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Atmospheric Measurement Techniques Discussions

Interactive comment on "Unconstrained, robust Kalman filtering for GNSS troposphere tomography" *by* W. Rohm et al.

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I'm very grateful for all comments, remarks and corrections. Your comprehensive review helped me to improve the quality of this manuscript.

Major issues 1) The word unconstrained in the title is rather misleading. Personally, I would take it out of the title and accurately specify in the abstract/introduction that you do not add horizontal or vertical correlations between parameters. But you use a priori information, which also constrains the model parameters. One could say that you try to regularize the solution as little as possible in order that your filter can track many uncommon weather situations, and still being robust with respect to data outliers.

[WR] We agree with this comment, "unconstrained solution" might be regarded slightly

misleading. An introduction of additional observations into the system with assigned standard deviation, act as a constraint. However in the literature (eg Lutz 2008, p.35) there is a separation between constraints (horizontal, vertical) and apriori model, hence in this title we were referring to this classic division. Therefore, we decided to change the title to "Limited constraint, robust Kalman Filtering for GNSS troposphere tomography". Abstract has been also modified accordingly

2) I would replace 'limited a priori information' (p.9134, l.12) with something like various types of a priori information'. Also 'different strengths of a priori information' might be considered.

[WR] Corrected.

3) In two places you use 'implicit' instead of 'explicit' constraints (p. 9149, l. 27; p. 9136, l. 16). As the Kalman filter implicitly contains a sort of constraint with the error propagation, the process model and process noise, and the starting covariance of the parameters (side note: as a pseudo-inverse is a minimum norm least-squares solution, also your datum parameter covariance as stated in your reference Koch and Yang (1998) is constrained/regularized in some sense), it seems important to me that additional constraints are called 'explicit'.

[WR] The terms "implicit" and "explicit" are used in this study to differentiate between constraints that we impose on the correlation between (implicit) and directly estimated (explicit) parameters. We agree that pseudo-inverse is in fact minimum norm constraint (implicit) and by using Kalman filter we introduce constraints in the form of process noise (explicit) and starting covariance of the parameters (explicit). In the light of this comment the lines (p. 9149, l. 27; p. 9136, l. 16) were altered.

4) You only show statistics that are an average over your entire tomographic domain. The statistics of each voxel height layer for the entire study period would allow better comparison to other GNSS tomography papers that almost all show profile comparisons. I would recommend a boxplot or bias/std plot versus height of the following

three solutions: M1G1SAD, M2G1SAD, UNB3MGPT. I am aware that you mention the weak vertical resolution, but the average values over all height layers give somehow a wrong feel for the achievable accuracy. Alternatively, plot relative errors versus height.

[WR] That is very good comment, we've provided new figures showing the quality of tomography retrievals on different levels of troposphere. We've also volunteered to add a panel with real-data solution RG2SAD to these figures.

5) Together with NWP model temperatures, the same type of Figure as in the previouslissue point 4) might be created for dew point temperature or relative humidity accuracies. As many meteorologists are not familiar with wet refractivity, this would raise the meteo community's interest for the paper.

[WR] As stated above we provided new figures, including one for water vapour.

Minor issues 1) p. 9134, l. 19: How do you arrive at 0.06m for the accuracy of the integrated value? Maybe you have to add something like 'a posteriori' or explain if you use the full covariance information from your Kalman filter refractivity outputs to calculate the integrated error number.

[WR] This sentence did not have any support in manuscript, therefore it has been removed

2) p. 9136, l. 5: Perler et al., 2011 is a misleading reference here. There is nothing written in this paper about Singular Value Decomposition. What was the intention to put this reference here? I would rather mention that a Kalman filter approach was used in the paper.

[WR] Removed

3) p. 9137, l. 19/20: The distinction between dry and wet part in refractivity and in slant delay might need a little more explanation in a meteorology journal. Specifically, show how you reduce the total delay to the dry delay using data from the weather model.

[WR] Description extended.

4) p. 9138, Eq. (4): I think, you also use a priori values for outer voxels.

[WR] Corrected

5) p. 9139, Eq. (6): You use two subscripts in Eq. (6), whereas in Eq. (8) you ignore this distinction. Also make subscripting consistent in Eq. (14). For example, 'SWD' is subscripted in Eq. (14), whereas 'A' is not. The same is true for Eq. (22).

