

GPS Meteorology : Error in the estimation of precipitable water by ground based GPS system in some meso-scale thunderstorms - A case study

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(Received 9 May 2019, Accepted 19 November 2019)

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सार – भू आधारित जी पी एस रिसीवरों द्वारा सुदूर संवेदन, रेडियो सौन्डे और जल वाष्प रेडियो मीटर की तुलना में 1.5 मि.मी तक के वर्षणीय जल (पी डब्ल्यू) की अनवरत और सटीक माप देते हैं। प्रस्तुत शोध पत्र में हमने जी पी एस स्टेशन पर वर्षा के साथ आए तीन गरज भरे तूफानों में वर्षणीय जल की विविधता की मात्रा की जाँच की है। तीनों में गरज के साथ तूफानों में भारी वर्षा हुई। हालांकि वास्तविक समय में जी पी एस अनुमानित वर्षणीय जल (प्रतिघंटा) के साथ प्रेक्षित वर्षा की तुलना में यह देखा गया कि तीनों में से एक घटना में वर्षा की समान मात्रा के लिए वर्षणीय जल (पी डब्ल्यू) की मात्रा बहुत कम (~20 मि.मी) है। विश्लेषण करने और त्रुटि के विविध स्रोतों को ध्यान में रखते हुए हमें लगता है कि मध्य मापक्रम (मेसोस्केल) के गरज भरे तूफान या झंझावात रेखाओं और भारी वर्षा के साथ होने पर विसंगतियाँ उत्पन्न होती हैं क्योंकि शीर्ष बिंदु (ज़ेनिथ) के किसी भी कोण पर वर्षा में देरी का अंकन करने के लिए उपयोग किए गए वैट मैपिंग फंक्शन स्थानीय वायुमंडलीय स्थितियाँ नहीं दर्शाते, विशेष रूप से नैरो टॉवरिंग गरज वाले बादल और शीर्ष बिंदु की दिशा में जी पी एस उपग्रहों की अनुपलब्धता। दूसरी ओर गरज वाले बड़े बादलों के लिए, जी पी एस रिसीवर के संबंध में वायुमंडल बहुत अधिक समान होता है, वैट मैपिंग फंक्शन के कारण त्रुटि न्यूनतम है।

ABSTRACT. Remote sensing by ground based GPS receivers provide continuous and accurate measurement of precipitable water (PW) of an order of 1.5 mm comparable to radiosondes and water vapour radiometers. In the present work we have examined the amount of PW variation in three thunderstorms accompanied with rain shower that occurred over the GPS station. In all the three thunderstorms event heavy rain was reported. However on comparison of observed rainfall with GPS estimated precipitable water (hourly) in real time, it is observed that among the three, in one event the amount of precipitable water (PW) is much less (~20mm) for the same amount of rainfall. After analysing and taken into account various source of error, we suspect that in a mesoscale thunderstorms or squall lines associated with heavy rainfall, discrepancies arise because the wet mapping functions that used to map the wet delay at any angle to the zenith do not represent the localized atmospheric condition particularly for narrow towering thunder clouds and non-availability of GPS satellites in the zenith direction. On the other hand for the larger thunder cells the atmosphere is very nearly azimuthally symmetric with respect to GPS receiver, the error due to the wet mapping function is minimal.

Key words – GPS precipitable water, Zenith total delay, Zenith wet delay, Slant wet delay, Thunderstorms.

1. Introduction

Water vapour is an important atmospheric gas. The concentration of water vapour in the atmosphere is highly variable both spatially and temporally. Active weather is strongly correlated to the water vapour distribution in the atmosphere. The conventional method of measurements of water vapour does not normally have a resolution high enough to resolve these variations. Accurate and timely measurement is very important when making weather forecasts and now casting.

