REMOTE SENSING OF WATER VAPOR CONTENT USING GROUND-BASED GPS DATA

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ABSTRACT Spatial and temporal resolution of water vapor content is useful in improving the accuracy of short-term weather prediction. Dense and continuously tracking regional GPS arrays will play an important role in remote sensing atmospheric water vapor content. In this study, a piecewise linear solution method was proposed to estimate the precipitable water vapor (PWV) content from ground-based GPS observations in Hong Kong. To evaluate the solution accuracy of the water vapor content sensed by GPS, the upper air sounding data (radiosonde) that are collected locally was used to calculate the precipitable water vapor during the same period. One-month results of PWV from both ground-based GPS sensing technique and radiosonde method are in agreement within 1~2 mm. This encouraging result will motivate the GPS meteorology application based on the establishment of a dense GPS array in Hong Kong.

1 Introduction

The troposphere is an area in which the complex meteorological phenomenon formed and produced. It also causes a delay to radio signal when radio signal propagates across this layer. This delay is an important error source in the space geodetic observation. To interpret the meteorological procedure or remove the influence to the radio signal induces the commencement of GPS meteorology.

The troposphere consists of a multitude of substances. Many components, such as oxygen and nitrogen, are regular distribution and movement in the troposphere. It is easy to describe their physical characters and interpret their variations. But water vapor content, less than 5% in the air, is quite difficult to be described and obtained precisely due to the rapid change and irregularly spatial and temporal distribution. These unique characters not only increase the difficulty of qualitative explanation and quantitative analysis in research, but also causes uncertainties in applications, such as weather prediction, space geodetic observations, etc. This reason also leads to the development of GPS meteorology.

One of the research objectives of GPS meteorology is to remotely sense the water vapor content in troposphere. Since the concept of GPS meteorology was firstly proposed by Bevis in 1992, a lot of institutes in U.S.A, Europe, Japan, etc. had been involving in the activity of ground-based GPS meteorology. This research activity was also started in China. In the past 8 years, various encouraging results had been demonstrated by some researchers through the ground-based GPS meteorology technique.

Establishment of a dense GPS array in the coming years in Hong Kong is under consideration for multi-purpose applications including GPS meteorology. This study is taken as an investigation of possibility for the GPS meteorology application. In this paper,
the conversion between wet zenith delay (WZD) and PWV is given at first, and then a piecewise linear function is proposed to estimate the PWV from ground-based GPS observations. In the end, the difference of the PWV from GPS and Radiosonde is investigated on the basis of one-month observations in Hong Kong.

2 Relationship between WZD and PWV

GPS radio signal suffers a delay caused by water vapor when it passes through the troposphere from GPS satellite to ground receiver. The delay is always regarded as a noise in space geodetic observation, but it is related to the amount of water vapor in the path of propagation in modern meteorology. The amount of water vapor content in the troposphere is often expressed by the terminology as precipitable water vapor, which is defined as the height of liquid water that would result from condensing all the water vapor in a column from the surface to the top of the atmosphere. The conversion of PWV and WZD can be written as

\[ \text{PWV} = F \cdot \text{WZD} \]  

where \( F \) is given by

\[ F = \frac{10^6}{d \cdot R_v \cdot \left( k_3/T_m + k_2 \right)} \]  

and

\[ T_m = \left( \frac{\int e}{T} \, dz \right) / \left( \frac{\int e}{T^2} \, dz \right) \]

where \( d \) is the density of liquid water; \( R_v \) is the specific gas constant for water vapor; \( k_3 \) and \( k_2 \) are physical constants and \( T_m \) is a weighted mean temperature of the troposphere; \( e \) is the partial pressure of water vapor; and \( T \) is the absolute temperature in Kelvin in the zenith direction.

3 Estimation of PWV

3.1 A piecewise linear function

The variation of water vapor content is irregular in a long span of time, such as 24 hours. Actually, the precipitable water vapor is small and its variation can be simply considered as linear change in a very short period of time, such as 30 minutes. In this study, a piecewise linear function is used to simulate the variation of precipitable water vapor for one-day session.

\[ M \text{ and } N \text{ denote two sequential nodes. The corresponding PWV are } X_M \text{ and } X_N. \text{ Thus, the PWV at time } t \text{ between } M \text{ and } N \text{ can be calculated by} \]

\[ X_t = \frac{(X_M(N - t) + X_N(t - M))(N - M)}{N - M} \]

The selection of node number depends on weather condition in one-day session. The duration of two sequential nodes can range from a few minutes to 30 minutes in severe weather conditions, but more than 2 hours in normal weather condition.

