1.10 Retrieval of 3D wet refractivity structures of the troposphere from GPS measurements

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Abstract

A tompgraphic model is developed to retrieve the 3D refractivity structures of the troposphere from ground-based Global Positioning System (GPS) measurements. The refractivity is a function of temperature, pressure, and humidity or water vapor of the atmosphere. The retrieval is possible because a ground network of many GPS receivers that record integrated slant water along ray paths of the electromagnetic waves provide the required information. To validate the developed tomographic model, a reference state of the atmosphere is obtained by using measured temperature, pressure, and water vapor profiles observed by a multi-channel microwave radiometer. That is, the 3D wet refractivity structure is derived from the known temperature, pressure, and water vapor profiles, and hence serves as reference or “ground truth”. In this study, a 5 by 5 GPS network is simulated. Distance between any two consecutive GPS receivers is 4 km. The atmosphere is divided into 11 layers whose thickness is one km. The atmosphere of interest is hence divided into 275 (=5 by 5 by 11) cubes. The GPS signals that pass through the 275 cubes intersect all over during a certain time interval of interest, and permit the retrieval. The retrieved wet refractivity structure is very good with errors ranging between 5 and 10% below 4 to 5 km altitude compared with the ground truth. Its assimilation into numerical weather prediction models is potentially help to improve especially short-term forecasting.

1. Introduction

Signals transmitted by the Global Positioning System have been used to measure total electron density of the ionosphere (Mark and Douglas 1996), water vapor of the atmosphere or precipitable water (Rocken et al. 1993, 1995; Tregoning et al. 1998; Liou and Huang 2000; Liou et al. 2001), and crustal deformation (Yu 2002) with high accuracy. The measurements are possible because the GPS surveying is of high positioning accuracy. Nevertheless, the accuracy of vertical component in the position determination through the GPS surveying approach is limited due to the highly-spatial and -temporal variability and inhomogeneity of the water vapor. One of the best ways to reduce the impact of this limitation is to take into account and correct the effect of the water vapor in the process of position determination. That is, the 3-D distribution of the atmospheric water vapor or equivalently wet delay is needed. In this paper, a tomographic model to reconstruct the 3-D distribution of the atmospheric wet delay is presented. Its performance is examined by the measured atmospheric profiles using a multi-channel microwave radiometer.

2. Tropospheric Tomography

Tomography has been applied to reconstruct the distribution of the electron density in the troposphere (Andreeva et al.1990; Raymund et al. 1990; Austen et al. 1988). The same concept is realized to reconstruct the 3-D distribution of the atmospheric wet delay in this paper. The least square method is utilized to solve the system equations for the unknown vector (matrix) of refractivity. To develop the tropospheric tomographic model, a 5 by 5 GPS network is simulated. Distance between any two consecutive GPS receivers is 4 km as shown in Figure 1 for a view of 5 consecutive GPS receivers along a straight line. As seen, the atmosphere is divided into 11 layers whose thickness is one km. The atmosphere of interest is

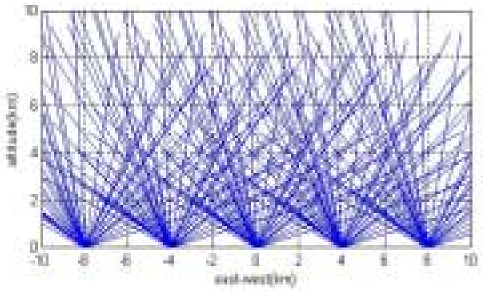

Figure 1. 2-D tomography. Horizontal axis is the position vector of the GPS receivers, and vertical axis is the altitude of the atmosphere.

hence divided into 275 (=5 by 5 by 11) cubes. The GPS signals that pass through the 275 cubes intersect all over during a certain time interval of interest, and permit the reconstruction. For easy understanding, a 2-D plot of the GPS signals transecting the cube is shown in Figure 2. This straight line can be described as:

$$\frac{x - x_0}{a} = \frac{y - y_0}{b} = \frac{z - z_0}{c} = k \quad (1)$$

where x, y, and z represent the coordinates of any point on the line; a, b, and c are the unit vectors of the line; and *k* represents an arbitrary point on the straight line. Then, any point on the straight line in the 3-D cube can be determined by three parameters p, q, and r, where

$$\text{x component: } p = \frac{x - x_0'}{x_1 - x_0'} = \frac{x_0 + ak - x_0'}{x_1 - x_0'}$$

$$\text{y component: } q = \frac{y - y_0'}{y_1 - y_0'} = \frac{y_0 + bk - y_0'}{y_1 - y_0'} \quad (2)$$

$$\text{z component: } r = \frac{z - z_0'}{z_1 - z_0'} = \frac{z_0 + ck - z_0'}{z_1 - z_0'}.$$

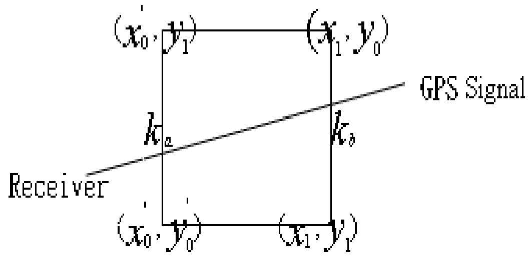

Figure 2. GPS signal transects the cube in a 2-D view.

