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GPS derived Zenith Total Delay (ZTD) observed at tropical locations in South India during atmospheric storms and depressions

A. Akilan[1*], K. K Abdul Azeez[1#], S. Balaji[2], H. Schuh[3] and Y. Srinivas[4]

[1]*CSIR-National Geophysical Research Institute, Uppal Road, Hyderabad- 500 007, India*
** Email: akilan@ngri.res.in; # Email: azeez@ngri.res.in*
[2]*Department of Disaster Management, Pondicherry University, Port Blair-744 112, India*
Email: drbalaji64@gmail.com
[3]*GFZ, German Research Centre for Geosciences, Potsdam, Germany*
Email: schuh@gfz-potsdam.de
[4]*Manonmaniam Sundaranar University, Tirunelveli-627 012, India*
Email: drysv@yahoo.com

Abstract

Global Positioning System (GPS) monitoring of Zenith Total Delay (ZTD) of the troposphere which is related to water vapor is important as it may help us in weather forecasting. The atmospheric water vapor varies according to the season and it also varies quickly on short temporal and spatial scales during stormy periods. Thus it plays a crucial role in meteorology. GPS is one of the relatively inexpensive tools available to monitor the water vapor content in the atmosphere. In the present study, the efficacy of GPS data to monitor perturbations in tropospheric water content (GPS meteorology) associated with atmospheric storms and depressions is investigated utilizing the data from a tropical region of India, recorded between 15th October, 2010 and 27th December, 2010 during which Southern India was affected by a few significant atmospheric events. The ZTD was estimated for this period at the NGRI operated GPS stations at Hyderabad (HYDE) and MS University, Tirunelveli (MSUN). The accuracy of GPS derived ZTD was validated from the close match

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* Corresponding author Mobile: +919866683526
E-mail address: akilan@ngri.res.in (A. Akilan)

seen with ZTD values estimated from numerical weather modeling data. During the stormy periods there were strong variations of the ZTD. Corresponding changes in precipitable water vapor were estimated for the International GNSS Service station HYDE. The average ZTD was found to be higher near the coastal station at MSUN and less at the inland station HYDE. Most of the observed peaks in the ZTD time series were well correlated to the atmospheric events that influenced the region. The study extended to two more locations in the equatorial Indian Ocean region showed spatial variations in the ZTD values, which suggest the weakening of ZTD towards the coast. Our observations are yet another illustration for the application of GPS observations to monitor tropospheric water content variations associated with severe atmospheric events.

Key Words: GPS meteorology, Zenith Total Delay, precipitable water, atmospheric storms.

1. Introduction

The Global Positioning System (GPS) technology (Leick, 1990), which was originally designed as a system for navigational and time transfer, has revamped the field of geodesy and geodynamics by its ability to determine Earth rotation parameters and geodetic positions precisely with little costs. Later, e.g. Bevis et al. (1992) realized the relation between the Zenith Total Delay (ZTD) experienced by the GPS signal and the atmospheric water content, and GPS monitoring found another useful application in meteorological studies that opened the field of GPS meteorology (Businger et al., 1996). Today, remote sensing of the atmospheric parameters, i.e. ZTD obtained from GPS signal records, is useful in meteorological studies and successful in weather forecasting, thus making GPS meteorology a frontier area of research (e.g. Rocken et al., 1993; Bevis et al., 1994; Duan et al., 1996; Emardson et al., 1998; Foster et al., 2000; Baltink et al., 2002; Gradinarsky et al., 2002; Hagemann et al., 2003; Champollion et al., 2005; Jade et al., 2005; Jin et al., 2007; Nilsson and Elgered, 2008; Thomas et al., 2011; Joshi et al., 2013; Means and Cayan, 2013; Suparta et al., 2013; Wang et al., 2013; Singh et al., 2014a,b; Li et al., 2014). In this paper, we demonstrate the correlation between the ZTD values estimated from continuous GPS monitoring, and atmospheric storm phenomena and rainfall associated with them to establish the utility of GPS monitoring for weather and rainfall forecasting.

The atmospheric water vapor causes a delay in the propagation of GPS radio signals, while passing through the atmosphere to the receivers on the Earth surface. This delay, known as ‘wet delay’, is approximately proportional to the quantity of water integrated along the ray path (Hogg et al., 1981; Askine and Nordius, 1987). Therefore, dynamic perturbations in the atmospheric water vapor content would get reflected in the ZTD values obtained from GPS studies, which correspond to the total GPS signal delay caused by the atmospheric column vertically above the GPS station. Knowledge of the spatial and temporal distribution of water vapor in the atmosphere is an important factor for a better understanding of atmospheric phenomena, climate and climate changes (Starr and Melfi, 1991). This atmospheric parameter commonly shows rapid changes with space and time, and hence becomes a crucial component of climate and weather modeling.

