THE EFFECT OF SEASONAL VARIATION ON GNSS ZENITH TROPOSPHERIC DELAY

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ABSTRACT:

The Global Navigation Satellite System (GNSS) signal experiences delays caused by the atmosphere, leading to the lengthening of the geometric path of the ray, commonly referred to as tropospheric delay. This delay is a significant source of error in GNSS positioning, contributing to a bias in the height component of several centimeters, even when meteorological data are simultaneously recorded and used in tropospheric models. In this study, considering seasonal variations, we investigated the impact of tropospheric delay on the GNSS height component. GNSS stations, part of the Turkish RTK CORS Network known as TUSAGA-Active (Turkish National Permanent GNSS Network Active), covered different heights over the 2014-2019 period. Daily coordinates of GNSS stations and tropospheric zenith delay were obtained through the GAMIT/GLOBK software solution.
In the study, temperature, pressure, and relative humidity data of meteorological stations at different heights were converted to mean sea level. By using these values, interpolation estimates were made for the continuous GNSS stations in the same region with the IDW method. The most significant delay in GNSS signals occurs in July and August. This effect, which causes periodic changes in the zenith delay, varies inversely with the station's height. With the increase in the amount of water vapor in the atmosphere in parallel with the rise in the temperature in the summer months, it is seen that the stations at a low height are more exposed to the tropospheric effect than the stations at higher heights. In addition, GNSS stations' reduced meteorological values (temperature, pressure and relative humidity) show that the zenith delay values changed directly proportional to the temperature and inversely proportional to the pressure and relative humidity.

1. INTRODUCTION

The impact of the atmosphere on GNSS results is most prominently manifested in the altitude parameter. In contemporary times, the primary reasons for the altitude sensitivity determined by GNSS being 2-3 times lower than horizontal position sensitivity are twofold. The first reason is the direct reflection of signal elongation and compression on altitude information because GNSS satellites are always in the positive hemisphere (Brunner and Welsch, 1993). The second most significant reason is the atmospheric effects on GNSS signals. GNSS signals pass through various layers of the atmosphere from satellites to receivers on the Earth's surface.

Regarding GNSS measurements, the layers affecting the signals are the ionosphere and troposphere. These two factors significantly disrupt the sensitivity of the height component. While the ionospheric effect, being frequency-dependent, is largely mitigated by using dual-frequency receivers, attempts are made to alleviate the tropospheric effect through various models.

Numerous studies conducted during different seasons and time intervals have revealed the relationship between GNSS positional accuracy and seasonal variations. Their study (Wang et al. 2004) examined the relationship between the seasonal variation and the vertical component of GNSS stations belonging to different networks in Taiwan based on continuous measurements taken in July 2003 and December 2003. The analyses revealed that the average values for July were higher than those for December, with a difference reaching 2 cm. They also found that the standard deviation values were less variable in December. They noted differences of up to 6 cm in daily average values. As a cause, they attributed sudden weather changes, stating that these lead to fluctuations in the vertical component due to water vapor in the atmosphere. Furthermore, they concluded that the vertical component is more sensitive to air temperature changes than the horizontal component.

The effect of meteorological seasons was investigated at a single GNSS station in mid-latitudes (Aykut, 2018). The station's one-year data were analyzed, and Root Mean Square (RMS) values for coordinate components were calculated. Subsequently, the coordinate components and RMS values were correlated with meteorological parameters (temperature, pressure, and humidity). They indicated an association between the North and East components with temperature data. RMS values were observed to be more significant in the spring and summer months.

In order to investigate the effect of seasonal changes on GNSS positioning accuracy, 3-day data sets taken from Marmara Continuous GPS Network stations for each month of 2009 were used (Dogan et al. 2014). GNSS measurements for 24 hours in data sets with different baseline lengths were evaluated as 4, 6, 8, and 12-hour data sets. The study results revealed that the positioning accuracy of observed stations could vary in the north-south, east-west, and vertical directions each month. It was observed that GNSS positioning accuracy was lowest in the summer season (July) and highest in the winter season (January and December).

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2. MATERIALS AND METHODS

2.1 GNSS and Troposphere

Meteorological events in the troposphere make it a significant source of error in precisely determining point positions. Unlike the ionospheric layer, the neutral atmosphere layer's troposphere cannot be corrected using phase combinations of L1 and L2 carrier waves in GNSS receivers.