The prevention of water disasters is one of the most important issues in urbanised areas. Cumulonimbus when accompanied by a large hailstones, severe squalls or tornadoes are the most intense or meteorological phenomena and yet they are one of the most difficult to forecast. The number of convective strong rainfalls has been increased due to urbanisation and partially due to urban heat island (Kanda *et al.*, 2001). Compared to synoptic scale disturbances, the spatial and temporal behaviour of convective cells in tropical region is more or less chaotic and thus it is still difficult to predict and detect it even by using the most advanced numerical

techniques. Although Doppler-radars are powerful to detect raindrops, they cannot monitor moisture and have blind regions near the ground where the initiative convective cells are generated and “cone of silence” in which it does not detect any cloud development.

In NWP modelling, weather is an initial value problem. This means that, to predict changes in the weather it is necessary to have an accurate picture of the atmospheric conditions at the beginning of the forecast period. Moisture is one of the important variables in the NWP model. The serious deficiency in the current observing system is the absence of moisture profiles over the oceans and over land with sufficient horizontal, vertical and temporal resolution. This is especially important and crucial for short-period precipitation and forecasting.

The technology of ground-based GPS and GPS Radio Occultation (GPS RO) are valuable observations for operational meteorology and has a great advantage of monitoring precipitable water vapour (PWV) even before cloud formation free of clutters due to surface obstacles and thus it can be largely expected to detect the initiation of convective cells. The qualities of GPS RO temperature/humidity observations are generally very accurate with good global coverage; these observations are therefore assimilated operationally in global NWP models. Because of their random distribution over the globe, the footprint of about 300 km and the irregular observation times these data are less suitable for now-casting. For short-range weather forecasting this data could be valuable when there are multiple GPS RO receivers operational. On the other hand GPS Zenith Total delay (ZTD) and PW can be estimated accurately and continuously with a temporal resolution of 10 minutes or less for a surface network of GPS receivers with a horizontal resolution between 50 and 100 km suitable for both nowcasting and NWP applications (Poli *et al.*, 2007).

In recent decades ground based GPS PW measurement attracted the attention of meteorologists and network of continuously operating GPS being operational in many countries for various applications. In our present work we have derived GPS PW in three thunderstorm events that occurred during Indian summer monsoon and studied the utility and various source of errors involving in the measurements.

2. GPS sites and data set

India Meteorological Department (IMD) established 5 GPS site at New Delhi, Chennai, Mumbai, Guwahati and Kolkata and starts monitoring PW from April 2007 onwards. All GPS sites use Leica AX 1202 antenna

connected to Leica GRX 1200 dual frequency receiver via a 30 m low loss cable. The antenna mounts were on concrete pillars fixed on the roof top of the building (approximately 16 to 20 meters height from the ground). A meteorological sensor (Met3A) is also co-located near the antenna mount for temperature, pressure and humidity measurements.

GPS data were processed using GAMIT-10.31 software. The Precise Point positioning (PPP) strategy was used for the data processing. This strategy estimates all station related parameters relative to the precise JPL satellite orbits and satellite clocks that have high accuracy. In order to reduce the multipath effects a 10° elevation cut-off angle was fixed. The New Mapping functions (NMFs) (Niell *et al.*, 1996) were used to map the signal path delay from zenith direction to other elevation angles.

The GPS ZTD estimates are obtained using the GAMIT software at a 30/60 minute interval with a processing window (sliding window) of 9 hours (Foster *et al.*, 2005). Zenith Hydrostatic Delay (ZHD) estimates at each GPS receiver were calculated using surface pressure data measured from the surface Meteorological sensor assuming the hydrostatic equilibrium, is given by (Davis *et al.*, 1985),

$$\text{ZHD} = \frac{(2.2768 \pm 0.0005)P_s}{f(\phi, H)} \quad (1)$$

with ZHD in mm and P_s in hPa. The term

$$f(\phi, H) = 1.00266 \cos 2\phi - 0.00028H \quad (2)$$

accounts for the variation in gravitational acceleration with latitude ϕ and the height H of the surface above the ellipsoid (in kilometres). The ZWD is obtained by subtracting the ZHD from ZTD, the PW (mm) estimates were then derived by scaling the ZWD with the multiplication factor Π given by:

