

Thank you for your comments on our manuscript. These comments are very valuable and helpful for great improvements of the manuscript. In this revised version, each of the comments has been carefully addressed and **changes made for corrections are marked in red in the manuscript**. The following is the response to the reviewer's comments.

Reviewer #1:

Minor comment, question:

What is the minimum cut of angle for satellites in proposed new approach? The low satellites are also important for better representation of the distribution of water vapour.

Response:

Thank you for your comments on our manuscript. The minimum cut of angle for satellites is 20 degree in new approach. Although the GNSS tomographic observations with low satellite elevations include more water vapour information, the observations, always together with sparse signals, often lead to bad results. This is because the sparse signals increase the tomographic region without comparable observations to calculating the additional parameters in this extended region (Sparse signals were shown in Figure 9(c) and 9 (d) with blue lines in manuscript). In the future, low satellites information may be utilized by non-uniform tomographic model through flexible node parameter approach. For example, the region of sparse signals has a smaller number of nodes than that of other parts of tomographic region.

Reviewer #2:

Comments:

Comment 1:

- line 104: I would slightly correct the statement, that ionospheric delay can be cancelled out using an ionosphere-free linear combination. This LC takes care only of the first order effect, not completely everything.

Response:

The original part “The ionospheric delay can be cancelled out using an ionosphere-free linear combination of dual-frequency observations.” has been replaced with “The first order ionospheric delay was eliminated using the so-called ionosphere-free linear combination of dual-frequency observations” in **lines 104-106**.

Comment 2:

- line 110: term R in given formula (1) is usually explained as a post-fit residual, not as "the unmodeled delay", because it is definitely not given only by the tropospheric delay. Have you applied post-fit residuals to your SWD used for tomographic reconstruction since you give them in the formula? Have you cleaned them from systematic effects as multipath? See i.e. paper <https://www.atmos-meas-tech.net/10/2183/2017/amt-10-2183-2017.pdf>, this is a rather important step before using post-fit residuals in slant delays.

Response:

(1) We actually applied post-fit residuals to SWD used for tomographic reconstruction in this paper. In one satellite-receiver (e.g. PRN03 and HKSC), we removed the residuals exceeding 2.5 times the standard deviation and also their corresponding observations from our tomographic procedure and then computed means were subtracted from the other post-fit residuals to clean observation from systematic effects.

- (2) We have read the paper “Inter-technique validation of tropospheric slant total delays”. The method about obtaining the cleaned residuals is a great way to extract the anisotropic components especially the stacking technique. In our study, the area of our interest ranges from 113.749 °E to 114.474 °E in the longitudinal direction, from 22.115 °N to 22.651 °N in the latitudinal direction. It is a small area for the GNSS tomography (All SWD observations in the $1 \times 1^\circ$ bin). Therefore, we used another approach in similar way – cleaning of post-fit residuals based on the residuals from one satellite-receiver, to some extent, ensures the residuals under the same conditions (i.e. the residuals from the same satellite and receiver). The stacking technique based on generating elevation and azimuth correction maps is a good way to clean the residuals. We will research it in the future.

The relevant changes made are as follows:

The original part “*R is the unmodeled delay;*” has been replaced with “*R is the post-fit residuals and in one satellite-receiver, the residuals exceeding 2.5 times the standard deviation were removed and then computed means were subtracted from the remaining residuals to clean observation from systematic effects;*” in **lines 111-113**.

Comment 3:

- line 146, caption of Fig. 2: please try to correct the form in which dates are given (in the used way the sentence at UTC 0 on 1(DOY 121), ..., in May 2015 is little bit tricky to understand)

Response:

The original part “*at UTC 0 on 1(DOY 121), 16 (DOY 136) and 31 (DOY 151) in May 2015.*” has been replaced with “*with the sampling rate of 30 seconds at UTC 0 on 1, 16 and 31 May, 2015.*” in **line 146**.

Comment 4:

- section 3.1: you don’t provide any information about the initialization of your tomographic system for the reconstruction, what is an important thing. Have you used some external data as NWM fields, or you used only standard atmosphere water vapor distribution?

Response:

We did not use any information for the initialization of tomographic system. In the inverse process, the zero vector as the initial value of the unknown parameters was used based on the algebraic reconstruction technique (ART).

Comment 5:

- line 316: I would try to correct the sentence where you say that “the number of SWD observations from a tomographic epoch was seven”. I would rather write that SWD observations from seven epochs stacked to one tomographic modelling interval were used

Response:

The original part “*the number of SWD observations from a tomographic epoch was seven*” has been replaced with “*SWD observations from seven epochs stacked to one tomographic modelling interval were used*” in **lines 315-316**.

Comment 6:

- line 318: you present a meteorological situation during May 2015 with total amount of precipitation, but it would be also good to know how the rain events were distributed in time. Were there any severe rains? Or was the precipitation somehow evenly distributed over whole month?

Response:

The original part “The reason for the selection of data from May 2015 is that its monthly total rainfall was 513.0 mm, a 68% larger than the normal level of 304.7 mm.” has been replaced with “The reason for the selection of data from May 2015 is that its monthly total rainfall was 513.0 mm, a 68% larger than the normal level of 304.7 mm. The weather in Hong Kong was hot on the first few days of the month. After a cloudy but relatively rain-free day on 8 May, another trough of low pressure brought heavier showers and thunderstorms to Hong Kong on 9-10 May. Two rainstorm episodes on 20 and 23 May brought rain to most parts of the Hong Kong. Another rapidly developed rainstorm was on 26 May. The weather improved gradually with sunny periods on 28-30 May. However, the weather turned cloudy again with isolated showers and thunderstorms on 31 May.” in lines 317-324.

Comment 7:

- line 323: I agree that water vapor decreases exponentially with height during standard atmospheric conditions. But there can easily occur inversions of water vapor (wet refractivity) in vertical profile, at some latitudes and time periods they are quite common. Have you analyzed the radiosonde (RS) data on this or not? I mean how you checked if vertical profiles from RS evinced some inversions and if yes, then it would be good to say how often, at which heights, etc.

Response:

We have not analyzed the radiosonde (RS) data on inversions of water vapor. But we also concerned about this phenomenon. In fact, the inversions of water vapor occurred in the heavy rain event on 26 May has been detected by our GNSS tomography results. Some possible assumptions were proposed for this phenomenon due to lack of the radiosonde (RS) data for reference. As shown in Figure 1, we divided the whole process of rain into three periods (i.e., Figure 1(a): 8 am to 9 am, Figure 1(b): 9 am to 10 am and Figure 1(c): 10 am to 11 am). In Figure 1(a), HKKP has received just 1 millimeters of rain but the water vapor below 3000m was increased (the inversion of water vapor) during 8:20 am to 8:40 am and then the inversion lifted to between 3000m and 5000m during 8:40 am to 9:00 am. In Figure 1(b), there was 20 millimeters of rain with the inversion declined from 3000m to 1000m during 9 am to 10 am. In Figure 1(c), with the 40 millimeters of rain, the inversion gradually fades away. We deduced that the vertical motion of water vapor, especially ascending motion, is an initial condition of the heavy rain event. It is note that the above results were not validated due to the lack of references and sufficient tests. But we all interested in this phenomenon, which is also one of the important objectives in the future study

