Review of the Research Status and Progress of Ground-Based GNSS Meteorology

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Abstract: The distribution of water vapor in troposphere is very uneven and has a strong sense of temporal and spatial variation. The weather forecast requires accurate temporal and spatial information of the atmospheric humidity field. The atmospheric water vapor information collected by traditional meteorological observation methods has lower temporal-spatial resolution and higher observation cost. Using GNSS to obtain atmospheric water vapor information has great potential of high quality, high temporal and spatial resolution, low cost, all weather conditions and real-time monitoring. GNSS meteorology has an important application value for atmospheric monitoring, extreme weather forecast and regional climate research. This paper summarizes the state and progress of several respects of ground-based GNSS meteorology including GNSS atmospheric vapor tomography, GNSS-derived data water vapor assimilation and GNSS meteorological applications. The strategies and methods for GNSS tomography are summarized. And the development and application prospects of the Multi-GNSS (GPS/Beidou/Glonass/Galileo) meteorology are also discussed.

1 INTRODUCTION

The content of water vapor in the atmosphere is a key parameter affecting the accuracy of weather forecast. It is very important for the regional weather forecast, especially for the accurate nowcasting. It is also an important indicator for studying the long-term climate change. Therefore dynamic monitoring of atmospheric vapor content and real-time constructing vertical distribution of the water vapor field will play an important role in improving the accuracy of weather forecast and modeling atmosphere. The atmospheric water vapor information collected by traditional meteorological observation methods (radiosonde, radiometer) has lower temporal-spatial resolution and higher observation cost. The lack of four dimensional (4D) distribution information of water vapor affects the precision of the initial humidity field and the accuracy of the numerical weather forecast. Therefore it is a research focus in the field of meteorology currently to find effective methods for real-time acquisition of high precision atmospheric vapor content and construct a real-time monitoring system.

The propagation delay of GNSS satellite signal through the atmosphere is related to the content of water vapor in the troposphere. So the zenith tropospheric delay (ZTD) can be inversed using GNSS observations of the ground station. The ZTD is devided into hydrostatic or dry component (ZHD) and wet component (ZWD). The ZHD can be calculated accurately according to Saastamoinen model using the precise surface pressure data. Then the ZWD can be obtained by subtracting ZHD form ZTD. Finally, the ZWD can be converted to the precipitable water vapor (PWV) by a ratio value Π, which is related to the weighted mean temperature T_m (Bevis et al., 1992). So the PWV of GNSS signal transmission route can thereby be calculated. And the PWV is very important for weather forecasting and extreme weather events monitoring. Furthermore the 4D water vapor distribution can be obtained by tomography when the density of the GNSS stations available on the ground is sufficient. GNSS water vapor tomography has the potential to provide PWV fields with high temporal and spatial

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resolution. And the PWV fields can make the 4D temporal and spatial changes of water vapor understood in more detail and more favorable for monitoring and early warning storm disasters. Therefore GNSS has become a very effective tool for the study of meteorology currently (Flores et al., 2000; Manning et al., 2014; Wang et al., 2016).

In recent years, using GNSS for meteorological detection has become an important component of World Meteorological Organization (WMO) new global upper air observing system in the 21 century. The application superiority of atmospheric sounding, weather change monitoring and numerical weather forecast using GNSS observation data makes GNSS meteorology become a completely new and highly potential field.

