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Atmospheric Measurement Techniques Discussions

Interactive comment on "On the information content in linear horizontal delay gradients estimated from space geodesy observations" *by* Gunnar Elgered et al.

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General comments

There was a time when tropospheric delays were considered as error-prone parameters that had to be corrected by meteorological observations from other instruments. Successive methodological improvements have led Zenithal Wet Delay retrieved by GNSS to be sufficiently accurate for use in meteorology and climatology. The information content in linear horizontal delay gradients estimated from space geodesy observations is the next step, the central issue that must be treated rigorously so as not to lead to misinterpretations or over interpretations whose consequences can be unfortunate for the applications that come out of them.

At first sight, the article is presented as providing general answers to this problem. However, the results obtained are valid only in Sweden, in a particular meteorological context (the Icelandic low pressure system), in a particular geodesic context (the poorer sampling of GPS data on the sky north of the zenith direction due to the geometry of the GPS satellite constellation which is particularly the problem at high latitude) and mainly using the statistical notion of correlation coefficient. These results deserve to be verified on a global scale even if this study is an interesting intermediate step. However, the title should reflect the true scope of this study. Moreover it would have been interesting to provide more bibliographic references to list the results previously obtained for other regions and to compare them with the results of this study.

This study deals with the concept of total, hydrostatic or wet gradients, of pressure gradient, of temperature gradient, of water vapor gradient, of wet gradient retrieved by WVR. However, these notions are not sufficiently defined or sufficiently documented by bibliographic elements, which undermines the clarity of the article. The reproducibility of the results of this article should be facilitated: -> Where can we download GPS, WVR and ECMWF data? -> How to estimate the gradients with the WVR? -> What are the options used to process the data in detail? If there are studies, technical reports or more general articles that can provide quick and accurate answers to these questions without lengthening the article excessively: perfect, if not the addition of elements in the supplemental material could be a good option.

It would have been necessary to give some elements on the comparisons between ZWD estimated by the different techniques before deepening the comparison of the gradients.

One of the listed points of the summary is the comparison of the GPS gradients with the corresponding ones from the ECMW analyses. How GPS gradients can confirm known seasonal effects both in the hydrostatic and the wet components whereas GPS gradients are total gradients exclusively? In fact, it is an assumption that ECMWF hydrostatic gradients are reasonably accurate (P13L13). Before subtracting the ECMWF hydrostatic gradients from the total GPS gradients, rigorously, it would have been necessary to ensure that the hydrostatic gradients calculated by the ECMWF and felt by the GPS measurements are equivalent, which seems very difficult to verify.

The main statistical comparison tool is based on the notion of linear correlation. However, the article does not explain the advantages, disadvantages and limitations of this approach without any specific bibliography for this type of study. Again, it undermines the clarity of the article and the scope of its conclusions. With just 13 lines in the article, the results of the CONT14 VLBI measurement campaign seem insufficiently exploited.

The sampling of the sky is a critical parameter according to the authors, what are the further studies to be conducted to avoid or reduce this problem?

Taking into account the preceding remarks and clarifying the points raised, the article could then serve as a reference for future studies. Here are my specific comments.

P1L1 : " . We assess the quality of estimated linear horizontal gradients in the atmospheric propagation delay " versus

P1L21 : " the reproducibility of estimated geodetic parameters " improper term ? / Repeatability?

P2 : Figure 1 is a very rough picture of the real situation. Orders of magnitude are given without any explanation. Is the Earth modeled as an infinite plane or sphericity is taken into account? " The scale heights, hs of the hydrostatic refractivity and the wet refractivity are approximately 8 km and 2 km, respectively. " 8 km / 2 km ... Proof? References?

P2L4-6 : " Gradinarsky et al. (2000) found that using different constraints for the variability of the horizontal gradient in the VLBI and GPS data analysis did not have a significant impact on the agreement with the WVR estimates. " Can you be more explicit and provide quantitative data?

P2L6-7 : " A more recent study by Li et al. (2015) reported on the improvement ob-

tained by Using multi-GNSS constellations instead of GPS only. " Can you explicit with quantitative results?