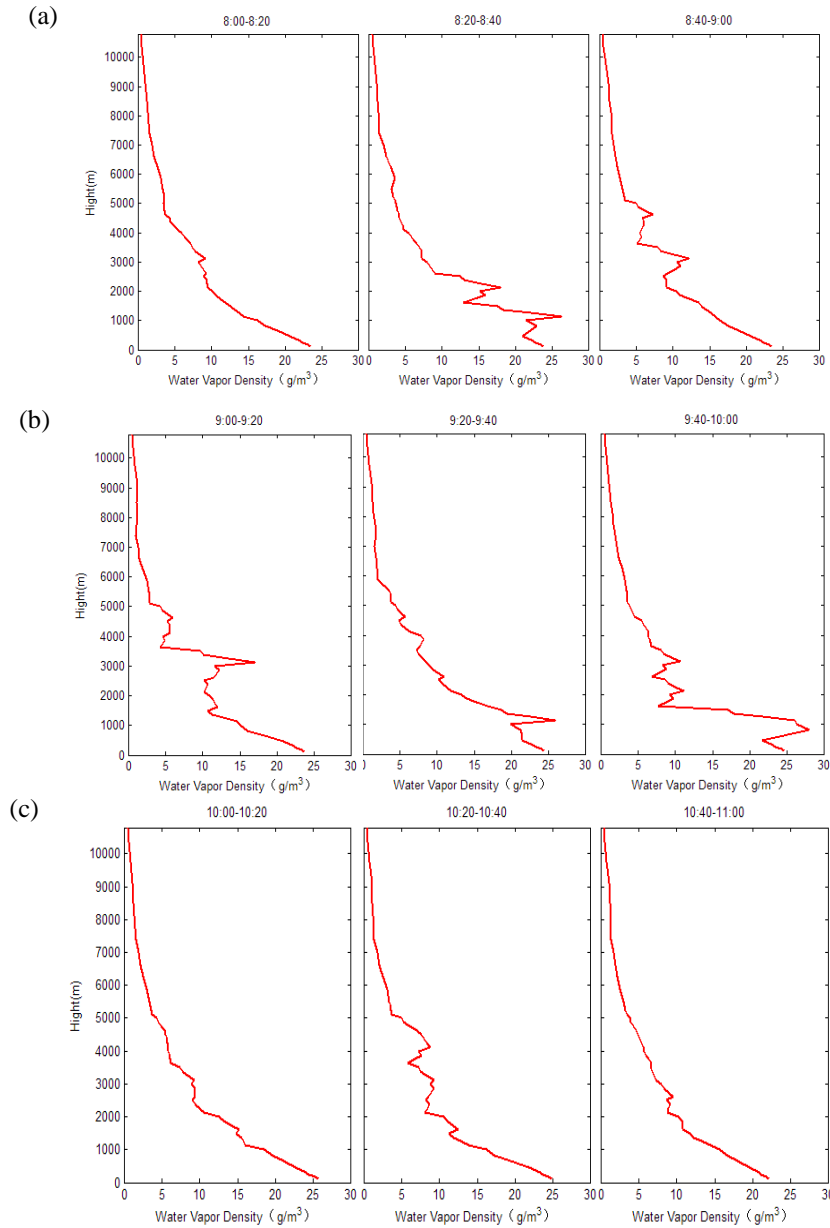


Figure 1. Water vapor profile of heavy rain event on 26 May (Response of Comment 7)

Comment 8:

- section 3.2: do I understand it correctly that you interpolated GNSS tomography results on the RS profile to compare these two techniques? With the term "all RS sampling points" you mean all points were RS provided its measurements? If I understand it correctly then I am not sure if this way of comparison is an optimal one, because RS provides its measurements at slightly different heights everytime. So I think it would be better to horizontally interpolate GNSS tomography results to the position of RS, and then vertically interpolate RS values to individual layers of your tomographic network. Then you would be comparing all the time the same. Can you comment on this?

Response:

Yes, we interpolated GNSS tomography results on the RS profile to compare these two techniques. The RS data in our study is used for the reference of the tomographic results, so we avoid adjusting the original data of RS. The other reason is that the RS data also exists the potential error especially in rainy day. Comparison only between the layers of tomographic results and corresponding vertically interpolate RS values may increase the influence of RS error due to insufficient results of comparison. Finally, GNSS tomography is a technique for building the water vapor distribution in three dimensions. Therefore, its performance at different heights is also important for validation.

Comment 9:

- line 352: are you sure that the reason of difference between "the worst and the best results" lies only in the distribution of slant signals used for tomographic reconstruction? Can't there be also an relation with weather conditions or quality of input SWD signals or something else? I would not be so strong in your statement regarding this.

Response:

You're right. The results have an relation with weather conditions or quality of input SWD signals or something else. The distribution of slant signals used for tomographic reconstruction is one of possible reasons for the accuracy of the model results. The sparse signals would reduce the accuracy in three-stations model due to there are insufficient observations and relatively more unknown parameters (caused by the sparse signals) for GNSS tomography. However, this situation did not exist in GNSS network since the sufficient observations and uniform distribution of slant signals were used in GNSS tomographic model.

The relevant changes made are as follows:

The original part "[which is the reason for the poor accuracy of the model results.](#)" has been replaced with "[which is one of possible reasons for the poor accuracy of the model results.](#)" in [lines 363-364](#).

Comment 10:

-line 368: you state that statistic values listed in Table 1 are "all small", what means you're your "new proposed tomography approach" is feasible". Could you put these values in relation with some other published tomography studies which ideally used a similar territory and a similar season? It could put your numbers into some perspective.

Response:

One published tomography studies was introduced to support "new proposed tomography approach" is feasible" .

The relevant changes made are as follows:

The original part "[The statistics of the model results at both epochs together in the whole month are presented in Table 1. The three values listed in the table are all small, meaning that the new approach for a few GNSS stations, such as three stations, is feasible.](#)" has been replaced with "[In Table 1, the statistics of the model results at both epochs together in the whole month are compared with that of the adaptive node parameterization approach \(ANP\) \(Ding et al., 2018\) during the same periods. Unlike the results of new approach are based on three stations of SatRef, 17 stations of SatRef are used to estimate the results of the ANP. The RMSE and IQR values of new approach are similar to that of the ANP, meaning that the new approach for a few GNSS stations, such as three stations, is feasible. But in terms of the Bias, the new approach has a poor performance.](#)" in [lines 370-376](#).

Table 1. Monthly statistics of new approach and ANP

Statistic	RMSE (g m^{-3})	Bias (g m^{-3})	IQR (g m^{-3})
New approach	1.477	0.239	1.430
ANP	1.216	-0.012	1.678

Reference:

Ding N, Zhang S B, Wu S Q, et al. Adaptive Node Parameterization for Dynamic Determination of Boundaries and Nodes of GNSS Tomographic Models[J]. Journal of Geophysical Research Atmospheres, 2018, 123(4).

Comment 11:

- line 386: I am a little bit surprised with your statements that "... near the ground surface, ... the density of the GNSS signals is very high" - generally the GNSS tomography technique is considered to have troubles to reconstruct water vapor fields well in the boundary layer of troposphere, since the number of slant delays at important low elevation angles is rather limited. What elevation cut-off angle did you use for your GAMIT processing and later in your tomographic reconstruction? Can you comment on this and ideally provide some statistics of how many voxels were penetrated by (how many) signals at various heights? This would support your given statements.

Response:

- 1) You're right. The GNSS tomography technique is considered to have troubles to reconstruct water vapor fields well in the boundary layer of troposphere. It is not only due to the number of slant delays at important low elevation angles is rather limited, but also due to the value of water vapor above 4000m is reduced rapidly with the increase of height (Jiang et al., 2014). The latter one is the main reason for the poor performance in the boundary layer of troposphere since the value of water vapor in this layer is too small to be estimated. Elevation cut-off angle is 10 degree for the GAMIT processing and the minimum cut of angle is 20 degree in tomographic reconstruction. Although the GNSS tomographic observations with low satellite elevations include more water vapour information, the observations, always together with sparse signals, often lead to bad results. This is because the sparse signals increase the tomographic region without comparable observations to calculating the additional parameters in this extended region (Sparse signals were shown in Figure 9(c) and 9 (d) with blue lines in manuscript).
- 2) There are about 20 nodes were penetrated by about 106 signals on the bottom of the tomographic region (300m) and 28 nodes were penetrated by the same number of signals on top of tomographic region (10800m). However, the area of tomographic boundaries on the bottom is about 64 km^2 (i.e., about 1.7 signals per square kilometer) and that on the top is 1550 km^2 (i.e., about 0.07 signals per square kilometer). Therefore, the density of the GNSS signals is very high near the ground surface. The above content was added in the paper for supporting our given statements.

The relevant changes made are as follows:

The original part "and the density of the GNSS signals is very high, resulting in relative high accuracy;" has been replaced with "and there are about 20 nodes were penetrated by about 106 signals on the bottom of the tomographic region (300m) and 28 nodes were penetrated by the same number of signals on the top of tomographic region (10800m). However, the area of tomographic boundaries on the bottom is about 64 km^2 (i.e., about 1.7 signals per square kilometer) and that on the top is 1550 km^2 (i.e., about 0.07 signals per square kilometer). Therefore, the density of the GNSS signals is very high near the ground surface, which results in relative high accuracy;" in lines 393-399.

Reference:

Jiang P, Ye S R, Liu Y Y, et al. Near real-time water vapor tomography using ground-based GPS and meteorological data: long-term experiment in Hong Kong[J]. Annales Geophysicae, 2014, 32(8):911-923.

Comment 12:

- line 407, table 2: you present a number of outliers, but not the total number of compared values. Were the outlier values included in or excluded from the presented overall monthly statistics?

Response:

The total number of compared values is 2790. The outlier values were included in the presented overall monthly statistics.

The relevant changes made are as follows:

The original part “Table 2 lists all the above characteristic values.” has been replaced with “Table 2 lists all the above characteristic values of all errors (the total number of errors is 2790).” in lines 413-414.

Comment 13:

I would propose to decrease size of most of the figures in the manuscript.

Response: Amended as suggested

Comment 14:

Language correction:

- line 43: use tomographic instead of tomographyc
- line 164: I propose to use "... are named pierce points..." instead of current "... are name pierce points..."

Response: Amended as suggested

List of changes

Reviewer #2

Corresponding to comment 1:

The original part “The ionospheric delay can be cancelled out using an ionosphere-free linear combination of dual-frequency observations.” has been replaced with “The first order ionospheric delay was eliminated using the so-called ionosphere-free linear combination of dual-frequency observations” in lines 104-106.