2 RESEARCH STATUS OF GROUND-BASED GNSS METEOROLOGY

Since 1990s, people have begun to use satellite navigation theory and technology sensing the Earth's atmosphere. A new method to measure the content of atmospheric water vapor using satellite navigation signal started from the inverse problem of noise processing for signal atmospheric delay of satellite navigation, which provides new technical support for better monitoring unfavourable weather and climate change. Ground-based GPS meteorology was early proposed by Bevis M. et al. (1992) to sense atmospheric water vapor and support weather forecast (Bevis et al., 1992). The GNSS reference station network has been established in many countries in the world in recent years. There are global International GNSS Service (IGS) and national/regional tracking station network on the space scale. IGS is the most widely distributed and the largest GNSS reference network in the world. The number of global IGS tracking stations has exceeded 500 by the end of January 2017. Among them about 200 stations are multi-system GNSS continuous operation reference station (MGEX). Also some satellite ground-based augmentation systems have been built in the world in recent years, such as American StarFire with about 100 stations (Jiang, 2017). Also, HxGN SmartNet claims to be the world's largest Continuously Operating Reference Stations (CORS) network with more than 4,000 reference stations covering the majority of developed countries, which continues to provide trusted GNSS data worldwide (https://hxgnsmartnet.com/). In addition, many countries and private organizations have built their own CORS networks. According to incomplete survey, there are more than 4000, 5000, 1300 CORS stations in America, China and Japan respectively. Europe and Australia all have more than 1000 CORS stations. All these CORS stations provide very favorable conditions for GNSS ZWD/PWV estimation. However, the distribution of these CORS stations is uneven at present and many governmental agencies and private organizations still do not make GNSS CORS data available to the public. So there is a need for policies on data sharing and collaboration among the different organizations that operate GNSS stations.

As the coverage area of the ground GNSS station network is greatly increased, the algorithm for obtaining the tropospheric zenith wet delay (ZWD) has also been developed and improved. So the accurate water vapor information can be obtained with high temporal and spatial resolution. GNSS tomography is such a technique to reconstruct detailed information of water vapor over the interested area using the slant wet delay (SWD) observations. Currently, GNSS tomography atmospheric water vapor information is one of the research focus in GNSS meteorology.

To make a forecast we need to know the current state of the atmosphere conditions. The accuracy of the water vapor field in the lower atmosphere is particularly important for the forecast of extreme weather (such as storms). The emergence and evolution of many extreme weather conditions are very rapid. The sampling rate of traditional water vapor observation methods is too low so that the information of water vapor change in extreme weather can not be captured in time. While GNSS tropospheric products and tomographic data can provide a reliable source of data with high spatial and temporal resolution. Research shows that assimilating GNSS ZTD/ZWD/PWV can effectively improve the initial atmospheric humidity field and have a positive effect on strong precipitation forecast (Boniface et al., 2009; Zeng et al., 2014). The assimilation of the GNSS observations is a relatively new and very promising approach to improve the short-term forecasts. Therefore assimilation of GNSS tropospheric products and tomographic data to improve the extreme weather forecast has become another research hotspot in the field of GNSS meteorology.

In the following sections, we introduced the research status of ground-based GNSS meteorology from the following aspects: GNSS water vapor tomography, GNSS-derived water vapor data assimilation and meteorological applications of GNSS-derived water vapor.

2.1 GNSS Water Vapor Tomography

A lot of research and test work has been done on GNSS tomography 3D water vapor distribution in the past 20 years, especially in Europe and America. Bevis M. et al. (1992) presented early in 1992 that dense GPS networks could be used to sense the vertical distribution of water vapor. Since Flores A. et al. (2000) first proved the feasibility of the 4D tropospheric tomography technology using GPS slant wet delays by experiment, many researchers in the geodesy and meteorology fields have carried out the related research. Many experiments have proved that the water vapor field obtained by GNSS has good consistency with the traditional meteorological observation methods and also proved the effectiveness of the study of atmospheric state by GNSS tomography (Flores et al., 2000;Bastin et al., 2005;Song et al., 2006). The research contents on GNSS tomography mainly involve voxel division of tomographic area, tomography algorithm, optimization of tomography parameters, applications of GNSS tomography in the field of meteorology and advantages of multi-constellation GNSS tomography.

Bastin S. et al. (2005) proved the 3D water vapor field obtained by GPS tomography using numerical simulation for the first time and studied the interaction between the regional sea breeze and the topography using data sets provided by GPS tomography for the description of the water vapor variability. Song S. et al. (2006) obtained 3D structure of water vapor information over Shanghai area by GPS tomography technique using GPS slant water vapor retrieved from Shanghai GPS network and improved numerical forecasted wet field obviously. Wang W. et al. (2011) carried out GPS water vapor tomography experiments using three algebraic reconstruction techniques on Shanghai GPS network and discussed the range of relaxation factor and the initial value of iteration for the reconstruction algorithm. He L. et al. (2015) analyzed eight algebraic reconstruction algorithms and discussed various problems of GPS vapor tomography with respect to constraint condition, initial value, optimal relaxation factor and iteration termination condition.

