Assessment of Performance of the SHAO-C Tropospheric Delay Correction Model Over low Latitude and Complex Topography

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Abstract—Tropospheric signal delay can introduce a considerable error in satellite positioning if it is not properly modeled. In this work, the spatial and temporal variations of the zenith tropospheric delay (ZTD) over low latitude and complex topography of Ethiopia and Eritrea from the Greater Horn of Africa (GHA) region, are analyzed using ECMWF (European Center for Medium-Range Weather Forecast) pressure-level atmospheric data and compared with ZTD over 5-year period from 2007-2011 measured at several GPS stations of UNAVCO in the region. A new tropospheric delay correction model, SHAO-C used in China, is evaluated for its performance over the region with most GPS observational stations located in Ethiopia. The ZTD along altitude, latitude and longitude is fitted with a second order polynomials at a reference height, and the mean ZTD is modeled directly by a harmonic function together with an initial value and an amplitude in each grid. The coefficients of this model are generated using the ERA-Interim data at moderate resolution. The altitude is obtained from high resolution digital elevation model (DEM). The agreement between GPS and model ZTD is found to be very good which is reflected in overall average bias between -4.3 to -1.0 cm, and RMSE less than 4.5 cm. The results are within the requirements of most GNSS navigation or positioning applications in terms of the tropospheric delay correction.

Index Terms—ZTD, SHAO-C, Troposphere Delay Correction, Navigation, Positioning

I. INTRODUCTION

The influence of atmosphere, in the form of delay on the propagation of an electromagnetic microwaves signals emitted from the Global Positioning System (GPS), is one of the main accuracy limiting factors of positions determined by GPS. It is a serious error in GPS measurements both through ray path bending and the modification of the electromagnetic velocity (1) and references therein. The GPS signal delay can occur due to the total electron content (TEC) present in the ionosphere (1), (2). The neutral atmosphere, a region of the Earth’s atmosphere without free electrical charges (3) extends from the Earth’s surface up to an altitude of ~ 50 km, has also a delaying effect on the radio wave propagations. This effect is commonly referred to as tropospheric delay due to significant contribution from troposphere, the lower part of the neutral atmosphere. The ionospheric GPS signal delay can be estimated from measurement on \( L_1 \) and \( L_2 \) frequencies. However, the tropospheric delay requires certain assumptions and modeling work. The tropospheric zenith total delay can be split into zenith hydrostatic delay (ZHD), also called dry delay, and zenith wet delay (ZWD), also called non-hydrostatic delay. The ZHD is caused by dry air which accounts for about 90% of the total delay and typically around 2.3 m at the zenith (4). The ZWD is due to temporal and spatial variability of water vapor and its effect is normally around less than ~0.4 m. As a result, it is straightforward to model the ZHD while the ZWD is rather difficult.

To this end, a number of neutral atmosphere delay model have been developed in the past. Some of more common ones are Berman Model (5), SHAO-C tropospheric correction model (6)-(8), Hopfiel model (9), Ifadis model (10) and UNB3m model (University of New Brunswick modified version) (11). However, some of them are applicable subject to certain constraints. For instance, though the UNB3m is global by design, its performance over low latitude is very limited and it does not account for seasonal variations. However, the SHAO-C tropospheric correction model is a regional model over China, with the over all bias and RMSE of 2.0 and 4.5 cm, respectively (6). It has been found to have better performance and therefore it is sufficient for most GNSS navigation or positioning applications over the low latitude region.

The good performance of modified SHAO-C over topographically complex region of China motivates its application in other regions of similar complexity. Ethiopia is one of such regions which characterized by highly ragged topography in the Eastern Africa region. In this work, modified SHAO-C is applied to determine ZTD over Ethiopia. Its skill is evaluated using ZTD observation from a network of GPS during the 2007-2011 period. As the ZTD correction over Ethiopia is intended for navigation and positioning users with high accuracy requirements, the time resolution of the data is 6 hr namely at 0, 6, 12, 18 UTC.

The paper is organized such that the description of modified SHAO-C is given in II, III presents results and discussion while conclusion is given in IV.

II. ADAPTATION OF SHAO-C TROPOSPHERIC DELAY MODEL OVER ETHIOPIA

A. Tropospheric Zenith Total Delay

The refractive index within the neutral atmosphere plays an important role in the propagation of radio waves. The refractive index of the troposphere is greater than unity causing
an excess delay of the signal, and the change in the refractive index with height causes the bending of the signal [15]. On the other hand, the continuous variation of the refractive index causes a deviation of its trajectory from a straight line.

