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Estimating Station Specific Zenith Tropospheric Delay in a Local GPS Network from Observed Surface Meteorology

Dodo J. D.[1,2,*], Nwodo G. O.[2], Ojo P. E.[2]

[1]Centre for Geodesy and Geodynamics, National Space Research and Development Agency, Toro, Nigeria
[2]Department of Geomatics, Faculty of Environmental Sciences, University of Benin, Benin City, Nigeria
*Corresponding author: jd.dodo@gmail.com

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Abstract The total zenith tropospheric delay (ZTD) is an important parameter of the atmosphere which directly or indirectly give reflection of the atmospheric condition in a local GPS network. The use of the global tropospheric models such as the Saastamoinen model, Hopfield model, Neil model etc in estimating the tropospheric effects at the local level leaves much to be desired. These models are derived using data from available radiosonde obtained from Europe and North America continents. The global atmospheric condition used as constants in these models provides a broad approximation of the tropospheric conditions, but ignores the actual atmospheric conditions on a given location i.e. do not take into account the latitudinal and seasonal variations in the atmosphere. It is necessary to assess the effects of the troposphere on geodetic measurements based on ground meteorological measurements including temperature, pressure, and relative humidity. Daily RINEX GPS data from eight (8) Malaysian Real Time Kinematic GPS Network (MyRTKnet) stations in Southern Malaysia from year 2006 to June 2008 thus; covering 2½ years were processed. A computer program for modelling 2½ years of local meteorology within the network was developed and called MetMOD, similarly a program, call SaastroMOD was developed to estimate the local zenith hydrostatic delay. The results showed that, the estimated local tropospheric delay considered the temporal and spatial variation of the network thus; giving true reflection of the tropospheric delay in a local GPS network as against the standard atmosphere which ignores the actual local condition with a standard deviation of 0.18 m having a maximum zenith tropospheric delay (ZTD) of about 2.6 m. The best zenith hydrostatic delay (ZHD) comes from station JHJY with a standard deviation of 0.353 cm, while the best zenith wet delay (ZWD) comes from station TGRH with a standard deviation of 5.943 cm. The models show that, while parameters evolved for ZHD are constant at different locations, however, those parameters evolved for ZWD show significant variations from one location to the other. Hence then use of the local meteorological parameter in modelling tropospheric delay improves GPS positional accuracy.

Keywords: *zenith tropospheric delay, zenith hydrostatic delay, zenith wet delay, GPS reference station, linear surface model, MyRTKNet*

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1. Introduction

There are two classes of tropospheric biases that affect the GPS network; they are those that influence the height component and others affecting the scale having a significant effect in terms of positional accuracy [1]. The tropospheric delay is usually estimated based on surface pressure, temperature and relative humidity measurements at the GPS receivers being used [2]. The delay can be considered to consist of two components, namely; the Hydrostatic and Wet components. The hydrostatic is cause by the non-water portion of the atmosphere, a function of surface pressure and accounts for 90% of the total delay. The hydrostatic has a smooth, slowly time-varying characteristic because of its dependence on variations in surface air pressure. As a result of this dependency, it can be modelled and removed while achieving an accuracy of a few millimetres and even better when surface pressure, temperature and humidity are used. The wet component is a function of the distribution of water vapour in the atmosphere. It represents about 10% of the total tropospheric delay [3]. The wet component is harder to remove using standard tropospheric models with surface measurements. The use of surface meteorological data in local tropospheric modelling is very crucial as it presents the local troposphere situation. Three surface meteorological observations are required to model the tropospheric GPS signal delay into its wet and dry components. They include the surface pressure components, which are used to estimate the zenith hydrostatic delay with an error of about 0.5% under normal conditions and the surface temperature in estimating the mean temperature of the atmosphere with an error of about 2%. Humidity is also one of the parameters of the surface meteorological data [4].

[5] investigated the effect of the troposphere in the Taiwan Network GPS tacking station by modelling the troposphere using the Standard Atmospheric (SA) model e.g., Saastamoinen model, surface measured meteorological data and polynomial scale factor. The result showed that the Saastamoinen model fair better, however, the poor performance of the surface meteorological data is attributed to the small changes in weather conditions as 3 days data were processed and also error in the calibration of the surface meteorological measurement equipment.

However, [6] asserted that, one of the methods to reflect the atmospheric condition within a local GPS network is to model the local tropospheric effect. This is possible by simultaneous meteorological observation to GPS measurements at the same stations. The result of the test conducted using the local network of KARKONESZE (Sudetes, South-West Poland) where the Standard Atmosphere model (SA), Minimum Operation Performance Standard for Global Positioning System (MOPS) model and ground meteorological data were used as input data for different methods of tropospheric delay estimation; revealed that, the local tropospheric model created considered temporal and spatial changes thereby allowing adequate modelling of the tropospheric delay as compared to the standard atmospheric models.

According to [7], after processing GPS data of the Sniekznik local precise geodynamic network using Standard Atmosphere, the Standard Atmosphere model does not reflect the real meteorological conditions. Instead, GPS measurement with the simultaneous meteorological observation of temperature, pressure and humidity at selected network points were modelled to create a local troposphere model from interpolating the measured meteorological parameter, thus yielding a better result when compared with the Standard Atmosphere model.

2. GPS Meteorology

There are two basic types of models for estimating the tropospheric delay. These include the use of Standard Atmosphere in the model domain and the use of Local Surface Meteorology.

2.1. Standard Atmosphere

The first relates to the global standard atmosphere. The Standard Atmosphere parameter of temperature *T*, pressure *P* and relative humidity *RH* form the basis for the Standard Atmosphere Model (SA). These are applied in most of the GPS processing software and given by [8].

$$P_s = P_r\left[1 - 0.0000226(H_s - H_r)\right]^{5.225} \quad (1)$$

$$T_s = T_r\left[-0.0065\left(H_s - H_r\right)\right] \quad (2)$$

$$RH_s = RH_r\left[e^{-0.0006396}\left(H_s - H_r\right)\right] \quad (3)$$

where; P_r, T_r and RH_r are the pressure (hPa), temperature (degree Celsius) and relative humidity in % at height H_r above the mean sea level of the reference point and P_s, T_s, RH_s are the corresponding pressure, temperature and relative humidity at height H_s of the site. This model is used in calculating meteorological parameters at different locations. The standard values used for the reference site as contained in most GPS processing software are; $H_r = 0$m, $P_r = 1013.25$ hPa, $T_r = 18^\circ C$ and $RH_r = 50\%$.

2.2. Local Surface Meteorology

The second relates to the local meteorological parameters to surface meteorological measurements. These surface meteorological models are based on radiosonde profiles measurements taken at the ground surface or at the GPS station. In order to obtain the meteorological parameter at a GPS stations where meteorological sensors are not available, the meteorological parameters of all the network points are designated by interpolation [9].

2.3. Tropospheric Delay Model

The refined Saastamoinen tropospheric model is used in this study. It is expressed as a function of height of the observing station and the zenith angle. The modified model is given in the form [10].

$$D_z^{trop} = \frac{0.002277}{\cos z}\left[P + \left(\frac{1255}{T} + 0.05\right)e - B\tan^2 z\right] + \delta R \quad (5)$$

where:

D_z^{trop} = propagation delay in terms of range (m)

z = zenith angle of the satellite

P = atmospheric pressure at the site in millibar (mbar)

T = temperature at the station in Kelvin (K)

e = partial pressure of water vapour in millibar (mbar)

$B, \delta R$ = are the correction terms of height and zenith angle

B and δR are the correction terms that depend on height H of the station and the zenith angle z of the satellite.

3. Materials and Methods

3.1. Materials

3.1.1. Study Area

The Malaysian RTK GPS Network is designed with the primary objective of ensuring real-time capability by way of providing centimetre positioning over the entire territory of Malaysia through a network correction broadcast from a centralized processing centre [11]. The study focused primarily on the Johor Bahru dense network (Southern Malaysian Peninsula), covering latitudes 1°30'N to 2°30'N and longitude 102°E to 105°E along the equator. Figure 1 shows the Network used in this research which is in the equatorial region.

