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# Accuracy Comparison of GPT and SBAS Troposphere Models for GNSS Data Processing

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## ABSTRACT

The Global Navigation Satellite System (GNSS) signal gets delayed as it goes through the troposphere before reaching the GNSS antenna. Various tropospheric models are being used to correct the tropospheric delay. In this study, we compared effectiveness of two popular troposphere correction models: Global Pressure and Temperature (GPT) and Satellite-Based Augmentation System (SBAS). One-year data from a particular site was chosen as the test case. Tropospheric delays were computed using the GPT and SBAS models and compared with the International GNSS Service tropospheric product. The bias of SBAS model computations was 3.4 cm, which is four times lower than that of the GPT model. The cause of higher biases observed in the GPT model is the fact that one cannot get wet delays from the model. If SBAS-based wet delays are added to the hydrostatic delays computed using the GPT model, then the accuracy is similar to that of the full SBAS model. From this study, one can conclude that it is better to use the SBAS model than to use the GPT model in the standard code-pseudorange data processing.

**Keywords:** GPS, GNSS, GPT, SBAS, tropospheric delay

## 1. INTRODUCTION

There are various types of errors in Global Navigation Satellite System (GNSS) positioning. Among them, signal delays occur due to the troposphere and ionosphere before GNSS signals reach the ground. The ionospheric error can be eliminated almost completely using a dual frequency receiver (Hofmann-Wellenhof et al. 2008). However, accurate modeling is not easy for tropospheric errors because of large spatiotemporal variability in the water vapor amount. If reference and mobile stations are located close to each other, the tropospheric error can be eliminated through double difference processing. In the case of point positioning or for a long baseline, the negative effect of tropospheric error can only be eliminated by statistical estimation. However, statistical estimation may not be used due to high cost or hardware limitation if casual GNSS users perform point positioning using inexpensive entry-level receivers. Thus, a method that can minimize the effect of tropospheric error should be utilized at the user device in the form of a simple troposphere model. In such cases, an empirical model is used.

Some of the most widely employed empirical models to eliminate the tropospheric error are Hopfield (1969), Modified Hopfield (Hofmann-Wellenhof et al. 2008), and Saastamoinen (1973), which require surface pressure measurements. However, it is almost impossible for casual GNSS users to measure valid atmospheric pressure at the ground surface. In contrast, atmospheric pressure and temperature at the user location can be simply calculated using the global pressure temperature (GPT) model developed by Boehm et al. (2007). If the atmospheric pressure calculated using the GPT model is applied to the Saastamoinen model adopted by Davis et al. (1985), the

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tropospheric delay can be easily computed (Leick 2004). In this paper, a model, in which a pressure calculated by the GPT is applied to the Saastamoinen model, is simply referred to as the GPT model.

The ZTD is expressed by a sum of zenith hydrostatic delay (ZHD) due to dry gases and zenith wet delay (ZWD) due to water vapor. Thus, a relationship of ZTD = ZHD + ZWD is established. The ratio of ZHD to ZWD is approximately 9:1 (IERS 2010). That is, if the ZTD is 2.0 m, ZHD and ZWD are approximately 1.8 m and 0.2 m, respectively. When the atmospheric pressure computed by the GPT model is applied to the Saastamoinen model, then ZWD cannot be obtained. Because only ZHD can be calculated with the GPT model, 90% of the ZTD is taken into consideration.

The satellite-based augmentation system (SBAS) correction messages can be used to correct satellite-related errors and tropospheric and ionospheric errors (RTCA 2006). Except for the tropospheric error, SBAS corrections are updated in real time. Meanwhile, the SBAS tropospheric error model is a kind of empirical model. Since the SBAS tropospheric model defines ZHD and ZWD separately, it can take ZTD into consideration. Atmospheric pressures are also needed for this model, but they can be simply calculated by an inherent algorithm.

