Analysis of GPS-derived Total Zenith Delay Estimates for Climate Studies in the Korean Peninsula

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Abstract: Tropospheric parameters, in the form of Total Zenith Delay (TZD) corrections, were estimated with the current GPS network of Korea. We estimated the TZD using the Korea Astronomy Observatory GPS Network of nine permanent stations. About four years of data were processed to get the continuous time series of the TZD. The longest time series is obtained from the site DAEJ, which has been in operation for about 10 years. We analyzed the seasonal and annual signals in the TZD estimates at DAEJ and spatial correlations among eight sites.

Keywords: GPS, Total Zenith Delay, Atmosphere.

1. Introduction

Continuous and well-distributed measurements of water vapor are of great interest for numerical weather forecast, climate researches, and atmospheric studies. Ground-based GPS (Global Positioning System) receivers can provide continuous information on integrated water vapor at a site. Especially, the Total Zenith Delay (TZD) of GPS signals can provide essential information on the long-term climate change of a given area of study.

The GPS signal going through the atmosphere gets delayed as a result of refractions due to the ionosphere and the troposphere. The refraction due to the ionosphere (the ionosphere is a dispersive medium) can be easily removed by linear combinations of the dual frequency measurements because the amount of ionospheric delay is dependent on the signal frequency (GPS uses two frequencies in the L-band). However, the tropospheric delay cannot be removed using the dual frequency measurements because the troposphere is non-dispersive in the GPS signal frequency band.

The tropospheric delays are usually separated into two parts: wet and hydrostatic components. The first component is caused by water vapor in the atmosphere, and the other (which accounts for about 90% of the total delay) is due to the remaining atmospheric constituents which are in hydrostatic equilibrium [1]. While the hydrostatic delay can be accurately modeled using surface pressure measurements, the wet component is difficult to model because of its large spatial and temporal variability. Because meteorological values are far from being sufficient to account for the wet path delay [2], the tropospheric delays are usually estimated either as a constant or as a stochastic parameter.

In this study, we used the GPS data from nine permanent GPS sites in Korea, and derived the continuous TZD estimates for about three years. Then, we analyzed the seasonal and annual variations of the estimates and studied the spatial correlations among them.

2. GPS Data Processing

Korea Astronomy Observatory (KAO) is operating nine permanent GPS sites in South Korea (refer to Fig. 1). The continuous measurements at those sites are used for various applications, e.g. crustal deformation studies for the northeast Asia, atmospheric researches, and precision surveys, etc. The site with the longest operation history is located at the KAO headquarters in Daejeon, with almost ten years in service. The other sites have been in operation for about four years.

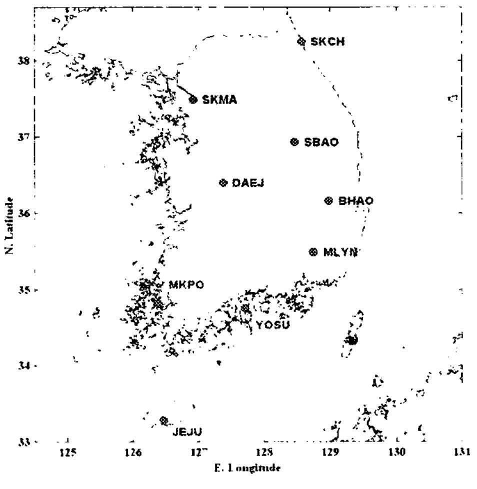


Fig. 1. Korea Astronomy Observatory GPS Network.

Except for DAEJ (whose data were taken from March 1999), we used all the available data from January 2000 through July 2002. There are some data gaps due to site outages and malfunctions, causing discontinuous time series of the TZD.

For GPS data processing, we used GIPSY-OASIS II (hereafter it will be referred to as GIPSY) developed by Jet Propulsion Laboratory [3]. The software is one of the most accurate high-precision GPS data processing tools, and the major characteristic is that it can adapt precise point positioning (PPP) technique, which was used for this study. In the standard PPP procedures, we only estimate site-specific parameters such as site positions, site clock errors, and tropospheric delays, thus can reduce the computing time significantly without loosing the required accuracy. Following the usual GIPSY setup, tropospheric delays were modeled as random walk noise while station clock biases as white noise. Those parameters including TZDs were estimated every five minutes, even though the raw measurements were taken at the rate of 30 seconds.