Table 1. Johor Bahru MyRTKnet reference station information

No.	Station ID	Station Location	Revised GDM2000@ 2000							
			Rev	Latitude (N)			Longitude (E)			Ellipsoidal Height (m)
				deg.	min.	sec.	deg.	min.	sec.	
1	JHJY	Johor Jaya	B	1	32	12.51889	103	47	47.51012	39.206
2	KLUG	Kluang	B	2	1	31.36250	103	19	0.52025	73.607
3	KUKP	Kukup	B	1	19	59.79173	103	27	12.35498	15.429
4	MERS	Mersing	B	2	27	12.48344	103	49	43.50465	18.1
5	TGPG	Tanjung Pengelih	B	1	22	2.68028	104	6	29.73036	18.107
6	GAJA	Kg. Gajah, Kluang	B	2	7	20.24411	103	25	21.75286	60.244
7	SPGR	Simpang Renggam	B	1	48	38.14468	103	19	15.52189	34.208
8	TGRH	Tenggaroh	B	2	4	46.76591	103	56	48.98236	60.146

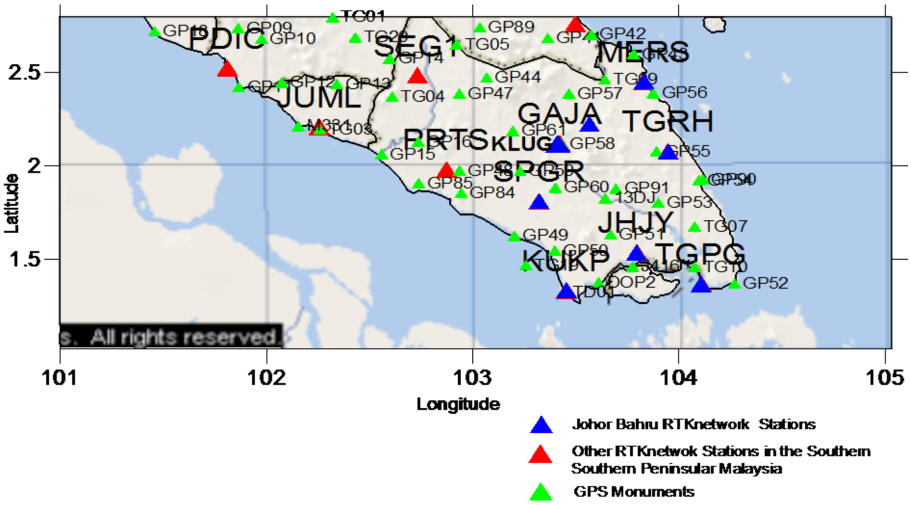

Figure 1. Johor Bahru MyRTKnet Stations (Edited from [12])

The Johor Bahru network of MyRTKNet shown in Figure 1 consists of eight GPS reference stations namely, Johor Bahru (JHJY), Kukup (KUKP), Mersing (MERS), Kluang (KLUG), Tanjung Pengelih (TGPG), Kg. Gajah, Kluang (GAJA), Simpang Renggam (SPGR), and Tenggaroh (TGRH). Each station is equipped with dual frequency GPS receiver (Trimble 5700), and a server linked to the control centre in Kuala Lumpur. Table 1 provides further information on the Johor Bahru MyRTKnet reference stations.

3.1.2. GPS Data Acquisition

In order to reduce the computational load, the datasets were divided into three parts according to year, months and days. GPS campaigns were carried out from January 2006 to June 2008. Twenty-four hours (24hrs) raw GPS data at 30-second data rate were acquired. Corresponding precise satellite ephemeris were downloaded from the International GNSS Service (IGS) The ocean tide loading data for each station was obtained from [13]. Similarly, the Earth Orientation Parameters and the Ionosphere models were downloaded from [14]. Summary of the parameters used are given in Table 2.

3.1.3.Meteorological Data

Daily meteorological data recorded from January 2006 to June 2008 (2½ years) at one-hour (1hr) interval at the four Malaysian Weather Stations of Batu Pahat, Kluang, Mersing and Senai in Table 2 were made available by the Department of Meteorology Malaysia. The data include, daily hourly temperature (^{0}C), daily hourly pressure (hPa) and daily hourly relative humidity (%). Due to the sensitivity of the meteorological parameters to station heights, the weather station heights given with respect to the mean sea level (MSL) were converted to the GPS ellipsoidal heights using the Malaysian Geoidal Model (MyGeiod). Figure 2 shows the location of the weather stations.

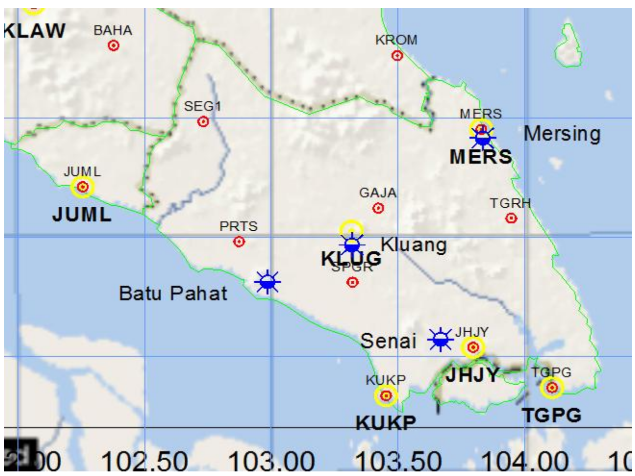

Figure 2. Location of the four meteorological stations in the study area in blue star symbol

Table 2. Meteorological stations and data type used

Weather Station	Close GPS Station	Geographical Location		Ellipsoidal Heights (m)	Type of Data (Daily)
		Latitude (N)	Longitude (E)		
Senai	Johor Jaya	01 º38'	103 º40'	45.673	temperature, pressure, relative humidity
Kluang	Kluang	02 º01'	103 º19'	93.995	temperature, pressure, relative humidity
Mersing	Mersing	02 º27'	103 º50'	50.848	temperature, pressure, relative humidity
Batu Pahat	Simpang Rengam	01 º50'	102 º59'	311.042	temperature, pressure, relative humidity

3.2. Methods

3.2.1. Computer Program Development

Computer programs called MetMOD (Meteorology Modelling) based on Linear Interpolation Algorithm and SaastroMOD (Saastamoinen Troposphere Modelling) based on the refined Saastamoinen model were developed using the MATLAB programming language in modelling the local meteorological data from the meteorological station to the GPS station and for estimating the dry components of the local tropospheric delay at the GPS station.

[7] gave an approach for obtaining the meteorological parameter for stations within the GPS network. For such points within the network, the meteorological values ψ for temperature T, pressure P and relative humidity RH for each point are obtained on the basis of measured values at n number of points as weighted mean values. Figure 3 shows the flowchart of the Combined MetMOD program developed and executed in MATLAB.

For Temperature T; with weight w_i

$$\psi_i = T_i \tag{6}$$

$$T = \frac{\sum_{i=1}^{n} T_i w_i}{\sum_{i=1}^{n} w_i} \tag{7}$$

but weight

$$w_i = \left(h_{in} - h_i\right)^{-n} \tag{8}$$

where, $\psi_i = T_i$: temperature at measured point

h_{in} : height of interpolated point

h_i : height of measured point.

For pressure P with the weight inversely proportional to the distance;

$$\psi_i = P_i, \tag{9}$$

$$P = \frac{\sum_{i=1}^{n} P_i w_i}{\sum_{i=1}^{n} w_i} \tag{10}$$

but the weight w_i is computed from

$$\frac{1}{w_i} = \left(x_{in} - x_i\right)^2 + \left(y_{in} - y_i\right)^2 \tag{11}$$

where: P_i pressure of the measured point

x_{in}, y_{in} : plane coordinates of the interpolated points

x_i, y_i : plane coordinates of measured points

For relative humidity RH, the weight is inversely proportional to the spatial distance

$$\psi_i = RH_i, \tag{12}$$

$$RH = \frac{\sum_{i=1}^{n} RH_i w_i}{\sum_{i=1}^{n} w_i} \tag{13}$$

$$\frac{1}{w_i} = \left(x_{in} - x_i\right)^2 + \left(y_{in} - y_i\right)^2 + \left(h_{in} - h_i\right)^2 \tag{14}$$

where:

RH_i relative humidity at the measured point

x_{in}, y_{in} : plane coordinates of interpolated points

x_i, y_i : plane coordinates of measured points

h_{in} : height of interpolated point

h_i : height of measured point.

