Principle, Application and Development of the Ground-Based GPS Meteorology

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Abstract: Ground-based GPS receivers at fixed locations can gather data that can be used to get the zenith total delay to sense integrated Precipitable Water Vapor (PWV).It is known as ground-based GPS meteorology .This paper shows the principle of remote sensing of precipitable water vapor (PWV) using ground-based GPS particularly. And it discusses different models and methods in common use which include how to calculate the zenith total delay, the influence of using models of zenith hydrostatic delay, and the mean temperatures formula fitting different regions. The developments and the situations in recent years of ground-based GPS meteorology in home and abroad are introduced. The application is showed too.

Keywords: ground-based GPS meteorology; precipitable water vapor; models of zenith hydrostatic delay; mean temperature

1 Introduction

As atmospheric water vapor plays a crucial role in weather and climate modeling and prediction, knowing its distribution in space and in time is important to a better understanding of weather and climate change. From the year when GPS/MET techniques have first been developed by Bevis et al. (1992) to recent years, ground-based GPS meteorology is becoming a new important and powerful mean in researches on atmospheric sounding, weather forecasting and climatic change, as well as on operational applications. Ground-based GPS meteorology uses receivers at fixed locations to gather data that can be used to sense atmospheric water vapor. It has many advantages such as real-time, continuity, high accuracy, low cost and all-weather [1]. The principle, application and development will be showed to get a better view of the ground-based GPS meteorology.

2 Principle of Ground-based GPS Meteorology

When transmitting, GPS signals are slowed and bended by the ionosphere and troposphere. The ionospheric delays are dispersive (frequency dependent) and can be determined with millimeter accuracy by observing both of the frequencies transmitted using a dual-band GPS receiver [2]. For the delay caused by the troposphere, no dispersion effects are present and elimination is not possible from single station observations.

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2.1 Troposheric delay

The difference in the geometrical distance and the actual ray path caused by the troposphere is:

$$\Delta L = \int_L n(s)ds - R = \int_L (n(s)-1)ds - (L-R) \tag{1}$$

ΔL is slant total path delay from receiver antenna to satellites. $n(s)$ is refractive index of atmosphere. ds is differential increment in distance with respect to the line of sight. L is ray path passing from antenna in direction to satellite through the atmosphere. R is geometrical distance, virtual path of a ray passing from antenna in direction to satellite through vacuum. The first part in the equation (1) $\int (n(s)-1)ds$ is due to signal slowdown, the second part in the equation (1) $(L-R)$ is due to bending caused by atmospheric refraction, and is not too problematic as it is very little when the elevation higher than $20°$ [3].so we can rewrite slant total path delay as:

$$STD = \Delta L = \int_L (n(s)-1)ds = ZTDm(\varepsilon) \tag{2}$$

STD is slant total delay, is also the tropospheric delay, equivalent to ΔL .Commonly, the slant total delay is expressed as the product of zenith total delay ZTD and mapping function $m(\varepsilon)$ that is relative with elevation ε .Zenith total delay ZTD can be separated into a hydrostatic and a wet component The hydrostatic delay is primarily caused by dry gases and water vapor is responsible for the wet delay.

$$ZTD = ZHD + ZWD \qquad (3)$$

ZHD is hydrostatic zenith path delay. ZWD is non-hydrostatic or wet zenith path delay. The precipitable water vapor (PWV) can be obtained from ZWD. ZHD can be modeled with high accuracy. ZTD minus ZHD is ZWD. The method to estimate the zenith total delay ZTD will be discussed in the third part. We now pay attention to how calculate PWV from ZWD.

2.2 Estimation of precipitable water vapor

$n(s)$ is refractive index of atmosphere. As $n(s)$ is very close to 1, for convenience, atmospheric refraction is defined as $N = [n(s)-1]\times 10^6$. Zenith total delay can be expressed as:

$$ZTD = \int_{h_s}^{\infty} N \times 10^{-6} dh \qquad (4)$$

h_s is surface height. dh is differential increment in height. N is relative with the atmospheric temperature, pressure and humidity:

$$N = k_1 \cdot \frac{p_d}{T} \cdot z_d^{-1} + k_2 \cdot \frac{e}{T} \cdot z_w^{-1} + k_3 \cdot \frac{e}{T^2} \cdot z_w^{-1} \qquad (5)$$

$k_{1...3}$ is refraction constants. $z_{d/w}^{-1}$ is inverse compressibility factors for dry and wet air. p_d is dry pressure, $p_d = p - e$ with p being the total pressure (measured quantity). e is partial water vapor pressure. As Bevis discussed, the refraction constants are: $k_1 = 77.60 \pm 0.09$, $k_3 = 69.4 \pm 2.2$, $k_3 = 370100 \pm 1200$,their unit is k/hpa [4].More, $z_{d/w}^{-1}$ are very close to 1. Here $p_d = \rho_d R_d T$, $e = \rho_w R_w T$, $\rho_{d/w}$ are density of dry and wet gas, $R_{d/w}$ are gas constant for dry gas and wet gas. $k_2' = k_2 - k_1 \cdot \frac{R_d}{R_w}$ .Now N is:

$$N = N_d + N_W = k_1 R_d \rho_d + (k_2' + \frac{k_3}{T}) \cdot \frac{e}{T} \qquad (6)$$