Therefore, atmospheric wet refractivity of any point in the cube of interest can be described as a function of the wet refractivity at the eight corners of the cube as shown in Figure 3. That is,

$$\begin{aligned} N(p,q,r) = \\ \{[(1-p)\times N_{111} + p\times N_{211}](1-q) + [(1-p)\times N_{121} + p\times N_{221}]q\}\times(1-r) \\ +\{[(1-p)\times N_{112} + p\times N_{212}](1-q) + [(1-p)\times N_{122} + p\times N_{222}]q\}\times(r) \end{aligned} \quad (3)$$

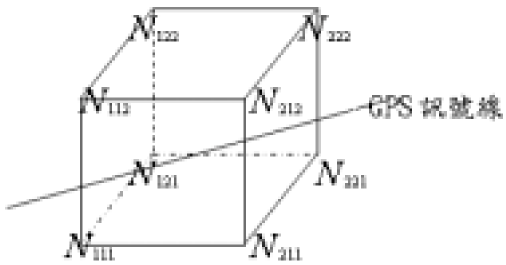

Figure 3. GPS signals transecting a cub.

3. Experimental Set-up and Tomographic Model Simulation Results

The refractivity is a function of temperature, pressure, and water vapor. The reconstruction is possible because a ground network of many GPS receivers that record integrated slant water along ray paths of the electromagnetic waves provide the required information. To validate the developed tomographic model, a reference atmosphere is obtained by using atmospheric temperature, pressure, and water vapor profiles measured by a multi-channel microwave radiometer. It then serves as reference or “ground truth”. In this study, a 5 by 5 GPS network is simulated. Distance between any two

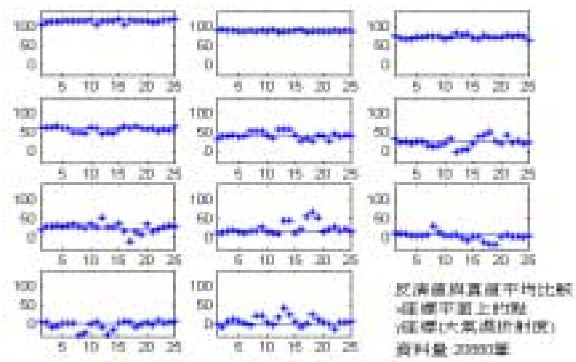

Figure 4. RMSE of the reconstructed wet refractivity structure compared with the reference for the first hour of study. The horizontal axis represents the GPS site. The straight lines are the reference atmospheric wet refractivity.

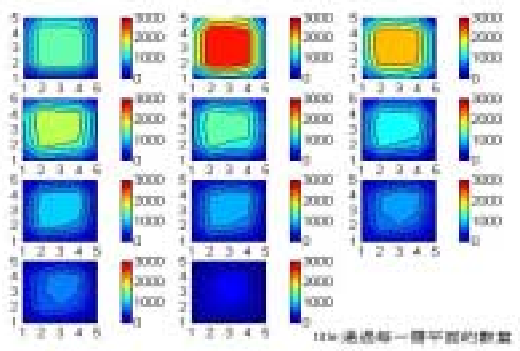

Figure 5. The numbers of the GPS signals transecting the cubes within the first hour of study.

consecutive GPS receivers is 4 km. The atmosphere is divided into 11 layers whose thickness is one km. The atmosphere of interest is hence divided into 275 (=5 by 5 by 11) cubes. The GPS signals that pass through the 275 cubes intersect all over during a certain time interval of interest, and permit the reconstruction.

To perform simulations, atmospheric profiles are simulated using the observations of a profiling microwave radiometer. The location of National Central University is considered as the center of the tomographic GPS network. Given the precision GPS orbital information, a time interval of investigation is chosen between UT 0938 and UT1537 on June 19, 2001. Then, reference of the atmospheric wet refractivity can be determined. It is assumed that the atmosphere is static within a period of one hour to collect enough slant observations for performing tomography. This is not a very good assumption since the atmosphere varies all the time. However, as a test of a new developed tomographic model, it shall be all right to do so.

Figure 4 shows the reconstructed wet refractivity structure for the first hour of study. The horizontal axis represents the GPS site. The straight lines are the reference atmospheric wet refractivity. The stars represent rmse. It is found that the results appear to be better if the GPS satellites distribute more evenly in the sky. In addition, the more the GPS signals transect the cube, the better the results as shown in Figure 5. Moreover, the results appear to be quite reasonable in the regions where water vapor is more abundant, roughly below 3-5 km. Since the majority of the water vapor exists in the lower atmosphere, it is very meaningful to advance the proposed tomographic model presented in this paper.

It is observable that the retrieved atmospheric wet refractivity appears to be less accurate with increasing height. Since the water vapor essentially becomes negligible at a height of 10 km, and since the surface meteorological conditions are typically known, two constraints are performed, namely known surface meteorological conditions and zero atmospheric wet refractivity conditions at 10 km height. By simply imposing the known surface meteorological conditions, the rmse of the retrievals at the surface essentially becomes zero. In addition, it is decreased to some degree below a height of 6 km. By adding the constraint of zero atmospheric wet refractivity conditions at 10 km height, the rmse at the levels of higher altitudes is reduced significantly especially near top of the studied volume.

4. Conclusions

The reconstructed wet refractivity structure is very good with errors ranging between 5 and 10% below 4 to 5 km altitude compared with the ground truth. The errors can be further decreased when surface meteorological measurements and an assumption of zero refractivity at a reasonable height are applied as constraints. Realization of the proposed tropospheric tomography to reconstruct the 3D wet refractivity structure of the atmosphere will be helpful to improve short-term forecasting through assimilating the atmospheric wet refractivity into numerical weather prediction models, and to advance position determination accuracy through Global Positioning System (GPS) measurements by integrating the known atmospheric wet refractivity into the position calculation.

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