Corresponding to comment 2:

The original part “ R is the unmodeled delay;” has been replaced with “ R is the post-fit residuals and in one satellite-receiver, the residuals exceeding 2.5 times the standard deviation were removed and then computed means were subtracted from the remaining residuals to clean observation from systematic effects;” in lines 111-113.

Corresponding to comment 3:

The original part “at UTC 0 on 1(DOY 121), 16 (DOY 136) and 31 (DOY 151) in May 2015.” has been replaced with “with the sampling rate of 30 seconds at UTC 0 on 1, 16 and 31 May, 2015.” in line 146.

Corresponding to comment 5:

The original part “the number of SWD observations from a tomographic epoch was seven” has been replaced with “SWD observations from seven epochs stacked to one tomographic modelling interval were used” in lines 315-316.

Corresponding to comment 6:

The original part “The reason for the selection of data from May 2015 is that its monthly total rainfall was 513.0 mm, a 68% larger than the normal level of 304.7 mm.” has been replaced with “The reason for the selection of data from May 2015 is that its monthly total rainfall was 513.0 mm, a 68% larger than the normal level of 304.7 mm. The weather in Hong Kong was hot on the first few days of the month. After a cloudy but relatively rain-free day on 8 May, another trough of low pressure brought heavier showers and thunderstorms to Hong Kong on 9-10 May. Two rainstorm episodes on 20 and 23 May brought rain to most parts of the Hong Kong. Another rapidly developed rainstorm was on 26 May. The weather improved gradually with sunny periods on 28-30 May. However, the weather turned cloudy again with isolated showers and thunderstorms on 31 May.” in lines 317-324.

Corresponding to comment 9:

The original part “which is the reason for the poor accuracy of the model results.” has been replaced with “which is one of possible reasons for the poor accuracy of the model results.” in lines 363-364.

Corresponding to comment 10:

The original part “The statistics of the model results at both epochs together in the whole month are presented in Table 1. The three values listed in the table are all small, meaning that the new approach for a few GNSS stations, such as three stations, is feasible.” has been replaced with “In Table 1, the statistics of the model results at both epochs together in the whole month are compared with that of the adaptive node parameterization approach (ANP) (Ding et al., 2018) during the same periods. Unlike the results of new approach are based on three stations of SatRef, 17 stations of SatRef are used to estimate the results of the ANP. The RMSE and IQR values of new approach are similar to that of the ANP, meaning that the new approach for a few GNSS stations, such as three stations, is feasible. But in terms of the Bias, the new approach has a poor performance.” in lines 370-376.

Corresponding to comment 11:

The original part “and the density of the GNSS signals is very high, resulting in relative high accuracy;” has been replaced with “and there are about 20 nodes were penetrated by about 106 signals on the bottom of the tomographic region (300m) and 28 nodes were penetrated by the same number of signals on the top of tomographic region (10800m). However, the area of tomographic boundaries on the bottom is about 64 km² (i.e., about 1.7 signals per square kilometer) and that on the top is 1550 km² (i.e., about 0.07 signals per square kilometer). Therefore, the density of the GNSS signals is very high near the ground surface, which results in relative high accuracy;” in lines 393-399.

Corresponding to comment 12:

The original part “Table 2 lists all the above characteristic values.” has been replaced with “Table 2 lists all the above characteristic values of all errors (the total number of errors is 2790).” in lines 413-414.

Corresponding to comment 13:

All of the figures’ size in the manuscript has been decreased.

Corresponding to comment 14:

- 1) The original part “tomogaphic” has been replaced with “tomographic” in line 44.
- 2) The original part “are named pierce points” has been replaced with “are name pierce points” in line 164.

A new approach for GNSS tomography from a few GNSS stations

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Abstract

The determination of the distribution of water vapor in the atmosphere plays an important role in the atmospheric monitoring. Global Navigation Satellite Systems (GNSS) tomography can be used to construct 3D distribution of water vapor over the field covered by a GNSS network with high temporal and spatial resolutions. In current tomographic approaches, a pre-set fixed rectangular field that roughly covers the area of the distribution of the GNSS signals on the top plane of the tomographic field is commonly used for all tomographic epochs. Due to too many unknown parameters needing to be estimated, the accuracy of the tomographic solution degrades. Another issue of these approaches is their unsuitability for GNSS networks with a few stations as the shape of the field covered by the GNSS signals is in fact roughly an upside-down cone rather than the rectangular cube as the pre-set. In this study, a new approach for determination of tomographic fields fitting the real distribution of GNSS signals on different tomographic planes at different tomographic epochs and also for discretization of the tomographic fields based on the perimeter of the tomographic boundary on the plane and meshing techniques is proposed. The new approach was tested using three stations from the Hong Kong GNSS network and validated by comparing the tomographic results against radiosonde data from King's Park Meteorological Station (HKKP) during the one month period of May, 2015. Results indicated that the new approach is feasible for a three-station GNSS network tomography. This is significant due to the fact that the conventional approaches cannot even solve a few stations network tomography.

1 Introduction

Information of the distribution and variation of atmospheric water vapor is essential for meteorological applications. Nowadays, the most commonly used technology for measuring atmospheric water vapor is radiosonde due to its high vertical resolution and high accuracy, even though its horizontal resolution is very low—several hundreds of kilometers, and its temporal resolution is also low—twice daily. With the development of Global Navigation Satellite Systems

(GNSS), using GNSS measurements to remotely sense water vapor in the atmosphere has attracted significant attention due to their 24-hour availability, global coverage and low cost. based on GNSS measurements collected from a regional or global GNSS reference network, a regional or a global tomographic model, which is three-dimensional (3D), can be constructed. The **tomographic** model reflects the spatial variation of water vapor in the time period investigated, thus it has the potential to be used to investigate the evolution of heavy rain events for severe weather forecast (Wang et al., 2017; Chen et al., 2017; Zhang et al., 2015).

Using the slant wet delays (SWDs) estimated from the GNSS signals of a GNSS network to construct a tomographic model is called GNSS tomography. Flores et al. (2000) built the first GNSS tomographic model using $4 \times 4 \times 40$ voxels and developed Local Tropospheric Tomography Software (LOTTOS) for simulation and processing of GNSS data. Gradinarsky (2002) developed the wet refractivity Kalman filter (WeRKaF) for tomographic inversion of GNSS data and the filter mainly focused on the initialization of the tomographic covariance matrix used in the implementation of the Kalman filter. Troller et al. (2006) developed the atmospheric water vapor tomography software (AWATOS) based on double-differenced GPS observations and double-differenced phase residuals. Rohm and Bosy (2009) addressed the issue with the ill-condition of tomographic equations using the Moore-Penrose pseudo inverse of the variance-covariance matrix. In order to minimize the discretization effects, Perler et al. (2011) for the first time proposed using node parameterization in GNSS tomographic modeling. Chen and Liu (2014) optimized a water vapor tomographic region through moving voxel location along the latitudinal and longitudinal directions until the number of the voxels that contain GNSS signals reached the maximum. Yao et al. (2016) improved the utilization rate of GNSS observations in the modeling by adding extra voxels on the top of the tomographic region where some satellite signals partly cross the tomographic field. Ding et al. (2017) developed an access order scheme called prime number decomposition (PND) for minimizing the correlation between the SWDs which are the sample data of tomographic modeling. The above GNSS tomographic approaches were tested using various numbers of GNSS stations, majority of which were a few tens of stations, and the maximum and minimum were 270 and 8 respectively.

In all the above tomographic approaches, the tomographic fields are all assumed rectangular cubes. The size and location of the rectangular cubes are determined based on the distribution of GNSS signals only on the top boundary of the tomographic field—the rectangular cube that best fits the top boundary is adopted (Bastin et al., 2005; Bender et al., 2009; Champollion et al., 2005; Ding et al., 2017; Gradinarsky and Jarlemark, 2004; Hoyle, 2005; Rohm et al., 2014; Seko et al., 2000; Troller et al., 2006; Xia et al., 2013; Ye et al., 2016). In fact, the field that GNSS signals cover has a shape of upside-down cone, roughly, meaning that in the part near the edge of the cube, especially in the lower part, none of the GNSS signals cross through. This region is named empty spatial region (ESR) in this paper merely for convenience. In fact, the inclusion of those voxels/nodes in the ESR in the discretization of the model not only does little contribution to the improvement on the accuracy of the model solution but also adds extra meaningless unknown parameters to be estimated. More parameters mean more horizontal constraints are needed and also degradation of the accuracy and stability of the solution, especially in the case the network consists of a few stations, e.g. only three stations. This is because the difference in the sizes covered by the GNSS signals in the bottom and top planes of the tomographic field is large, meaning a large number of voxels/nodes in the ESR and far away from the observed signals, especially in the lower part of the tomographic field. In the estimation process of the model, the horizontal constraints imposed on these nodes/voxels are usually from

extrapolated results based on their nearest observations. If these voxels/nodes are far away from the observed signals, the constraints are too weak and will cause difficulty in the solving of the tomographic equations. The large number of nodes/voxels contained in ESRs stemming from a small number of GNSS stations is the main reason for the unsuitability of the current GNSS tomographic approaches to using a few-station networks.