In the troposphere, the refractive index, \( n \), is given by

\[
n = 1 + (k_1 \frac{P_H}{T} + k_2 \frac{P_w}{T} + k_3 \frac{P_w}{T^2}) 10^{-6}
\]

in terms of temperature, \( T \), the partial pressure of dry air, \( P_H \), and water vapor pressure, \( P_w \) [12], [13]. The constants are given by \( k_1 = 77.604 \text{ KPa}^{-1} \), \( k_2 = 64.79 \text{ KPa}^{-1} \), \( k_3 = 377600 \times 2 \text{ KPa}^{-1} \). Refractive index is more conveniently expressed by another quantity, refractivity \( N \), as [14]

\[
N = (n - 1) 10^6 = k_1 \frac{P_H}{T} + k_2 \frac{P_w}{T} + k_3 \frac{P_w}{T^2} .
\]

The tropospheric delay can be computed through the integration along the signal path as the difference between the electromagnetic path length and the geometric path length using the following expression [14], [15]:

\[
ZTD = \int_{\text{path}} (n - 1) dh = 10^{-6} \int_{\text{path}} N dh
\]

where \( dh \) is a differential element of length along the ray path.

B. Data, Algorithm and Methodology

In this study, reanalysis field of the surface pressure \( P_s \), the temperature, \( T \), and the specific humidity \( q \) are obtained from ECMWF ERAInterim Reanalysis pressure level data [16]. These field are extracted at each grid cell defined by latitude, \( \lambda_i \), and longitude, \( \phi_j \), for the period under study within \( 3^\circ - 17^\circ \text{ N} \) and \( 33^\circ - 48^\circ \text{ E} \) at horizontal resolution of \( 0.75 \times 0.75 \) degree and temporal resolution of 6 hrs. ZTD can be written in discrete form as

\[
ZTD = 10^{-6} \sum_{k=0}^{l} N_k \Delta h_k
\]

where \( l \) is the total vertical layer of troposphere.

Now, the functional relationship describing vertical variation (altitude variation) in the total zenith delay, is given using a direct second order polynomial fitting, expressed as [6]

\[
ZTD(\lambda, \phi, h, t) = ZTD(\lambda, \phi, h_0, t) + a_1(h-h_0) + a_2(h-h_0)^2
\]

where \( t \) is time, \( h_0 \) and \( h \) are the reference surface average height on each grid and the user’s height, respectively, \( a_1 = -\frac{\partial ZTD}{\partial h} \) is the decreasing and \( a_2 = \frac{\partial^2 ZTD}{\partial h^2} \) is acceleration rate of ZTD. Based on the analysis of the temporal and spatial characteristics of ZTD, the zenith delay at the surface can be estimated for desired day of year using harmonic function analysis as follows [6]:

\[
ZTD(\lambda, \phi_j, h_{oij}, t) = ZTD_{\text{mean}}(\lambda_i, \phi_j, h_{oij}) - ZTD_{\text{amp}}(\lambda, \phi) \cos\left[2\pi \frac{(t - t_{\text{min}})}{365.25}\right]
\]

where the reference height \( h_{oij} \) is the average surface height of each grid obtained from digital elevation model (DEM) in km, \( ZTD_{\text{mean}}(\lambda, \phi, h_{oij}) \) is the average zenith delay on average height at each grid in meter, \( ZTD_{\text{amp}}(\lambda, \phi) \) is the amplitude of zenith delay on average height at each grid in meter, \( i \) and \( j \) are the index’s for horizontal grids which are related to surface topography and \( k \) is the index for the vertical height level. Finally the model define the total zenith delay as [6]

\[
ZTD = ZTD_{\text{mean}} - ZTD_{\text{amp}} \cos\left[2\pi \frac{(t - t_{\text{min}})}{365.25}\right] + a_1(h-h_0) + a_2(h-h_0)^2
\]

III. RESULTS AND DISCUSSION

In the following, characteristics of observed and model ZTD as well as model validation are described.

