using cut-off elevation angle of 3° instead of 10° was also reported.~~

A small decrease of standard deviation~~(2 %)~~ of estimated gradients (2 %) was achieved when using GPS+GLONASS instead of GPS only and compared to NWM gradients.~~A small impact only was observed by adding GLONASS observations (a decrease of standard deviation of 2 % in comparison with NWM gradients)~~. This indicates that the post-processing tropospheric gradients can be ~~well~~ reliably estimated ~~already~~ solely with ~~using~~ GPS ~~satellites~~constellation ~~when the quality of such gradients obviously benefit from very low elevation angle observations~~. However, it may still depend on applied software, strategy, products and processing, e.g. (near) real-time. In this regard, Li et al. (2015) and Lu et al. (2016) demonstrated that tropospheric gradients from multi-GNSS PPP processing improved their agreement with those estimated from NWM and WVR when compared to standalone GPS processing.

Using a simulated real-time processing mode, the agreement of GNSS versus NWM tropospheric gradients revealed an increase in standard deviation of about 17 % (75 %) for IGS01 (IGS03) RT products when compared to the corresponding GNSS post-processing gradients. We also show that the quality of real-time tropospheric parameters is dominated by the quality of real-time orbit and clock corrections, and to a much lesser extent by the processing mode, i.e. Kalman filter without backward smoothing. Tropospheric gradients from the RT solution using the IGS03 RT product showed occasionally a large misbehaving of tropospheric gradients at all GNSS stations obviously not related to weather conditions. This was caused by frequent PPP re-initializations due to interruptions and worse quality of the IGS03 RT product, while normal results were achieved by using the IGS01 RT product. Thus providing high-resolution gradients in (near) real-time solution still remains challenging, which would require optimally a multi-GNSS constellation and high-accuracy RT products.

We studied systematic differences in estimated tropospheric gradients. Unlike for ZTDs, ~~mean~~ average systematic differences up to 0.5 mm over ~~a~~ one day, and up to 0.9 mm for individual gradient components during extreme cases, ~~(and even larger for a single epoch)~~ can affect the magnitude of estimated tropospheric gradients solely due to utilizing different gradient mapping functions or observation elevation-dependent weightings. This difference was observed between Bar-Sever and Chen and

Herring *mfg* while the tilting *mfg* behaves in between these two. It affects the gradient ~~These differences are observed in~~ magnitudes ~~of the gradients~~, ~~but~~ not their ~~in~~ directions, ~~.~~ ~~However~~however, the gradient direction results in different projections into gradient components~~different signs and scales of the two estimated gradient components~~. In a global scope, ~~A~~ a long-term mean gradient pointing ~~in a global scope~~ to the equator causes systematic differences up to 0.3 mm in the north gradient component between Bar-Sever and Chen and Herring *mfg* (see Appendix A).

Both smaller gradient formal errors and slightly improved height repeatability suggest more accurate modelling when using the Bar-Sever *mfg*. It also resulted in a better agreement with ~~ERA5~~ NWM in terms of standard deviation which, however, could be also attributed to smaller values usually calculated from NWM data. Without an accurate and independent gradient product, it is still difficult to make a strong recommendation among different *mfg*s, i.e. resulting in different absolute gradient values. In any case, we could strongly recommend to use the same *mfg* whenever comparing or combining tropospheric gradients derived from different sources (GNSS, WVR or NWM). On the other hand, if tropospheric gradients are used solely for reconstructing slant total delays, different *mfg*s should provide very similar results.

~~Finally, it is hard to assess which *mfg* is more suitable for the troposphere modelling in GNSS analyses as we are missing accurate products that could be accepted as ground truth. Smaller gradient formal errors from Bar-Sever *mfg* are mainly attributed to larger mapping functions, while the better agreement with NWMs is due to the fact that the limited horizontal resolution of the NWMs yields smaller gradients in general. In any case it is necessary to agree on the *mfg* at least when tropospheric gradients derived from various sources (GNSS, WVR or NWM) are to be compared or combined.~~

Appendix A

In the upper panel of Figure 8 the systematic difference in the derived tropospheric gradients based on ERA5 data (average over 10 years) is shown for any point on Earth's surface between tropospheric gradients estimated utilizing the BS *mfg* and tropospheric gradients estimated utilizing the CH *mfg*. Whereas there is no considerable systematic difference in the east gradient component, it reaches up to 0.3 mm in the north gradient component (positive in the northern and negative in the southern hemisphere). We note that the mean tropospheric gradients point to the equator, i.e., the north gradient component is negative in the northern hemisphere and positive in the southern hemisphere. This can be seen in the lower panel of Figure 8, showing the mean north- and east gradient component utilizing the CH *mfg*, and can be explained by the fact that the mean zenith delays increase towards the equator. The systematic difference between these two *mfgs* is due to the fact that for the same slant total delays the magnitude of tropospheric gradients which are estimated utilizing a smaller *mfg* are larger than the magnitude of tropospheric gradients which are estimated utilizing a larger mfg. The product of the *mfg* and the tropospheric gradients, i.e., the azimuth dependent part of the tropospheric delay, remains approximately the same.~~In Figure 7 the systematic difference in the derived tropospheric gradients based on ERA5 data (average over 10 years) is shown for any point on Earth's surface between tropospheric gradients estimated utilizing the BS *mfg* and tropospheric gradients estimated utilizing the CH *mfg*. Whereas there is no considerable bias in the east gradient component, the mean bias reaches up to 0.3 mm in the north~~