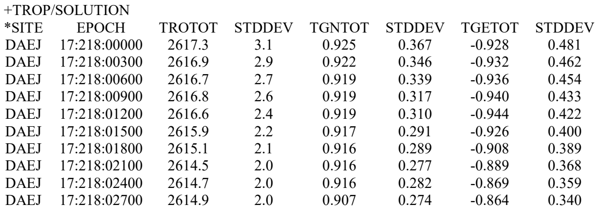
This paper computed tropospheric errors using the SBAS and GPT models and then evaluated their accuracies. Section 2 describes some fundamental equations and principles of the tropospheric models used in the experiment in addition to the international GNSS service (IGS) tropospheric product, which was considered as the truth. In Section 3, the performance of each model is evaluated, and their validity is investigated.

## 2. TROPOSPHERIC DELAY PRODUCT AND MODELS

We consider the zenith path delay (ZPD) provided by the IGS as the criteria that evaluate the performance of the GPT and SBAS models. ZPD estimates are actually equal to ZTD. Thus, in this study, hereafter, ZPD is referred to as ZTD. For the user location, DAEJ, the IGS site in South Korea, was selected, and a period of 356 days in 2017 was chosen as the analysis period. This section introduces the IGS tropospheric delay product and then describes the overview of the GPT and SBAS models as well as validation schemes.

### 2.1 IGS Product

In the IGS network, 504 global permanent stations have been registered and data collected from 430 active sites are processed on a daily basis to produce ZPD products. It takes about three weeks for the IGS to provide the final ZPD product. In South Korea, DAEJ and SUWN are the IGS stations with more than 10-year history of operation. For this study, we obtained the ZPD data at DAEJ for one year from January 1 to December 31 in 2017.



```
+TROP/SOLUTION
*SITE   EPOCH          TROTOT  STDDEV  TGNTOT  STDDEV  TGETOT  STDDEV
DAEJ    17:218:00000   2617.3  3.1     0.925   0.367   -0.928  0.481
DAEJ    17:218:00300   2616.9  2.9     0.922   0.346   -0.932  0.462
DAEJ    17:218:00600   2616.7  2.7     0.919   0.339   -0.936  0.454
DAEJ    17:218:00900   2616.8  2.6     0.919   0.317   -0.940  0.433
DAEJ    17:218:01200   2616.6  2.4     0.919   0.310   -0.944  0.422
DAEJ    17:218:01500   2615.9  2.2     0.917   0.291   -0.926  0.400
DAEJ    17:218:01800   2615.1  2.1     0.916   0.289   -0.908  0.389
DAEJ    17:218:02100   2614.5  2.0     0.916   0.277   -0.889  0.368
DAEJ    17:218:02400   2614.7  2.0     0.916   0.282   -0.869  0.359
DAEJ    17:218:02700   2614.9  2.0     0.907   0.274   -0.864  0.340
```

**Fig. 1.** Sample data of the IGS tropospheric product for the DAEJ station.

Fig. 1 shows a sample of the tropospheric product of DAEJ for DOY 218 of year 2017. The tropospheric delay starts with +TROP/SOLUTION and a total of eight columns are provided. The first to eighth columns provide the following information: first column, observatory name; second column, epoch time (last two digits of the year:DOY:sec); third column, total tropospheric delay (TROTOT); fourth column, standard deviation of TROTOT; fifth column, total troposphere gradient in the north (TGNTOT); sixth column, standard deviation of TGNTOT; seventh column, total troposphere gradient in the east (TGETOT); and eighth column, standard deviation of TGETOT. For more details about the physical quantities in the data, please refer to Bar-Sever et al. (1998). In this study, we took TROTOT values located in the third column and its unit is mm. Thus, Fig. 1 shows that TROTOT gradually decreases from 261.7 cm to 261.5 cm at 300-sec or 5-min rate.

### 2.2 Global Pressure and Temperature (GPT) Model

Since 90% of the tropospheric delay is ZHD that is affected by the surface pressure, the total delay can be calculated without significant errors even if ZWD is excluded. However, it is realistically impossible for all GNSS users to measure atmospheric pressure in order to calculate ZHD. As another method, standard atmospheric pressure may be used but it cannot accurately reflect ever-changing atmospheric pressures which depend on region and season. To overcome this, Boehm et al. (2007) developed a model that calculates a global surface pressure and temperature using a simple spherical harmonic function. This model is called the GPT model whose computations can be done with publicly available MATLAB and FORTRN routines. The input to the model are the user's coordinate and the epoch time.