Storms on the Earth such as rainstorm, snowstorm, cyclonic storm, depression, etc. are severe weather conditions that are associated with notable transient changes in atmospheric water content. These sudden changes in precipitable water vapor (PWV) associated with the atmospheric events can be well picked up by the GPS data (e.g. Rocken et al., 1993). For the Indian sub-continent, weather forecasting is being successfully performed by the Indian Meteorological Department (http://www.imd.gov.in) using latest technologies. The present study utilizes GPS data to compute atmospheric parameters related to water content in the troposphere (ZTD and PWV), and evaluates the variations seen in these values to observe the signatures of storms and depressions. The GPS signals from two stations located in South India were analyzed to study the ZTD and also the PWV variations related to tropical cyclonic storms and deep depressions that were originated in the Indian Ocean and affected the Southern part of the East coast of the Indian Peninsula between 25th October, 2010, and 11th December, 2010.

2. Basic concepts of GPS meteorology

The GPS radio waves travelling from satellites in space to the receiver on ground undergo significant delay induced by the ionosphere and troposphere (the lower part of atmosphere, Hogg et al., 1981). In geodetic studies, these ionospheric and tropospheric delays (together known as the total delay) are removed by appropriate corrections applied to the GPS signals (Davis et al., 1985). In the metereological application of GPS we make use of the tropospheric delay information as this is directly related to the constituent components of the troposphere. This total tropospheric delay, called ZTD, is further divided into Zenith Wet Delay [ZWD] and Zenith Hydrostatic Delay [ZHD], which are respectively due to the wet water vapor and dry gaseous components in the troposphere (e.g. Nilsson and Elgered, 2008). The ZTD can be determined after removing the ionospheric delay part from the total delay computed from two-frequency GPS observations. The ZWD is proportional to the tropospheric integrated water vapor content ($IWV = \int_0^\infty \rho_w dZ;\ \rho_w - \text{density of water vapor},\ dZ - \text{vertical coordinate}$) and is the minor component (~10 %) of the ZTD. The water vapor content of the atmosphere in zenith direction is also defined as the height of an equivalent liquid water column and referred to Precipitable Water (P_w), which can be computed from ZWD using the relation (Nilsson et al., 2013):

$$P_w = k\Delta L_w^z \qquad (1)$$

where, ΔL_w^z is the ZWD and $k = \frac{10^6 M_w}{\left[k'_2 + \frac{k_3}{T_m}\right] R \rho_{wl}}$, for which k'_2 =16.52 K/mbar , and k_3 = (3.776 ± 0.004) x 10^5 K^2/mbar are constants (Askne and Nordius, 1987).

M_w is the molar mass of water (18.0152 g/mol).

T_m is the mean temperature $\approx 70.2 + 0.72T_0,$ where T_0 is Earth surface temperature

R is the universal gas constant, R = 8.314 J/mol, and

ρ_{wl} is the density of liquid water in kg/m^3

3. Data and analysis

As a part of its GPS-Geodesy program, the National Geophysical Research Institute (NGRI), Hyderabad, India initiated GPS monitoring at Hyderabad (HYDE) in the year 1995 by establishing an IGS (International GNSS [Global Navigational Satellite Systems] Service – http://www.igs.org) tracking station. In September 2010, we started recording GPS signals at another GPS permanent station positioned at MS University campus, Tirunelveli, South India (hereafter called MSUN; Figure 1). Both these stations are within the Southern part of Indian Peninsula surrounded by the Indian Ocean. The geographic position and other details of these GPS stations are given in Table 1. The stations were equipped with multichannel dual frequency GPS receivers. A Leica System 1200 GRX GPS receiver was operative at HYDE and a Topcon GB 1000 GPS receiver was functioning at MSUN station. At both sites, the data were recorded with a uniform sampling rate of 30 seconds. The elevation cutoff angle of the GPS antenna was set to 5° to avoid the tracking of satellites at too low elevation. Multipath signals were mainly eliminated using choke ring antennas. The data in binary format were converted into Receiver Independent Exchange Format (RINEX) (Galas and Kohler, 2001).