$$\text{PW} = \Pi * \text{ZWD} \quad (3)$$

$$\Pi^{-1} = 10^{-6} \rho R_v [(k_3/T_m) + k_2'] \quad (4)$$

where, ρ is the density of liquid water, R_v is the specific gas constant for water vapour, k_3 and k_2' are physical constant and given by [Bevis *et al.*, 1994]. The water-vapour weighted mean temperature of the atmosphere is defined and approximated as (Davis *et al.*, 1985);

$$T_m \equiv \frac{\int \frac{P_v}{T} dz}{\int \frac{P_v}{T^2} dz} \quad (5)$$

can be calculated from vertical profiles of water vapour pressure P_v and temperature T , usually derived from NWP analysis fields (Wang *et al.*, 2005). Assuming a linear relation with surface temperature it is also possible to approximate T_m from station surface temperature observations T_s (Bevis *et al.*, 1992).

$$T_m = 55.8 + 0.77T_s \quad (6)$$

The PW thus estimated was validated with nearest Radio sonde data (0000 and 1200 UTC) observed between the year 2007 and 2009 (Puviarasan *et al.*, 2010). The result shows a standard deviation of 6.23 mm and RMSE of 7.09 mm which is mainly attributed to error associated with Radio sonde humidity sensor. It is worth to mention here that after the induction of Graw GPS sonde in IMD, the error associated with humidity sensor reduced considerably and both the observations well agrees with each other. This result is yet to be published.

3. Case study

3.1. Event-1

On 1st August, 2007, during Indian summer monsoon, a thunderstorm with rainfall activity started around 2000 UTC over Delhi region and that continued till 0300 UTC of next day. Total rainfall of 182 mm with maximum rainfall intensity of 60 mm/hr was observed at around 2300 UTC. Since 0000 UTC of 1st August before the development of thunder clouds, GPS PW steadily increased from 56.82 mm at 0000 UTC to 69 mm at 1500 UTC [Fig. 1(a)] and decreased thereafter, however the average PW is maintained around 65 mm throughout the day. The PW estimated from RSRW at 0000 UTC and 1200 UTC was 55.14 and 65.26 mm respectively and is well agreed with GPS PW observation.

3.2. Event-2

During southwest monsoon, on 27th July, 2009 over Delhi region a thundershower accompanied with hailstone between 1415-1515 UTC with Rainfall intensity of 80 mm/hr and total rainfall of 137.1 mm was recorded. [Fig. 1(b)] shows the time series of PW along with rainfall recorded at the GPS site. In this event also the GPS PW was increased steadily and reached a maximum of 70 mm before the rainfall activity starts. At 0000 UTC of RSRW observation, the PW was around 70 mm and at the same

time it was 62 mm in GPS observation. The difference of 8 mm between the two independent observations is attributed to error introduced by humidity sensor that some time become saturated while passing through the clouds. AT 1200 UTC of RSRW observation PW was 69 mm while GPS was 63 mm (difference of 6 mm). Through the RSRW measurement showed a higher value of PW at 0000 UTC, no thunderstorm or rainfall activity near the RSRW or GPS site. This was confirmed from 0000 UTC Kalpana satellite image [Fig. 1(c)] in which no significant cloud present over Delhi region. This confirms the validity and accuracy of GPS measurements. At around 0900 UTC the GPS PW increased to 65.5 mm and followed by 35 mm of rainfall it reduced to 58 mm at 1100 UTC. Kalpana image of 1100 UTC [Fig. 1(d)] shows presence of cloud over Delhi region. AT 1200 UTC the RSRW PW was 69 mm whereas GPS PW was only 63.5 mm and thereafter increases steadily and reached a value of 70 mm at 1500 UTC followed by thunderstorms accompanied by hailstones and heavy rainfall. In Figs. 2(a&b) MODIS image at 1645 UTC showing thick convective cloud spread over Delhi and adjoining region.