The Saastamoinen tropospheric delay model program named SaastroMOD for calculating the amount of tropospheric delay was developed based on equation 7. Figure 4 shows the flowchart of the SaastroMOD program developed and executed in MATLAB.

3.2.2. Data Processing

The Bernese GPS Scientific processing software version 5.0 was used to solve for and model the orbital parameters of satellites, solve for the transmitter and receiving positions, phase cycle ambiguities and clock drifts in addition to solving the tropospheric delay parameters of interest. The total zenith tropospheric delay (ZTD) was estimated using two strategies as shown in Figure 4 and summarized as follows and the processing parameters shown in Table 3.

Strategy I: Application of Standard Atmosphere to the Saastamoinen model. The ZTD is referred to as GPS ZTD.

Strategy II: Application of the modelled meteorological parameter results (MetMOD) to the Saastamoinen model (SaastroMOD). The ZTD is referred to as SaastroMOD ZTD.

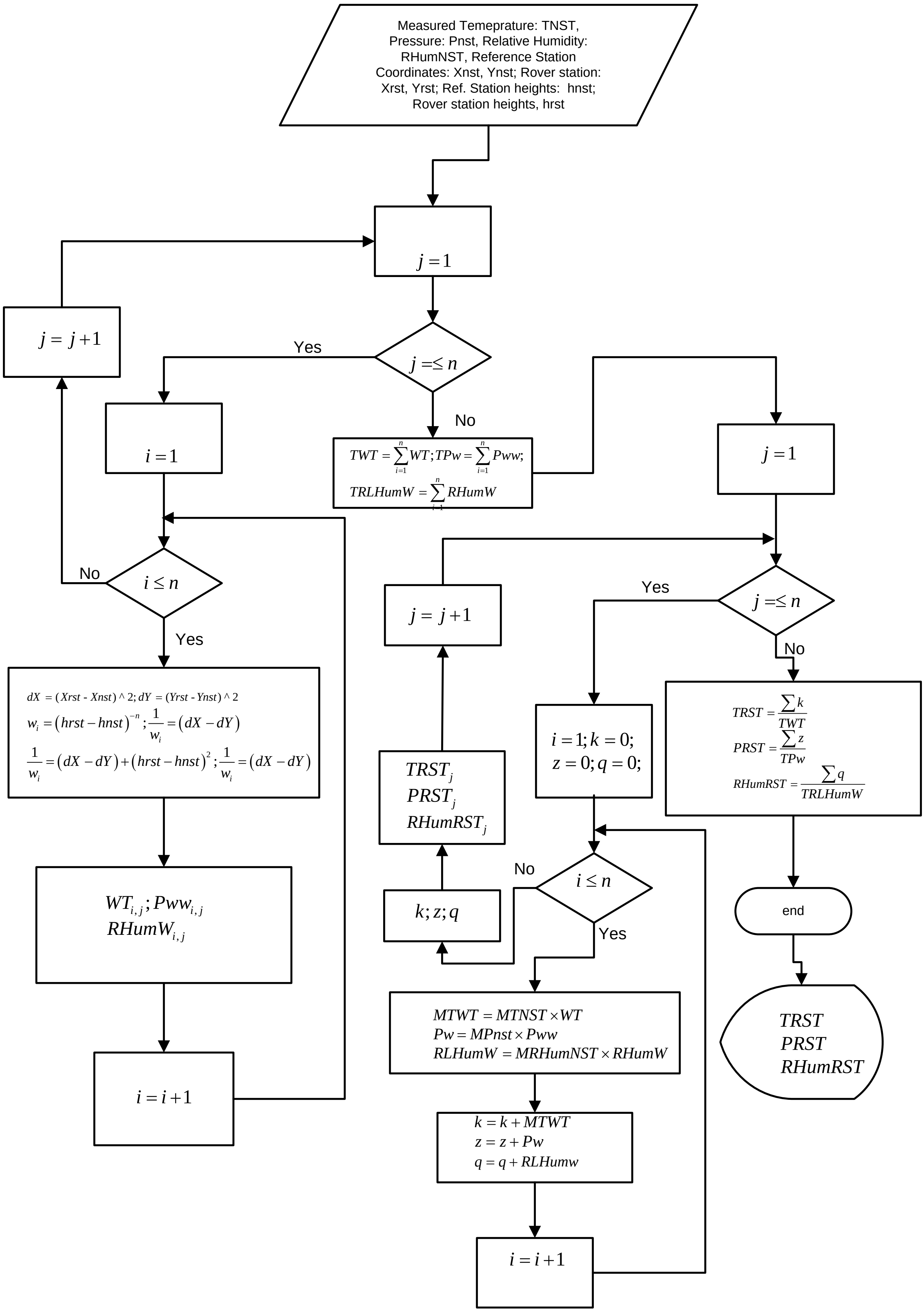

Figure 3. Flowchart of the Combined **MetMOD** Modelling Program Developed and executed in MATLAB

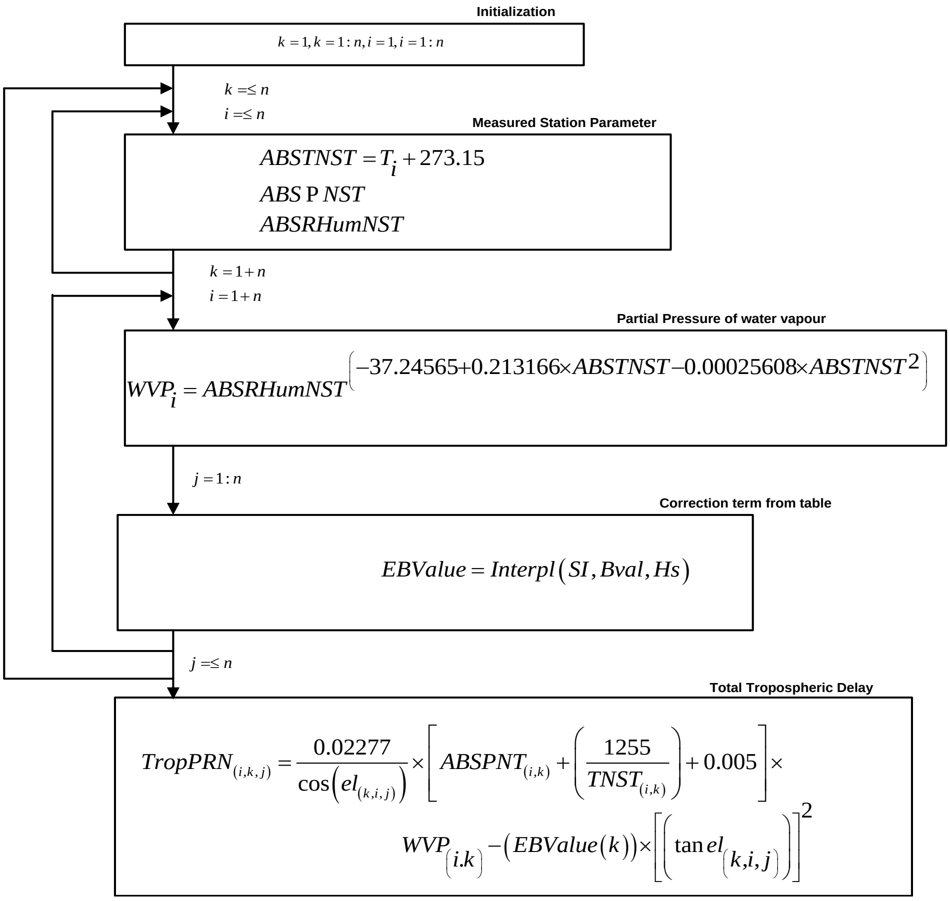

Figure 4. A flow chart of **SaastroMOD** Program developed and executed in MATLAB