From equation (4), (5), (6) we get:

$$\begin{aligned} ZTD &= \int_{h_s}^{\infty} (N_d + N_w) \times 10^{-6} dh \\ &= \int_{h_s}^{\infty} k_1 R_d \rho dh + \int_{h_s}^{\infty} ((k_2' + \frac{k_3}{T}) \cdot \frac{e}{T}) dh \\ &= ZHD + ZWD \end{aligned} \qquad (7)$$

Zenith hydrostatic delay $ZHD = 10^{-6} \int_{h_s}^{\infty} N_d dh$ can be modeled. Saastamoinen hydrostatic delay model is used commonly. Assuming hydrostatic equilibrium and ideal gas, Elgered give $ZHD = [(2.2779 \pm 0.0024)] \cdot \frac{P_0}{f(\lambda, h)}$ [5]. The unit of ZHD is mm. p_o is surface pressure, $f(\lambda, h) = (1 - 0.00266\cos(2\lambda) - 0.00028h)$, λ is latitude, h is altitude.

As discussed before, ZWD can be got from $ZWD = ZTD - ZHD$ .Another way:

$$\begin{aligned} ZWD &= 10^{-6} \int_{h_s}^{\infty} N_w dh \\ &= 10^{-6} \int_{h_s}^{\infty} ((k_2' + \frac{k_3}{T}) \cdot \frac{e}{T}) dh \\ &= 10^{-6} P_w [R_v (k_2' + \frac{k_3}{T_m})] \end{aligned} \qquad (8)$$

$R_v = 461.495 J/(kg \cdot K)$ is the specific gas constant for water vapor. P_w is the precipitable water vapor PWV. T_m is mean temperature.

$$T_m = \int_{h_s}^{\infty} \frac{e}{T^2} dh \Big/ \int_{h_s}^{\infty} \frac{e}{T} dh \qquad (9)$$

Mean temperature can be estimated as a function of surface temperature T_s : $T_m = a + b \cdot T_s$. Bevis et al.(1992) give the experience coefficient: $a = 70.2, b = 0.72$ [4].We compute $\prod$ as a function of mean temperature according to the equation: $\prod = 10^6 [R_v (k_2' + \frac{k_3}{T_m})]^{-1}$ .Then we can get PWV:

$$P_w = \prod \cdot ZWD \qquad (10)$$

3 The main factors affect the quality of GPS sensing PWV

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This part we discuss the main factors affect the quality of GPS sensing PWV. There are three points: computing the zenith total delay, the influence of using models of zenith hydrostatic delay, and the mean temperatures formula fitting different regions.

3.1 Computing ZTD

To accurately get PWV in the atmosphere using GPS, propagation delays must be separated from all the error and delays. The key question is to estimate the zenith delay. There two commonly used method to estimate the zenith total delay: One is the least squares estimate, in each given time interval, each station to determine an atmospheric delay parameter. ZTD is assumed as a constant. Another method is the using Kalman filtering, dealing with ZTD as a random process. Some of the well-known international high-precision processing software, such as GAMIT, BERNESE, GIPSY, GAS, almost all of them, can estimate tropospheric delay[6]. Choosing good data processing method and software have a great influence on GPS measurements. GAMIT and BERNESE have greatly many users in this field.

3.2 The hydrostatic model

Calculating the hydrostatic delay is another factor to affect the quality. There are some methods to calculate the hydrostatic delay: one is integrating value of hydrostatic refraction document in the numerical weather model or the value of sonar system, other one is estimating hydrostatic delay using hydrostatic models and widely used. In practical application, empirical models are used to calculate zenith hydrostatic delay. Saastamoinen, Hopfield and Black model are used frequently.

Saastamoinen hydrostatic delay model:

$$ZHD = [(2.2779 \pm 0.0024)] \cdot {p_0}/{f(\lambda, h)} \qquad (11)$$

ZHD is the zenith hydrostatic delay and unit is mm. p_o is surface pressure.

$$f(\lambda, h) = (1 - 0.00266\cos(2\lambda) - 0.00028h) \qquad (12)$$

λ is latitude, h is altitude[7]. Elgered et al. proved that model has high accuracy. No temperature measurements are needed in contrast to Hydrostatic Delay model. And it becomes very popular.

Hopfield hydrostatic delay model:

$$ZHD = 77.6 \times 10^{-6} \cdot {P_0}/{5T_s} \cdot (h_d - h_s) \qquad (13)$$

Here $h_d = 40136 + 148.72(T_s - 273.16)$. h_d is effective height of the dry atmosphere above the surface. h_s is altitude of the station. T_s is surface temperature [8]. A number of approximations lead to this simple equation. The Hopfield model needs knowledge of surface temperature and pressure. Its accuracy is not very good.