The impact of the neutral atmosphere on electromagnetic waves in the radio frequency range is referred to as tropospheric delay. Tropospheric delays are determined by integrating refractivity along the signal path and subsequent mapping in the zenith direction using various mapping functions (Niell, 1996; Böhm et al 2006). This effect causes the electromagnetic wave to slow down and bend. Tropospheric delay, a function of temperature, relative humidity, and pressure, is directly related to the elevation of the measurement point. In tropospheric delay calculations, the Saastamoinen (Saastamoinen, 1972) and Hopfield (Hopfield, 1969) models are widely used for evaluating GNSS observations, incorporating atmospheric parameters independent of time and actual meteorological conditions (Selbesoglu, 2019).

Both models are employed to predict tropospheric delay based on actual meteorological conditions. They consider atmospheric effects to achieve high accuracy in GNSS applications and are used to correct the amount of delay. These models typically incorporate input parameters such as temperature, water vapor pressure, station altitude, and latitude to calculate tropospheric delay.

GNSS signals experience a tropospheric delay due to the troposphere's dry and wet components. The delay associated with the dry component is approximately 2 meters, constituting 90% of the total tropospheric delay. The wet component is related to atmospheric water vapor and accounts for 10% of the delay, with an impact of approximately 10 cm. The dry component, influenced by surface pressure, can be more easily modeled than the wet component, which is challenging to calculate due to the irregular distribution of water vapor in both horizontal and vertical directions (Yao et al. 2014).

In developing these models, parameters such as pressure, humidity, the receiver's height, latitude, etc., are applied to reduction functions. The implemented models may vary in content and components, and their accuracy criteria may differ depending on the application field. Failure to apply a tropospheric correction model in the GNSS data processing stage may result in delay errors of up to 20 meters in directions from zenith to horizon (Hay and Wang, 2000).

Accurate modeling of tropospheric effects is crucial, and if not correctly modeled, especially the height component, it can be prone to errors. Standard atmospheric models typically define temperature T_0, pressure P_0 and humidity H_0 at the sea surface level, assuming linear changes with altitude. For reference values, $h_0=0$ *m*, $T_0=18$ *°C*, $P_0=1013$ *mbar* , $H_0=\%50$ are commonly accepted.

2.2 Inverse Distance Weighted Method (IDW)

The geographical features of the points where meteorological observations are made are different. Significantly, the complexity of the topography in our country and the rapid changes in elevation over short distances make local conditions different from each other. Therefore, factors arising from elevation should be eliminated to mitigate these differences. During the reduction of points with high elevation to sea level, it is assumed, hypothetically, that the added air is dry. However, in the reduction of the humidity profile, it is assumed that the same amount of water continues linearly in the vertical profile.

However, assuming all the dry air in a 1-square-meter atmospheric column leads to certain inaccuracies. Moreover, in cases where the elevation is high, the effect of the hypothetically added air parcel through interpolation will be more significant, causing substantial errors in the error rate. The basis for these errors is inherent, like the statically downscaled data, rather than user-induced. Any interpolation method used is unlikely to yield better results than these outcomes.

The vertical profile of variables within a 1-square-meter atmospheric column is provided in Figure 1.

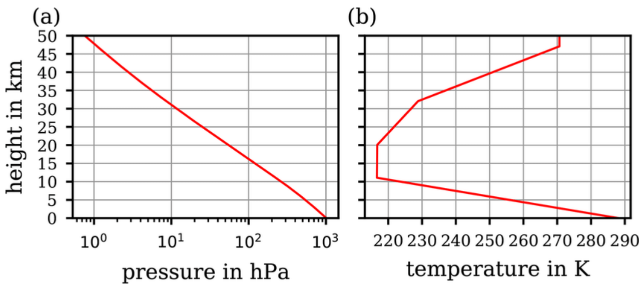

Figure 1. Vertical profile of temperature and pressure

The downscaling method used in these studies is the IDW Interpolation method, which is assumed to have an inversely proportional effect on the variable with distance.

In scenarios where the height conditions are ideal, predictions of values at GPS points were made with the obtained meteorological observations. A decrease in productivity is expected in mountainous regions. The points with the most minor errors are likely to be in the plains.

The interpolation method was used to estimate the weather conditions at GPS points from actual observations. Thus, a value belonging to the GPS point was obtained for each available time step.