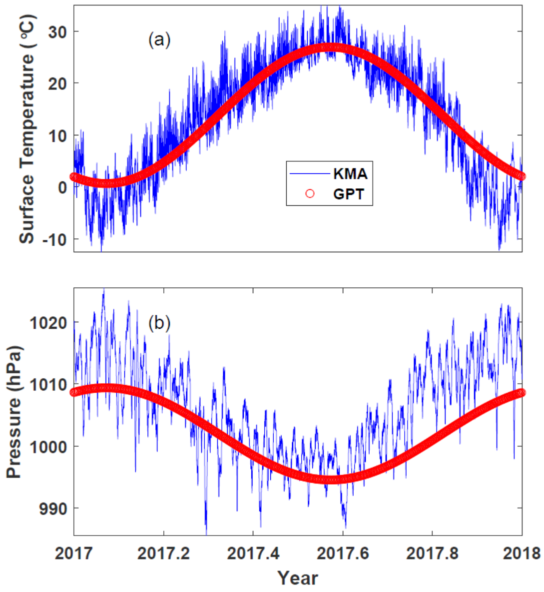


**Fig. 2.** Temperature and surface pressure measurements at the Daejeon Korea Meteorology Administration station and their predicted values at the DAEJ site based on the GPT model.

Temperatures and atmospheric pressures at the DAEJ station were calculated using the GPT model and they are denoted as red circles in Fig. 2. To compare the accuracy of the GPT model, temperatures and atmospheric pressures measured at the Korea Meteorological Administration (KMA) Daejeon center approximately 3.1 km away from the DAEJ site were downloaded from the KMA website. KMA measurements are shown as blue solid lines in Fig. 2. As seen in Fig. 2a, actual temperatures and GPT estimates match nicely without significant bias. The bias and standard deviation of actual temperatures and GPT estimates were 0.7°C and 4.8°C, respectively. In contrast, pressures shown in Fig. 2b have some bias even though their trends are well matched. The bias was observed to be relatively high at 4.3 hPa. This was believed to be caused by an altitude difference between the DAEJ GNSS site and the KMA station. The altitude difference between those two locations was 23 m, which could be converted to 2.8 hPa of pressure deviation. This discrepancy is quite close to the observed bias of 4.3 hPa.

The latitude and ellipsoidal height at a specific location, and atmospheric pressure calculated by GPT can be plugged into Eq. (1) to calculate ZHD (Hofmann-Wellenhof et al. 2008). In Eq. (1), $P_s$, $\varphi$, and $h$ refer to surface pressure, latitude, and ellipsoidal height.

$$ZHD = \frac{(2.2779 \pm 0.0024) \times P_s}{1 - 0.00266 \times \cos 2\varphi - 0.00028 \times h} \quad (1)$$

### 2.3 SBAS Model

The SBAS tropospheric model can calculate total tropospheric delay including ZWD, while the GPT model provides ZHD only. ZHD and ZWD in the SBAS tropospheric model are calculated using five meteorological parameters: geoidal height and atmospheric pressure P, temperature T, water vapor pressure e, temperature lapse rate $\beta$, and water vapor lapse rate $\lambda$ at a specific location. The procedures for computing those five meteorological parameters by interpolation based on the user location and epoch time can be found in the SBAS standard document (RTCA 2006). The calculated meteorological parameters are substituted into Eqs. (2) and (3) to calculate $ZHD_0$ and $ZWD_0$ at the geoidal surface.

$$ZHD_0 = \frac{10^{-6} \times 77.604 \times 287.054 \times P}{9.784} \quad (2)$$

$$ZWD_0 = \frac{10^{-6} \times 382000 \times 287.054}{9.784 \times (\lambda + 1) - \beta \times 287.054} \times \frac{e}{T} \quad (3)$$

To calculate the tropospheric delay at the user location rather than at the geoidal surface, $ZHD_0$ and $ZWD_0$ are converted into $ZHD$ and $ZWD$ at a specific altitude H by using Eqs. (4) and (5).