3. TZD Calculations

The microwaves transmitted from GPS satellites travel slower than they would in a vacuum, and their paths are curvilinear instead of being straight. Both of these effects are caused by the variable index of refraction along the ray path. The delay in signal arrival time can be stated in terms of an equivalent increase in travel path length. This excess path length τ is given by [4]:

$$\tau = \int_L n(s)ds - G\,, \tag{1}$$

where $n(s)$ is the refractive index as a function of position s along the curved ray path L, and G is the straight-line geometric path length through the atmosphere (the path that would occur if the atmosphere was replaced by a vacuum).

The TZD, τ^z, is the atmospheric path delay of the GPS signals coming from the zenith direction. As stated earlier, the tropospheric delay can be divided into hydrostatic and wet parts, thus the TZD can be expressed as the sum of the Zenith Hydrostatic Delay (ZHD, τ_h^z) and the Zenith Wet Delay (ZWD, τ_w^z):

$$\tau^z = \tau_h^z + \tau_w^z\,. \tag{2}$$

Mapping functions are used to project the zenith delays to arbitrary lines of sights between a ground receiver and a satellite. Because the tropospheric delays were considered to consist of two parts, separate mapping functions are used for the hydrostatic and wet delays. The total delay for a path with an elevation angle ε can be calculate from:

$$\tau = m_h(\varepsilon)\tau_h^z + m_w(\varepsilon)\tau_w^z\,, \tag{3}$$

where m_h and m_w are the hydrostatic and wet mapping functions, respectively. As noted in Eq. (3), the mapping functions are given in terms of the elevation angle. For this study, we used Niell's mapping function:

$$m(\varepsilon) = \frac{\dfrac{1}{1+\dfrac{a}{1+\dfrac{b}{1+c}}}}{\dfrac{1}{\sin(\varepsilon)+\dfrac{a}{\sin(\varepsilon)+\dfrac{b}{\sin(\varepsilon)+c}}}}\,. \tag{4}$$

Niell's mapping function is known to be the most accurate one in GPS applications as well as in VLBI (Very-Long Baseline Interferometry). The coefficients a, b, and c in Eq. (4) are empirically determined and dependent on the site location (especially, latitude) and season of the year.

Eq. (2) can be re-written as follows using the appropriate abbreviations introduced earlier:

$$\begin{aligned} TZD &= m_h(\varepsilon)\tau_h^z + m_w(\varepsilon)\tau_w^z \\ &= ZHD + ZWD. \end{aligned} \tag{5}$$

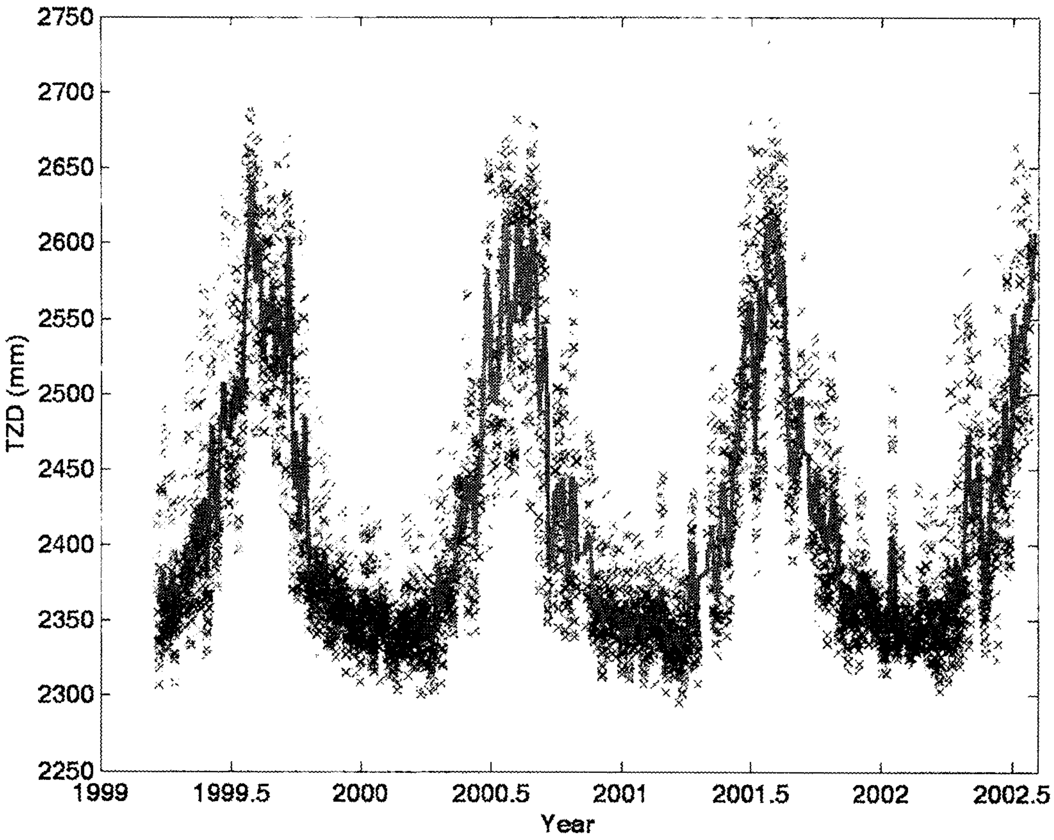
In the above equation, the ZHD can be accurately determined (within an error of 2-3 mm) with surface pressure and temperature measurements taken right at the GPS site location. The equation for ZHD is as follows:

