

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

**Journal:** Atmospheric measurement techniques

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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 portions 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

### **General Comments**

This paper proposes a new approach to solving GPS tomographic inversion to retrieve 3-D atmospheric water vapor distribution above a network of GPS receiving stations. It should circumvent the strong constraints of classical techniques that have to deal with the inversion of an often very sparse matrix. Hence, this approach could be of great interest to the community. However, to demonstrate the good performances of their technique, the authors set to provide an ensemble of statistical indicators, some with respect to GPS slant delays, some with respect to radio-sounding profiles, some with respect to "classical techniques", etc. but usually considering only global RMS and MAE scores. Although statistical estimates are of interest, they do not provide the physical/meteorological understanding of the actual objective (and challenge) of tomography inversion: it is the 3-D distribution of water vapor and more particularly its vertical variability. Hence, it would have been, in my view, much more informative and useful to the community to have comparisons of profiles of RS + ERA + GA + Least-Square + Ref GPS, possibly with the corresponding statistical metrics in order to perceive the actual capacity of the new technique to resolve the water vapor distribution, rather than producing a dispersed set of statistics which makes it difficult how the technique compares globally. This article is globally well written and easily readable, nonetheless, the English phrasing is at times a bit awkward which might lead to some misunderstandings.

[Response]: Thank you for the comments.

In the community of water vapor tomography, the comparison with SWV, radiosonde and ECMWF data are commonly used to validate the tomographic results. The global RMS and MAE scores computed from the reference data (Gamt-estimated SWV, radiosonde, ECMWF data), which is adopted in almost all relevant tomographic articles,

is an effective way to evaluate the performance of tomographic method. As you said, comparisons of profiles of radiosonde, ECMWF data, GA, Least squares method could be much more informative and useful to the community. In the revised manuscript, we conducted the corresponding comparison to make up for this deficiency. We collected all the radiosonde data during the period of tomographic experiment and plotted the profiles of tomographic results and reference data. Specifically, the new figure (Fig. 14) shows the profiles of GA and Least squares method during the rainless days and utilized the radiosonde and ECMWF data as reference data.

#### **Specific comments:**

1. P.5, L.8: after criteria, do you mean a "," or a ":"? i.e., are there 3 (",") or 2 (":") conditions for termination. In any case, a precise description of the termination criteria and how they are defined should be clearly stated here.

[Response]: Thank you for pointing it out.

We rewritten this part in the revised version.

“The search terminates when a group of approximates meets the requirements of the fitness value. Generally, we set the stopping criteria for generation or calculation time.”

2. P.9, L.15: for clarity one could add something like "The change of tomography computed VS GAMIT-estimated slant water vapor residuals". . . Likewise, if this tells us that the GA method compares reasonably well with the original data, it would have been very interesting (and useful to evaluate the method) to know how would have fared a "classical" inversion technique.

[Response]: Thank you for the suggestion.

We added the information in the revised manuscript.

3. P.9, L.17: "It is clear . . . residuals decreased with . . . elevation angle". Readers can read a graph. Hence, if that is stating the obvious, then the sentence can be deleted. . . otherwise, if that is a point of interest, than it should be discussed. . . Likewise with the following sentence: "The right . . . angles".

[Response]: Thank you for the suggestion.

We deleted the corresponding part in the revised manuscript.

4. P.10, L.11-13: Is there some altitude difference between the 2 stations? I would guess that if that is the case, hkmw is higher than hkpc. Actually, at this point, one could also discuss the reason why in fig 5 all zenith residuals are positive!

[Response]: Thank you for the comment.

The altitude of hkmw is a little higher than hkpc, their specific values are 194.95m and 18.13m, respectively. Considering that the vertical height of each layer of the tomographic model is 800m, both stations are located at the bottom of the first layer of the voxels. Thus, we think it still needs further research to discuss whether the height is the case. In fig 5, the MAE means mean absolute error, which is always a positive value. The zenith residuals of each station were calculated as the MAE that used in fig

5.