~~gradient component (positive in the northern and negative in the southern hemisphere). We note that the mean tropospheric gradients point to the equator (see Section 3.3), i.e., the north gradient component is negative in the northern hemisphere and positive in the southern hemisphere. This is due to the fact that the mean zenith delays increase towards the equator (see e.g. Meindl et al., 2004). The systematic difference between these two *mfg*s is due to the fact that for the same slant total delays the magnitude of gradients which are estimated utilizing a smaller *mfg* are larger than the magnitude of gradients which are estimated utilizing a larger *mfg*. The product of the *mfg* and the tropospheric gradients, i.e., the azimuth-dependent part of the tropospheric delay, remains approximately the same.~~

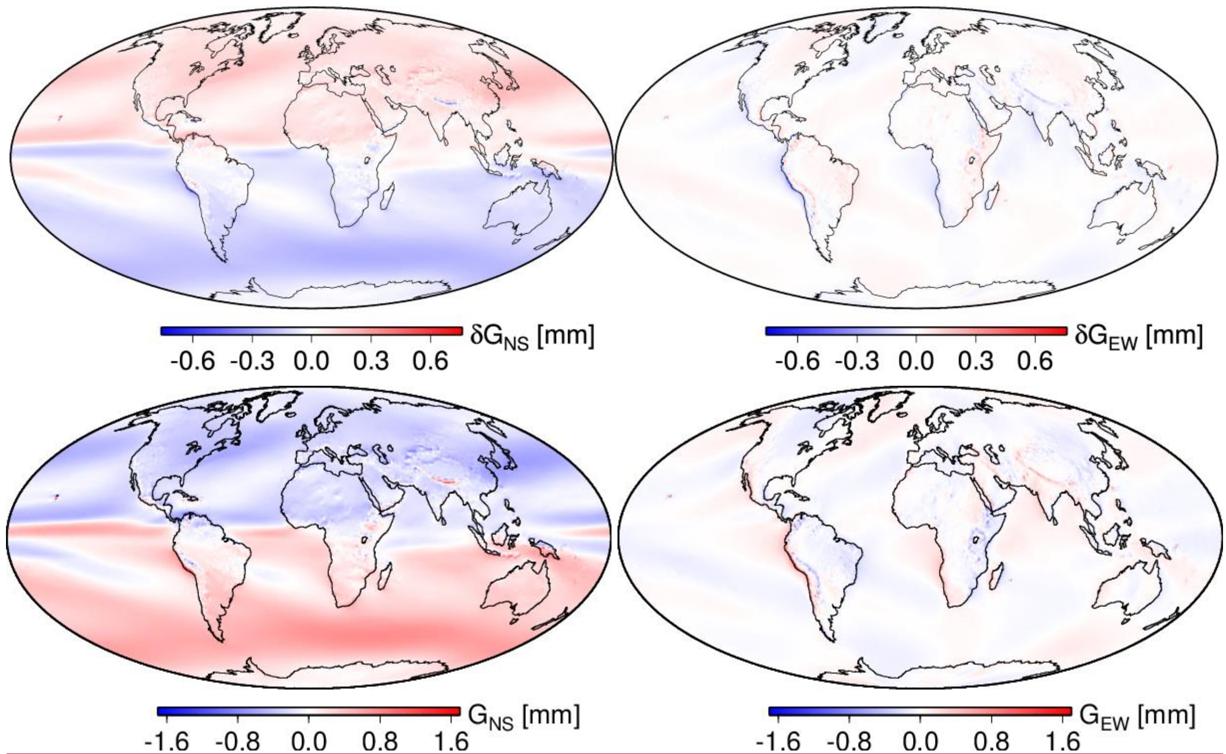


Figure ~~7~~8. Upper panel: Systematic difference (average over 10 years) for any point on Earth's surface between tropospheric gradients estimated utilizing the gradient mapping function of Bar-Sever and tropospheric gradients estimated utilizing the gradient mapping function of Chen and Herring. ~~The left panel shows the north gradient component, the right panel the east gradient component. The result is based on ERA5 data.~~Lower panel: Mean north- and east gradient component (average over 10 years) for any point on Earth’s surface utilizing the mapping function of Chen and Herring. Left panels show the north gradient component, right panels the east gradient component. The results are based on ERA5 data.

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