The quality of the meteorological time series has been affected by a significant number of missing observations and gaps in the dataset in some stations. The more observations available, the higher the number of reference points we have, thus improving the quality. Testing GPS points with similar elevations and a high density of nearby observation points will enhance accuracy.

Since not every GNSS station is equipped with meteorological sensors, meteorological parameters necessary for point positioning can be calculated using ground-based meteorological station data. Various methods exist for obtaining meteorological data at GNSS stations. One of these methods involves utilizing data from existing meteorological stations in the study region and applying interpolation methods to reproduce meteorological parameters for the study area. In this study, daily average temperature, pressure, and relative humidity values for the GNSS stations' locations were obtained from meteorological stations in the corresponding provinces for 2014-2019. The Inverse Distance Weighted Method (IDW) was applied as an interpolation method to obtain meteorological data for GNSS stations.

IDW interpolation method is based on weighting the inverse of distances between reference points and the point for which estimation is sought (Shepard 1968; Franke and Nielson 1980; Lu and Wong 2008; Attorre, 2009; Kayıkçı and Kazancı, 2016;). In this method, as the distance to reference points increases, the influence of a distant point on the estimated value is intended to decrease. In the standard IDW method, for the region covered by the set of points *N={X, Y, Z}*, the height of the interpolation point *P(x, y)* is calculated as follows:

$$z_e = \sum_{i}^{n} w_i * Z_i / \sum_{i=1}^{n} w_i \quad (1)$$

The height value z (x,y) at the point (x, y) is calculated using the equation (Wang et al. 2014):

$$w_i = \frac{1}{d_i^P}, \quad i = 1, 2, 3 \ldots \quad p = 1, 2, 3 \ldots \quad (2)$$

Here, Z_i represents the elevation values of the reference points, w_i represents the weight values, and n is the number of reference points. In equation (2), the weight values w_i are expressed as a function d of the distance between the reference and interpolation points.

Equation (2) is calculated using the formula's power function d. As the power function value increases, distant points' influence on the calculation decreases. In other words, the aim is to minimize the adverse effects of data obtained from distant points on modeling the surface at the location of the interpolation point. In the literature, the power parameter p can commonly take values ranging from 0 to 5. This value is determined by the user. The function d in the formula represents the distance between the reference and interpolation points.

$$d_i = \sqrt{(x_e - X_i) + (y_e - Y_i)^2} \quad (3)$$

The vertical pressure variability is sensitive to the station's elevation; therefore, temperature, pressure, and relative humidity measurements at different elevations must be transformed to a standard reference level. This reference level is called the Mean Sea Level (MSL). As a result, the interpolated parameters on any grid correspond to this reference level (Bai and Feng, 2003; Alinia, 2017).

Using values obtained from meteorological stations, daily temperature, pressure, and relative humidity values at sea level were generated for the locations of GNSS stations. The relationship between station level and mean sea level data is as follows:

$$\begin{gathered} P = P_0/(1 - 2{,}26.10^{-5}H)^{5.225} \\ T = T_0 + 0{,}0065H \\ H = H_0/e^{-6{,}396.10^{-4H}} \end{gathered} \quad (4)$$

Here, H represents the station's elevation, and P, T, *and* H denote the values at the station point (Baltink, 1999). Interpolation predictions for GNSS stations have been made using the IDW method based on temperature, pressure, and relative humidity data for known points.

3. RESULTS AND DISCUSSION

3.1 GNSS Zenith Delays and Seasonal Variation

The delay of GNSS signals in the atmosphere occurs due to the effect of atmospheric refraction. The impact of atmospheric refraction depends on atmospheric variables, particularly pressure, temperature, and humidity. Changes in pressure affect air density, altering the speed and direction of GNSS signals. Temperature influences atmospheric density and optical properties such as the refractive index. Humidity modifies atmospheric density and refractive characteristics depending on the amount of water vapor. These atmospheric effects result in delays and errors during the journey of GNSS signals, necessitating atmospheric corrections for accurate position determination. These corrections aim to minimize the impact of atmospheric refraction based on pressure, temperature, and humidity (Rocken et al. 1993).