5. P.13, L.15-17: I guess this sentence relates to the green box plot of Fig. 8. . . but are you sure that the range [-7.08, 4.47] is a sign of good water vapor restitution for the new method??? That is, I guess, what should be appreciated rather than a good statistical distribution!

[Response]: Thank you for pointing it out.

We corrected the corresponding part in the revised manuscript.

6. P.14, Fig.9: it is a pity that the equivalent graphs for the no rain days are not provided. Indeed, the major limitation of GPS tomographic inversion is its ability to retrieve the vertical variability and that can only be assessed by profiles comparisons with RS, not by global statistics.

[Response]: Thank you for the suggestion.

We added the corresponding graphs for the no rain days in the revised manuscript. In the figure (Fig. 14), the tomographic results at UTC 0:00 and 12:00 from DOY 225 to 231 derived from GA and Least squares method are compared and the radiosonde and ECMWF data are used as reference data.

7. P.15, L.3-5: At this point, one could think in terms of relative error rather than absolute error.

[Response]: Thank you for the comment.

We added the information about the relative error and rewritten the corresponding part in the revised manuscript.

“The WVD profiles reconstructed by the GA tomographic solutions are in conformity with those derived from the radiosonde data, especially in the upper troposphere from the perspective of absolute error. With respect to the relative error, the values of the voxels upper than 5km and lower than 5km are 31% and 15%, respectively. The reason for this phenomenon is that the value of water vapor in the upper layers is relatively low, even a small difference between the radiosonde and tomographic result can also lead to a large relative error, while water vapor content accounts for more than 90% below 5km near the Earth’s surface.”

8. P.18, L.7-8: If there are cases when GA performs better than least square methods and others when it is the opposite, the authors should at least try to sort out if there are some "signature" to those contrasted behaviors (like the presence or amplitude of rain, the type of weather regimes, or more technical reasons such as GPS constellation configurations, . . . etc) in order to provide informative comments to the reader. Indeed, it is important to know how reliable the GA method is compared to the established least square ones: if it performs globally as well and is more computing effective, or performs better, than it is a real progress. If it underperforms compared to others, than it has less interest.

[Response]: Thank you for the comment.

The focus of this paper is to solve the ill-conditioned problem of water vapor

tomography using the proposed GA 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.

In this paper, the comparison with tomographic results of the Least squares method is to prove that the results of the GA are appreciated. Table 3 listed the numerical results including RMS and MAE during the whole experimental period and showed that the result is a little better than that of the least squares method when the ECMWF data is regarded as the true value. The solutions that least squares method yields better results than the GA does only accounts a small part. This is similar to the situation that least squares method can obtain results with different accuracy in different time period. We are concerned with the comparisons during the entire experiment, which show that the accuracy of GA is comparable to, or even a little higher than, the least squares method. The very few different solutions do not affect this conclusion. We think that it is reasonable to have these few different results. Since the proposed GA is not designed as the method to significantly improve the accuracy of the least squares method. Moreover, it does not show obvious relationship with the presence or amplitude of rain, the type of weather regimes, or GPS constellation configurations. More research is needed in the follow-up study to find the reasons. We corrected the corresponding part in the revised manuscript.

9. P.19, L.10: The statement that GA can achieve good tomographic results is certainly true, but it should be discussed in light of the comment regarding the comparison with other methods (see comment above).

[Response]: Thank you for the comment.

In the revised manuscript, a more detailed comparison between GA and Least squares method is conducted using the voxels above the radiosonde station. The changes of water vapor density derived from GA and Least squares method with altitudes in different days (rainless days) are shown in the new figure (Fig. 14), in which the radiosonde data and ECMWF data are considered as reference data. Moreover, the statistical values are computed and listed to better show the comparison of GA and Least squares method.

10. P.20, L.9-10: "more water vapor information exists in rainy weather"!!! That needs to be explained (or stated in an understandable way). In my view, weather conditions do not modify the amount of information but the value of such!

[Response]: Thank you for pointing it out.

We stated it in an understandable way in the revised version.