A. Characteristics of ZTD Over Ethiopia

The characteristics ZTD estimated from GPS observations at a network of GPS stations are used to validate model estimates. The GPS ZTD time series considered for further analysis are selected from among the 15 sites of the network used in the GAMIT network solution. These are Addis Ababa, Arba Minch, Asab, Bahir Dar, Nazareth, Robe GPS stations. They are installed along the Crustal Movement Observation Network of over Great Rift Valley regions of Eastern Africa within UNAVCO (University NAVstar Consortium)(Fig. 1). The GAMIT software parameterizes ZTD as a stochastic variation from the Vienna Mapping Function 1 (VMF1) [17]. The ZTDs data have a high temporal resolution of 2 hrs obtained with piecewise linear interpolation. The elevation cut-off angle was 45° to 10°.

Fig. 2 indicates that the time series of ZTD characterize the well known annual signal, which can be described by a cosine function. As shown the preceding section the GPS data has gaps between the observation periods in all stations except Robe. Besides there is a GPS data gaps of different sizes of year. For instances observations at Robe is a year taken in the middle of 2007 to end of 2009. Clearly, the magnitude of ZTD depends on the altitude as exhibited by differences between ZTD at different stations (Fig. 2). For instance, at Asab (ASAB), low land station, the magnitude of ZTD is much higher than that of high land station (e.g. Robe (ROBE), or Addis Ababa (ADIS)). On the other hand, the seasonal
TABLE I
The seasonal and annual mean value of ZTD (in meter) and standard deviation, STD, (in centimeter) at Addis Ababa (ADIS), Arba Minch (ARMI), Asab (ASAB), Bahir Dara (BDAR) and Nazareth (NAZR) GPS stations during 2007-2011.

<table>
<thead>
<tr>
<th>Site</th>
<th>Long (deg)</th>
<th>Lat (deg)</th>
<th>Altitude (m)</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
<th>Amp</th>
<th>ZTD STD</th>
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<tr>
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<td>1.84</td>
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<td>1.85</td>
<td>0.6</td>
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</tbody>
</table>

The amplitude of ZTD shows an apparent variation with lower values in the winter and higher values in the summer months (Table I), due to strong moisture field (higher water vapor pressure in summer than in winter). This also noted from study on atmospheric precipitable water vapor (PWV) from ground-based GPS measurements and ERA-Interim Reanalysis by [18].

The minimum of annual average value of ZTD, \( ZTD_{mean} \), is 1.85 m at Addis Ababa (ADIS) station, and the maximum is 2.50 m at Asab (ASAB) station. The mean annual amplitude variation of ZTD, \( ZTD_{amp} \), ranges approximatively from 0.03 to 0.05 m depending on the site location, with most stations around 0.03 m. The over all annual mean standard deviation (STD) of ZTD derived from the GPS observations using the GAMIT solution varies between 0.6 to 1.0 cm (Table I). Large STD found in summer relative to the rest of the seasons.

B. Establishment of the Model Parameters

The determined model coefficient and their temporal and spatial characteristics over the region are presented in this section. The average of ZTD, \( ZTD_{mean} \), and amplitude of ZTD, \( ZTD_{amp} \), values of the model parameters are determined at each grid point by fittin the delay on the average surface height (Equ. 6) to ECMWF ERA interim reanalysis.

The vertical variation parameters of the model (i.e \( a_1 \) and \( a_2 \) in \( \frac{m}{km} \)) at each grid determined from the model over Ethiopia.

Fig. 2. Time series of ZTDs at Addis Ababa, Arba Minch, Asab, Bahir Dar, Nazareth and Robe GPS stations.

Fig. 3. The average ZTD coefficient \( ZTD_{mean} \) (panel (a)) in meter, amplitude ZTD coefficient \( ZTD_{amp} \) (panel (b)) in meter; ZTD decreasing rate coefficient \( a_1 \) (panel (c)) in \( \frac{m}{km} \), and ZTD accelerating rate coefficient \( a_2 \) (panel (d)) in \( \frac{m}{km^2} \) at each grid determined from the model over Ethiopia.
at each grid point for the given day of the year are also fitted with a second-order polynomial (Equ. 5) on the average surface height using data from the reanalysis.