However, due to many influencing factors (such as satellite constellation, geometric distribution of GNSS stations, voxel division), the coefficient matrix of the tomographic equation is often sparse and severely deficient, which causes GNSS tomography can not be solved directly. So there are still some problems to be solved on ground-based GNSS tomography water vapor distribution, such as solutions to the ill-posed tomography equations, reasonable density of stations, optimization of voxel division and the optimal settings of tomography parameters. In addition, the quality of the water vapor field obtained by GNSS tomography is related to many factors, such as the priori value of water vapor field, the number of slant path tropospheric delay observation, weighting scheme of observations, spatial resolution of a tomographic region and the parameter settings of tomography algorithm (e.g. the stop criteria of iterative reconstruction algorithms) (Wang and Wang, 2011a;Bender et al., 2011;Wang and Wang, 2011b;He et al., 2015;Yu et al., 2016;Xia and Ye, 2017;Yao and Zhao, 2017;Chen and Liu., 2014;Möller, 2017). Bender M. et al. (2011) found by studying Germany ground-based GNSS station network that the spatial coverage of the atmosphere by slant paths can change very fast as the GNSS satellite constellation varies and a uniform quality of the reconstructed fields can therefore not be expected. Möller G. (2017) studied the mathematics formulation of ill-conditioned, inverse problems on GNSS tomography equations. And the research showed that the GNSS tomography solutions are not only sensitive to the observation error and the change of observation geometry but also sensitive to the solution scheme and the parameter settings, which caused by the ill-conditioned GNSS tomography equations.

Table 1: Summary of strategies and methods for GNSS tomography.

Research content	Research strategies and methods			Scheme or characteristic
Optimization of voxel division of tomography	Vertical stratification	Even	Equidistant spacing	Unconsistent with actual vertical distribution of water vapor
		Uneven	Uneven spacing	Better reflect vertical variation of water vapor in troposphere
			Exponential spacing	
	Horizontal resolution	Inhomogeneous, Commonly (10-50km)×(10-50km)		According to the density of the ground GNSS stations
Solutions to tomography equations	Non-iterative reconstruction algorithm (NIRA)	Truncated singular value decomposition (TSVD)		Directly inverse; Need to determine optimal threshold for singular values and regularisation parameters
		Tikhonov regularization (TR)		
	Iterative reconstruction algorithm (IRA)	Algebraic reconstruction technique		Avoiding inversion problem; High stability and reliability; Need to determine relaxation factor and stop criteria
		Multiplicative algebraic reconstruction technique (MART)		
	Combined reconstruction algorithm	NIRA+IRA		Solutions obtained by TSVD or TR are used as initial value of IRA, which can provide high quality initial value for IRA.
	Classical constrained solution	Horizontal constraints	Horizontal smoothing	Directly inverse; Adding constraints; Inappropriate constraints may debase the accuracy of results.
			Gauss weighted function	
		Vertical constraints	Decrement based on exponential function	
			Radiosonde observation	

Most of the aforementioned research mainly aim to improve the precision and reliability of GNSS tomography solutions. Table 1 gives the summary of different approaches. GNSS tomography has the potential of providing 4D water vapor field with near real-time and high temporal-spatial resolution, which can be used for numerical weather forecast, extreme weather event monitoring and climatology research. Despite with more than 10 years of development, GNSS tomography atmospheric water vapor technology still faces many challenges. There are many factors affecting GNSS tomography results. For example, the slant path delay can provide local changes related to atmospheric information and is considered to be a promising value of meteorological observation, but the precision of slant path water vapor in the region at low altitude is still low (Wang et al., 2016; Möller, 2017). So the accurate estimation of the slant path water vapor needs further study. The weighted mean temperature T_m is an important parameter for calculating the atmospheric water vapor. A detailed study of precise determination of T_m needs further development. Moreover, there exists the problem of precision instability of GNSS tomography results.