11. P.20, L.10-11: the sentence "Moreover . . . experiments" is unclear or seem unachieved. . . the reader expects something like "and . . ." to know what is the consequence of making measurements during experiments!

[Response]: Thank you for the suggestion.

We rewritten the corresponding part in the revised manuscript.

“Moreover, all the water vapor density along the radiosonde path were collected during the experiments and their changes with altitude were shown in Fig. 15, in which the rainy and rainless weather were represented by blue and red dots.”

12. P.20, L.18 and following: Indeed, neglecting water vapor above 8km in near tropical conditions is far from ideal as it much below the tropopause. Hence a significant part of the water vapor distribution (and dynamics) is not considered. That actually questions the adequacy of Rain / No Rain comparisons throughout the paper at this stage as it could be explained solely by the vertical development of cloud systems.

[Response]: Thank you for the comment.

As you said, the tropopause is different in different region. It is important to determine the top boundary of the tomographic model. Chen and Liu (2014) said that atmospheric regions above 8.5 km should not be considered in the tomography model for Hong Kong. Otherwise, extra unknowns will unnecessarily be introduced into the tomography model. Using 8.5km as the top boundary of tomographic modeling can save 43.3% of unknowns compared with using 15km. In addition, since in tomographic reconstruction only those rays entering from the top boundary of the voxel are considered, a higher top boundary implies that more rays will be rejected. Moreover, a more detailed comparison of the top boundary for the tomographic model is described in Yao and Zhao (2017). Two different height were selected as the top boundary in the paper, one is 10.4 km (Scheme 1) and the other one is 8km (Scheme 2). The results of experiment conducted once per hour show that the average utilization of signals increased by 7.51% from 51.51% (Scheme 1) to 59.02% (Scheme 2) and the percentage of voxels crossed by signals increased by 2.73%. The results of experiment conducted once per day also show a similar improvement. The average vertical water vapor profile and STD for 40 years (1974-2014) derived from a radiosonde station (45004) were collected and analyzed, which also shows that 8km is a reasonable choice of top boundary for Hong Kong tomographic model. In addition, the article entitled “Maximally using GPS observation for water vapor tomography” also discussed the choice of the top boundary for the Hong Kong tomographic model, which indicated that 8km is a good choice for Hong Kong region in term of utilization of signal rays and percentage of voxels crossed by signals. In other articles about the Hong Kong water vapor tomography (Chen and Liu, 2016; Chen and Liu, 2017; Zhao and Yao, 2018), 8km or 8.5km was selected as the top boundary, and good tomographic results were achieved.

Therefore, we think that 8km is a good choice for the top boundary in Hong Kong tomographic model considering the change of water vapor density with altitude in a long period, the utilization of signal rays and the percentage of voxels crossed by signals.

It was selected and demonstrated by previous articles.

**Technical corrections:**

1. P.1, L.16 (and throughout the text): I think one should use the term "a priori" rather than "priori" information or data.

[Response]: Thank you for pointing it out.

We corrected it in the revised manuscript.

2. P.1, L.28: "and are . . ." this sentence is not grammatically correct and one wonders to what this part relates to.

[Response]: Thank you for pointing it out.

We rewritten it in the revised version.

3. P.2, L.3: I guess you meant "to improve the restitution of the spatio-temporal variations".

[Response]: Thank you for pointing it out.

We corrected it in the revised manuscript.

4. P.8, Fig.3: Isn't there a graph issue: why is the coloring not matching the grid, for example, in the last part of the figure, there are voxels with some black and some white in it while I understand from the text that it should be either black or white only.

[Response]: Thank you for the comment.

The lower panel of each graph ((a) and (b)) is to show the distribution of voxel with (black) and without (white) sufficient signal. In our experiment, 1.79% of total SWV is taken as a criteria to distinct whether the voxel is crossed by sufficient signal or not. If the number is greater than the threshold, the color of the voxel is black, otherwise the color of the voxel is white. For example, if the number of signal rays crossing the voxel is greater than 88, the voxel is painted black in the last part of the figure (the lower panel of (b)). Thus, there is no graph issue.