1) Determination of the Model Coefficients: The model coefficient (the average zenith delay $Z_{TD mean}$, the amplitude zenith delay $Z_{TD amp}$, the decreasing rate $a_1$, and the accelerating rate $a_2$ except the average surface height $h_o$) are derived from ERA-Interim pressure level atmospheric data. The altitude (the average surface height, $h_o$) in each grid is obtained from high resolution digital elevation model (DEM) (Fig. 1). The variation of the average ZTD, $Z_{TD mean}$, (Fig. 3, panel (a)) at $h_o$ has inverse relationship with $h_o$ as demonstrated over the central and northern part of Ethiopia. These regions are highlands implying mainly that ZTD is low as expected and also reported by [18] in terms PWV. In contrast, the southeastern and southwestern parts of the country exhibit high ZTD. The mean variation of $Z_{TD mean}$ ranges from 1.8 m to 2.5 m over the region. The ZTD amplitude, $Z_{TD amp}$, (Fig. 3, panel (b)), decreasing and acceleration rates (Fig. 3, panel (c-d)) also exhibit variation with height. For example, the annual mean of $Z_{TD amp}$ ranges from 0.02 to 0.08 m over the region. Furthermore, the $Z_{TD amp}$ and the $Z_{TD mean}$ at $h_o$ have similar trend.

2) The Temporal and Spatial Characteristics of the Model Coefficients: The $a_1$ and $a_2$ model coefficient at a 6-hour interval were fitted using ERA-Interim pressure level data for each grid point. The results in Fig. 4 depict the time series for the decreasing, $a_1$, and the acceleration, $a_2$, rates over Ethiopia for some randomly selected locations. The variation of $a_1$ and $a_2$ coefficient (Fig. 4) were caused by daily and seasonal changes of moisture field.

C. Validation of the Model skill

In order to verify whether the model implementation is truly realistic or not, a validation exercise is very important. The validation of this model was performed based on GPS measurements. The GPS measurement is selected for the validation since ZTD obtained from GAMIT network solution has an accuracy less than 1 cm [17]. The model ZTD was interpolated to GPS station by using Shepard interpolation techniques from the nearest grid points. The six stations were selected for validation of the model ZTD. The dark black data points represent ZTD from GPS measurements, the red line represents ZTD from modified model estimates for Ethiopia (Fig. 5). For all station, as shown in Fig. 5, the model provides a better fit to the GPS measurements, especially with better performance in summer season. This is primarily linked to the model decreasing and accelerating rate coefficient which also perform better in capturing daily and seasonal variations. The model slightly overestimates the signal delays at Asab and Bahir Dar station while the model tends to be near the middle of the spread of ZTDs from GPS measurements at Addis Ababa, Arba Minch, Nazareth and Robe. The possible causes for the slight overestimation might be linked to the interpolation used to obtain the ZTD value at the GPS stations. However, the mean values match the GPS measurement value for all stations.

Fig. 6 show hourly ZTD for four randomly selected days from different season in year 2010 for Addis Ababa (panel (a)-(d)) and Arba Minch stations (panel (e)-(h)) determined using the model (the red line points) and GPS measurements (the black line points). For ADIS station, on one of the day during dry season (e.g., January 25) the model slightly overestimates the delays for all hours. However, the model underestimate delay in spring season (e.g., March 20), but closer to observations between 6, 12 and 18 hours (UT). On the other hand, the model ZTD is much closer to GPS measurement in summer season (e.g., July 31) especially at 6 and 12 UT. For Arba Minch, ARMI station, the model ZTD estimates and GPS observations agree well during all season at all time. However, the model performance in summer season is again superior to its performance in other seasons.

Fig. 7 shows the daily mean ZTD bias during 2007-2011 over Addis Ababa, Arba Minch, Bahir Dar and Nazareth GPS stations. The bias of the model estimated ZTD with respect
Fig. 7. The daily mean bias in ZTD during 2007-2011 period at Addis Ababa, Arba Minch, Bahir Dar and Nazareth GPS stations, Ethiopia.

TABLE II
MONTHLY AVERAGE BIAS AND RMSE OF MODEL ZTD WITH RESPECT TO THE GPS ZTD AVERAGED OVER THE PERIOD 2007-2011 AT SELECTED STATION, IN UNIT OF CENTIMETER (CM).

<table>
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<th>Mar</th>
<th>Apr</th>
<th>May</th>
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<th>Jul</th>
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<tr>
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<td>-1.4</td>
<td>1.6</td>
<td>-0.6</td>
<td>-2.5</td>
<td>-2.4</td>
<td>-1.8</td>
<td>-0.7</td>
<td>-0.1</td>
<td>-0.1</td>
<td>-1.4</td>
<td>-0.9</td>
</tr>
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<td></td>
<td>RMSE</td>
<td>2.1</td>
<td>1.1</td>
<td>2.1</td>
<td>2.0</td>
<td>1.3</td>
<td>2.5</td>
<td>2.6</td>
<td>1.9</td>
<td>1.0</td>
<td>0.9</td>
<td>1.3</td>
<td>2.3</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>STD</td>
<td>1.9</td>
<td>1.1</td>
<td>1.6</td>
<td>1.2</td>
<td>1.2</td>
<td>0.7</td>
<td>0.9</td>
<td>0.8</td>
<td>0.8</td>
<td>0.9</td>
<td>1.3</td>
<td>1.8</td>
<td>1.2</td>
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</table>