Zenith delay uncertainties for GNSS stations can be calculated in the data evaluation process. Zenith delay represents the delay occurring as GNSS signals enter the atmosphere directly from the zenith point and traverse through the atmosphere. Atmospheric variables, especially atmospheric effects such as pressure, temperature, and humidity, can cause periodic anomalies in zenith delay uncertainties. These anomalies may be associated with seasonal or other periodic changes. Therefore, the relationship between zenith delay uncertainties and seasonal changes can be investigated. This analysis can aid in understanding the impact of atmospheric effects on zenith delay and contribute to developing better models for correcting these effects. Examining the relationship between zenith delay uncertainties and seasonal changes is crucial for minimizing the impact of atmospheric refraction, ensuring more accurate corrections of GNSS data. The following analyses are explained over stations classified according to ellipsoidal height (Table 1).

Station Name	Ellipsoidal Height (m)
RZE1	70.6990
DIYB	773.6755
GURU	1357.4395
TUF1	1504.7368

Table 1. GNSS Stations Classified by Ellipsoidal Height

Figure 2 shows the zenith delay unknown values of the stations for 2014–2019. The most significant delay in GNSS signals at the RZE1 station occurs in July and August. According to Figure 3, this effect, which causes periodic changes on the zenith delay unknowns, varies inversely with the station's height. Due to the increased amount of water vapor in the atmosphere in parallel with the temperature increases in the summer months, the RZE1 station close to sea level is exposed to more tropospheric effects than high-altitude regions. This is because the station is located by the sea. Similarly, the most significant delay in GNSS signals occurs in July and August at the TUF1 station, which is located in a high topography. In addition, it is seen that the delay values are highest in the summer months and lowest in the winter months.

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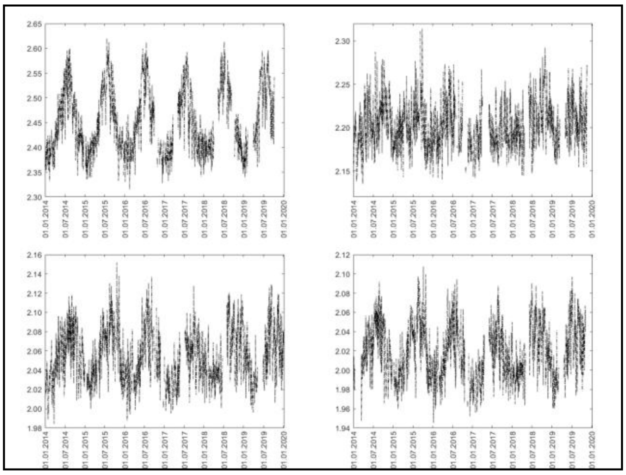

Figure 2. Zenith delay values between 2014–2019 of RZE1, DIYB, GURU, and TUF1 stations, respectively.

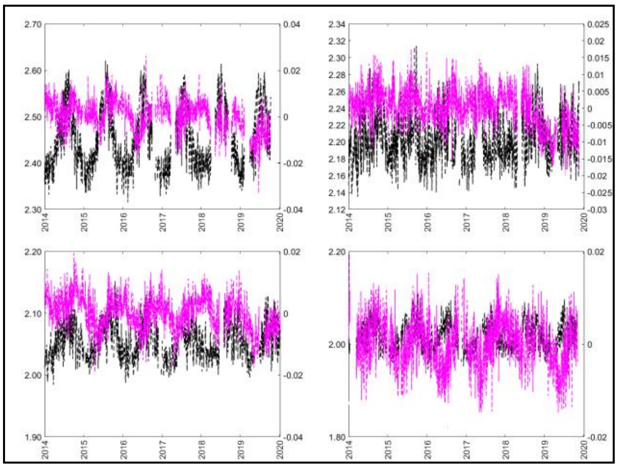

Figure 3. The relationship between the zenith delay values and the height component of RZE1, DIYB, GURU, and TUF1 stations between 2014 and 2019, respectively (The black line gives the zenith delay values, and the purple line gives the height information.)

According to Figure 3 for the DIYB station with an ellipsoidal height of 773.67 m, the annual range of zenith delay uncertainties is approximately 2.19 m. Similarly, for the GURU station with an ellipsoidal height of 1357.43 m, the annual range of zenith delay uncertainties is approximately 2.05 m. This indicates that the effect of zenith delay decreases as the height increases. This information demonstrates the relationship between height and the effect of zenith delay. As height increases, the delay effect of atmospheric influences on GNSS signals decreases. This underscores the importance of considering the height factor for accurately positioning GNSS data.