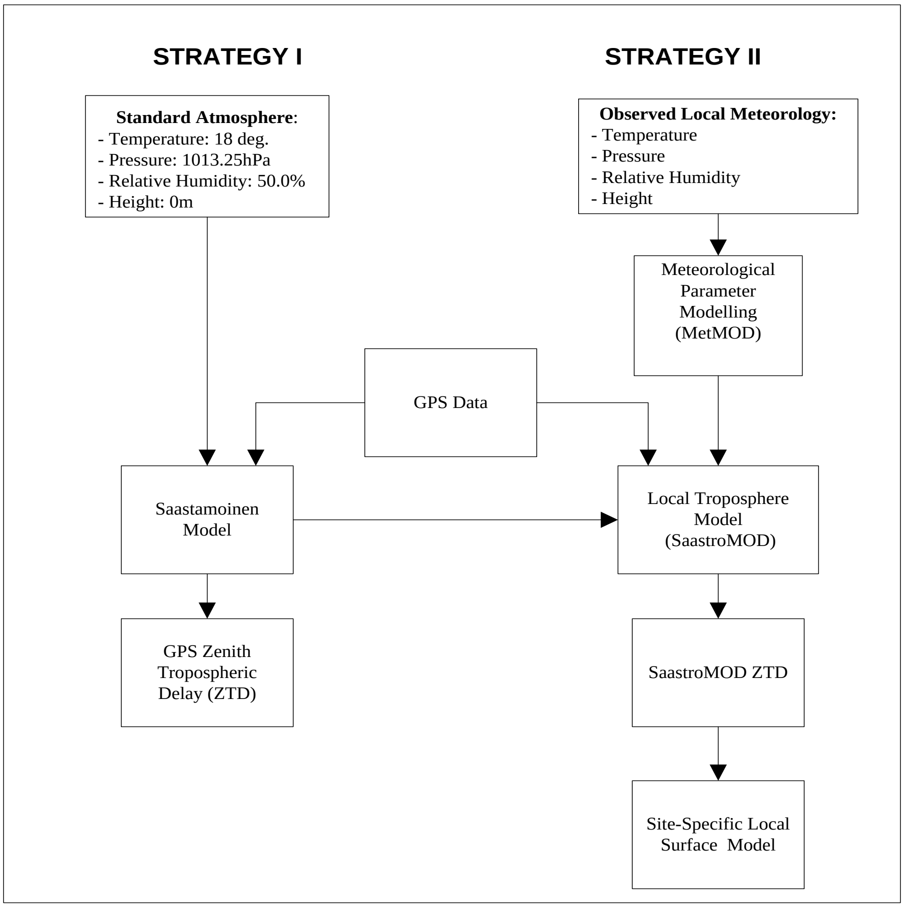

Figure 5. The processing strategy employed in the Bernese GNSS Scientific Software version 5.0

Table 3. Summary of General Processing Parameters

RINEX data at 15 second sampling rate
IGS final orbit
24 hours sliding window processing
Ocean tide loading FES2004
ITRF 2000 reference frame
Cut-off satellite elevation angle at 3^0
Quasi-Ionosphere free (L_3) ambiguity free
Troposphere delay mapping function of $^1/_{\cos z}$
Station coordinates constrained

4. Results and Discussions

One of the methods of reflecting the local troposphere condition at a GPS station is the application of weather condition measured concurrently with GPS data or modelled from any weather station to GPS station [15]. Results of the ZTD based on Strategy I (GPS ZTD) and Strategy II (SaastroMOD ZTD) were analysed.

4.1. Comparison of SaastroMOD ZTD and GPS ZTD

An investigation into the relationship between the application of the standard atmosphere (Strategy I) and the local surface meteorology (Strategy II) in the estimation of the ZTD was carried out. The investigation is based on a two-tailed correlation test at 0.05 degree of freedom for all the eight stations on annual basis for the $2^1/_2$ years. Table 4 shows the yearly mean value of the SaastroMOD and GPS ZTD from January 2006 to June 2008.

The analysis is to find out if the correlation between the ZTDs obtained from SaastroMOD and that extracted from GPS processed data is statistically significant. The result presented in Table 4 reveals that, there is statistically significant correlation between the SaastroMOD ZTD and the GPS ZTD. This implies that, the weather condition does have significant impact on the network [10]. From the annual mean ZTD correlation coefficients for the $2^1/_2$ years presented, it also clear that, the standard atmosphere ignores the actual conditions in a local GPS network. Hence, it does not truly reflect the local tropospheric effect. To this end, the use of local troposphere model in estimating the local ZTD becomes necessary.

Further analysis shows biases ranging from 0.16 m to 0.32 m for the $2^1/_2$ years. The year 2006 has mean ZTD bias ranging between 0.217 m and 0.255 m, year 2007 has mean ZTD bias between 0.168 m to 0.219 m; thus, having the least annual bias. Year 2008 has the high mean ZTD biases ranging between 0.28 m and 0.326 m. This could be attributed to few datasets used for year 2008 analysis i.e. (January to June).

Table 4. Yearly mean value of zenith tropospheric delay (ZTD) from modelled Local Meteorology and Standard Atmosphere

Station	Latitude (N)	Longitude (E)	Ellipsoidal heigh (m)	January - December 2006				
				Mean Local ZTD (cm)	Std ZTD (cm)	Mean ZTD bias (cm)	Std. Dev. (cm)	Correlation 0.05 Degree of freedom (cm)
KUKP	01 °19' 59.79"	103 °27' 12.35"	15.420	267.9	242.4	25.5	6.6	0.189
JHJY	01 °32' 12.51"	103 °47' 47.51"	39.206	265.5	241.8	23.7	6.7	0.286
SPGR	01^0 48' 38.14''	103^0 19' 15.52''	34.208	NA-	NA	NA	NA	NA
KLUG	02 °1' 31.36"	103 °19' 0.52"	73.609	265.3	240.2	25.1	6.8	0.212
TGRH	02^0 04' 46.76''	103^0 19' 15.52''	60.146	NA-	NA	NA	NA	NA
GAJA	02^0 07' 20.24''	103^0 25' 21.75''	60.244	NA-	NA	NA	NA	NA
MERS	02 °27' 12.48"	103 °49' 43.50"	18.100	265.3	243.6	21.7	5.4	0.256
Station	Latitude (N)	Longitude (E)	Ellipsoidal heigh (m)	January - December 2007				
				Mean Local ZTD (cm)	Std ZTD (cm)	Mean ZTD bias (cm)	Std. Dev.(cm)	Correlat 0.05 Degree of freedom (cm)
KUKP	01 °19' 59.79"	103 °27' 12.35"	15.420	269.5	252.7	16.8	9.8	0.155
TPGP	01 °22' 2.67"	104 °6' 29.73"	18.107	270.1	252.9	17.2	9.6	0.322
JHJY	01 °32' 12.51"	103 °47' 47.51"	39.206	268.9	252.1	16.8	9.1	0.199
SPGR	01^0 48' 38.14''	103^0 19' 15.52''	34.208	271.8	250.4	21.4	8.9	0.346
KLUG	02 °1' 31.36"	103 °19' 0.52"	73.609	270.1	250.9	19.2	9.2	0.247
TGRH	02^0 04' 46.76''	103^0 19' 15.52''	60.146	272.1	250.9	21.2	7.9	0.247
GAJA	02^0 07' 20.24''	103^0 25' 21.75''	60.244	272.1	250.2	21.9	7.8	0.134
MERS	02 °27' 12.48"	103 °49' 43.50"	18.100	272.0	253.5	18.5	7.4	0.210
Station	Latitude (N)	Longitude (E)	Ellipsoidal heigh (m)	January - June 2008				
				Mean Local ZTD (cm)	Mean Standard ZTD (cm)	Mean ZTD bias (cm)	Std. Dev. (cm)	Correlation 0.05 Degree of freedom
KUKP	01 °19' 59.79"	103 °27' 12.35"	15.420	270.7	240.5	30.2	9.3	0.208.
TPGP	01 °22' 2.67"	104 °6' 29.73"	18.107	269.2	240.6	28.6	9.0	0.129
JHJY	01 °32' 12.51"	103 °47' 47.51"	39.206	269.8	240.2	29.6	8.9	0.195
SPGR	01^0 48' 38.14''	103^0 19' 15.52''	34.208	271.4	240.2	31.2	6.3	0.186
KLUG	02 °1' 31.36"	103 °19' 0.52"	73.609	270.5	238.9	31.6	7.6	0.196
TGRH	02^0 04' 46.76''	103^0 19' 15.52''	60.146	271.4	240.2	31.2	7.8	0.106
GAJA	02^0 07' 20.24''	103^0 25' 21.75''	60.244	270.7	238.8	31.9	6.4	0.223
MERS	02 °27' 12.48"	103 °49' 43.50"	18.100	271.7	239.1	32.6	6.6	0.204