The equatorial Indian Ocean region frequently is the origin zone of several severe weather conditions that affect the Indian subcontinent. The year 2010 has seen a few of such weather events and most of them were concentrated in the Bay of Bengal (http://www.imd.gov.in/section/nhac/dynamic/RSMC-2010.pdf). Among these, the very severe cyclonic storm ‘GIRI’ and the severe cyclonic storm ‘JAL’ were experienced during 20-23 October and 4-8 November, 2010, respectively, and influenced the Indian weather conditions considerably. The cyclonic storm ‘JAL’ crossed the coasts of North Tamilnadu and South Andhra Pradesh on 7th November, 2010, while ‘GIRI’ did not hit the Indian coast and moved to the Myanmar coast. During 7-8 December, 2010, another depression was formed over the Bay of Bengal, which crossed the Southern Andhra Pradesh coast on 7th December, 2010. These events produced stormy weather and torrential rains in South India, particularly on the East coast. We used about two and half months (15th October till 27th December, 2010, a period equivalent to the GPS day period 288-358) of GPS data recorded at the Hyderabad (HYDE) and Tirunelveli (MSUN) stations to estimate the ZTD perturbations over these locations. The ZTD data were further analysed to study their correlation with the atmospheric events and to identify typical signals corresponding to these meteorological events.

The raw GPS data in RINEX format were processed using the Bernese 5.0 software (Dach et al., 2007, 2009). Station MSUN was used as the fixed station for data processing. In the processing, the station position was fixed to the result of a preceding Precise Point Positioning (Melbourne, 1985). The Bernese software (Dach et al., 2007) was used for analyzing the GPS data. It assumes an azimuthally homogeneous atmosphere. Receiver clock errors, satellite clock errors and cycle slips were eliminated during processing and the ambiguities in the carrier phase were estimated and corrected. We applied the Niell mapping function (Niell, 1996), included in Bernese 5.0, to compute the ZTD values over Hyderabad and Tirunelveli stations. The temporal resolution was set to two hours; however, hourly estimations were made for the GPS period from day 326 to 329, which has seen heavy rainfall in and around Tirunelveli station.

4. Results and discussions

The ZTD values computed for the period from 15th October to 27th December, 2010 at Hyderabad and Tirunelveli stations are presented in Figures 2 and 3. The variation in the hydrostatic delay that contributes 90% to the total ZTD value is a slow process and hence is negligible (e.g. Luo et al., 2013). Thus the observed variations in ZTD that contribute about 10% to the absolute ZTD value mainly represent the changes in water vapor content in the troposphere. Our GPS derived ZTD time series show peaks and lows corresponding to the atmospheric water vapor changes associated with the severe weather periods experienced in the region. To verify the reliability of GPS derived ZTD in establishing its relation with atmospheric weather changes, we compared our results with numerical weather model (NWM) data (e.g. Böhm et al., 2006; Bock et al., 2013). Numerical weather models are prepared continuously e.g. by the European Centre for Medium Weather Forecasting (ECMWF) [http://www.ecmwf.int/]. We used the ZTD data generated by numerical weather modeling studies from http://ggosatm.hg.tuwien.ac.at/, and compared them with our GPS derived observations. The comparison carried out for Hyderabad station data showed a remarkably good agreement of ZTD between the GPS derived and the numerical prediction values (Figure 2). In this case, the standard deviation between GPS and NWM estimations is 0.004 m. Similar observation were also reported previously by Teke et al. (2013). The good match between GPS and NWM derived ZTD estimates was also confirmed from a t-test that showed more than 95% confidence level. We could not extend this to the MSUN site as this is not an IGS station and NWM data are not available for this location. As can be noticed from Figures 2 and 3, our GPS data suffer from a major data gap (~9 days between GPS days 308 and 316) due to power failures at the MSUN site and hence the correlation was not possible for those few days without data recording. In addition to this, occasional data losses (GPS days 294-299, 332-336, and 341-343) were also evident in the time series. However, significant weather changes or rainfalls were not reported during those periods. The NWM data complement the GPS data and exhibit the ZTD behavior whenever GPS data are not available. We tested the good consensus shown between the GPS and NWM data using two other IGS GPS stations located in the equatorial Indian Ocean region. The GPS data from Cocos Island (COCO) and Diego Garcia (DGAR) were processed and the ZTD values were compared with the NWM ZTD values (Figure 4). The standard deviations obtained are 0.028 m and 0.017 m at sites COCO and DGAR, respectively. Figure 4 again illustrates the good agreement between GPS derived and NWM calculated ZTD values, and thus allows us to use the information from numerical weather data whenever GPS could not record.