$$ZHD = \frac{(2.2779 \pm 0.00024) \times P_S}{1 - 0.00266 \times \cos 2\varphi - 0.00028 \times h}\,, \tag{6}$$

where P_S is the surface pressure in hPa, φ is the latitude in radians, and h is the ellipsoidal height in kilometers. To determine the surface pressure, we should connect a meteorological sensor to the GPS receiver and take synchronous pressure measurements with GPS observables.

However, none of the current Korean GPS Network sites has a co-located meteorological equipment. Thus, the ZHD could not be determined using Eq. (6). However, the quantity we are interested in is the TZD, not ZHD nor ZWD. Without knowing ZHD in advance, we still can compute the TZD.

As stated earlier, the ZWD cannot be modeled accurately even though we are given surface meteorological measurements. Thus, we need to statistically estimate the ZWD. When we estimate the ZWD, we utilize *a priori* ZWD and *a priori* ZHD. The *a priori* ZWD is referred to as AWD (*a priori* Wet Delay) and *a priori* ZHD as AHD (*a priori* Hydrostatic Delay). Using these relations, Eq. (5) is rewritten as:



$$TZD = AHD + AWD + ZDC \tag{7}$$

The ZDC in the above equation is for Zenith Delay Correction. In the estimation process, we picked AWD as 0.1 m. The AHD varies depending on the site location and can be computed using the empirical equation [5]:

$$AHD = 2.29951 \times e^{(-0.000116 \times h)} \tag{8}$$

where h is the ellipsoidal height. The sum (AHD + AWD) of *a priori* values for each test site is listed in Table 1. The ZDC estimates are one of the primary outputs of GIPSY data processing and they can be combined together with AHDs and AWDs to produce the final TZD.

Table 1. AHD and AWD of nine KAO sites

Site ID	AHD [mm]	AWD [mm]
BHAO	2016.031	100.0
DAEJ	2268.289	100.0
JEJU	2187.312	100.0
MKPO	2282.135	100.0
MLYN	2287.904	100.0
SBAO	1961.553	100.0
SKCH	2286.990	100.0
SKMA	2282.845	100.0
YOSU	2267.230	100.0

4. Results and Discussion

Fig. 2 shows the TZD variations at DAEJ for more than three years. The blue crosses are the TZD estimates at every 5 minutes, and the thick red lines are the 3-hour smoothed results. The box-car filtering was applied for the smoothing. The annual and seasonal signal clearly shows up, and the peaks always happens in the summer season. This was exactly what we expected because the amount of water vapor is much larger in the summer season in Korea. The time of the year when the peaks happen is around July through August.

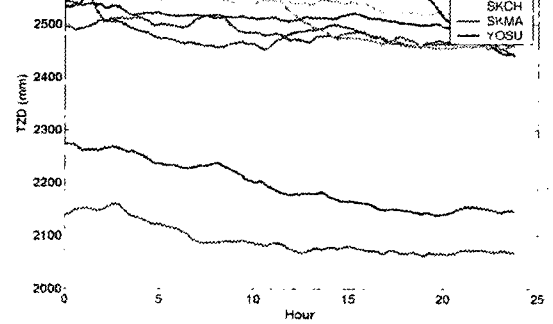


Fig. 3. The ZWD of eight sites for one day.

Fig. 3 shows the estimated TZDs of eight test sites on 9 July 2002. The differences in their mean values are caused by the differences in the station heights. Two of the lowest values of TZDs were observed at the mountain sites: BHAO and SBAO. Except for the biases due the height difference, the general trends show some similarities.

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