$$ZHD = \left(1 - \frac{\beta H}{T}\right)^{\frac{9.80665}{287.054 \times \beta}} \times ZHD_0 \quad (2)$$

$$ZWD = \left(1 - \frac{\beta H}{T}\right)^{\frac{(\lambda+1) \times 9.80665}{287.054 \times \beta} - 1} \times ZWD_0 \quad (3)$$

## 3. ACCURACY ANALYSIS

The three tropospheric delays used in this study are the IGS product, and the GPT and SBAS models. Here, the IGS product is used as the truth for evaluating the accuracy of the GPT and SBAS models. As mentioned in Section 2, the IGS product provides ZTD while the GPT model can calculate only ZHD. In contrast, the SBAS model can provide both ZHD and ZWD, and thus ZTD can be calculated by summing ZHD and ZWD. Considering the above characteristics, the following four methods were used to validate two tropospheric models.

### 3.1 IGS-ZTD vs. GPT-ZHD

Sample IGS tropospheric products for the DAEJ station were shown in Fig. 1. One-year time series of the IGS product were extracted and used as the criteria to assess the accuracy of the tropospheric error models. It is called IGS-ZTD in this paper. The GPT pressure shown in Fig. 2 and latitude

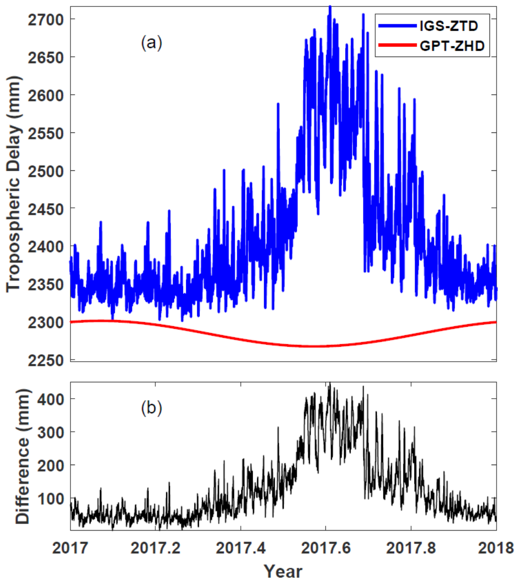


**Fig. 3.** Tropospheric delays derived from IGS troposphere product and GPT model (a); and their differences (b).

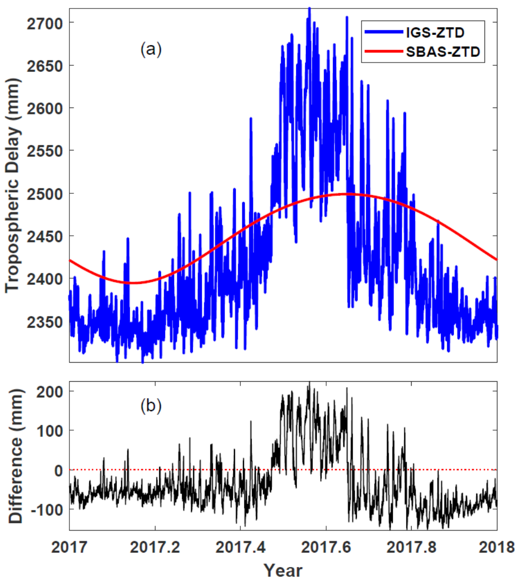


**Fig. 4.** Tropospheric delays derived from IGS troposphere product and SBAS model (a); and their differences (b).

and ellipsoidal height at DAEJ are substituted into Eq. (1) to calculate GPT-based ZHD. These results will be referred to as GPT-ZHD. Fig. 3a shows IGS-ZTD and GPT-ZHD, and Fig. 3b their difference.

The IGS-ZTD denoted by the blue solid line in Fig. 3a goes down to ~2.35 m during the dry winter when the water vapor amount is less than the average. It exceeded 2.7 m during the hot and humid summer. The reason for this kind of seasonal variations is ZWD variability which is strongly related to the water vapor. The GPT-ZHD marked with the red solid line in the lower part of the same graph shows relatively lower values in summer than those in winter. This phenomenon occurs because the Korean Peninsula has high pressure during winter and low pressure during summer.