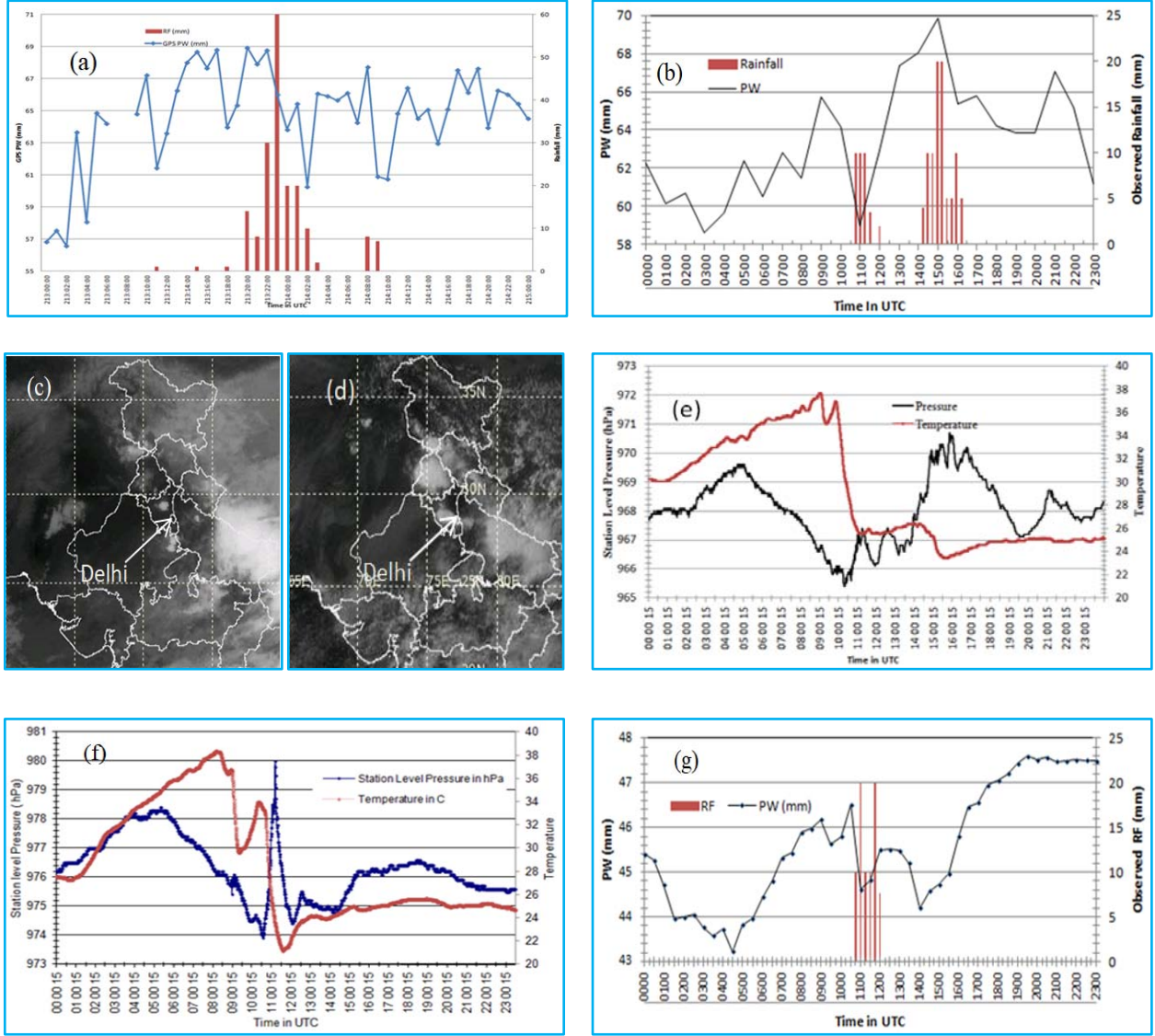
3.3. Event-3

On 21st August, 2009 between 1045-1145 UTC a thunderstorm followed by hailstone and intense shower of 78 mm/hr was occurred over Delhi GPS site. This event also took place during the summer monsoon at Delhi GPS site.

