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Tropospheric wet refractivity tomography using multiplicative algebraic reconstruction technique

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Abstract

Algebraic reconstruction techniques (ART) have been successfully used to reconstruct the total electron content (TEC) of the ionosphere and in recent years be tentatively used in tropospheric wet refractivity and water vapor tomography in the ground-based GNSS technology. The previous research on ART used in tropospheric water vapor tomography focused on the convergence and relaxation parameters for various algebraic reconstruction techniques and rarely discussed the impact of Gaussian constraints and initial field on the iteration results. The existing accuracy evaluation parameters calculated from slant wet delay can only evaluate the resultant precision of the voxels penetrated by slant paths and cannot evaluate that of the voxels not penetrated by any slant path. The paper proposes two new statistical parameters Bias and RMS, calculated from wet refractivity of the total voxels, to improve the deficiencies of existing evaluation parameters and then discusses the effect of the Gaussian constraints and initial field on the convergence and tomography results in multiplicative algebraic reconstruction technique (MART) to reconstruct the 4D tropospheric wet refractivity field using simulation method.

Keywords: Algebraic reconstruction techniques (ART); Wet refractivity tomography; Ground-based GNSS; Slant wet delay (SWD)

1. Introduction

Water vapor, with the feature of extremely uneven distribution and spatial and temporal variability, is an active and changeable component of atmosphere. The phase changes of water vapor, being directly related to precipitation, play an important role in atmospheric transmission, weather system evolvement, radiation budget of the climate system and global climate change (Liu et al., 2005). But the low spatial and temporal resolution of conventional detections restricts our knowledge of the spatial and temporal distribution of water vapor and its energy cycle. The lack of information on the three-dimensional structure of water vapor distribution leads to low precision of the initial humidity field of the numerical weather prediction (NWP) model and low accuracy of the NWP (Bevis et al., 1992). The GNSS technology provides a new means for detection of atmospheric water vapor. With the features

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of real-time continuity, all-weather operation and high precision, it is a strong complement to the traditional method of atmospheric observations (Bevis et al., 1992), and has become the most conventional means of water vapor detection and a part of the global atmospheric comprehensive observation system (Gutman et al., 2004).

The present situation of the ground-based GNSS in water vapor detection is as follows: (1) The precision of the precipitable water vapor (PWV) above the GNSS receivers can reach 1–2 mm (Bevis et al., 1992; Rocken et al., 1993, 1995, 1997); (2) whether the mm-level accuracy of the slant water vapor (SWV) can be achieved has been controversial (Alber et al., 2000; Braun et al., 2001; Eresmaa and Jarvinen, 2006); (3) tropospheric water vapor tomography has unstable accuracy due to weak spatial structure of SWV, needing to be further improved (Hirahara, 2000; Flores et al., 2000; Nilsson and Gradinarsky, 2006; Bender et al., 2009; Rohm and Bosy, 2009; Rohm and Bosy, 2011).

Remote Sensing of PWV using the ground-based GNSS has been mature and been successfully applied to NWP. GNSS-PWV data has earlier been used in many countries and playing a positive role in NWP. For example, the NOAA Forecast Systems Laboratory (NOAA/FSL) has made GNSS scientific application research in weather forecasting, climate monitoring and atmospheric research since 1994 (Gutman et al., 2004). The EUREF Permanent Network (EPN) data processing center has provided near real-time Zenith Total Delay (ZTD) observations for climate applications since 2005 (Dousa, 2010). A near real-time Zenith Wet Delay (ZWD) decoding network was set up in Poland in 2008 (Bosy et al., 2010). ZTD and PWV data of 270 GNSS stations has currently turned into products in Germany (Bender et al., 2011a).

The GNSS PWV product cannot provide the spatial-temporal structure for the water vapor field, which limits its thorough application in NWP. The observation data of slant wet delay (SWD) is more complete than those of ZWD, which can reflect the variation characteristics of water vapor. What is more, the 4D structure of water vapor can be achieved through the SWDs (Eresmaa and Jarvinen, 2006). But the SWDs tend to be more easily affected by noise interferences such as the receiver's instability, the satellite orbit error, the multipath effect and the antenna phase center variation, etc., so it is difficult to obtain accurate SWD and to determine the SWD covariance matrix (Eresmaa and Jarvinen, 2006). In data assimilation system, the data per se and data quality are equally important (Kuo et al., 1996; Guo et al., 2000). The poor quality of the data in the assimilation system reduces the forecasting accuracy and the uncertain quality of SWD data leads to the limitation and obstacles in its further application to the weather service. So the SWD accuracy is in constant exploration (Eresmaa and Jarvinen, 2006).

For a long time, numerical weather model (NWM) has a limited improvement in the short-term forecasting for rainstorm disasters due to lack of detailed information of the 4D structure development of water vapor field. There is a long-term need for high precision and high spatial and temporal resolution of water vapor field. Special methods are needed for the water vapor tomography using ground-based GNSS technology due to its incomplete SWDs and easily sick linear equations (Hirahara, 2000; Flores et al., 2000; Nilsson and Gradinarsky, 2006; Bender et al., 2009; Rohm and Bosy, 2009; Rohm and Bosy, 2011). The maturity of atmospheric water vapor tomography using the ground-based GNSS technology relies on the following four aspects: (1) The SWD model needs to be improved to better simulate the variation characteristics of the atmosphere, such as indroducing a higher order, the present gradient is only first order. (2) Effective SWDs need to be increased to improve the ill-conditioned system of equations. The water vapor tomography using ground-based GNSS technology is based on the signals basically in the top–bottom direction. In order to improve the vertical resolution, GNSS receivers should be laid out in layers at different height and slant-path signals at low elevation angles should be used as many as possible. Occultation observation data, if conditions are allowed, can also be used to increase the SWDs in the horizontal direction (Notarpietro et al., 2011). The method of using low-priced receivers with single frequency can help improve the horizontal resolution of water vapor field (Deng et al., 2009). In the future, the comprehensive navigation satellite system including GNSS, GLONASS, BeiDou and GALILEO may be used to enrich signal sources (Bender et al., 2011b) so as to radically improve the ill-conditioned normal equation. (3) NWM can reflect the real state of atmosphere to a certain extent, it can be used to set up real time mapping functions and vertical or horizontal constraint equations in the future water vapor tomography, which should be able to improve the tomography precision. (4) Iterative methods such as algebraic reconstruction techniques(ART) (Bender et al., 2011a; Wang and Wang, 2011; Notarpietro et al., 2011) are used to avoid the problem of ill-conditioned matrix inversion in the water vapor tomography.

2. Tomography reconstruction based on the ART family

Traditional water vapor tomography using the ground-based GNSS technology is based on the least squares method, in which there are too many SWD observations and unknown voxel values of water vapor. What is more, its normal equation is huge sparse matrix, which has data organization and inverse difficulties or uninversable problems due to rank deficiency. Later, the singular value decomposition (SVD) method is developed so that any matrix is inversable, whether there is any rank deficiency problem or not (Rohm and Bosy, 2011). But the disadvantages of the least squares method (Flores et al., 2000; Nilsson and Gradinarsky, 2006; Perler et al., 2011) include that stable water vapor field cannot be gained due to poor spatial structure of SWDs and small changes in the input data will cause the oscillation of the results.