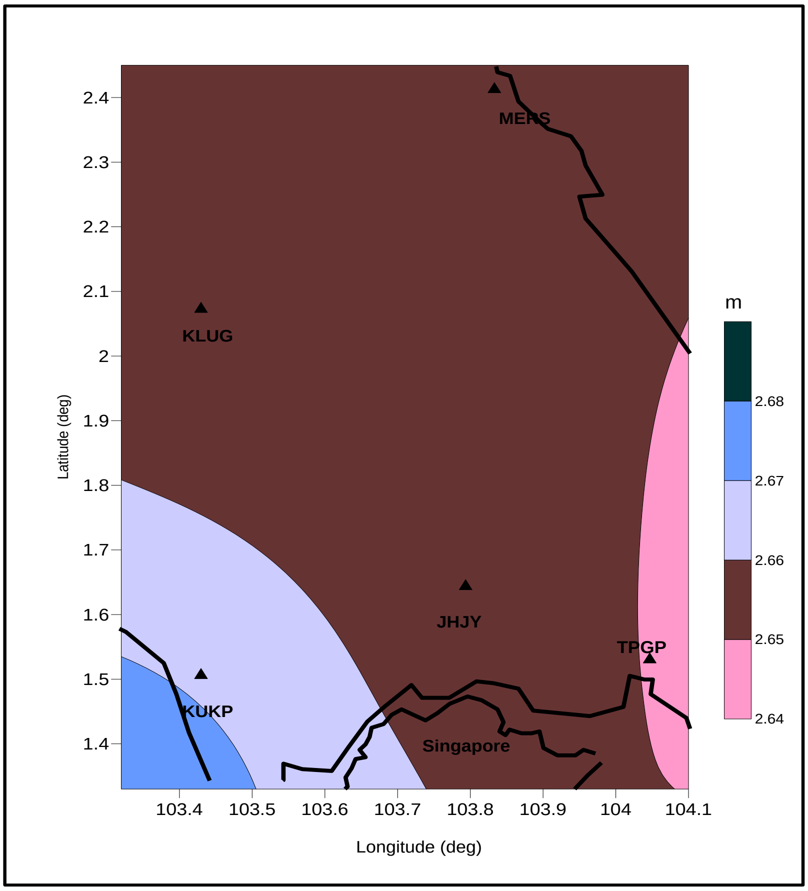

Figure 6a. Distribution of year 2007 mean SaastroMOD ZTD

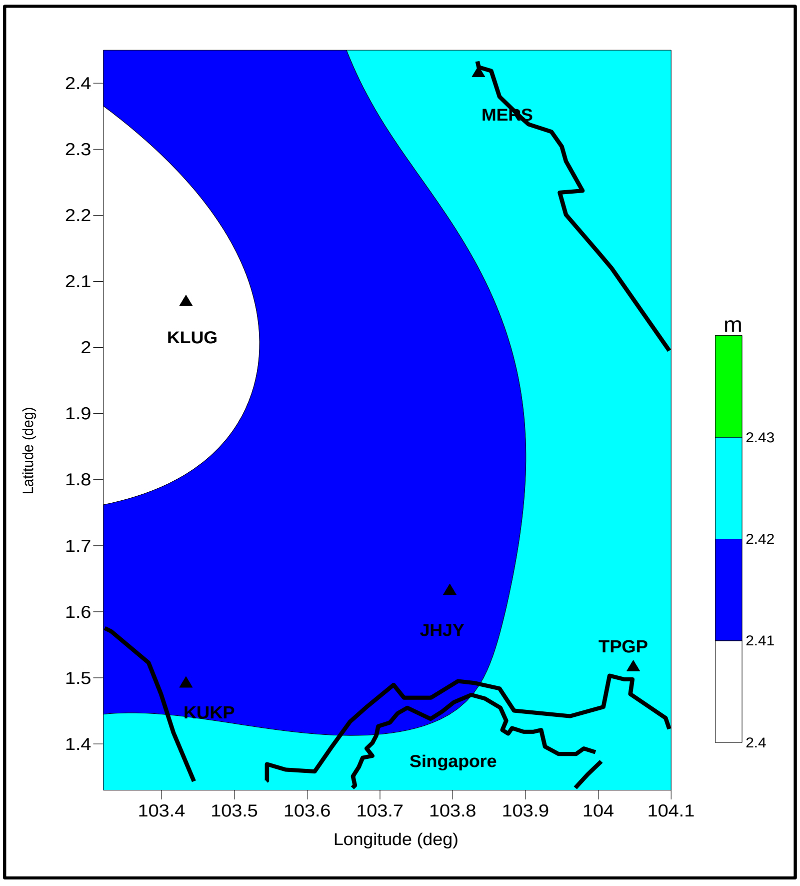

Figure 6b. Distribution of year 2007 mean GPS ZTD

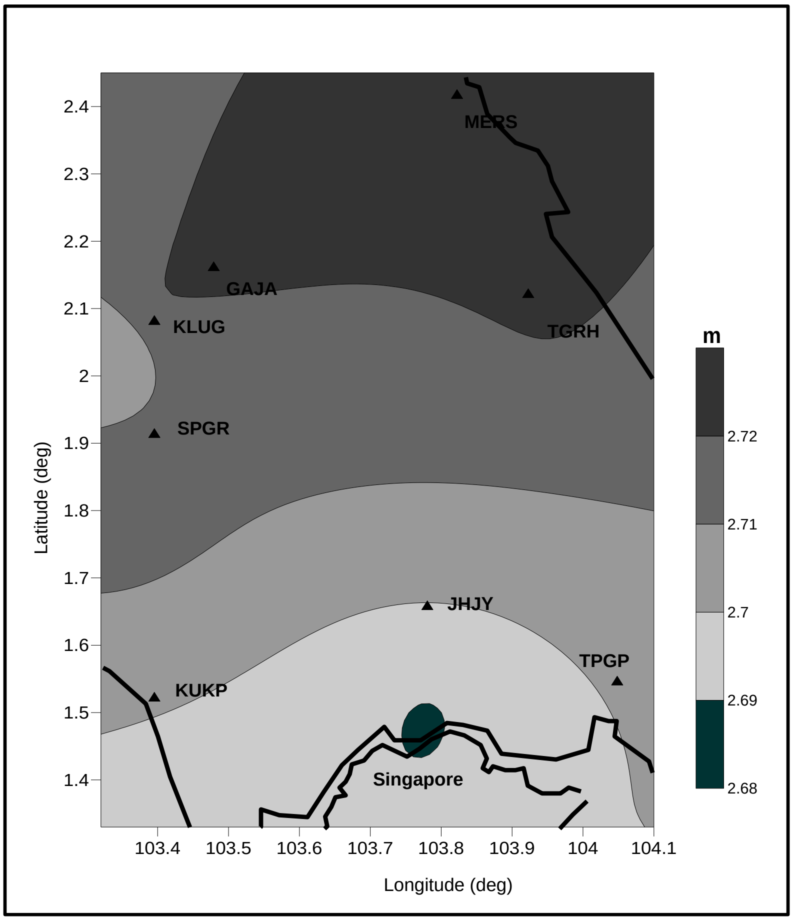

Figure 7a. Distribution of year 2007 mean SaastroMOD ZTD

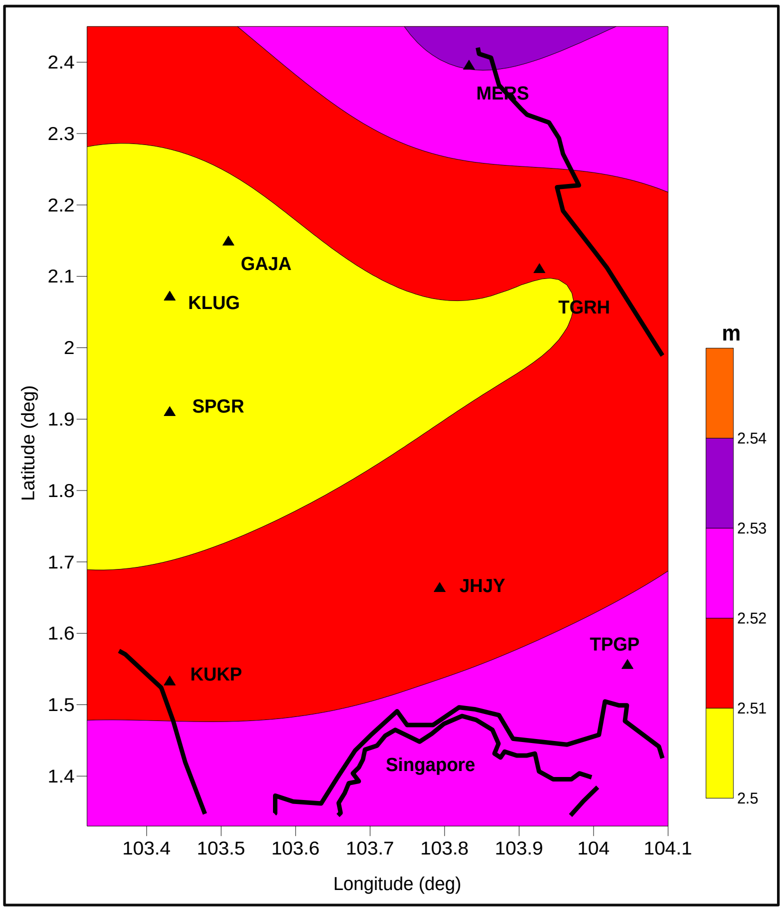

Figure 7b: Distribution of year 2007 mean GPS ZTD

Figure 6 and Figure 7 show the spatial pattern of the annual mean ZTDs computed from the SaastroMOD (Surface Meteorology) and GPS ZTD (Standard Atmosphere). Uniform colour coding was used to depict the spatial pattern in each case. The figures show the spatial pattern of the tropospheric delay produce by the application of the local meteorology and standard atmosphere. It is evident that, the standard atmosphere does not depict the nature of the local atmosphere.

4.2. Time Series Analysis of SaatroMOD ZTD and GPS ZTD

Time series analysis of the plots, Figure 8 and Figure 9 were obtained from GPS ZTD (application of Standard Atmosphere) and SaastroMOD ZTD (application of modelled surface meteorology) for all stations on yearly basis from 8:00 am to 5: 00 pm local time.

From the GPS ZTD time series plots shown in Figure 8 and Figure 9 for the $2^1/_2$ years (January 2006 to June 2008), variations range from 2.32 m to 2.62 m, with most stations around 2.40 m to 2.50 m. The SaastroMOD ZTD time series shown in Figure 5 for the same $2^1/_2$ years (January 2006 to June 2008) variations ranging from 2.55 m to 2.88 m, with most of the stations around 2.60 m to 2.75 m.

The variation between the SaastroMOD and GPS ZTDs is 25 cm at the maximum. Stations KUKP and TPGP located in the southern peninsular Malaysia and closer to the equator have higher ZTD variations in the two strategies. This shows that GPS stations at the equatorial region are highly susceptible to tropospheric effect due to high effects of water vapour. [16] asserted that, such an effect is primarily due to the wet component of the ZTD arising from the presence of water vapour.