Additionally, the relationship between zenith delay values and reduced meteorological parameters (temperature, pressure, and relative humidity) for the stations under study is shown in Figures 4 to 6. Accordingly, it is observed that zenith delay values vary directly with temperature and inversely with pressure and relative humidity.

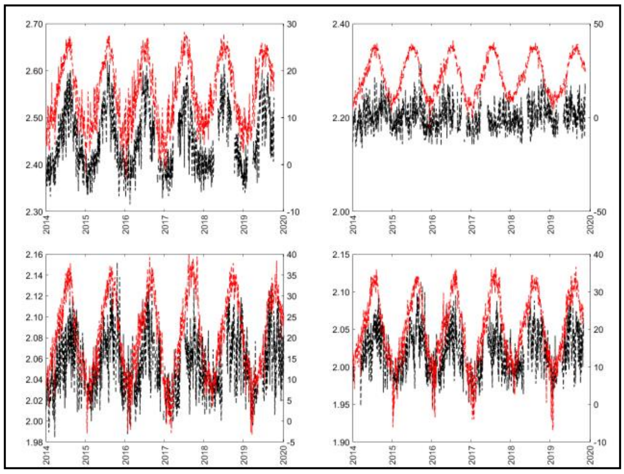

Figure 4. Temperature relationship with zenith delay values of RZE1, DIYB, GURU and TUF1 stations between 2014 and 2019, respectively (The black line gives the zenith delay values, the red line gives temperature information.)

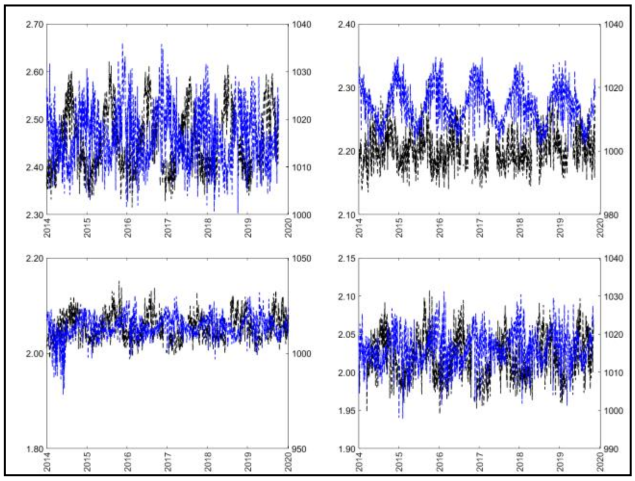

Figure 5. The relationship between zenith delay values and pressure of RZE1, DIYB, GURU and TUF1 stations between 2014 and 2019, respectively (The black line gives the zenith delay values, the blue line gives the pressure information.)

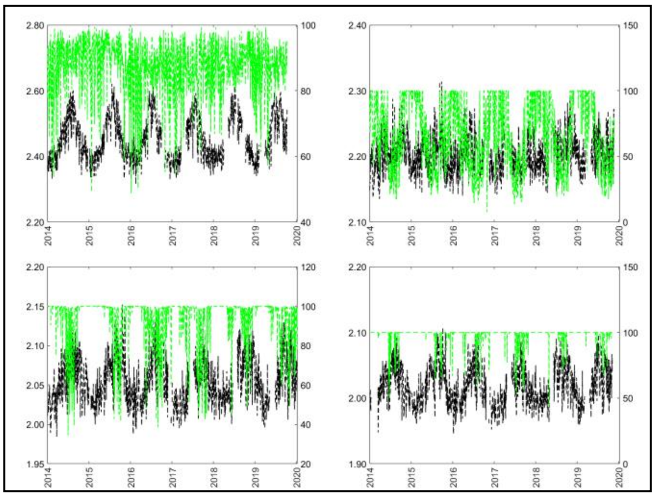

Figure 6. Humidity relationship with zenith delay values of RZE1, DIYB, GURU and TUF1 stations between 2014 and 2019, respectively (Black line gives zenith delay values, green line gives humidity information.)

4. CONCLUSIONS

Atmospheric effects create seasonal anomalies in zenith delay unknowns. Therefore, the relationship between zenith tropospheric delay unknowns and seasonal variations has been investigated. Zenith Total Delay (ZTD) values change proportionately to temperature, inversely proportional to pressure, and relative humidity. Generally, the most significant delays in GNSS signals occur during summer, particularly in July and August. This is attributed to the long daylight hours in the summer months, changes in total electron content in the ionosphere, and potential decreases in underground water sources due to extreme heat. The analyses mentioned above may enhance the quality of station velocity predictions for the vertical component.