With the significant progress of BeiDou and Galileo systems, as well as updating Glonass, the integrated multi-GNSS may improve water vapor tomography (Bender et al., 2010;Wang et al., 2014;Zhao et al., 2018;Dong and Jin, 2018). Bender M. et al (2010) estimated the impact of GPS, Galileo and GLONASS data on the GNSS tomography by simulation which showed that the spatial coverage of the atmosphere with slant paths is highly improved by combining observations from two or three satellite systems. But observations in the lower part of the atmosphere, e. g, below 3 km, are still rather sparse. Zhao Q. et al (2018) used multi-GNSS

(GPS, GLONASS and BDS) data to validate the tomographic results derived from various multi-GNSS combined strategies and compared with radiosonde data. Tomography experiments showed that multi-GNSS observations can increase the accuracy of 3D wet refractivity reconstruction but not as well as was expected when using currently available techniques. Dong Z. et al (2018) obtained 3D water vapor tomography results using multi-GNSS data from Wuhan CORS and the reliability of tomographic water vapor density reconstructed by combining multi-GNSS is significantly enhanced when compared to the GPS-only system.

Above mentioned study shows that the number of satellite rays used has been almost doubled or tripled when multi-GNSS observations were used in the tomographic model, but the percentage of empty voxels did not decreased as much as was expected. The possible reason was that the spatial resolution of the tomographic model was not improved as was expected, which can be addressed by increasing the spatial density of ground-based GNSS stations. In summary, GNSS water vapor tomography technology is still in the process of research. In fact, the water vapor in the atmosphere of 4D variation characteristics are very complex. And there is a lack of analysis of the fine 4D structure of the atmosphere on the medium and small scale in operational applications. Therefore more research is needed to improve the accuracy and reliability of GNSS tomography solution.

2.2 GNSS-Derived Water Vapor Data Assimilation

The data assimilation technique is a vital part of numerical weather forecasting. Europe and the United States have began research in the related fields of data assimilation of GNSS tropospheric products since 2000 (Bennitt and Jupp, 2012). During the 2000-2001 years, some European Research Group successfully implemented and confirmed the concept of ground-based GNSS meteorology. In the following European Union project (E-GVAP, 2005-2017, http://egvap.dmi.dk), the fifteen European countries participated in the campaign of the European GPS meteorology and began to be used in actual production. Currently, near real-time tropospheric products provided through E-GVAP have been used in the assimilation of many numerical weather prediction (NWP) models. Now GNSS receiver network with real-time retrieval of PWV has been running in Europe and the United States and successfully applied to weather forecast, such as American GPS/MET and European E-GVAP.

The study of GNSS meteorology for the last 20 years showed that assimilation of GNSS precipitable water can effectively improve the quality of the initial atmospheric humidity and has a positive effect on improving the performance of strong nowcasting precipitation forecast (Bennitt and Jupp, 2012;Mahfoufet al., 2015;Lindskog et al., 2017;Zhong et al., 2017;Guerova et al., 2016). The research contents on GNSS data assimilation mainly involve improvement of the initial conditions for NWP using GNSS-PWVs, assimilation algorithm, assimilation impacts of ZTD/ZWD/SWD/PWV and wet refractivity data obtained by GNSS tomography using various schemes. In the current study, a 3-dimensional variational data assimilation (3D-Var) scheme was mainly used for data assimilation. The European Centre for Medium-Range Weather Forecasts (ECMWF) has pioneered work on assimilation methods such as 4D-Var (Zhong et al., 2017) And many questions on the ground-based GNSS data assimilation need further study, such as the methods to effectively assimilate the PWVs into the NWP model, estimation of observation error, adjustment of the initial field, determination of the background error, selection of assimilation algorithm and analysis of the impact of the GNSS data assimilation on NWP models. There are still many unresolved problems related to the GNSS data assimilation. Therefore there's a lot of space for research on how to effectively assimilate GNSS tropospheric products and tomography data into the operational system of the numerical weather forecast.

The research on GNSS meteorology in recent years was mainly on retrieving high temporal and spatial PWV and analyzing relationship between water vapor and precipitation events (Guerova et al., 2016;Lu et al., 2016;Yu et al., 2017;Zheng et al., 2018). While the work on data assimilation algorithm of GNSS tropospheric products is relatively few. Also little has been done in the past to use GNSS reprocessed troposphere products for data assimilation in climate models. This field of research has however seen starting some recent initiatives. The European Reanalysis project, in which the U.K. Met Office take part, will be used to promote the data assimilation of ZTDs/PWVs in climate re-analysis. Recently, the European Union Commission carried out a new research project

“GNSS4SWEC” running from 2013 to 2017. The research fields of the project include GNSS advanced processing techniques, GNSS for severe weather monitoring and GNSS for climate monitoring (http://gnss4swec.knmi.nl).