P2L16-17 : OK it is known but provide the major references . . .

P2L18: " Hydrostatic gradients " These terms are not defined in the article and are not commonly used.

P2L18-20: unclear

P2L20: see IERS conventions (2010)

P3L1: Provide more recent references. What are the scientific questions raised by this climatic specificity?

P3L3: "Temperature and especially water vapour can show relatively much stronger horizontal gradients over small (kilometre) scales. The temporal variability is typically also much higher than that of the hydrostatic gradients, see e.g. Li et al. (2015). ": equations? References? Which temperature? Ground? Column? How are obtained these order of magnitude? [Typo : kilometer]

P3L6 : " be significant during a passage of a weather front, especially for distinct cold fronts." order of magnitude

P3L7-8: Provide references that study these phenomenons with GNSS data. P3L16-17: software and references . . .

P4L3 : Ning et al (2013) : It would be interesting to speak about an eventual update of the procedure . . . atx file should have been updated for instance . . .

P4L4 : " we calculated mean values over 15 min, 1 h, 6 h, 1 day, and 1 month. " Ok but why? Specify scientific questions in term of atmospheric processes

P4L5-7: Figure 4 shows Figure 1 is too simplistic. May be presenting the problem like this?

P4L9-11 : references or technical report to provide ? What are the problems of this technique? Advantage and limitations?

P6L1-2 : " Therefore, data taken during rain, or when the estimated amount of liquid water is >0.7 mm, are discarded from the analysis. " references ? If we do not pay attention: what are the consequences? Bias? Ok for rain but without rain : precision ?

P6L2-3 " when the WVR hardware has failed. " Why?

P7L21-2: → It would be interesting to provide a reference which explains the observations and the estimation of SWD with this instrument. It would be interesting to explain how the WVR gradients have been computed. → " where constraints with time are applied. " Specifically with your solution with GIPSY. → It would be interesting to recall what is observed and what is modeled with GNSS and WVR. Or provide references . . .

P8 Figure 7: → optionally add rainfall? → Difference between [2013,2016] and [2016,2017] about the maximum number of daily data : around 10000 / > 10000 / Homogenous methodology of WVR observation ? → Histogram?

P9L15-17 : Are you sure of the units about the constraints ?

P9L16-17 : inhomogeneity between mapping functions . . .

P9 part 3.4 : Focus on scientific and methodological questions ? Not enough details are given : impossible to reproduce the study.

P11L3 : Figure 9 : why do not use monthly running average ?

P11L4 : 10° or 20° ? What are the differences of the two GPS solutions? Which one is chosen? Why ?

P11L5 : " We can clearly see negative north gradient in the winter both in the GPS and the ECMWF results. " provide quantitative results

P11L7 : " the Icelandic low pressure system (Hewson and Longley, 1944). " Only one

reference ... 1944 . . .

P11L9-12 : add references / Why WVR data have not been used ?

P13 Table 4 : 6-hour resolution of ECMWF data It seems difficult to draw conclusions from hourly comparison between GPS and ECMWF.

P13L2-3 : " We assess the data quality, in terms of correlation coefficients, between the total GPS and ECMWF gradients estimated at the 5 GPS sites using data from 2006 to 2016. These are shown in Table 4. " The linear correlation coefficient is mainly used in this study: what are the advantages and disadvantages of the methodology followed?

P13L10-12 : " . 10 Another result worth noting is that the two sites with the highest correlation coefficients, and especially for the monthly averages, are ONSA and SPT0. These two sites are the only ones that are equipped with microwave absorbing material below the antenna. This could reduce the impact from unwanted multipath effects. The phenomenon calls for further studies. " It would be divergent with page 17 line 10 : "Comparing the results obtained for ONSA with those from ONS1 they are almost identical (in both Figures 11 and 13) meaning that in this case there is no obvious improvement from the absorbing material below the antenna on ONSA."