As seen in Fig. 3a, there is a significantly large bias and differences between IGS-ZTD and GPT-ZHD. Those differences are depicted separately in Fig. 3b. A mean difference was 133.7 mm and standard deviation was 103.1mm. This difference was caused because the IGS-ZTD provides the total tropospheric delay, which is the sum of ZHD and ZWD, while one can get ZWD only with GPT-ZHD computations. The total delay and difference shown of Fig. 3 is in accordance with the fact that ZHD and ZWD account for 90% and 10% of ZTD, respectively. Thus, this result indicates that when the GPT model is used in GNSS data processing, a tropospheric error of up to 40 cm may occur because the model cannot provide ZWD.

### 3.2 IGS-ZTD vs. SBAS-ZTD

While one gets ZHD only with the GPT model, ZTD including ZWD can be obtained with the SBAS model. Fig. 4 shows comparison results of those two models for one year. The overall characteristics showed that IGS-ZTD exhibited larger values than those of SBAS-ZTD during summer, and vice versa in winter. The statistical comparison between IGS-ZTD and SBAS-ZTD showed that the bias and standard deviation were -34.1 mm and 73.1 mm, respectively. Compared to Fig. 3, a bias size was decreased from 133.7 mm to 34.1 mm, showing an approximately one fourth reduction. Moreover, a standard deviation was also reduced by 30 mm compared to that of GPT. The above result indicates that more accurate tropospheric error corrections can be achieved by applying the SBAS model because the GPT model considers only ZHD.

### 3.3 GPT-ZHD vs. SBAS-ZHD

As discussed above, the SBAS model that can calculate ZTD performs better than the GPT model. The reason for this was due to the inclusion of ZWD. In this section, GPT-ZHD was compared directly with SBAS-ZHD, which is ZHD computed with the SBAS model, to analyze the characteristics of differences. Fig. 5 shows GPT-ZHD and SBAS-ZHD with blue and red solid lines, respectively. Also, SBAS-ZTD is depicted with black solid lines to highlight the effect of inclusion of ZWD. When two ZHD computations are compared, the root mean square of the two values was 8.5 mm and the bias was just 1.4 mm. One can see from the

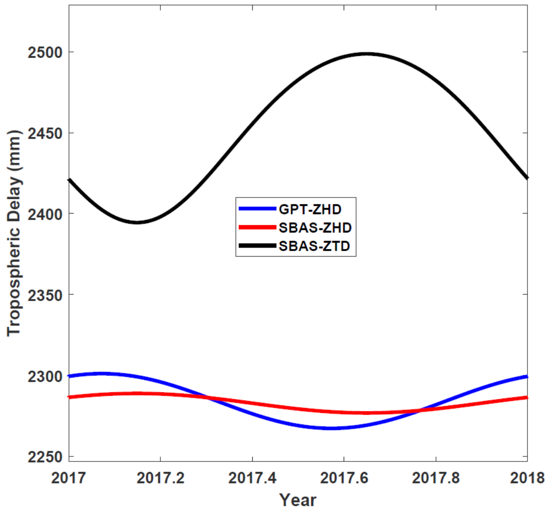


**Fig. 5.** Comparison of the ZTD amount from the SBAS model and two ZHD computations from GPT and SBAS models.

figure that the GPT model displays better agreement than the SBAS model because it reflects more realistic atmospheric pressure conditions.

### 3.4 IGS-ZTD vs. GPT-ZHD + SBAS-ZWD

As discussed in Section 3.1, when ZHD was modeled with atmospheric pressures calculated by the GPT model, one cannot avoid relatively larger errors due to the omission of ZWD. This section investigated the level of error size when combining ZHD provided by the GPT model and SBAS-ZWD. Fig. 6 shows the comparison result between IGS-ZTD and GPT-ZHD + SBAS-ZWD. The bias and standard deviation were -35.1 mm and 74.2 mm, respectively. These values were similar to -34.1 mm and 73.1 mm, which were the values when ZHD and ZWD were calculated with the SBAS model. Thus, as showin Fig. 5, ZHD conputations by the two models are not significantly different, which implied that the accuracy was affected by the inclusion of ZWD.