In this study, a new node parameterization approach for dynamic determination of tomographic fields and the discretization of the fields at each tomographic epoch was proposed. It is adaptive node parameterization for varying density on different tomographic planes. This differs from all current approaches in which the same pre-set rectangular cube roughly determined by the distribution of the signals only on the top tomographic plane is adopted for all planes and all epochs of the tomography. In addition, for the discretization of the tomographic field determined for each plane at each epoch, the location and number of all the nodes on the plane are determined according to the size of the tomographic field. As a result, the tomographic model is tailor-made for all planes and all epochs. Moreover, the new approach is applicable to GNSS networks with any number of stations, i.e. equal to or larger than three.

2 Methodology

2.1 Observations of GNSS Tomography

GNSS signals are bent and delayed when they propagate through the atmosphere. The atmosphere can be divided into the ionosphere and troposphere. **The first order ionospheric delay was eliminated using the so-called ionosphere-free linear combination of dual-frequency observations.** The tropospheric delay can be divided into two components—the dry delay and the wet delay. The wet component is the SWD and can be expressed by

$$SWD = m_w(e) \cdot \left\{ ZWD + \left[G_N^w \cdot \cos(\phi) + G_E^w \cdot \sin(\phi) \right] \cdot \cot(e) \right\} + R \quad (1)$$

where $m_w(e)$ is a wet mapping function and the VMF1 mapping function was used in this study; G_N^w and G_E^w are the wet delay gradients in the north–south and east–west directions, respectively; **R is the post-fit residuals and in one satellite-receiver, the residuals exceeding 2.5 times the standard deviation were removed and then computed means were subtracted from the remaining residuals to clean observation from systematic effects;** ZWD is the zenith wet delay of the GNSS station, which can be obtained by subtracting the zenith hydrostatic delay (ZHD) from the zenith total delay (ZTD). The ZHD can be calculated by a standard tropospheric model such as the most commonly used Saastamoinen model (Saastamoinen, 1972) and the ZTD is estimated (as an unknown parameter) in GNSS data processing;

In GNSS tomographic modeling, the SWDs of GNSS signals in a tomographic field are used as the observations for the estimation of water vapor parameters in the field.

2.2 Tomographic modeling

2.2.1 General approaches

Voxel and node parameterization are the two common GNSS tomographic approaches. In the former, the tomographic field, which is usually assumed as a rectangular cube, is divided into many voxels (small rectangular cubes) and in the latter, and the field is discretized by nodes, as

all the black and circle nodes shown in Fig. 1. In this study, the node parameterization approach was adopted due to its better fitting of the spatial correlation of water vapor.

In the current node parameterization approaches, if the GNSS network is very small, e.g. a three-station network from the Hong Kong Satellite Positioning Reference Station Network (SatRef) as shown in Fig. 1, a large number of nodes are in the ESR (see the hollow circles) within the rectangular cube which is the tomographic field. These nodes, as part of the unknown parameters, need to be estimated. The inclusion of these unknown parameters in the estimation process does not only add more ‘redundant’ parameters but also degrades the accuracy of the solution.

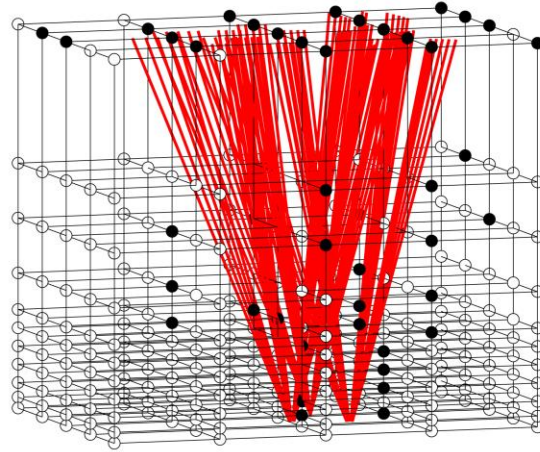


Figure 1. A three-station GNSS network from the Hong Kong Satellite Positioning Reference Station Network (SatRef) as an example for GNSS tomography—the rectangular cube is the tomographic field adopted in current node parameterization approaches, the solid nodes are those near GNSS signals and the hollow nodes are those in the ESR.

In addition, a fixed rectangular cube is used as the tomographic field for all time in the current approaches, In fact, the spatial region that the signals travel through varies with time, as shown in Fig. 2 for the different distributions of the signals at the three stations shown in Fig. 1 on the top plane of the tomographic field at UTC 0 on 1 (day of year (DOY) 121), 16 (DOY 136) and 31 (DOY 151) in May 2015.

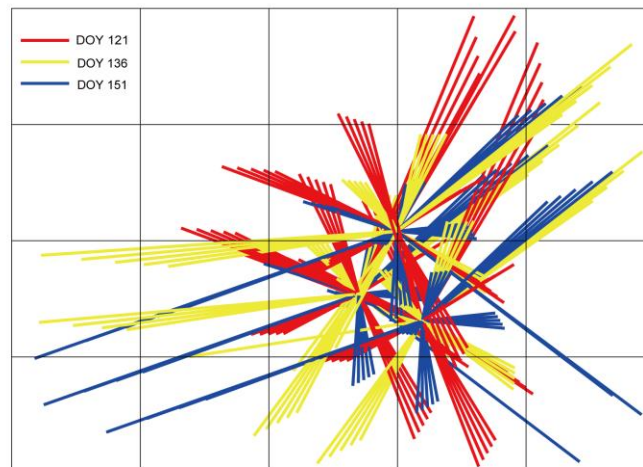


Figure 2. Distributions of GNSS signals at the three stations shown in Fig. 1 on the top plane of the tomographic field **with the sampling rate of 30 seconds at UTC 0 on 1, 16 and 31 May, 2015.**

To address the above issues, a new node parameterization approach that dynamically adjusts the tomographic field based on the spatial distribution of the GNSS signals at the tomographic epoch and also dynamically adjusts the location and number of all the nodes based on the size of the tomographic field is proposed. Its procedure is elaborated in the next section.

2.2.2 New approach

The procedure for the new approach mainly includes two steps—determination of tomographic field and determination of node position, which are introduced below.

i) Determination of tomographic field

A tomographic field is regarded to be comprised of many layers in the vertical dimension and these layers with the same or different thickness, depending on the distribution of water vapor at the height of the layer, as shown in Fig. 3(a), each layer is formed by two neighboring horizontal planes. After all these planes are determined, the next task is to determine the tomographic boundary for each plane, according to the distribution of the GNSS signals on the plane. Fig. 3(b) shows the tomographic boundary on each of the planes shown in Fig. 3(a), which is determined from the following three steps that were used in the Graham scan (Graham, 1972) determining all the intersections (the blue points) of the GNSS signal paths on the plane (they **are name pierce points** in this paper); 2) using a stack of the pierce points to detect and remove all those pierce points that are in concavities; and 3) connecting the rest pierce points to form a convex hull, which is the tomographic boundary (black polygon).

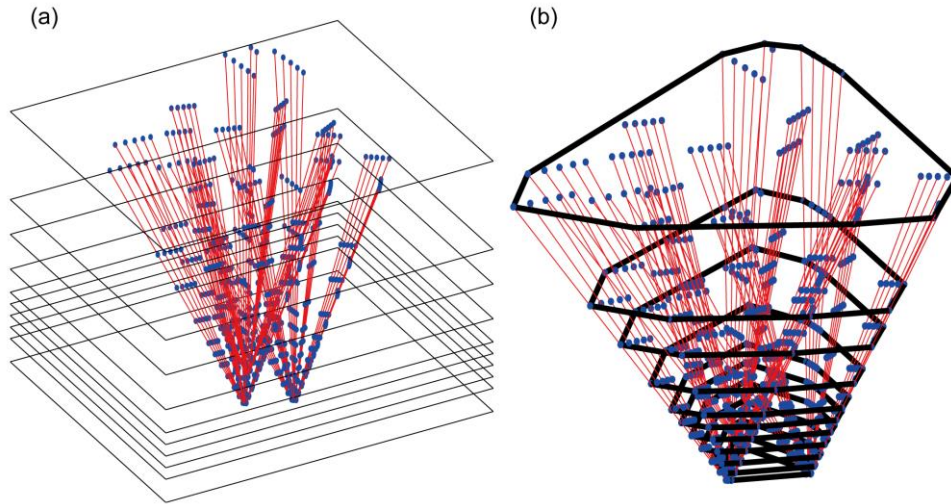


Figure 3. (a) A tomographic field is divided by many layers, the thickness of which is dependent upon the distribution of water vapor in the layer, the red lines are the sampling GNSS signals and the blue points are the intersections of the GNSS signals on each horizontal plane; and (b) Tomographic boundary is depicted by the black polygon on each horizontal plane.