The rainfall data for the Hyderabad and Tirunelveli stations were also compared with the respective ZTD estimates to understand the correlation between the two (i.e. rainfall and ZTD changes). The quantity of water in the atmosphere, i.e. precipitable water (P_w), can be determined from ZTD using equation (1). The ZWD values (i.e. ΔL_w^z term) needed in the equation were obtained by subtracting the ZHD (retrieved from the NWM) from the GPS estimated ZTD values. We estimated the precipitable water at the Hyderabad station (Figure 2, lower panel), assuming the values of *Mw* (0.0180152 Kg/mol) and *Md* (0.028964 Kg/mol). P_w values were computed using value of constants given in Askne and Nordius (1987) and also following Rüeger (2002). The comparison of the results does not show any significant difference in Pw values (Figure 2, lower panel). The required mean temperature (*Tm*) value was obtained from the Vienna University of Technology database (http://ggosatm.hg.tuwien.ac.at/DELAY/ETC/TMEAN/). The standard deviation of the Tm values used in this study is 2.07 K. Accuracy of the results was tested by studying the sensitivity of P_w value to the possible error in *Tm* measurements. P_w values were computed for a change in *Tm* by 4K, 8K and 12K, and compared with the actual estimations in figure 5. Figure 5 illustrate negligible variation in P_w estimates for the above error (change) in T*m*. The average difference seen for a change of 4K, 8K and 12K is 0.94 mm, 1.26 mm and 1.58 mm respectively. These differences are negligible compared to the peak P_w values approximately falling between 30 and 41 mm.

During the period between 16th October and 27th December, 2010, the ZTD values estimated at the Hyderabad GPS station vary between 2.21 and 2.53 m (Figure 2). Four major ZTD peaks, marked as HP1, HP2, HP3, and HP4 in Figure 2, with values between 2.45 m and 2.53 m are visible in the ZTD time series. The ZTD is expected to be higher than the average value of 2.37 m during stormy weather conditions (Hogg et al., 1981), which however vary with altitude. Except the peak HP3, all others are observed just before or coincident with the noted atmospheric events reported from the South Indian region during the period of our study. The peak HP3 does not correspond to any abnormal atmospheric event and hence might be related to the normal water vapor accumulation process. Higher ZTD values indicate higher water vapor content in the atmosphere, which is quite clear from the PWV derived from ZTD for the same period (Figure 2). It can be seen from Figure 2 that the ZTD values were high during the 18-22 October period. During this period the formation of a deep depression in the Bay of Bengal region was noticed on 19th October, which further intensified into a severe cyclonic storm (GIRI) by 22nd of October and moved towards the coast of central Myanmar and the system weakened by the end of 23rd October. Though this atmospheric system did not move towards the Indian coast, the ZTD variations observed at Hyderabad can be associated to these atmospheric events.

Under normal circumstances the accumulated water vapor gets discharged as rain at the same location. However, it is possible in the case of significant atmospheric wind conditions that the accumulated water vapor may travel to distant locations and get discharged under suitable atmospheric conditions. Such a situation could be the reason for no rainfall at Hyderabad corresponding to the higher ZTD observed during the ‘GIRI’ period. Significant rainfall was recorded, however, during the ‘JAL’ period. Similarly, the GPS derived ZTD and the derived PWV match with the rainfall that occurred at Hyderabad during the deep depression event affecting South India.

For the Tirunelveli station, the GPS derived ZTD data (Figure 3) show a comparable pattern as observed at the Hyderabad station. However, the ZTD peak values are relatively higher (> 2.6 m) and show correlation with the atmospheric events noted in the South India region. No rainfall events were reported from this location during the major events GIRI and JAL. But, higher ZTD values were observed in the atmosphere during the GPS days 327 to 330 and significant amount of rain was reported from this location. The cumulative rainfall data show the slow onset of rain during 310-325 GPS days (6-21 Nov., 2010), followed by consistent and frequent rainfall during the GPS days 326-340 (22 Nov. - 06 Dec., 2010), as indicated by steep slope and the final phase of withdrawal of rain from GPS day 341 (Dec. 7) onwards depicting the decreasing trend of the monsoon pattern (e.g. Cook and Buckley, 2009). The absence of rain at this place during the GIRI and JAL period can be attributed to the possible wind pattern associated with the atmospheric events.