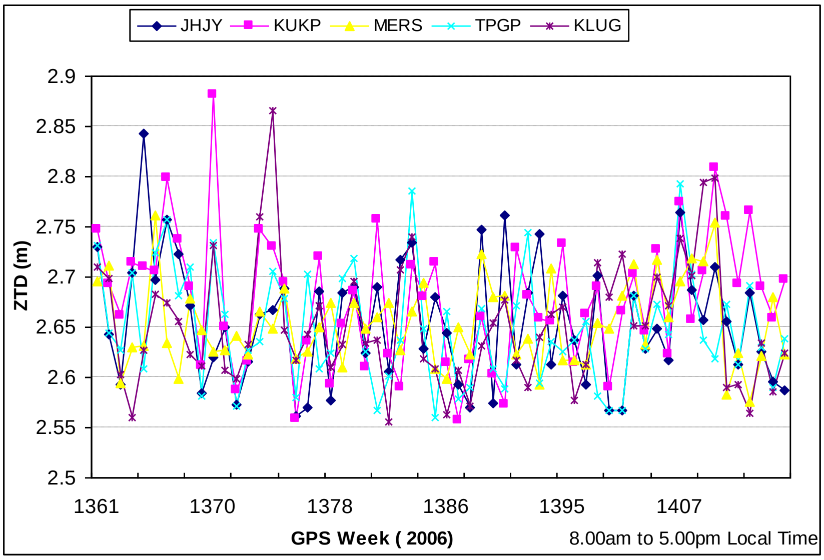

Figure 8a: 2006 SaastroMOD ZTD time series plots

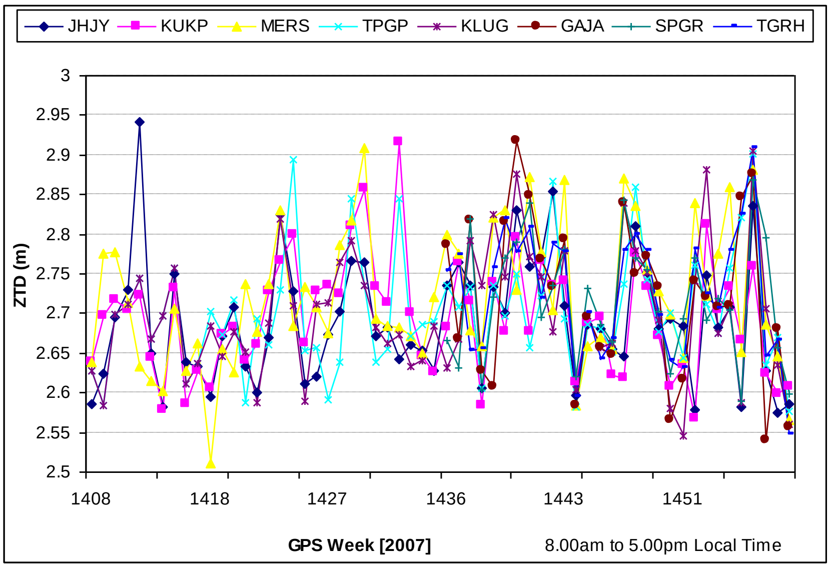

Figure 8b. 2007 SaastroMOD ZTD time series plots

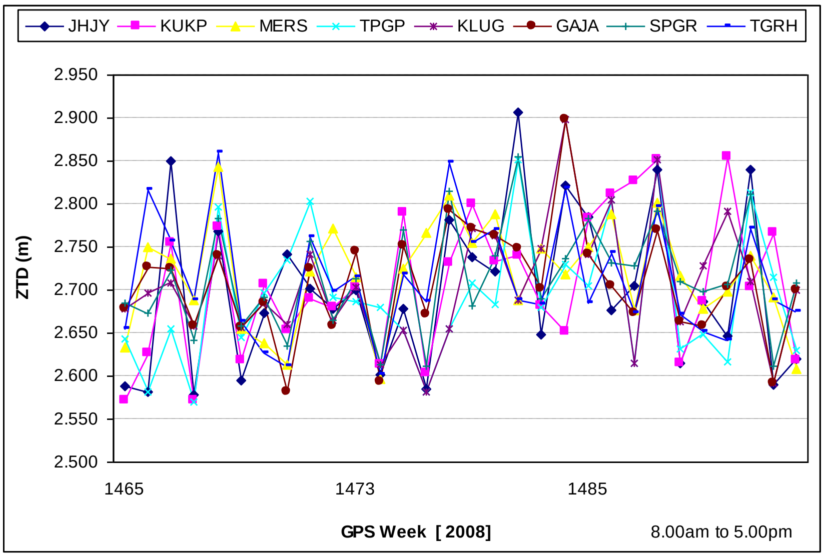

Figure 8c. Jan – Jun 2008 SaastroMOD ZTD time series plots

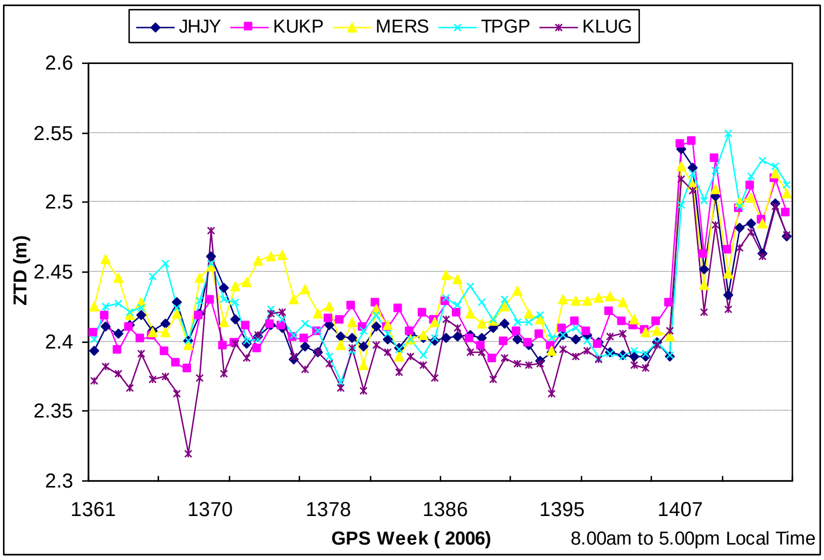

Figure 9a. 2006 GPS ZTD time series plots

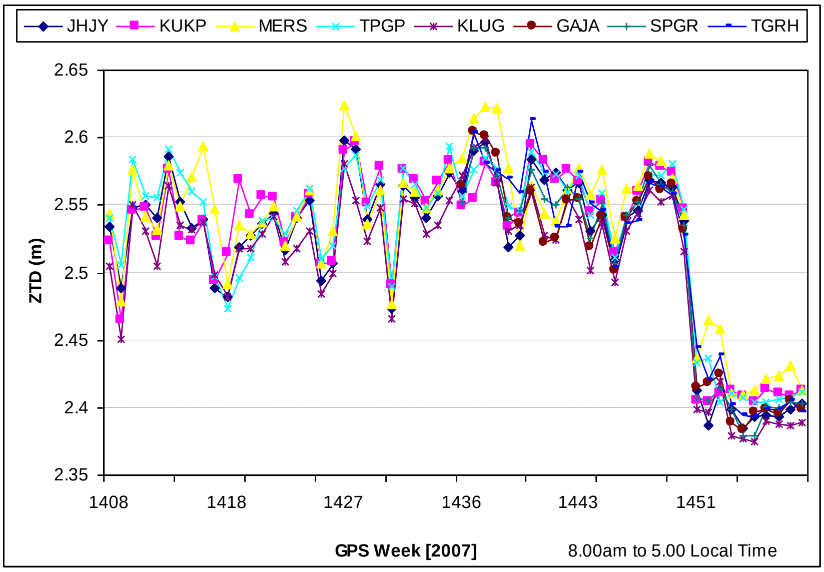

Figure 9b. 2007 GPS ZTD time series plots

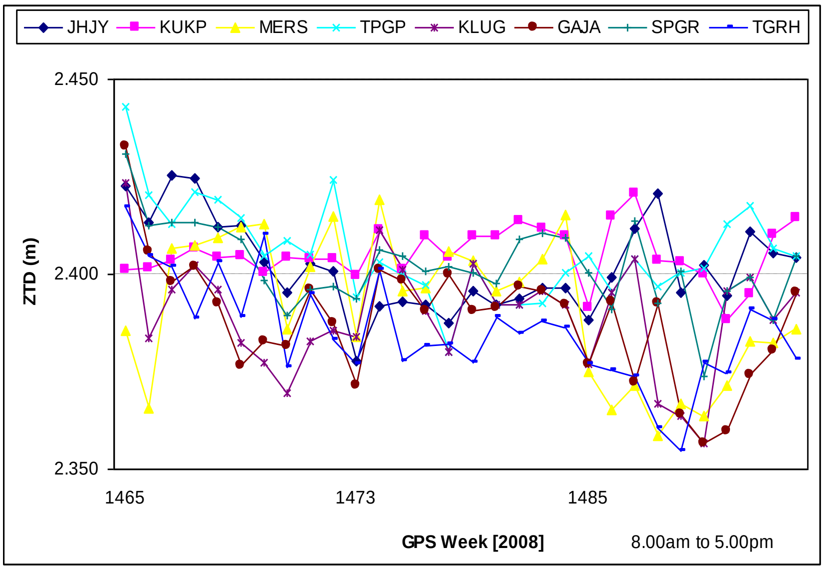

Figure 9c. Jan -Jun 2008 GPS ZTD time series plots

4.3. Daily Variations of Zenith Hydrostatic Delay (ZHD) and Zenith Wet Delay (ZWD)

The results obtained from the implementation of the SaastroMOD were analysed to determine the daily variation and pattern of the ZHD and ZWD in the network. Figure 10 and Figure 11 show the daily mean variation of the ZHD and ZWD for 2006 and 2007 respectively.

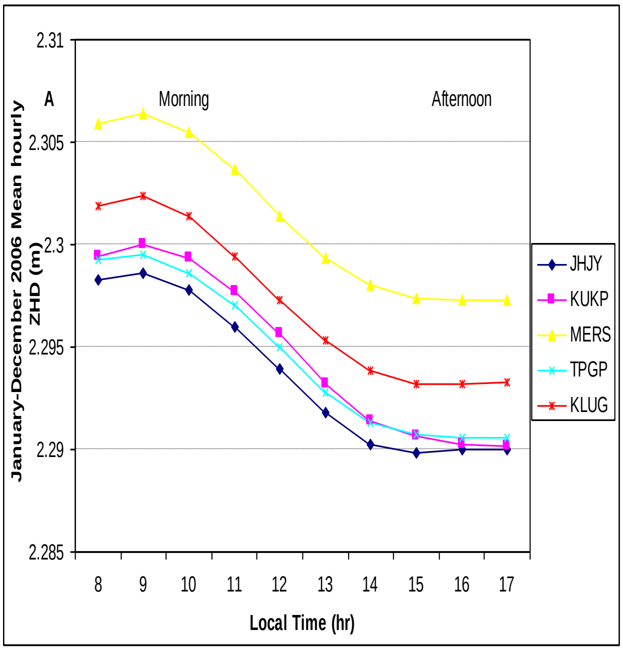

Figure 10a. Year 2006 daily mean hourly ZHD variation

In Figure 10a and Figure 10b the mean day-to-day pattern of the ZHD is separated into morning and afternoon in order to visualise the impact of ZHD at different time of the day. The Figures clearly show that, the ZHD follow similar pattern throughout the 2years. The ZHD, increases during the morning hours and decreases in the afternoon as the sun sets. High values of ZHD range from 2.300 m to 2.305 m between 9:00 hours and 11:00 hours, while low values range from 2.280 m to 2.30 m are seen between 13:00 hours and 17:00 hours. High values of ZHD experienced in the morning hours could partly be due to increase in temperature in a high-pressured area being heated by the sun, thus; causing expansion of the area; resulting to increase pressure. As the temperature decreases with pressure, the ZHD decreases in the afternoon towards the sunset.