Since the shape of the tomographic boundary determined using the new approach is irregular, it is difficult to generate equidistant nodes within the boundary. This differs from current node parameterization approaches in which uniformly distributed nodes can be easily pre-set. In this study meshing techniques are used to adjust the position of nodes for each plane and each tomographic epoch, and their procedure is discussed in the next section.

ii) Determination of node position

Meshing techniques for the generation of equidistant nodes of a GNSS tomographic model include three steps and each of the steps is introduced below.

1) A mesh background in a desired size with nodes is used to provide initial nodes for each plane see Fig. 4(a) where the polygon is obtained from the last section for the tomographic boundary on the plane and at all the vertices of the polygon a new set of nodes are also attached to the initial nodes, see Fig. 4(b) for the final initial nodes.

2) Delaunay triangulation (Delaunay, 1934) is used to establish a topology for the above initial nodes on each plane. It determines non-overlapping triangles that fill the region in a polygon such that every edge is shared by at most two triangles and none of the vertices is inside the circumcircle of any of the triangles. Delaunay triangulations maximize the minimum angle of all the triangles to avoid sliver triangles which has undesirable properties during some interpolation or rasterization processes (Edelsbrunner et al., 2000). Several methods have been developed to compute the Delaunay triangulation such as the commonly used flipping edges and conversing a Voronoi diagram. In this study, the flipping edges method is adopted to connect the initial nodes shown in Fig. 4(b) by the edges of Delaunay triangles on each plane and the topology formed is shown in Fig. 4(c).

3) The force displacement algorithm (Persson, 2005) is applied to the above topology for the adjustment of the initial nodes into equidistance with a reasonable length fitting the size of the tomographic boundary on each plane. This method is based on the assumption that each edge in the topology has a force value (let it be F_{ij}) equal to the length of the edge. It can be used to make all the edges' F_{ij} close to the same and reasonable pre-set force value F_0 for a (roughly) regularly distributed mesh. This is the main reason for the introducing of this method to this study for adjusting the nodes in the irregular tomographic boundary (like Fig. 4(c)) into equidistance (roughly). The force displacement algorithm is an iterative process as:

$$[X^k \ Y^k] = [X^{k-1} \ Y^{k-1}] + Scal \cdot [F_x^k \ F_y^k] \quad (2)$$

where X^k and Y^k are the vectors of the x and y coordinates respectively of all the nodes on the plane at the k th iteration and $k-1$ denotes the previous iteration; $Scal$ is a relaxation factor for constraining the amount of the movement from the $k-1$ th iteration to an appropriate value, for which a 0.2 value is commonly used; F_x^k is the vector of the vector sums of all the forces working on each of the nodes in the x direction, F_y^k is that in the y direction.

After the above algorithm is performed, all the nodes on the plane can be adjusted from the initial position (Fig. 4(c)) to equidistant position (Fig. 4(d)) through a series of iterations.

It is noted that the sizes of the tomographic boundaries on different planes are different (Fig. 3(b)) while the numbers of the signals on different planes are the same, so the densities of the signals on different planes are different, and the densities of the nodes on different planes

better be different through using different F_0 values. In this study, the F_0 value for the i th plane is calculated by:

$$F_0^i = C \cdot \text{mean}(Ls^i) \quad (3)$$

where C is a constant coefficient and 0.68 is adopted for all planes; and $\text{mean}(Ls^i)$ is the mean of all the lengths of the edges on the polygon.

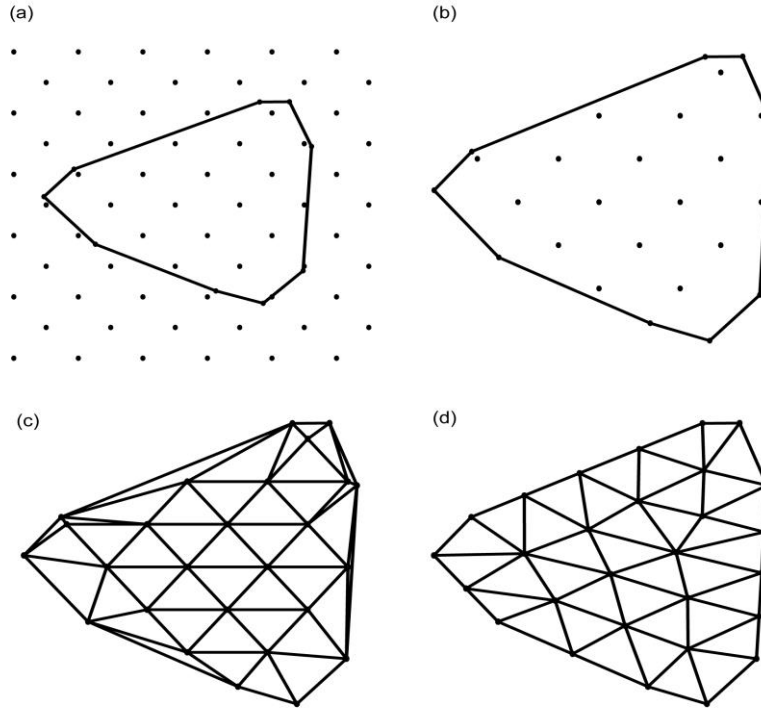


Figure 4. (a) Two sets of nodes for initialization—one set is generated using a mesh background with a desired size which is usually slightly larger than the region of the GNSS signals at all time and the other set is at all the vertices of the polygon (all black points); (b) Initial nodes; (c) Topology formed using Delaunay triangulation; (d) Nodes with equidistance adjusted based on the force displacement algorithm.

2.3 Observation equations

After equidistant nodes for all planes are determined (like Fig. 4(d)), the next step is to estimate water vapor parameters at these nodes from observation equations of GNSS-derived *SWDs*. The derivation of the observation equations is as follows.

Theoretically, *SWD* is defined as the integral of wet refractivity N_w along the signal path s

$$SWD = 10^{-6} \cdot \int_s N_w ds \quad (4)$$

It can be further decomposed into integrations of n layers:

$$SWD = \sum_{i=1}^n \int_{s_i}^{s_{i+1}} N_w^s(i) ds = \sum_{i=1}^n SWD_i \quad (5)$$

where $N_w^s(i)$ is wet refractivity in the i th layer ; s_i, s_{i+1} are the start and end points of the layer/integral; and SWD_i is the part of the SWD in the i th layer

In GNSS tomography, in each of the piecewise integrals expressed in Eq. (5), i.e. SWD_i , the signal path in the layer is further divided into several equally spaced points and then SWD_i is approximated as a function of wet refractivity at these points using the Newton-Cotes formulae (Perler et al., 2011). In this study, SWD_i is approximated by the Newton-Cotes formulae of 4 degree at five equally spaced points, as ($P_1 \dots, P_5$) shown in Fig. 5 where the plane i and plane ($i+1$) are the two horizontal planes corresponding to the above s_i, s_{i+1} respectively, and the black solid dots denote some of the equidistant nodes obtained from Fig. 4(d).

The methods for obtaining wet refractivity at each of the points are as follows.

i) Wet refractivity at points P_1 and P_5 (which are on the i th and ($i+1$)th planes respectively) can be calculated using the interpolation method of the inverse-distance-weighted (IDW) mean of the sample wet refractivity data from its surrounding nodes:

$$P_{wet} = \frac{\sum_{j=1}^m w_j \cdot n_j^{wet}}{\sum_{j=1}^m w_j} \quad (6)$$

where j is the index of the sample data, and w_j is its weight determined by the inverse-distance; and m is the number of the sample data.

