Title: A GPS water vapor tomography method based on a genetic algorithm

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Dear Reviewer,

We would like to thank the anonymous reviewer for providing an opportunity to revise the manuscript. The comments and suggestions of the reviewer are all valuable and very helpful. We have studied them carefully and have made revisions to improve the manuscript. Revised portion are marked in **red** in the manuscript and the main corrections and additions are given below with a comment followed by a response (in red color).

Best regards,
Authors

Comments and Suggestions for Authors
The paper by Yang et al. (2019) introduces new methodological solution to the GNSS tomography ill-conditioned problem. Authors suggest to use of genetic algorithm that is applying optimization principle based on the minimization function of the slant residuals (y-Ax), and stochastic modelling of water vapour field evolution. The concept is sound, methodology quite innovative at least in the tomography community, but comparison with standard method reveals that there is a little or no improvement once the genetic approach is used. Moreover, competitive studies for the same location, shows better performance
p.16 "Xia et al. (2013) obtained a RMS of 1.01 g/m3 by adding the COSMIC profiles, Yao et al. (2016) obtained a RMS of 1.23 g/m3 by maximally using GPS observations and a RMS of 1.60 g/m3 without the operation, Zhao et al. (2017) achieved a RMS of 1.19 g/m3 and 1.61 g/m3 considering the signal rays crossing from the side of the research area and a RMS of 1.79 g/m3 without this consideration, Ding et al. (2017) obtained a RMS of 1.23 g/m3 and 1.45 g/m3 by utilizing the new parametric methods and the traditional methods, Yao et al. (2017) achieved the RMS from 1.48-1.80 g/m3 using different voxel division approaches, etc, the total RMS of 1.43 g/m3 for the two time periods in this paper can be considered as a good agreement with the radiosonde data regardless of the weather conditions".

[Response]: Thank you for the comments.

In the literatures mentioned-above, the RMS achieved by Yao et al. (2016), Zhao et al. (2017) and Ding et al. (2017) are 1.60, 1.79 and 1.45 g/m^3, respectively, when the traditional Least squares method is used. To obtain tomographic results with higher accuracy, Xia et al. (2013) added extra COSMIC data, Yao et al. (2016) and Zhao et al. (2017) added the signals crossed through from the side faces by using Radiosonde and

ECMWF data, respectively. In the articles written by Yao et al. (2017) and Ding et al. (2017), they explored the influence of the voxel division approaches and different parametric methods on the accuracy of tomographic results. It is found that the tomographic results are stable when using the traditional Least squares method with same observation data and same grid model. The normal way to improve the accuracy is to introduce more observations, such as COSMIC data, radiosonde, ECMWF data and extra GNSS data. In our paper, the proposed GA method is conducted based on the common case, i.e. without any other extra observations. The RMS obtained in this paper is 1.43 g/m^3, which is not worse than the results in the literatures (1.60, 1.79 and 1.45 g/m^3) using the traditional Least squares method with similar conditions. Moreover, the difference of the experimental period and the grid division may affect the above comparison.

We also conducted the tomographic experiments using the traditional Least squares method in this paper. The comparison with traditional Least squares method revealed that there is a little improvement once the genetic approach is used. The focus of this paper is to solve the ill-conditioned problem of water vapor tomography using the proposed method, by which to overcome the difficulty of inverting the sparse matrix in Least squares method, the weakening of tomographic technique by a prior information in algebraic reconstruction technique and the restriction of obtaining external data. To significantly improve the accuracy of the tomographic results is not the focus of our research. Similarly, the algebraic reconstruction technique and the Kalman filter approach are also proposed to provide a new solution for water vapor tomography and to solve the shortcomings of the previous methods, rather than focusing on the significant improvement of the tomographic accuracy. In my view, the tomographic accuracy could not be significant different by different methods when the number of water vapor observations and their distribution are the same for each method. Therefore, once the COSMIC data in Xia et al. (2013) or the GPS signals crossed through by the side face in Yao et al. (2016) and Zhao et al. (2017) are introduced to the tomographic model based on the GA, we think the tomographic accuracy will be improved. But this is not the point of this paper and can be validated in the follow-up research.