[WR] Corrected

6) p. 9139, l. 14: Is this equation reference correct? Should it not be Eq. (5)?

[WR] Corrected

7) p. 9140, l. 19: New paragraph for 'In the paper by Koch and Yang (1998)', since the following part describes the changes to matrix A, whereas the previous part describes changes applied to matrix R.

[WR] Corrected

8) p. 9142, l. 4/5 and Eq. (20): I do not quite understand, why the step in Eq. (20) is needed. I would also not call it 'TSVD(SWD)', because there is no such thing as a singular value decomposition of that vector. Why do you need to reflect the changes to 'A' in 'SWD', as 'Atilde' is still of dimension: number_of_observations times number_of_unknowns? [WR] This step is required to remove correlated rows of matrix A, so first we identify the correlated rows in matrix A using equation(20) and then remove these rows and corresponding SWDs and Rs. We agree that TSVD might be a bit misleading so TSVD has been replaced with T (truncation). 9) p. 9142, Eq. (18): I do not understand this equation. Do you have some reference where it is stated?

[WR] This equation identifies rows of matrix A that were affected by SVD, hence are correlated. It simply checks for the departure of the rows of A matrix after TSVD to the one before the procedure was applied. If the difference is significant (greater than

2x\sigma) then this row is going to be removed in the A, SWD and R matrices.

10) p. 9143, Eq. (29): Is the exponent of the exp-function correct? Is 'e' in the exponent an arbitrary parameter?

[WR] It is correct, the function should resemble the exponential shape however to scale the variances we choose a function that change between (0 : 1)

11) p. 9144, l. 11: Section title is rather unfortunate. Something like 'Description of GNSS station network' might be more comprehensible. For section 5.3, I suggest 'Simulated slant delays' and for section 5.4 I would use 'Real GNSS data' or something of that sort.

[WR] Corrected

12) p. 9145, l. 26: What weight do you assign to the covariance matrix of the simulated data? Even if the data are of equal weights, it is interesting to know how strongly you weigh them compared to the a priori info.

[WR] The standard deviation is 1mm. Information added to the text.

13) p. 9146, Sect. 5.4: Do you process GPS plus GLONASS or GPS only?

[WR] GPS only processing is run.

14) p. 9148, l. 29: Should the numbers in brackets not go to Section 5.3? Are they equal for all SWDs and independent from the elevation angle to the satellite?

[WR] I've moved the numbers to the section 5.3 and added two sentences explaining data noise amplification procedure. The noise was assigned randomly.

15) p. 9149, l. 2: RG2SAD in Table 2 shows a std of 6.5mm..

[WR] Corrected. . 16) p. 9155, Table 2: Do you only use inner voxels to derive these numbers?

[WR] That is correct, extra explanation added to the table description

17) p. 9155, Table 2: Is the positive bias (0.4ppm) for the solution RG2SAD correct? All other real data solutions show negative bias and also the a priori data G2 derived from GPT+UNB3m for the inner voxels must be negatively biased as the solution UNB3MGPT suggests.

[WR] Thank you very much for finding this problem. UNB3MGPT should be positively biased and all RG2* solution family as well. Corrected to the positive bias

18) p. 9155, Table 2: Please include solution M1G1SAD into Table 2, as it is also shown in Figures 4-7. [WR] Values appended to the Table 2. 1) p. 9134, l. 6: replace 'ground-based GNSS infrastructure - Continuous Operating Reference Station (CORS) networks and can be used' with: 'ground-based GNSS infrastructure (e.g. Continuous Operating Reference Station (CORS) networks) that can be used'

[WR] Corrected

2) p. 9134, l. 16: replace: '(i.e. ACCESS)' with: '(ACCESS)'

[WR] Corrected

3) p. 9135, l. 19: replace: 'However, these can' with: 'Possible solutions can'

[WR] Corrected

4) p. 9136, l. 4: replace: 'that allows only for' with: 'that allows for'

[WR] Corrected

5) p. 9136, l. 20: replace: 'prevents the noise propagation in outputs' with: 'reduces the noise propagation from the data into the output parameters'

[WR] Corrected

6) p. 9136, l. 24: replace: 'is given' with 'are given'

[WR] Corrected

7) p. 9139, l. 1f: replace: 'However, ten hours is to long time period to be represented by the single value of refractivity, it is therefore convenient to use the robust Kalman filter as a dynamic model of troposphere.' with something like: 'However, ten hours is a too long time period to be represented by a single refractivity field. It is therefore convenient to use a Kalman filter that allows to include a dynamic model of the troposphere.'