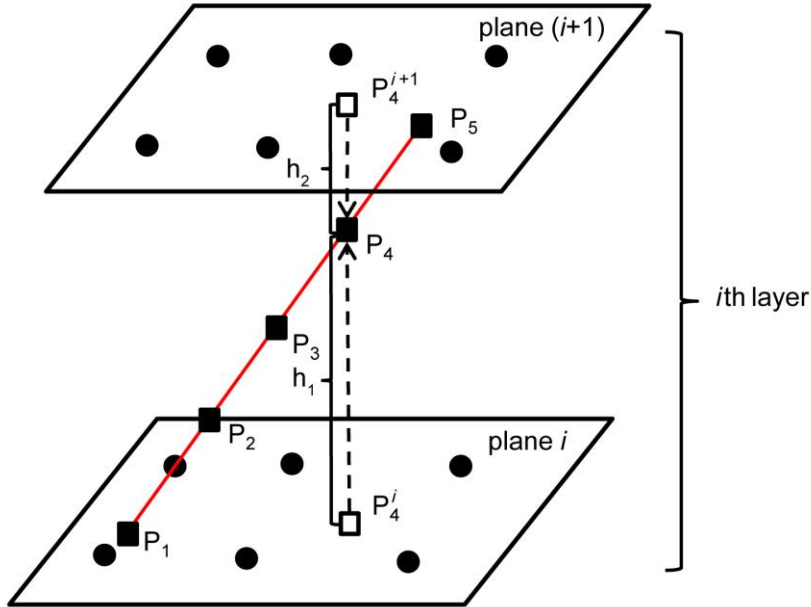


Figure 5. Five equally spaced points (black solid squares) for an approximation of wet refractivity for the i th layer. P_4^i and P_4^{i+1} (black hollow squares) are the projected points of P_4 on the i th and ($i+1$)th planes respectively, h_1 is the height difference between P_4 and P_4^i , and h_2 is that between P_4 and P_4^{i+1} .

ii) Wet refractivity at points P_2 , P_3 and P_4 , cannot be directly interpolated like that for P_1 and P_5 , the following three-step procedure needs to be performed (P_4 is taken as an example): 1) the position of P_4 is projected onto both the i th and $(i+1)$ th planes to obtain two projected points named P_4^i and P_4^{i+1} , respectively; 2) the above interpolation procedure for P_1 and P_5 is used to obtain wet refractivity P_{4wet}^i and P_{4wet}^{i+1} at P_4^i and P_4^{i+1} respectively; and 3) P_{4wet}^i and P_{4wet}^{i+1} are used to obtain a weighed mean wet refractivity for the position of P_4 using [Reitan, 1963; Tomasi, 1981]:

$$P_4 = \frac{|h_1|}{(|h_1|+|h_2|)} P_{4wet}^i \cdot e^{-h_1/H} + \frac{|h_2|}{(|h_1|+|h_2|)} P_{4wet}^{i+1} \cdot e^{-h_2/H} \quad (7)$$

where h_1 is the height difference between P_4 and P_4^i and h_2 is that between P_4 and P_4^{i+1} ; and H is water vapor scale height, which can be calculated by Tomasi [1977]:

$$H = \frac{10W}{\rho_s} \quad (8)$$

where W and ρ_s are the vertical total water vapor content (in g m^{-2}) and surface humidity (in g m^{-3}) respectively, and both can be obtained from GNSS data.

After the above procedures are carried out, SWD_i can be expressed as a function of wet refractivity at a set of nodes. This procedure needs to be performed for all SWD_i ($i=1,2,\dots,n$), then the next step is to substitute these SWD_i expressions and the SWD observation into Eq. (5), to form its GNSS tomographic observation equation.

The final GNSS tomographic observation equations of all SWD s from the GNSS network for the tomographic modeling is expressed as:

$$A \cdot X = b \quad (9)$$

where A is the coefficient matrix of the model; b is the vector of the SWD observations; and X is the vector of the wet refractivity parameters at all nodes.

The X vector in Eq. (9) can be estimated using the least squares method. However, due to the problem with the sparseness of A , the algebraic reconstruction technique (ART) was used to estimate X in this study.

2.4 Tomographic solution

The ART has been successfully applied to reconstruction of water vapor field (Chen and Liu, 2014; Bender et al., 2011). Its main advantage is the high numerical stability, even under adverse conditions and also relatively easy to incorporate prior knowledge into the reconstruction process. The ART used to solve Eq. (9) is (Kaczmarz, 1937):

$$x^{k+1} = x^k + \lambda \frac{b_i - \langle a_i, x^k \rangle}{\|a_i\|_2^2} a_i \quad i = 1, 2, \dots, m \quad (10)$$

where a_i and b_i denote the i th rows in A and b respectively; x_k is the k th iterative solution; and λ is a relaxation factor and the value of 0.2 was selected in this study.

It is noted that Eq. (9) needs to be sorted in a certain sequence for Eq. (10). This is different from the commonly used observation equation system in which the order of the observation equations is not a matter. In this study, an access order scheme based on prime number decomposition (PND) proposed in (Ding et al., 2017) was used for the ordering of the observation equations such that the observation equations between two consecutive iterations are largely uncorrelated.

The unknown parameters X solved from Eq. (10) are the wet refractivity values at all tomographic nodes. In some meteorological applications, water vapor density may be preferred, in this case X needs to be converted using a conversion factor I which is a function of water-vapor-weighted-mean temperature T_m (Bevis et al., 1994; Wang et al., 2016) at the position of the nodes.

3 Test results

3.1 Data selection and tomographic scheme

Test data used in this study were from three stations in the Hong Kong Satellite Positioning Reference Station Network (SatRef), and the horizontal and vertical distributions of the three stations are presented in Fig. 6(a) and Fig. 6(b), respectively. The area of our interest ranges from 113.749 °E to 114.474 °E in the longitudinal direction, from 22.115 °N to 22.651 °N in the latitudinal direction and from 0 to 10800 m in the vertical direction. Radiosonde data from King's Park Meteorological Station (HKKP) (the blue triangle shown in Fig. 6(a)) were used as the reference for the validation of our test results.

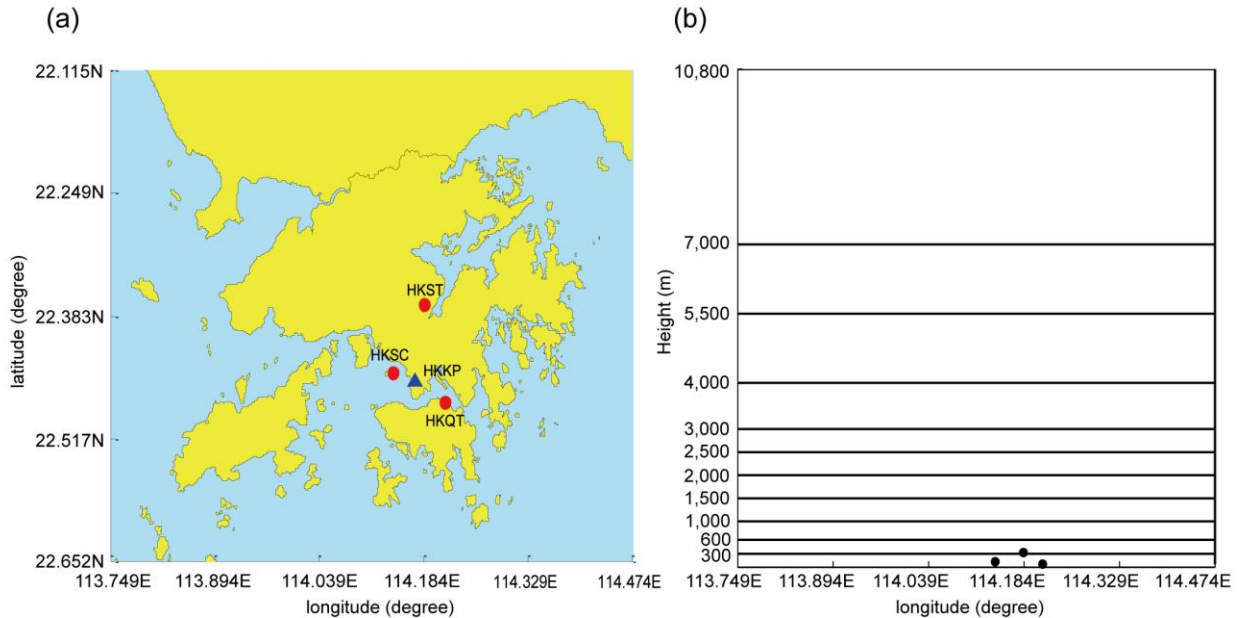


Figure 6. (a) Horizontal distribution of the three stations selected from the Hong Kong reference stations (red dots) and HKKP (blue triangle); and (b) Vertical distribution of the three stations (black spots) and vertical layers used in tomographic modeling.

The test data were from the whole month of May, 2015 (day of year (DOY) 121–151) with the sampling rate of 30 seconds, and the GAMIT software was used to obtain SWDs at the

same rate in the data processing. For the tomographic modeling, a 5-minute sampling rate for SWDs and a 30-minute interval for a tomographic epoch were adopted, meaning that SWD observations from seven epochs stacked to one tomographic modelling interval were used – including the two sample data at the two ends of the interval. The reason for the selection of data from May 2015 is that its monthly total rainfall was 513.0 mm, a 68% larger than the normal level of 304.7 mm. The weather in Hong Kong was hot on the first few days of the month. After a cloudy but relatively rain-free day on 8 May, another trough of low pressure brought heavier showers and thunderstorms to Hong Kong on 9-10 May. Two rainstorm episodes on 20 and 23 May brought rain to most parts of the Hong Kong. Another rapidly developed rainstorm was on 26 May. The weather improved gradually with sunny periods on 28-30 May. However, the weather turned cloudy again with isolated showers and thunderstorms on 31 May. The tomographic scheme for testing is as follows. The first step is to determine the vertical planes/layers for the tomographic field. Non-uniform vertical intervals from 300 to 3800 m (Fig. 6(b)) were selected for adaption to the inherent characteristic of water vapor spatial distribution—it exponentially decreases with the increase of height. The use of this structure can also avoid too many unknown parameters overfitting the SWD observations. The next step is to determine the tomographic polygon/boundary on each of the above planes using the methods in section 2.2.1 and based on the GNSS signals in the tomographic interval, then according to the polygon's perimeter, a F_0 value in the force displacement algorithm for determination of the density of nodes on each plane is calculated. All F_0 results in our test are in the range of about 1800–10000 m corresponding to the range of height 300–10800 m. The position of the nodes on each plane is determined by Eq. (2).