P13L13-15 : " Assuming that the ECMWF hydrostatic gradients, linearly interpolated between the 6 h values, are reasonably accurate we have the possibility to subtract this hydrostatic gradient from the estimated total GPS gradient in order to compare the wet gradients at these five sites " Provide a reference to justify the approach

P13L16 : " We note that when the wet gradients are averaged over one hour and one day " Did you subtract the daily average before calculating the hourly average?

P14L3 " Typically they are all well below 0.01 mm/year. " Have you tested the significance?

P15L5 " We expect that the two GPS sites share several error sources " OK, more detail should be given about GPS errors

P15L6 " there is a significant common mode suppression of errors " GPS data have been processed by PPP ... Can you explain more what you mean by "a significant common mode suppression of errors"? Do you speak about the common modelling to process GPS data?

P15L6 : " be slightly overoptimistic. " that needs more investigation

P15 Figure 10 : There are differences that seem to be systematic over short periods of time ... (presence of dotted curves in this figure unlike Figure 11)

P15L17-18 : Amplitude of the North component versus amplitude of the East component ?

P15L4 " reduced at the order of 10 % " 10° to 20° reduces the correlation coefficients ... What happens if you reduce the cutoff from 10° to 5° or below ?

P17L2-3 "). The other reason is the much higher variability in the time series from the WVR because no temporal constraints are used when estimating these gradients. " References about WVR and how its gradients have been estimated are necessary for a better understanding. Is it possible to add a stochastic constraint to estimate WVR gradients? I do not know if you can change the procedure to estimate tropospheric delays by WVR.

P17L6 : typo : Lu et al. (2016) Figure 8 of Lu et al. (2016)

P17L10 " there is no obvious improvement from the absorbing material below the antenna on ONSA." the cutoff angle is fixed at 10° ... The effect of the absorbing material would be shown using a lower cutoff angle.

P12-13 " ECMWF gradients compared to the KIR0, MAR6, and VIS0 sites. Our assumption is that the lack of a concrete pillar with a metal mounting plate just below the antenna on ONS1 eliminates the need for an absorber (see Figure 3). " Good

hypothesis that deserves to be confirmed: references on IGS network ?

P18 Figure 13 : The norm of monthly wet gradient as a bar plot would be interesting.

P19 part 5.2 : This part is a little disconnected from others and is not thorough enough to allow a clearer view of the contribution of VLBI to this study. More questions about the representativity of the gradients estimated by the geodetic techniques are araised. We would expect more answers on this issue.

P19 L6-7 : " We note that the agreement in general is better for the east component compared to the north " amplitudes of East and North Component ?

P19L7-8 : " where a large north gradient is not detected in the VLBI data. " How are estimated the VLBI gradients? Stochastic constraints? Impact of the 6 hour resolution? How gradients are modeled in the VLBI data processing? Step? Piecewise linear function?

P21 Figure 15 : " and the black dots are linearly interpolated VLBI results with a temporal resolution of 5 min in order to match the GPS data. " The interpolation must be consistent with the gradient modeling used for VLBI data processing. Can you clarify?

P21 Figure 15:" using mean values for the period of ±3 h around the time epochs of the VLBI values (6h:) " same remark as before: The 6-hour resampling of GPS estimates must be consistent with the gradient modeling used for VLBI data processing. Here, that implies that VLBI estimates are modeled as a step function.

P22L6-7: " When studying gradients averaged over shorter time scales, e.g. 15 min, we find the wet component of the gradients to cause most of the variability " Not exactly because you subtracted the hydrostatic gradients sampled at 6 h from the ECMWF. You did not analyze the variability of the hydrostatic gradients.

P22L10: "during the warmer, and more humid, part of the year " It would have been interesting to use IWV retrieved by GPS.

P22L11-12 " s in the east compared to the north direction. " It would have been interesting to better cross the amplitude of the gradients with the correlation coefficients obtained.

P22L12-14 " We interpret this difference to be caused by an inhomogeneous spatial sampling on the sky, which is important when we assume that the model describing linear horizontal gradients has deficiencies. The different sampling on the sky is an important issue for any comparison between different techniques. " This question remains unresolved and would have to be studied later. P22: Lack of " Data availability section"

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