## 4. CONCLUSIONS

ZTD estimates from the IGS tropospheric product for the whole year of 2017 were regarded as the true value at the DAEJ permanent GNSS station. And then, the GPT and SBAS models were used to calculate ZHD and ZWD at the same site and period, and their accuracies were evaluated. In the case of ZHD where atmospheric pressure obtained by GPT was applied to the Saastamoinen model, the bias and standard deviation were relatively high at 133.7 mm and 103.1 mm. However, in SBAS-ZTD that includes ZWD estimates, the bias significantly reduced to 34.1 mm. In addition, GPT-based ZHD and ZWD calculated with SBAS were combined, the same level of accuracy with that of SBAS-ZTD could be achieved. Therefore, when casual GNSS users consider tropospheric errors with an empirical model, it may be more reasonable to adopt the SBAS model rather than the GPT model.

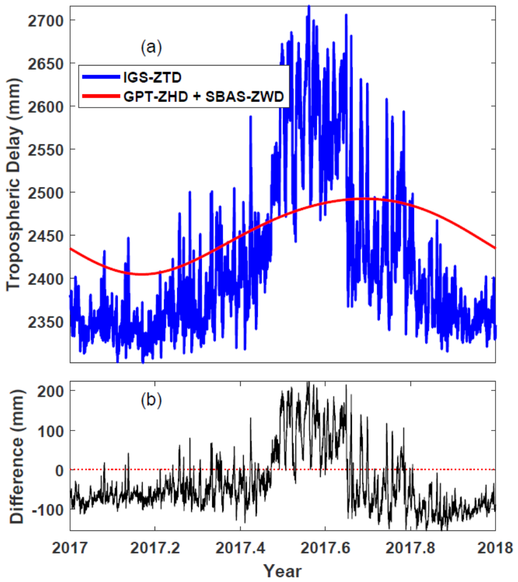


**Fig. 6.** Tropospheric delays derived from IGS troposphere product and the sum of GPT-ZHD and SBAS-ZWD (a); and their differences (b).

## ACKNOWLEDGMENTS

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## REFERENCES

Bar-Sever, Y. E., Kroger, P. M., & Borjesson, J. A. 1998, Estimating horizontal gradients of tropospheric path delay with a single GPS receiver, JGR, 103(B3), 5019-5035. https://doi.org/10.1029/97JB03534

Boehm, J., Heinkelmann, R., & Schuh, H. 2007, Short Note: A global model of pressure and temperature for geodetic applications, Journal of Geodesy, 81, 679-683. https://doi.org/10.1007/s00190-007-0135-3

Davis, J. L., Herring, T. A., Shapiro, I. I., Rogers, A. E. E., & Elgered, G. 1985, Geodesy by radio interferometry: Effects of atmospheric modeling errors on estimates of baseline length, Radio Science, 20, 1593-1607. https://doi.org/10.1029/RS020i006p01593

Hofmann-Wellenhof, B., Lichtenegger, H., & Wasle, E. 2008, GNSS Global Navigation Satellite Systems: GPS, GLONASS, Galileo, and more (Wien: Springer-Verlag). https://doi.org/10.1007/978-3-211-73017-1

Hopfield, H. S. 1969, Two-quartic tropospheric refractivity profile for correcting satellite data, JGR, 74, 4487-4499. https://doi.org/10.1029/JC074i018p04487

IERS 2010, IERS Technical Note 36: IERS Conventions (Frankfurt, BKG)

Leick, A. 2003, GPS satellite surveying, 3rd ed. (Hoboken, NJ: John Wiley and Sons, Inc.)

RTCA 2006, Minimum Operational Performance Standards for Global Positioning System/Satellite-Based Augmentation System Airborne Equipment, D0-229D

Saastamoinen, J. 1973, Contribution to the theory of atmospheric refraction, Part II. Refraction corrections in satellite geodesy, Bulletin Geodesique, 107, 13-34. https://doi.org/10.1007/BF02522083

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