Figure 7 shows the boundary and nodes on three tomographic planes at tomographic epoch UTC 0 on DOY 121, 2015 for an example. Tomographic model results are presented in the next section.

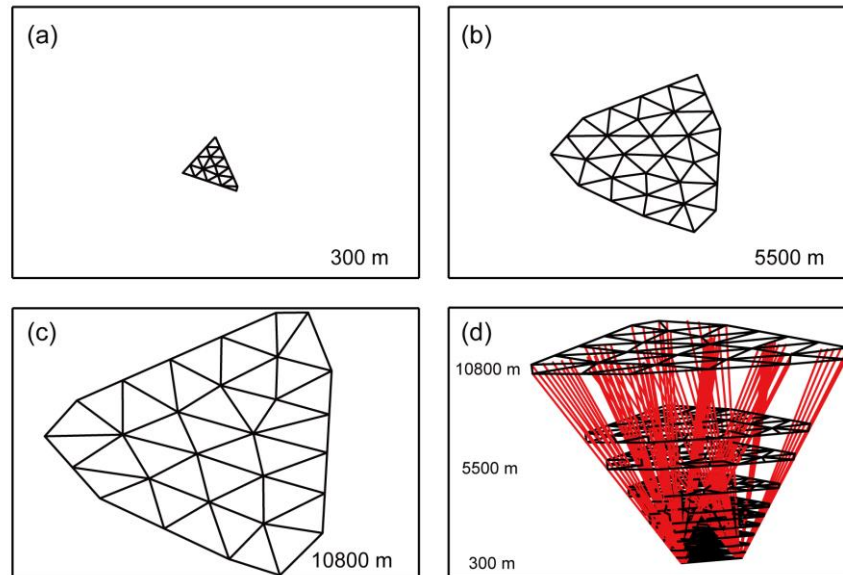


Figure 7. Tomographic boundary and nodes on three planes ((a), (b) and (c)) and the tomographic field and nodes (d) at tomographic epoch UTC 0 on DOY 121, 2015.

3.2 Results of profiles

Water vapor density values obtained from the tomographic models at tomographic epochs UTC 0 and UTC 12 on each day of the month (DOYs 121–151) were compared against radiosonde (RS) data for evaluation of the model's accuracy. The values of the tomographic results at all RS sampling points were calculated first using the interpolation method mentioned in section 2.2.1, then the root mean square error (RMSE) of the differences between the interpolated values and RS observations at all the sampling points of the RS profile from the ground surface to 10800 m at each epoch was calculated for the accuracy of the profile. All the results at the 62 epochs during the 31-day period are shown in Fig. 8.

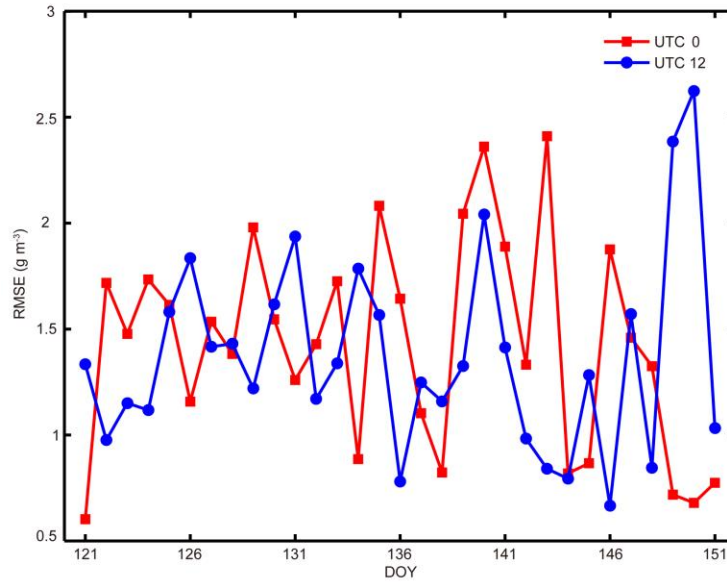


Figure 8. RMSE of model-derived water vapor density values at all RS sampling points of the RS profile below 10800 m at tomographic epochs UTC 0 and UTC 12 on each day of the month (DOYs 121–151).

The maximum RMSEs, i.e., the worst results, at UTC 0 (red) and UTC 12 (blue) are on DOY 143 and DOY 150 respectively; while the best result (the minimum RMSEs) at the two epochs are on DOYs 121 and 146. In order to find the reason for the large difference between the worst and best results, the tomographic field, the distribution of the signals and the nodes at these four epochs are given in Fig. 9, where Fig. 9(a) and Fig. 9(b) correspond to the best results at UTC 0 and UTC 12 respectively, both of which show uniform distributions of the GNSS signals. However, the distributions of the GNSS signals corresponding to the worst results at UTC 0 (Fig 9(c)) and UTC 12 (Fig 9(d)) are different in the sparse signals shown in blue lines, which is one of possible reasons for the poor accuracy of the model results.

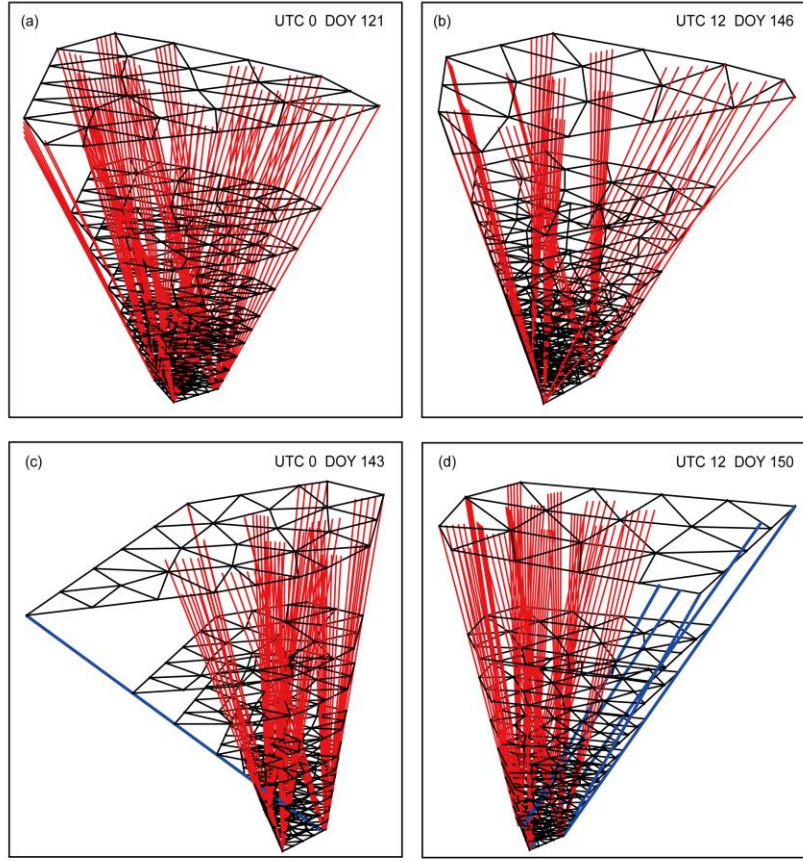


Figure 9. Tomographic field and signal distribution at tomographic epoch UTC 0 on DOY 121 (a), UTC 12 on DOY 146 (b), UTC 0 on DOY 143 (c), and UTC 12 on DOY 150 (d).

The results shown in Fig. 8 are the statistics of the model results for each epoch on each day. In Table 1, the statistics of the model results at both epochs together in the whole month are compared with that of the adaptive node parameterization approach (ANP) (Ding et al., 2018) during the same periods. Unlike the results of new approach are based on three stations of SatRef, 17 stations of SatRef are used to estimate the results of the ANP. The RMSE and IQR values of new approach are similar to that of the ANP, meaning that the new approach for a few GNSS stations, such as three stations, is feasible. But in terms of the Bias, the new approach has a poor performance.

Table 1. Monthly statistics of new approach and ANP

Statistic	RMSE (g m^{-3})	Bias (g m^{-3})	IQR (g m^{-3})
New approach	1.477	0.239	1.430
ANP	1.216	-0.012	1.678

To indicate the spread of all the errors (the ones used to calculate the above monthly statistics), scatter plots shown in Fig. 10(a) are used to analyze the characteristics of these errors in different intervals. The x and y axes denote the RS observation and the model result (in g m^{-3})

respectively; each hollow circle corresponds to a sampling point's result; and the red line represents the “perfect” results, i.e. the model results equal to the RS results. Those hollow circles that are on the red line have an error value of zero, those above the red line have a positive error value, and the rest have a negative error value. The closer a hollow circle to the red line, the smaller its error value.