The magnitude maximum monthly ZTD bias at Addis Ababa, Arba Minch and Nazareth are 3.7 cm (negative) in October, 5.5 cm (negative) in July and 3.2 cm (negative) in June, respectively. Table II shows that for all the six stations, the annual mean bias of the model is in the range of -6.6 to -0.9 cm, with the mean value of -4.5 cm. Most of the stations have relatively moderate bias during summer season compared to the rest of season, which reflect the model ZTD has good performance in wet season. Fig. 8b shows monthly average RMSE in the model ZTD with respect to the GPS ZTD at Addis Ababa, Arba Minch and Nazareth stations averaged over 2007 to 2011. The maximum RMSEs at Addis Ababa, Arba Minch and Nazareth are 4.0 cm (in October), 5.8 cm (in January and July) and 9.3 cm (in June and October), respectively. Likewise, from Table II, it can be also seen that the over all annual mean of the RMSE of the model ZTD is in the range of 1.8 to 6.8 cm, with the mean value of 4.5. The highest RMSE is found in ASAB and NAZR , while the
Fig. 5. Comparison ZTD time series at six GPS station with modifie model (the red line) for Ethiopia and GPS measured (dark black data points) ZTDs.

Fig. 6. Hourly comparison of ZTDs estimated (the black line) from model and GPS measurements (the red line) for Addis Ababa (panel (a-d)) and Arba Minch (panel (e-h)) stations in Ethiopia.

smallest is in ADIS and ROBE. The estimation of STD for all stations (Table II) remain lower than 1.5 cm during the month of the year. The over all annual mean variation of STD is 1.1 to 2.5 cm with mean value 1.5 cm. The the highest STD is 3.7 cm at ASAB in January and the smallest is 0.4 cm at ADIS in September. In all stations, the smallest STD is found in summer months (June, July and August) except in ARMI which have small STD in Autumn months (September, October and November).

Fig. 7. Monthly bias in ZTD at the Addis Ababa, Arba Minch and Nazareth GPS stations, Ethiopia, averaged over the period 2007 - 2011.

Fig. 9. Hourly bias in ZTD model estimates with respect to GPS ZTD for arbitrarily selected days in 2010 at Addis Ababa (panel (a)-(d)) and Arba Minch (panel (e)-(h)) stations in Ethiopia.

Fig. 8. Monthly bias in ZTD model estimates with respect to GPS ZTD for arbitrarily selected days in 2010 at Addis Ababa (panel (a)-(d)) and Arba Minch (panel (e)-(h)) stations in Ethiopia.
with mean values between 1.3 to 3.2 cm for Addis Ababa; and -5.3 cm (e.g., October 25th at 18 UT) with mean value between 0.2 to 1.3 cm for Arba Minch. In spring season (e.g., March 20th) the bias is positive for both stations through out the day except for Arba Minch which has minor fluctuation at 12 and 18 UT. The minimum RMSE is in July 31 for both stations. A summary of mean annual daily bias, monthly average bias, RMSE and STD, and hourly bias, RMSE and STD statistics for the selected stations are given in Tables II-III.

IV. CONCLUSION

The performance of the model in reproducing the model ZTD has been evaluated. The model decreasing and accelerating rate coefficient show seasonal variation due to different sources of moisture field and dry gas. The mean ZTD ranges from 1.8 m to 2.5 m, over the region. However, the mean annual amplitude variation of ZTD ranges from 0.02 m to 0.10 m over the region. The comparison of the model ZTD with corresponding GPS measurements shows very good agreement especially in summer season. For most of the GPS stations, the over all annual mean RMSE of model ZTD during the study period are 4.8 cm. Similarly, the mean daily ZTD bias ranges from -6.6 cm to -0.9 cm. The RMSE decreases as the altitude increases while its variation with latitude and longitude is not very obvious over Ethiopia. Therefore, this model is good enough and can be used to estimate ZTD for navigation and positioning applications by providing real-time tropospheric delay correction at user height over the region. Moreover, the good performance of the model suggests that the model can be used in complex region such as Ethiopia.

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REFERENCES