Therefore, two questions should be asked: are there any information left in the slants observations that can be utilized by the tomography framework, if positive, one might ask whether approach with introducing new algorithm to old parametrization will aid in the development of tomography processing. I suggest to address these two major questions in the revision process.

[Response]: Thank you for the comments.

We think that there is no information left in the slant observations that can be utilized by the tomography framework. Since the slant observations can be used in the tomographic model are those crossed through from the top boundary. The common tomographic experiments, including our research, are modeled by this part of the slant observations. In the articles of Yao et al. (2016) and Zhao et al. (2017), they added the slant observations crossed through from the side face to the tomographic model by using the radiosonde and ECMWF data. But the accuracy of this part of the slant observations outside the tomographic region remains to be further tested. The tomographic results in their articles showed that the accuracy is improved, it is still not the common method for water vapor tomography. The current tomographic researches are based on the slant observations with high accuracy passing through from the top boundary. Ding et al. (2017) proposed a new parametric method which use the vertex value of the voxel to represent the water vapor density of the voxel. In the common method, the value of the central point in the voxel is considered as the water vapor density of the voxel. The properties of the tomographic observation equation in the above two method are still the same. The Ding's method is not a commonly used method in water vapor tomography.

In this paper, we adopted the common method of tomographic research, which only used the slant observations crossed through from the top boundary and considered the value of the central point in the voxel as the water vapor density of the voxel, to conduct the tomography based on GA. We believe that the research based on the above method is universal and reasonable. In the follow-up research, the studies can be done by adding the slant observations passing through from the side face and using the Ding's parametric method. Actually, many similar methods were proposed to explore the improvement in tomographic accuracy, but they are not commonly used. To study the application of the genetic algorithm in water vapor tomography, it is reasonable to construct the tomographic equation by using the common methods.

Overall, the manuscript presentation quality is high, however few points need to be addressed (in addition to two major questions, stated above):

1. The genetic algorithm should be clearly explained and compared to the classic Least Square, Kalman Filter or Algebraic Reconstruction Technique solutions, reader need to understand the principles of approach and its application to the tomography problem. This comment is related to: The Introduction section where Authors only briefly p.3 l. 1-10 discuss differences between new method and standard methods, 2 Methodology where Authors should add one subsection discussing classic Least Squares applied in next section. 3. Experiment and Analysis, where reads would expect how Table 1 and steps discussed on pages 5 and 6 links to real data, it should be clear how choices of parameters from Table 1 translates into algorithm performance in more detailed, step-wise manner.

[Response]: Thank you for the suggestions.

To make this paper better understood by readers, we have fully considered the three comments and carefully revised the relevant parts of the article. According to the comments, we added appropriate information in the chapters of Introduction, Methodology, Experiment and Analysis. Below is the added content and you can see them in the revised manuscript.

"The ART techniques are iterative algorithms that proceed observation by observation. Only two vector y, x and a data structure containing the slant subpaths in each voxel are required to solve the observation equations. The algorithms consist two loops. The inner loop processes SWV by SWV and applies an adequate correction to each voxel. After all SWVs have been executed the next iteration is started in the outer loop (Bender et al., 2011). It is not necessary to perform the matrix inversion and therefore avoids the ill-conditioned problem. But it only updates the results of the voxels traveled through by signal rays and the tomographic results heavily depend on the exact initial field, the data quality and relaxation parameter (Wang et al., 2014)."

"It assumes that the water vapor density in each voxel meet the Gauss-Markov random walk behavior for a certain period of time, and establishes the corresponding state equation of Kalman Filter. The observation vector is utilized based on the mathematical model to perform the best estimation of the state vector, which is a process of continuous prediction and correction."