Fig. 1(g) shows the time series of GPS PW along with observed rainfall. At 0000 UTC the GPS PW/RSRW PW was 45.40/45.23 mm. The maximum PW reached only 46.5 mm at 1030 UTC just before the occurrence of thunderstorm. This event somewhat differ from the first two cases in which GPS PW increased to 70 mm before storm activity. In all the three events the rainfall intensity is nearly equal; however the measured GPS PW in the third event is relatively much smaller. In fact GPS observation does not show any appreciable increase in PW during or before rainfall activity starts. It is worth to note that PW of 45 mm in break monsoon season is sufficient for thunderstorm with heavy rain if there is any lifting mechanism. Nowadays ground based GPS water vapour monitoring is one of the tool available for nowcasting and input to NWP applications, so it is important to find the reasons for lower value of PW by GPS in some mesoscale thunder storms event

4. Error due T_m

Water vapour weighted vertically averaged mean temperature of the atmosphere T_m is an important parameter of the relationship between total precipitable



Figs. 1(a-g). Time series of GPS PW and Observed rainfall on (a) 1st August, 2007 (b) 27th July, 2009, (g) 21st August, 2009, (e) Pressure and temperature variation on 27th July, 2009, (f) Pressure and Temperature variation on 21 August, 2009, (c) & (d) 0000 UTC and 1030 UTC IR image (Kalpana) on 27th July, 2009

water and the zenith wet delay because, the accuracy of GPS estimates of precipitable water is directly related to the accuracy of T_m (Ross *et al.*, 1997). The water-vapour weighted mean temperature of the atmosphere is defined and approximated as (Davis *et al.*, 1985);

$$T_m = \frac{\int \frac{P_v}{T} dz}{\int \frac{P_v}{T^2} dz} \approx \frac{\sum_{i=1}^N \frac{P_{vi}}{T_i} \Delta Z_i}{\sum_{i=1}^N \frac{P_{vi}}{T_i^2} \Delta Z_i} \quad (7)$$

T_m is function of vertical profile of atmospheric temperature and humidity.

Using equations (4) and (7), the relative error of PW due errors in T_m can be given by Wang *et al.* (2005).

$$\frac{\Delta PW}{PW} = \frac{\Delta \Pi}{\Pi} = \frac{1}{1 + \frac{k_2}{k_3} T_m} * \frac{\Delta T_m}{T_m} \quad (8)$$

Since $\frac{k_2}{k_3}$ is small ($\sim 5.9 \times 10^{-5}$). Hence the relative

error of PW approximately equals to that of T_m . On the basis of equation (7), for T_m values 240 K to 300 K, the

1% and 2% accuracies in PW require errors in T_m less than 2.74 K and 5.48 K on average respectively (Wang *et al.*, 2005). T_m can be calculated from soundings which are usually unavailable at high temporal and spatial resolution. A more powerful approach would be to use operational meteorological models to predict the actual value of T_m . In the event that operational model is not available, T_m solely on the basis of observed surface temperature. But this approach suffers from systematic T_m overestimation at mid and high latitudes (up to 5 K) and underestimation at low latitudes (up to 6 K) (Wang *et al.*, 2005). Nevertheless, GPS PW is rather robust against T_m uncertainties. In Table 1, some of the relations available in the literature to derive mean atmospheric temperature (Jade *et al.*, 2005) were shown. In Table 2, T_m derived from respective regression equations from Table 1 and from RSRW for the three events is shown. It is understood that the estimated T_m for the three events using the regression equations is within 5 K with the observed T_m from RSRW except Schueler *et al.* (2001, Eqn. 11).