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REFERENCES

Alinia, H., S., 2017: New GPS Time Series Analysis and a Simplified Model to Compute an Accurate Seasonal Amplitude of Tropospheric Delay. *Doctor of Philosophy*, The University of Western Ontario (Canada).

Attorre, F., Alfo, M., De Sanctis, M., Francesconi, F., Bruno, F., 2009: Comparison of Interpolation Methods for Mapping Climatic and Bio Climatic Variables at Regional Scale. *Int J Climatol* 27, 1825–1843.

Aykut, N., O., 2018: The Importance of Meteorological Variation on PPP Positioning. *Measurement* 122, 168-177.

Bai, Z., Feng, Y., 2003: GPS Water Vapor Estimation Using Interpolated Surface Meteorological Data from Australian Automatic Weather Stations. *Journal of Global Positioning Systems* 2(2), 83-89.

Baltink, H., K., *et al.*, 1999: GPS water vapor meteorology. *Beleids Commissie Remote Sensing (BCRS)* 3-11.

Böhm, J., Niell, A., Tregoning, P., Schuh, H., 2006: Global Mapping Function (GMF): A New Empirical Mapping Function Based on Numerical Weather Model Data. *Geophys. Res. Lett. 33*.

Brunner, F., K., Welsch, W., M., 1993: Effect of the Troposphere on GPS Measurements. *GPS World* 4(1), 42.

Dogan, U., Uludag, M., Demir, D., 2014: Investigation of GPS Positioning Accuracy during the Seasonal Variation. *Measurement* 53, 91-100.

Franke, R. Neilson, G., 1980: Smooth Interpolation of Large Sets of Scattered Data. *Int J Numer Meth Eng.* 15, 1691–1704.

Hay, C., Wang, J., 2000: Columns-Innovation: Enhancing GPS-Tropospheric Delay Prediction at the Master Control Station. *GPS World* 11(1), 56-62.

Hopfield, H., 1969: Two-quartic Tropospheric Refractivity Profile for Correcting Satellite Data. *J. Geophys. Res.*74, 4487–4499.

Kayıkçı, T., R., Kazancı, K., S., 2016: Comparison of Regression-based and Combined Versions of Inverse Distance Weighted Methods for Spatial Interpolation of Daily Mean Temperature Data. *Arab J Geosci*. 9, 690.

Lu, G., Y., Wong, D., W., 2008: An Adaptive Inverse Distance Weighting Spatial Interpolation Technique. *Comput. Geosci*. 34(9), 1044–1055.

Niell, A., E., 1996: Global Mapping Functions for the Atmosphere Delay at Radio Wavelengths. *J. Geophys. Res. Solid Earth* 101, 3227–3246.

Rocken, C., Ware, R., Van Hove, T., Solheim, F., ,Alber, C., Johnson, J., Bevis, M., Businger, S., 1993: Sensing Atmospheric Water Vapor with the Global Positioning System. Geophys Res Lett. 20(23), 2631–2634.

Saastamoinen, J., 1972: Contributions to the Theory of Atmospheric Refraction. *Bull. Géodésique* 105, 279–298.

Selbesoglu, M., O., 2019: Spatial Interpolation of GNSS Troposphere Wet Delay by a Newly Designed Artificial Neural Network Model. *Appl. Sci.9*, 4688.

Shepard, D., 1968: A Two-dimensional Interpolation Function for Irregularly-spaced Data. in *Proceedings of the 1968 23rd ACM National Conference* 517-524.

Wang, C., S., Chung-Li, T., Liou, Y., A., 2004: Seasonal variation of GPS height determination in Taiwan. in *American Geophysical Union, Fall Meeting* 13-17.

Wang, S., Huang, G., H., Lin, Q., G., Li, Z., Zhangand, H., Fan, Y., R., 2014: Comparison of Interpolation Methods for Estimating Spatial Distribution of Precipitation in Ontario, Canada. *Int J Climatol* 34, 3745 3751.

Yao, Y., Zhang, B., Xu, C., Yan, F., 2014: Improved One/multi-parameter Models that Consider Seasonal and Geographic Variations for Estimating Weighted Mean Temperature in Ground-based GPS Meteorology. *J Geod.* 88, 273–282.