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Atmospheric Measurement Techniques Discussions

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

F. Hurter (Referee)

fabian.hurter@geod.baug.ethz.ch

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========== General comments: ==========

The paper 'Unconstrained, robust Kalman filtering for GNSS troposphere tomography' presents improvements in the algorithms used to reconstruct wet refractivity values from GNSS wet slant delays. Different measures are tested in order to achieve a robust Kalman filter whose outputs are less influenced by data outliers. At the same time, the authors want to reduce the amount of constraints that are commonly put on the unknown parameters. As GNSS tomography with ground-based GNSS receivers is ill-conditioned (usually even rank-deficient), the choice to investigate robust methods is a usefull contribution to foster GNSS tomography for meteorological purposes. A

systematic and concise analysis of the investigated methods is shown in the paper.

========== 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.

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.

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'.

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.

5) Together with NWP model temperatures, the same type of Figure as in the previous

issue 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.

========== 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.

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.

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.

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

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).

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

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.

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?

9) p. 9142, Eq. (18): I do not understand this equation. Do you have some reference where it is stated?

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

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.

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.

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

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?

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

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

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.

18) p. 9155, Table 2: Please include solution M1G1SAD into Table 2, as it is also shown in Figures 4-7.

19) p. 9157, Figure 2: There is no reference in the text pointing to this figure. You might include the vertical discretization on the side of Figure 3 (e.g. with vertical station distribution included) and remove Figure 2.

20) p. 9159-9162, Figures 4-7: It would be of much interest to have the solution UNB3MGPT included in all 4 figures as it serves as a kind of benchmark in your results.

========== Technical corrections: ==========

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'

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

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

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

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

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

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.'

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'.

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

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

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

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

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

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

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

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

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.'

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

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

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'

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

22) p. 9148, l. 2f: replace: 'of this experiment' with: 'of these experiments'

23) p. 9148, l. 6: replace: 'Figures 5-7' with: 'Figures 4-7'

24) p. 9148, l. 8: replace: 'than those in' with: 'than in'

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

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

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

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.'

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

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

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

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.'

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

34) p. 9161, Fig. 6, l. 1: replace: 'for number' with: 'for a number'

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