This T_m uncertainty of 5 K corresponds to 1.7 - 2.0% in PW only (Hagemann *et al.*, 2003). Thus for the event 3, the maximum error due to T_m would be 2% and may lead to an error in PW of 0.93 mm only. Nevertheless a dip in GPS PW at 1100 UTC [Figs. 1(b&g)] may be attributed to sudden decrease of surface temperature [Figs. 1(e&f)] due to heavy rain that causes significant error in determining mean atmospheric temperature based on T_s .

5. Error in estimation of ZHD

In GPS meteorology it is assumed that the atmosphere is in hydrostatic equilibrium. It does not include the effect due to non-equilibrium conditions. It is in fact, difficult to assess this effect without actually integrating vertical profiles of vertical wind acceleration (Davis *et al.*, 1985). Fleagle and Businger (1980) stated that only under extreme weather conditions (thunderstorm or heavy turbulence) to these vertical accelerations reach 1% of gravity, corresponding to an error in ZHD of about 20 mm/1000 hPa or approximately 3 mm in PW.

6. Error due to dynamical pressure

Fig. 2(e) shows the wind speed and wind direction (time is in IST) along with pressure variation at GPS site. In most circumstances atmospheric pressure is closely approximated by the hydrostatic pressure caused by the weight of air above the measurement point. However during thunderstorms the falling rain creates downdrafts. The downdraft will push down out of the thunderstorm and when reach the surface they spread out and turn into the destructive straight-horizontal winds. The sudden

TABLE 1
Relationship between T_m and T_s (Jade *et al.*, 2005)

Model	Mean temperature
Bevis <i>et al.</i> (1992, 1994) Eqn. (7)	$T_m = 70.2 + 0.72 * T_s$ (°K)
Mendes <i>et al.</i> (2000) Eqn. (8)	$T_m = 50.4 + 0.789 * T_s$ (°K)
Solbrig (2000) Eqn. (9)	$T_m = 54.7 + 0.77 * T_s$ (°K)
Liou <i>et al.</i> (2000) Eqn. (4)	$T_m = -38.4 + 1.09 * T_s$ (°K)
Harmonic Model Schueler <i>et al.</i> (2001), Eqn. (10)	$T_m = \bar{T}_m + \tilde{T}_m \cos \left[2\pi \frac{\text{DoY} - \text{DoY}_w}{365.25 (\text{Days})} \right]$
Linear surface temperature model Schueler <i>et al.</i> (2001), Eqn. (11)	$T_m = 86.9 + 0.647 * T_s$ (°K)
Mixed Harmonic Model Schueler <i>et al.</i> (2001), Eqn. (12)	$T_m = \bar{T}_m + \tilde{T}_m \cos \left[2\pi \frac{\text{DoY} - \text{DoY}_w}{365.25 (\text{Days})} \right] + q_T * T_s$

T_m - Weighted Mean atmospheric Temperature, T_s - Surface temperature, $\bar{T}_m$ - Average mean atmospheric temperature, $\tilde{T}_m$ - Amplitude of mean atmospheric temperature, DoY - Day of the year and DoY_w - Day of maximum winter, q_T - Temperature amplifier