How well all the hollow circles “fit” the red line indicates the overall quality of the model results. It is clear that the hollow circles have a cigar-shaped (fusiform) distribution. The hollow circles in both ending intervals ($[0-5]$ and $[20-25]$ g m^{-3}) more concentrate around the red line than those in the middle part ($[5-20]$ g m^{-3}). The reason for this is 1) most of the sampling points in the $[20-25]$ g m^{-3} interval are located near the ground surface, where water vapor density decreases exponentially with the increase of height and there are about 20 nodes were penetrated by about 106 signals on the bottom of the tomographic region (300m) and 28 nodes were penetrated by the same number of signals on the top of tomographic region (10800m). However, the area of tomographic boundaries on the bottom is about 64 km^2 (i.e., about 1.7 signals per square kilometer) and that on the top is 1550 km^2 (i.e., about 0.07 signals per square kilometer). Therefore, the density of the GNSS signals is very high near the ground surface, which results in relative high accuracy; 2) most of the sampling points in the $[5-20]$ g m^{-3} interval are located in the mid-height of the tomographic field, where the GNSS signals are sparser than the $[20-25]$ g m^{-3} interval, leading to a larger tomographic field, which results in a lower accuracy; and 3) most of the sampling points in the $[0-5]$ interval are located in the top section of the tomographic field, where the water vapor values are smaller than the other two intervals, leading to the smallest errors.

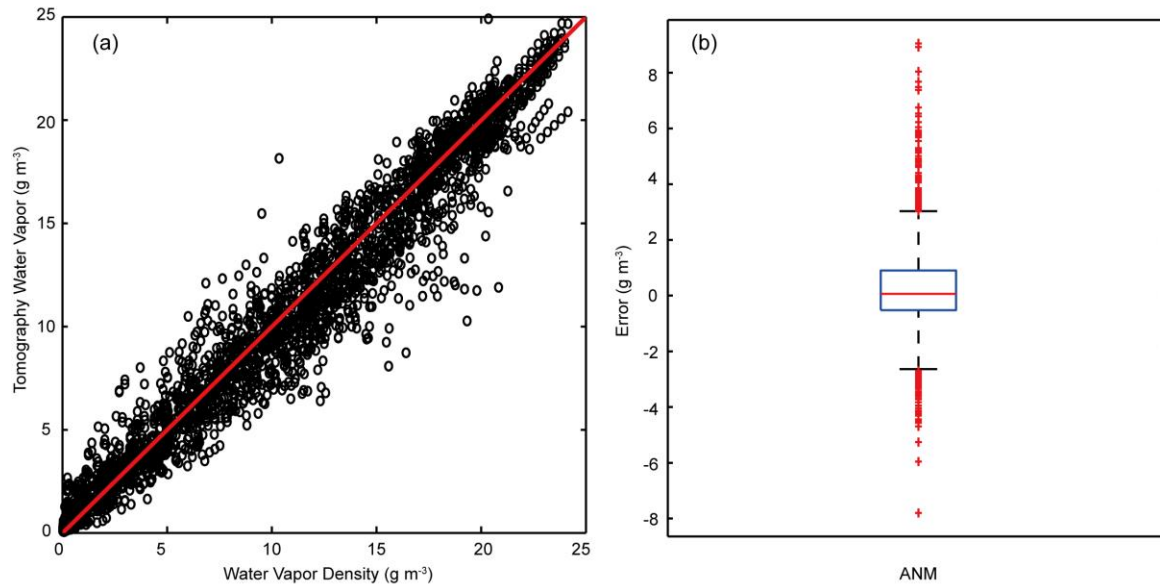


Figure 10. Graphic presentation for the distribution of the tomographic results at the two epochs on every day during the month: (a) scatter plot of water vapor density; and (b) box plot for outlier detection of the tomographic errors.

The box plot is mainly for the indication of those large errors at all sampling points. Q1 and Q3, which are the first and third quartiles respectively, determine the IQR value in Table 1; Q2, the second quartile, roughly reflects the bias of all the errors; the whiskers, i.e. the two black

bars, located at $Q1-1.5(IQR)$ and $Q3+1.5(IQR)$, are for the determination of the lower and upper bounds of the criteria for outlier detection, e.g. the red cross marks are regarded outliers. Table 2 lists all the above characteristic values of all errors (the total number of errors is 2790).

Table 2. Characteristic values of the box plots in Fig. 10(b).

Statistic	Q1 (g m^{-3})	Q2 (g m^{-3})	Q3 (g m^{-3})	Upper bound (g m^{-3})	Lower bound (g m^{-3})	Number of outliers
	-0.527	0.062	0.903	3.048	-2.672	159

3.3 Results of different layers

In the last section, the RMSE of model-derived water vapor density values at all sampling points for each profile (Fig. 8) and the errors at all the sampling points and two epochs on each day during the month (Fig. 9) are analyzed for the assessment of the overall performance of the models. In this section, the monthly RMSE at all the sampling points but in 11 different tomographic layers and the monthly mean of the relative errors in these layers are investigated, see Fig. 11.

In those layers below 1500 m, the two lines in both subfigures show the same tendency of variation with height –the error value increases with the increase of height. This is because the higher the layer, the more the spread of the GNSS signals, the worse the accuracy of the result. However, in the layers above 1500 m, the two lines show opposite tendencies of variation with height because the higher, the smaller the water vapor density. The smaller water vapor density values in these high layers lead to the small RMSE and large relative errors.

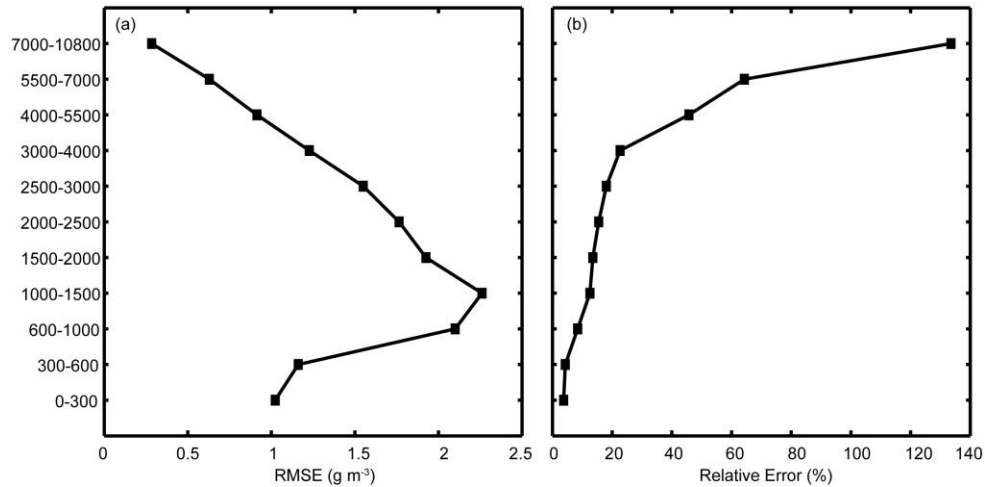


Figure 11. (a) Monthly RMSE of (absolute) tomographic errors and (b) mean of relative tomographic errors in different layers.

4 Conclusion and outlook

In this study a new node parameterization approach for determination of a tomographic field based on the distribution of GNSS signals at the tomographic epoch and also for discretization of the tomographic field is proposed. The number and the position of the nodes on each tomographic plane are determined based on the perimeter of the tomographic boundary on the plane and meshing techniques respectively. Since the tomographic model is tailor-made for the tomographic field at the epoch, the new approach is applicable to not only GNSS networks with several stations, but also GNSS networks with few stations, e.g., three stations, which cannot be solved by conventional approaches. The new approach was tested using GNSS data from three stations in the Hong Kong Satellite Positioning Reference Station Network during the period of May, 2015 and its model results were validated by comparing them against radiosonde data at UTC 0 and UTC 12 from HKKP. Results suggest that the new approach is feasible for a three-station GNSS network. In addition, monthly statistics of the tomographic results on each tomographic layer indicated that the size of the tomographic boundary and the magnitude of water vapor are two critical factors affecting the accuracy of the tomographic result of the layer.

Our future work will be focusing on using unevenly distributed nodes that fit the density of the GNSS signals.

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Data availability

GNSS data in the RINEX format used for this study can be downloaded from website (<http://www.geodetic.gov.hk/smo/gsi/programs/en/GSS/satref/satref.htm>). Radiosonde data of King's Park Meteorological Station can be downloaded from website (<http://weather.uwyo.edu/upperair/sounding.html>).

Competing interests

The authors do not have any possible conflicts of interest.

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