In the present study we also analyzed the ZTD variations at the IGS stations COCO and DGAR located deep inside the Indian Ocean. Table 2 gives the peak and minimum ZTD values obtained over each GPS station and help to assess the variability of the peak and minimum values of ZTD (i.e. difference in the peak ZTD values between the stations, and difference in the minimum ZTD values) between the locations. The comparison of the ZTD values of the Indian Ocean stations (COCO and DGAR) with the two inland GPS sites (HYDE and MSUN) shows the spatial variations in ZTD values. The values indicate the weakening of ZTD towards the land side. No significant changes are seen in the minimum and maximum ZTD values between the Indian Ocean locations and near the coast (Table 2). This would suggest that the effect of the events on atmospheric ZTD/PW was almost same at the interior of the ocean and on the coast. The ZTD peaks (2.75 m) and lows (2.44 to 2.46 m) observed at stations COCO and DGAR located inside the Indian Ocean are quite high when compared to an inland site, namely HYDE station, located approximately 400 km away from the East coast of India. Also, the ZTD maxima (2.53 m) and minima (2.21 m) values at HYDE are lower than the one observed for the coastal station MSUN. However, a part of the observed difference might be due to the variations in elevation between the observation points. There is a good agreement between ZTD and PWV at HYDE (Figure 2) suggesting that the increase in ZTD is due to the increase in water vapor content. This notable decrease in amplitudes of ZTD maxima and minima at the interior location indicates that stations close to the ocean or inside the ocean are more affected by the storms than stations located inland. The coastal as well as stations within the Indian Ocean islands show more peaks in the ZTD time series (Figure 3 & 4). This would probably indicate that these locations were strongly affected by the storms and depression than Hyderabad, which is located ~ 400 km inside from the East coast. The increase in ZTD may be an indication for a precursor of rain. The overall analysis shows that during the onset of a rainy day, the ZTD is significantly higher at stations MSUN, HYDE, COCO, and DGAR (Figures 2, 3, and 4). Sometimes, during rainfall, ZTD may come down if the atmosphere is not dynamic. It is difficult to predict the place of rain since atmospheric dynamics depends on various other factors, which are beyond the scope of this paper.

5. Conclusion

The application of GPS meteorology in identifying rapid atmospheric variations such as storms and deep depression events are evaluated in this study. The ZTD estimated from numerical weather modeling data and the ZTD computed from GPS data show quite good correspondence. The PWV derived from ZTD values and the rainfall data show a reasonable correlation at Hyderabad GPS station located well inside the Indian sub-continent. Similarly, good correlation exists between ZTD and rainfall data for the MSUN site located near the Southern coastal region of India. The calculated ZTD time series showed peaks and drops that overlap with severe atmospheric activities such as storms and deep depressions. Comparison of the ZTD values observed at different GPS stations studied indicate that the amplitudes of the ZTD values are less over the interior location as compared to the values observed at the coast and inside the Indian Ocean. GPS monitoring is an efficient and economic procedure to continuously monitor the changes in tropospheric water content and could help in identifying severe weather conditions by virtue of continuous weather data.

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TABLES

Table 1: The details of the GPS stations used in this study.

Place	Station ID	Latitude (Degrees)	Longitude (Degrees)	Orthometric height (m)	Station details
CSIR-NGRI, Hyderabad	HYDE	17.42	78.55	518.662	IGS permanent station
Cocos	COCO	-11.82	96.83	4.5928	IGS permanent station
Diego Garcia	DGAR	-6.73	73.51	11.0305	IGS permanent station
MS University, Tirunelveli	MSUN	08.76	77.65	71.0625	NGRI permanent station

Table 2: Maximum and minimum Zenith Total Delays (ZTD) observed at the four different GPS locations.

GPS station ID	Minimum ZTD (m)	Maximum ZTD (m)	Variability in ZTD (m)
HYDE	2.21	2.53	0.32
COCO	2.44	2.75	0.31
DGAR	2.46	2.75	0.29
MSUN	2.43	2.73	0.30

Figure captions

Figure 1: Location of the GPS stations marked over the topographic map of South India and Northern Indian Ocean.

Figure 2: ZTD values computed from GPS data and numerical weather models for the for the Hyderabad (HYDE) station (upper panel). The lower panel shows the precipitable water vapor (PWV) estimated at the same location. PWV values were computed using value of constants given in Askne and Nordius (1987) and also following Rüeger (2002). The rainfall data are also presented and compared. The peaks in the ZTD are highlighted using ellipses and labeled as HP1 to HP4. The active periods of storms and depression are also marked.

Figure 3: ZTD values computed from GPS data for the Tirunelveli station (MSUN) (lower panel). The rainfalls reported at this location during our observation period are given using bar chart plot. Upper panel shows the cumulative rainfall data at this location.

Figure 4: ZTD values computed from GPS data and using numerical weather models are presented for two Indian Ocean GPS stations, i.e. COCO (upper panel) and DGAR (lower panel).

Figure 5: Comparison of the original PWV estimates with the values computed for possible changes/error in the determination of Tm data.