3.2 Observation equation of PWV

The maximum wet zenith delay is about 50 cm, and the equivalent PWV is about 80 mm. Therefore, the observation of GPS carrier phase must be used for the estimation of PWV. The carrier phase observation can be written as

\[ \varphi(t) = \left( \frac{f}{c} \right) (P - d_{\text{ion}} + d_{\text{trop}}) + f(B - T) - N \]  

where \( f \) is the frequency of GPS signal; \( c \) is the velocity of light; \( P \) denotes the geometric range from GPS satellite to ground receiver; \( d_{\text{ion}} \) and \( d_{\text{trop}} \) represent the ionospheric delay and tropospheric delay; \( B \) and \( T \) are the clock offsets of receiver and satellite; and \( N \) is the ambiguity resolution.

The tropospheric delay can be expressed as

\[ d_{\text{trop}} = W_{\text{t}} + D_z \]

where \( W_z \) and \( D_z \) are the wet zenith delay and dry zenith delay; \( m_w \) and \( m_d \) are their mapping functions which are the functions of elevation angle.

Substituting Eqs. (1) and (5) into Eq. (4) yields

\[ \varphi(t) = \left( \frac{f}{c} \right) (P - d_{\text{ion}} + F m_w X_{\text{PWV}} + m_d D_z) + f(B - T) - N \]  

This is the observation equation of the PWV. In this equation, the \( D_z \) can be calculated through an empirical formula. The ionospheric delay and clock offset terms can be eliminated after ionosphere-free double-difference combination. Thus, it is easy to estimate the PWV values in all nodes by the least-square technique.

3.3 Interpolation of the ground temperature and pressure

For the determination of dry zenith delay there is
need to use the ground temperature and pressure in a way of an empirical model, such as Saastamoinen model, Hopfield model and Black model. However, there are not the ground meteorological measurements in the IGS stations or regional GPS stations. Therefore, the meteorological values are necessarily interpolated using the records of the surrounding weather sites. A simple average method weighted with distance is adopted as

\[ y = \frac{s}{\sum s} \left( \frac{1}{s} \sum x \right) \tag{7} \]

where \( s \) denotes the distance from weather site to GPS station, and \( x \) means the meteorological measurements, such as temperature, pressure and relative humidity. \( y \) is the corresponding interpolated result.

The pressure measurement is a function of the station height. In order to analyze and compare the pressure over the world, World Meteorology Organization recommends that all station pressure observations should be mapped onto the mean sea level. Therefore, the pressure from Eq. (7) should be projected onto the station level after interpolation.

4 PWV from radiosonde

Thousands of radiosonde stations are serving in the field of weather prediction, and the radiosonde data is always used as a reference to assess the accuracy of GPS-based PWV. The radiosonde-derived PWV is well known in the accuracy of 1–2 mm. The PWV along the path of the sounding balloon can be calculated by

\[ X_{\text{PWV}} = \frac{1}{\rho} \sum (h_{j+1} - h_j) \cdot (\rho_{j+1} + \rho_j)/2 \tag{8} \]

where \( \rho \) is the density of water vapor; \( d \) is the density of liquid water. According to the gas state equation, the water vapor density \( \rho_v \) can be calculated by

\[ \rho_v = \frac{e}{R_v \cdot T} \tag{9} \]

where \( R_v = 461.495 \) is the specific gas constant for water vapor; \( e \) and \( T \) are water vapor pressure and the absolute temperature.

The observation profiles from radiosonde are discrete measurement series of temperature and relative humidity at difference height. Taking the \( e \) and \( T \) at all height levels into Eq. (9), it is easy to obtain the corresponding water vapor density. According to the profile of water vapor density, Eq. (8) can be approximated by as follows.

\[ X_{\text{PWV}} = \frac{1}{\rho} \sum (h_{j+1} - h_j) \cdot (\rho_{j+1} + \rho_j)/2 \tag{10} \]

In the above expression, \( h_{j+1} \) and \( h_j \) denote the height of each and the next discrete layer; \( \rho_{j+1} \) and \( \rho_j \) are the corresponding water vapor density.