It has become a new hotspot of GNSS meteorology research to assimilate GNSS tomography results improving the initial field of the numerical weather forecast model and the quality of nowcasting. The new generation of high resolution weather prediction model requires high resolution input data and observation data. With the improvement of the resolution of weather forecast model, it becomes more and more important to initialize of the mesoscale atmospheric phenomena using high spatial and temporal resolution observations. Therefore GNSS data assimilation is a very promising approach to improve the quality of the short-term weather forecast, especially for extreme weather events, such as heavy rainfall.

2.3 Meteorological Applications of Gnss-Derived Water Vapor

Meteorological applications of GNSS-derived water vapor mainly involves the following aspects: disaster monitoring, weather forecasting and climate monitoring. High precise and high temporal-spatial resolution PWV data is the important information for disaster monitoring (such as torrential rain, thunderstorm, typhoon, dense fog). A lot of research has been done on the nowcasting of disastrous weather using GPS-PWV (Poli et al., 2008;Manning et al., 2012;Yao et al., 2017;Liang et al., 2015;Choy et al., 2013). Poli P. et al. (2008) discuss the effect of GNSS-derived data on NWP by using European ground-based GNSS-ZTD data introduced into the Météo-France global forecasting system. They reported that the benefits of including such data were most apparent in improved predictions of temperature and wind, and especially, in superior quantitative precipitation forecasts over France. Boniface K. et al. (2009) evaluated the impacts of assimilating GPS data on the precipitation forecast on Mediterranean heavy rainfall forecasting. Manning T. et al. (2012) presented a case study based on the analysis of an extreme convective super cellstorm in the Victorian region during March 2010 using GPS tomography and CORS network in Australia. The study concluded that GPS tomographic wet refractivity profiles showed an excessive increase as a response to supercell thunderstorm formation.

A number of experimental analysis on GNSS-PWV data for nowcasting of disastrous weather shows that the ground-based GNSS-PWV has the same accuracy as radiosonde and radiometer and high temporal-spatial GNSS-PWV data plays a significant role in monitoring severe weather. Assimilating PWV data can improve the initial humidity field of NWP mode and improve the accuracy of the numerical weather forecast. Moreover, GNSS is not only used to sense the precipitation but also to detect the wind and clouds.

Climate is defined as the average weather conditions at a place usually over a period of years as exhibited by temperature, air pressure, humidity, precipitation, winds, sunshine and clouds. So GNSS is also a promising climate monitoring tool capable of providing accurate, long-term, and consistent data for climate studies. The applications of GNSS-derived water vapor in climate monitoring need further studies.

3 DEVELOPMENT AND APPLICATION PROSPECTS

At present, GNSS is mainly used for tropospheric water vapor monitoring and weather forecast. Actually, GNSS meteorology also have better prospects for development and application. With the ground-based GNSS observing networks continuously densified, GNSS will be an important technical means for monitoring the total and vertical distribution of atmospheric water vapor along with upper wind measurement and climate change monitoring. GNSS will play a more important role in medium and small scale weather analysis, numerical weather forecast, disastrous weather service and global climate change monitoring. In addition, GNSS data supporting meteorological applications mainly use GPS single constellation system and observations of GPS ground reference station currently. With the development and integration of multi-constellation GNSS (GPS/Beidou/Glonass/Galileo) system, the number of GNSS observations will be greatly increased. Moreover, with the rapid growth of the number of GNSS reference stations, the rapid development of mobile surveying system integrated with GNSS/inertial navigation carried by vehicle, ship-borne and unmanned aerial vehicles, the available

GNSS observations will further increase, which will also promote the development of GNSS meteorology. Fostered by these developments, advanced processing strategies are necessary to exploit the full potential of future GNSS systems for describing the physical state of the low atmosphere. Other potential applications like estimating cloud-base height should also be explored. So there has great research potential in the fields of ground-based GNSS meteorology.

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