[WR] Corrected

8) p. 9140, l. 1ff: replace: 'is the predicted and the corrected estimates of wet refractivity in the voxels of GNSS tomography model. The matrices P_k(-) and P_k(+) are the prediction and the correction P_(k-1)(+) of the covariance matrix' with: 'are the predicted and the corrected estimates of wet refractivity in the voxels of the GNSS tomography model. The matrix P_k(-) is the prediction and P_(k-1)(+) the correction of the covariance matrix'.

[WR] Corrected

9) p. 9140, l. 17: replace: 'observation's covariance' with: 'observations' variances'

[WR] Corrected

10) p. 9141, l. 6: replace: 'vectors' with: 'matrices'

[WR] Corrected

11) p. 9141, l. 10: replace: '(including matrix A)' with: '(e.g. matrix A)'

[WR] Corrected

12) p. 9141, l. 19: 'Hansen and O'Leary, 1993 can not be found in the reference list...

[WR] Corrected

13) p. 9142, Eq. (21): I think that 'w' as a subscript to 'N' should be replaced by 'v'.
[WR] Corrected

14) p. 9143, l. 3: replace: 'comprises of a Kalman gain K_dash derivation' with: 'consists of calculating the Kalman gain K_dash'

[WR] Corrected

15) p. 9143, l. 9: 'location in the model h' -> Does 'h' stand for height?

[WR] Corrected

16) p. 9144, l. 5: replace: 'sources is used' with: 'sources are used'

[WR] Corrected

17) p. 9145, l. 26ff: replace: 'are equal in weighting matrix. The first observations dataset is a simulation of real observations based on the NWP model data; it also constitutes the reference data collection.' with: 'are of equal weight. The NWP model data and the simulated slant delays also constitute the reference data.'

[WR] Corrected

18) p. 9147, l. 10: replace: 'in regards to' with: 'with regard to'

[WR] Corrected

19) p. 9147, l. 11: replace: 'different levels of noise' with: 'and without noise'

[WR] Corrected

20) p. 9147, l. 12: replace: 'Alternatively experiments may be grouped together in relation to the a priori models adopted, the following' with: 'Furthermore, experiments are grouped together according to the a priori models adopted. The following'

[WR] Corrected

21) p. 9147, l. 19: replace: 'levels validation is' with: 'levels of validation are'

[WR] Corrected

22) p. 9148, l. 2f: replace: 'of this experiment' with: 'of these experiments' [WR] Corrected 23) p. 9148, l. 6: replace: 'Figures 5-7' with: 'Figures 4-7' [WR] Corrected 24) p. 9148, l. 8: replace: 'than those in' with: 'than in'

[WR] Corrected

25) p. 9148, l. 12: replace: 'is a set to' with: 'is set to'

[WR] Corrected

26) p. 9149, l. 14: replace: 'high' with: 'height'

[WR] Corrected

27) p. 9150, l. 12: replace: 'noise 5.2' with: 'noise of 5.2'

[WR] Corrected

28) p. 9150, l. 17f: replace: 'shows current level of the quality achievable for tomography reconstruction.' with: 'shows the current level of quality achievable with tomographic reconstruction.'

[WR] Corrected

29) p. 9150, l. 18f: replace: 'with meteorological' with: 'with the meteorological'

[WR] Corrected

30) p. 9154, l. 1: replace: 'conventions explained in two' with: 'conventions are explained in the two'

[WR] Corrected

31) p. 9154, Table 1, OBSERVATIONS: replace: 'GPT + UNB3m outer inner' with: 'GPT + UNB3m inner'

[WR] Corrected

32) p. 9158, Fig. 3: replace: 'The exemplary TOMO2 tomography model voxels settings (6x12), superimposed over wet refractivity field (6 March 2010 3:30UTC).' with: 'The TOMO2 tomography model voxel settings superimposed on the wet refractivity field of 6 March 2010, 3:30UTC.'

[WR] Corrected

33) p. 9160, Fig. 6, l. 2: replace: 'level' with: 'levels'

[WR] Corrected

34) p. 9161, Fig. 6, l. 1: replace: 'for number' with: 'for a number' Interactive comment on Atmos. Meas. Tech. Discuss., 6, 9133, 2013.

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