5 Experimental results

5.1 Observation data

Hong Kong DGPS (HK DGPS) station and 5 IGS permanent stations were selected to estimate the PWV values in this experiment. GPS observation data started on Feb. 9, 1997 and ended on March 11, 1997. The IGS precise orbits are used in this data processing.

The radiosonde data and ground meteorological data were from Hong Kong Observatory. There are no surface meteorological records in Hong Kong DGPS station, thus three surrounding meteorological stations were selected to interpolate the ground temperature and pressure on the HK DGPS station. Table 1 gives their positions.

5.2 Dry zenith delay

Dry zenith delay can be precisely modeled by an empirical method using the surface meteorological measurements. Fig. 1 shows the interpolation pressure via Eq. (7) on Hong Kong DGPS station, and the corresponding dry zenith delay by Saastamoinen model is plotted in Fig. 2. The daily variation of pressure is the same as dry zenith delay. This manifests that dry zenith delay is dominated by the ground pressure.

The accuracy of dry zenith delay is affected by both model precision and the pressure error. It is well known that the precision of Saastamoinen model is better than a few millimeters. This kind of mode error is not considered in the current condition. Hong Kong is a small territory, and the difference of mean sea level pressure is less than 1 mbar among the above three meteorological stations. The interpolating error of Eq. (7) is less than 0.1 mbar for pressure, the corresponding dry zenith delay is
smaller than 1 mm. Therefore, the size error is neglected in the calculation.

| Station name          | Latitude/° (") | Longitude/° (") | Elevation /m | Distance to HK DGPS /km |
|-----------------------|----------------|-----------------|--------------|-------------------------|
| Hong Kong Observatory | 22 18 13       | 114 10 19       | 31.8         | 10.25                   |
| Cheung Chau           | 22 12 04       | 114 01 36       | 71.9         | 10.54                   |
| Ta Kwu Ling           | 22 31 50       | 114 09 13       | 12.0         | 28.35                   |
| King’s Park           | 22 18 47       | 114 10 14       | 64.8         | 10.42                   |

Fig. 1 The pressure variation on HK DGPS station

Fig. 2 The variation of dry zenith delay

Fig. 3 The variation of wet zenith delay

Fig. 4 The PWV from ground-based GPS technique

5.3 Result analysis of GPS-derived PWV

The accuracy of radiosonde-derived PWV is determined by the observation error of relative humidity profile. Some results demonstrate that the measurement error is less than 3.5%, and the equivalent PWV error is smaller than 1 mm. Therefore, the radiosonde-based PWV is regarded as enough accurate in this study.

Fig. 4 shows the variation of GPS-derived PWV. Their uncertainty in Fig. 5 demonstrates that the accuracy of GPS-derived PWV ranges from 0.5 mm to 1 mm. In this period, the maximum PWV is 35 mm, the minimum 13 mm and the average is 25 mm. The radiosonde balloon is launched at 8:00 a.m. and 8:00 p.m. every day. Only two PWV values are obtained from radiosonde per day. In order to compare the consistency of GPS-derived PWV and radiosonde-based PWV, their differences are showed in Fig. 6. In this period, two techniques are in good agreement. The maximum difference is 2.5 mm, and the minimum is -2.5 mm. One-month average is 0.1 mm and more than 85% results distribute from -2 to 2 mm. These results demonstrate the ability of remote sensing PWV by ground-based GPS technique. Therefore, the ground-based GPS station can be taken as an efficient approach to dense the radiosonde station spatially and temporally.

The model error of dry zenith delay is neglected in this study. The mapping scale factor F is calculated from the radiosonde data. How to calibrate the model error of dry zenith delay and calculate F...
through ground meteorological observation will be discussed in the future.

A dense multi-functions GPS array will be gradually built in a few years in Hong Kong. According to the result from this paper, these GPS stations are capable of being used in remotely sensing the amount of water vapor content in Hong Kong region. After the densification by these GPS arrays, highly frequent and highly dense water vapor content all over Hong Kong as well as its vicinity will be provided for the weather prediction and severe weather monitoring. Such water vapor distribution information will largely improve the short-term (< 24h) weather forecast.

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