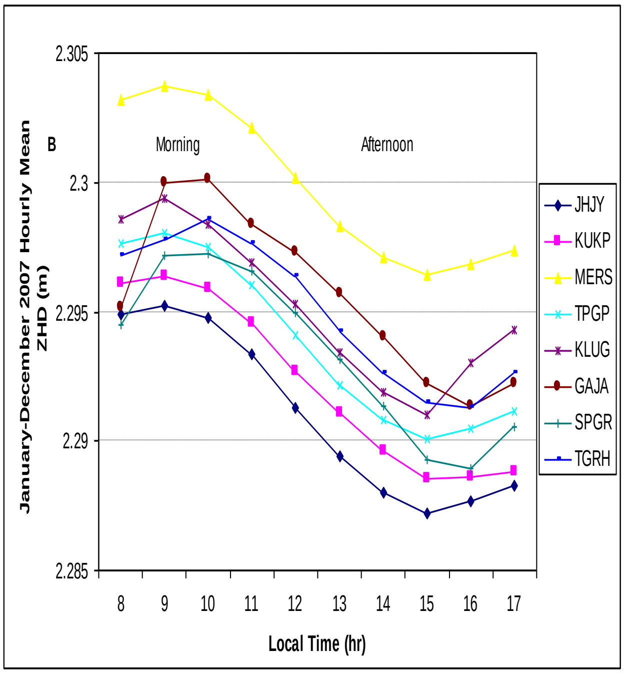

Figure 10b. Year 2007 daily mean hourly ZHD variation

The ZWD shown in Figures 11a and 11b do not follow a particular pattern. However, high values of ZWD are found between 13: 00 hours and 14:00 hours with ranging from 0.361 m to 0.54 m. The inconsistency in the pattern is due to variations of the water vapour which has more influence on the ZWD [17].

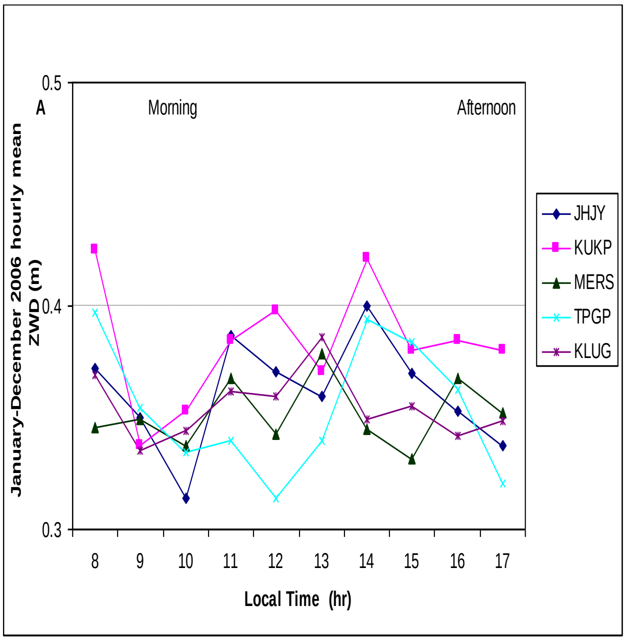

Figure 11a. Year 2006 daily mean

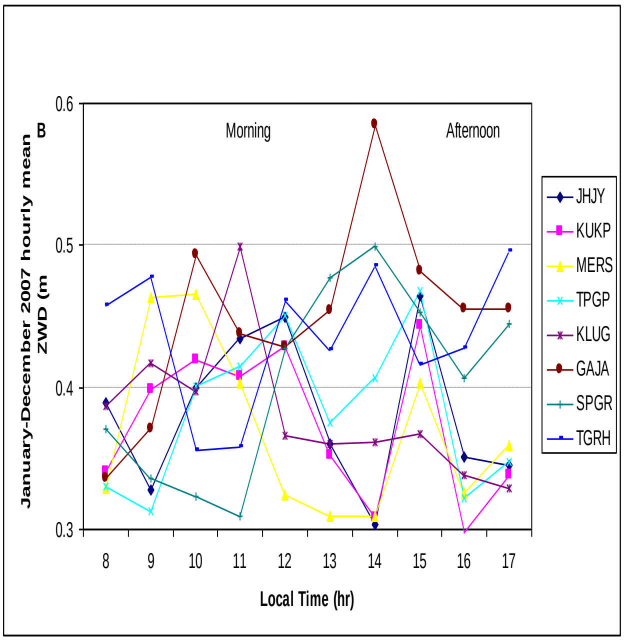

Figure 11b. Year 2007 daily mean

4.4. Site-Specific Surface Linear Models for ZHD and ZWD

Linear relationship for the ZHD models for individual station were established in terms of the modelled surface pressure obtained from MetMOD program though regression analysis. Following similar approach for the ZHD, linear models were also established for the ZWD on the daily mean for different station in terms of the partial pressure of water vapour. The values of the partial pressure of water vapour at individual station were extracted from the results of the SaastroMOD program.

Table 5 shows the ZHD linear model for each station. The quantities inside the parenthesis in each cell show the value of the correlation coefficient and its corresponding standard deviation. For all stations, the value of the correlation coefficient lies between 0.8713 and 1.00 with standard deviation values between 0.0031 m and 0.0037 m. The value of the correlation coefficient for the ZWD lies between 0.02 and 0.5 and standard deviation varies from 0.013 m to 0.06 m. This result shows strong relationship in the ZHD model.

Table 5. Mean values of the regression coefficients estimated for ZHD with respect to modelled pressure and ZWD with respect to partial pressure of water vapour along with their standard errors for each station

Station	Zenith Hydrostatic Delay (ZHD) (cm)	Zenith Wet Delay (ZWD) (cm)
JHJY	0.23±0.1115 (0.99;0.353)	1.34 ±0.8068 (0.038;2.420)
KUKP	0.23±0.1118 (0.99;0.373)	1.31±0.7930 (0.018;2.791)
MERS	0.23±0.1110 (0.99;0.350)	1.28 ±0.4379 (0.463;1.314)
TPGP	0.23±0.1118 (0.99;0.353)	1.29 ±0.8889 (0.079;2.666)
KLUG	0.23±0.1100 (0.87;0.317)	1.34 ±0.6843 (0.078;2.053)
GAJA	0.23±0.1185 (0.99;0.375)	1.39 ±1.0540 (0.224;3.162)
SPGR	0.23±0.1205 (0.99;0.381)	1.36 ±1.2532 (0.019;3.756)
TGRH	0.23±0.1146 (0.98;0.362)	1.42 ±1.9809 (0.3231;5.943)

Since these models are developed for each station on the basis of the mean day-to-day modelled local meteorological parameters from respective station, it is referred to as "site-specific surface linear models". The modelling shows that, while parameters evolved for ZHD is constant at different locations, those parameters evolved for ZWD show significant variations from one location to the other.

5. Conclusion

The estimation of the local tropospheric delay from observed surface meteorology has been carried out using two strategies. The first strategy is the application of the standard atmosphere to the Saastamoinen model in the GPS data processing technique from where the ZTD are extracted and referred to as GPS ZTD. The second strategy is the application of the locally modelled meteorological parameter from the MetMOD program to a developed program called SaastroMOD based on the refined Saastamoinen model. The ZTD obtained from this program is known as SaastroMOD ZTD. GPS ZTD variation for the $2^{1}/_{2}$ years in the network ranges from 2.32 m to 2.62 m with most of the site around 2.40 m. The SaastroMOD ZTD variation ranges from 2.55 m to 2.75 m. Variations are higher at stations located in the coastal areas. There is statistical difference between the SaastroMOD and the GPS ZTDs. This is clear evidence that, the standard atmosphere does not reflect the true local tropospheric effect in a GPS network. This is because the standard atmosphere provides a broad approximation of the tropospheric condition, thereby, ignoring the latitudinal, seasonal, and daily variation in temperature, pressure and relative humidity. Daily variation of the zenith hydrostatic delay (ZHD) indicates that, the ZHD increases in the morning hours and decreases in the afternoon. High values of ZHD occur between 9:00 hours and 11:00 hours; while low values occur between 13:00 hours and 14:00 hours. The ZWD do not follow any specific pattern. It can be concluded that, the high values experienced in the ZHD in morning is attributed to increase in temperature in a high-pressure area being heated by the sun. A simple approach has been used in this research in establishing a relationship that connects the ZHD and ZWD with the modelled local pressure and partial pressure of water vapour extracted from SaastroMOD. Linear Models were developed for each station based on the mean day-to-day modelled meteorological parameters at individual station. These models are referred to as site-specific surface linear model.

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