Black hydrostatic delay model [9]:

$$ZHD = 0.002312(T_s - 3.96)\, {P_0}/{T_s} \qquad (14)$$

Black Model can be computed only with surface pressure and temperature. Saastamoinen and Hopfield model need the knowledge of weather factor and station coordinate. Some French scientists (2003) compared the Saastamoinen and Hopfield model. The Hopfield model only shows a very small standard deviation of 0.2 mm with respect to the Saastamoinen reference model, the RMS values show a systematic trend with increasing latitude[3]. Qu jianguang (2005) concluded that Saastamoinen ,Hopfield and Black models have differences relative with the location of stations[6].

3.3 The mean temperature

We can see the accuracy of PWV also depends on the mean temperature. The most accurate way to obtain the mean temperature is the using equation (9) with help of numerical weather models or radiosonde. It has been shown that T_m is highly correlated with the surface temperature T_s .Bevis et al. proposed a linear relation using statistical methods: $T_m = 70.2 + 0.72T_s$, which was derived from radiosonde data at USA. This linear relation estimates the mean temperature of the atmosphere with an error of about 2% and accuracy of 4.74k [10]. It is commonly used. Because of regional differences, the equation has systematic errors in other places.

Many scientists proposed the linear relation for region. Solbrig (2000) analyzed datasets derived from numerical weather models for the region of Germany, $T_m = 54.7 + 0.77T_s$ Mendes et al. (2000) gave a linear relation: $T_m = 50.4 + 0.789T_s$ [11].Li Jianguo et al. (1999) proposed the linear regression equation in eastern region of China: $T_m = 44.50 + 0.81T_s$,its standard deviation is 3.12k[12]

4 Development and situation

In 1992, American Bevis et al. first developed the principle of sensing water vapor using GPS. Later, in 1993~1997, a series of experiments were done in America and proved that atmospheric water vapor can be estimated using the GPS receiver stations continued with the accuracy 1~2mm[2]. GPS/STORM(1993) and GPS-WISP were significant experiments. In 1998, GPS/MET experiment was carried out for combined application of ground-based and space-based GPS to sense atmospheric water vapor. In recent years, American GPS water vapor observation network is established and begun the development of business applications.

In Japan, nationwide GPS array run by the Geographical Survey Institute (GSI), composed of nearly one thousand stations. This GPS net is used in the earthquake researches, climate researches and ground–based GPS meteorology. GPS meteorology project, GPS/MET Japan, was launched in April [13].In Europe, MAGIC project tested the consistency of the GPS processing methods and quality control of the output GPS PWV data. It also demonstrated the impact of the GPS PWV data in the HIRLAM NWP model [14].

From the mid-90 of 20th century when the principle and methods of GPS meteorology have been spread to China to recent years, Chinese Scientists have carried out many studies and experiments. Shanghai Astronomical Observatory of Chinese Academy of Sciences, studied the ground-based GPS meteorology and analyzed its application in bad weather earlier[15]. They did the first GPS/MET experiment and experiment called GPS/STORM and demonstrated ground-based GPS network can estimate PWV near real-time, continuity and high accuracy. Chinese Academy of Meteorological Sciences organized a number of major scientific experiments including using GPS receiver to sense atmospheric water vapor[16].Experiments were also done in Tibet, Anhui, Chengdu, Haerbin, Wuhan, and in Antarctica by Chinese scientists. There are many GPS network of the pre-construction work, and the local network to the applied and operational tests.

5 The application of ground-based GPS meteorology

There are three sides for the application of ground-based GPS meteorology. Firstly, the changes of the atmospheric water vapor can be analyzed for analysis and prediction of disastrous weather in short-range forecasts. In thunderstorms, typhoons and other severe convective weather, the very rapid changes in water vapor is the key to monitoring and forecasting. The ground-based GPS meteorology can provide high effective and high-resolution water vapor changes to improve the accuracy of weather forecasting disastrous.Secondly, the ground-based GPS meteorology can be used to monitor and analyze Climate changes. In the climate system, water vapor plays an important role, affecting the ground and atmospheric water circulation and energy balance. Therefore, GPS water vapor observations are widely used in the research and analysis of global water cycle and water resources.Thirdly, the PWV sensed by ground-based GPS can be used in numerical weather model to improve on numerical weather prediction. In numerical weather model, weather forecasting depends on the initial model largely, in particular the analysis of humidity directly affect the accuracy of precipitation forecast. Adding the water vapor using GPS into initial model can improve the forecasting capability.

6 Conclusions

There are many advantages in the technology of ground-based GPS meteorology. To get high precision PWV, the method to compute the zenith total delay should be considered, models of zenith hydrostatic delay and the mean temperatures should fit the characteristic of regions trough experiments. Ground-based GPS meteorology has wide applications. Scientists of many countries concern about and study the Ground-based GPS meteorology. It will have a further development in the future.

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