"2.2 Water vapor tomography based on Least squares method

After obtaining the observation equation (Eq. (2)), three kinds of constraints are usually added:

$$0=\mathrm{H}\cdot x \quad (1)$$

$$0=V\cdot x \quad (2)$$

$$0=T\cdot x \quad (3)$$

Equations (6)-(8) are the vertical constraints, horizontal constraints and top constraints. For the horizontal constraint equation, it assumes that the distribution of water vapor density is relatively stable in the horizontal direction within a small region. Thus, the water vapor density within a certain voxel can be represented by the weighted average of its neighbors in the same layers. For the vertical constraint equation, it is a relationship established for the voxels between two adjacent layers basing on the analysis of meteorological data for many years. The top constraint is to set the water vapor density of the top boundary to a small constant. Based on the principle of Least square, the tomographic results can be achieved by the following formula:

$$x=\left(A^{T}A+H^{T}H+V^{T}V+T^{T}T\right)^{-1}\times\left(A^{T}y\right) \quad (4)$$

To obtain the inverse matrix in Eq. (9), the singular value decomposition is required and its detail instruction can be seen in the relevant literature (Flores et al. 2000)."

"According to the flowchart 1, the above GPS observation data were processed to construct the tomographic equation and further convert it into the fitness function for the optimization algorithm. The population size is chosen based on the total number of unknown parameters (water vapor density). The value of 200 is the default option of the algorithm when the number of unknows exceeds a certain amount. The elite count is chosen to be 10 to specifies the number of individuals that are guaranteed to survive to the next generation, since it is based on the population size (0.05 * population size). The other parameters are selected as Table 1, which are the default settings of the algorithm for the common use.
"

2. Comparisons with radiosondes fig 9, and with ECMWF fig 12 are corner stones of this manuscript. Therefore, it is difficult to understand why LS and Genetic algorithms were only compared to ECMWF but no to RS, as in fig 9. It should be done only for overlapping voxels. Why not to add to fig 9 two extra lines one for tomography LS and one for ECMWF, this will clearly indicate the quality of retrieval in time

[Response]: Thank you for the suggestion.

In the revised manuscript, we compared the GA and Least squares method using the radiosonde and ECMWF data as reference data and listed the statistical results. In the new figure (Fig. 14), we added two extra lines, one for tomography LS and one for ECMWF, to show the comparison of profiles of GA, Least squares method, radiosonde and ECMWF data during the rainless days. Fig. 9 belongs to section 3.4, the focus of which is to demonstrate the good consistency of GA tomographic results and radiosonde data.

3. The choice of research area to be one of the well-studied Hong-Kong cases has to be evaluated positively. However, division into rainy and rainless days is not supported by any meteorological analysis such as air mass origin, rain type, rain intensity, other associated phenomena. This is important as not all-weather types associated with rain will produce increase of SIWV. Moreover, there is limited evidence that the differences between so called "rainy" and "rainless" days are significant.

[Response]: Thank you for pointing it out.

We reviewed the meteorological data and provided more relevant weather information in the revised manuscript. The daily rainfall and relative humidity in different period are presented in detail. Moreover, we counted the SWV produced in the selected stations and the results in different days are listed in the table below.

Table 1. The value of SWV produced in the selected stations (unit: mm)

DOY	163	164	165	166	167	168	169	Average
SWV(mm)	69.9	68.6	69.4	92.9	87.9	85.1	79.7	79.1
DOY	225	226	227	228	229	230	231	Average
SWV(mm)	108.5	109.4	107.8	108.2	115.3	123.1	118.4	112.9

The above listed data can show that Hong Kong experienced different weather conditions during these two periods, one with continuous rainfall and the other without rainfall. The value of SWV used for the water vapor tomography are different in the two period of time. Similar to the literature (Zhao et al. 2017, Guo et al. 2016, Yao et al, 2019), this paper is focused to prove that the water vapor tomography can achieve good results in rainy and rainless weather condition, not to show the differences between rain and rainless days are significant. However, the comparisons showed that the tomographic results in rainless day is better than those of the rainy days, which are consistent with the previous articles (Zhao et al. 2017, Guo et al. 2016, Yao et al. 2019). We tried to explain the reasons for the different tomographic results in different weather conditions at the end of the article. The research about the effects of rain type, rain intensity and other phenomena on tomographic results is relative rare and is not the focus of current tomographic study. In the follow-up research, we would pay more attention on this issue.