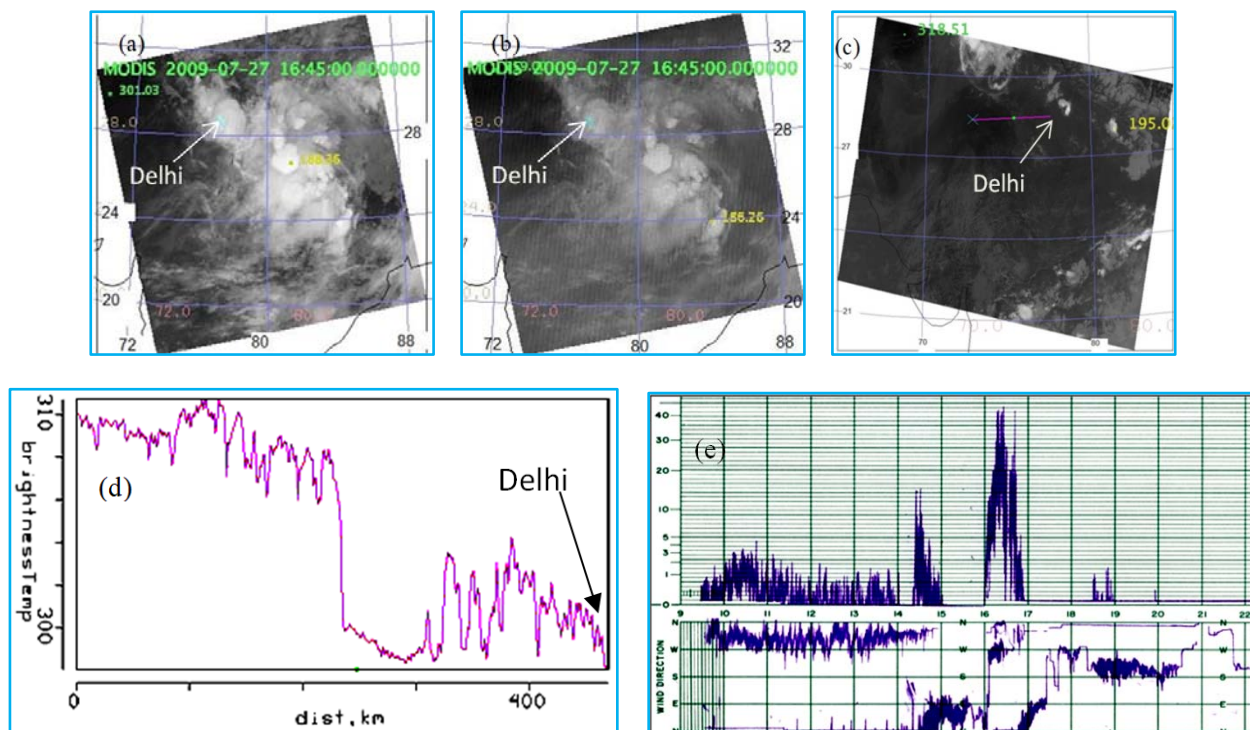
increase in pressure readings [Fig. 1(f)] from 974 hPa to 980 hPa between 1030 to 1130 UTC is not due to atmosphere above the measurement point but due to gusty winds. This dynamical pressure produce a temporary increase of surface pressure thus ZHD, results a dip in PW measurements of the order 0.35 mm/hPa. So in our case the surface pressure was increased 3 hPa on an average between 1030 to 1130 UTC which corresponds to 1 mm dip in PW. Thus the sudden dip in PW at 1100 UTC in Fig. 1(e) is not only by fall in surface temperature but also by dynamical pressure.

7. Error due to mapping function

When estimating ZTD from GPS signals it is assumed that the atmosphere is symmetric in the horizontal plane and these delays in the signal from GPS satellite to receiver at arbitrary elevation angle θ , can be mapped onto delays in zenith direction through a known mapping function. Thus total delay for a path with an elevation angle θ can be computed from the zenith hydrostatic and zenith wet delays *via*:

$$\Delta L = \text{ZHD} * M_h(\theta) + \text{ZWD} * M_w(\theta) \quad (9)$$

where, $M_h(\theta)$ is the hydrostatic mapping function and $M_w(\theta)$ is the wet mapping function. Due to different behaviour of dry and wet components of the atmosphere,



Figs. 2(a-e). (a) MODIS IR (band 31) Image from Terra shows the presence of convective clouds over Delhi and surrounding regions and (b) Water Vapour Imagery (band 27) on 27th July, 2009 (c) MODIS IR (band 31) image from Aqua on 21st August, 2009; (d) Brightness Temperature variation from Delhi to Aravalli region along the pink line in Fig (c). (e) Wind speed (kilograms per square meter) and wind direction on 21st August from Dines pressure Tube anemograph shows that the thunder storm approaches the station from north and north westerly direction

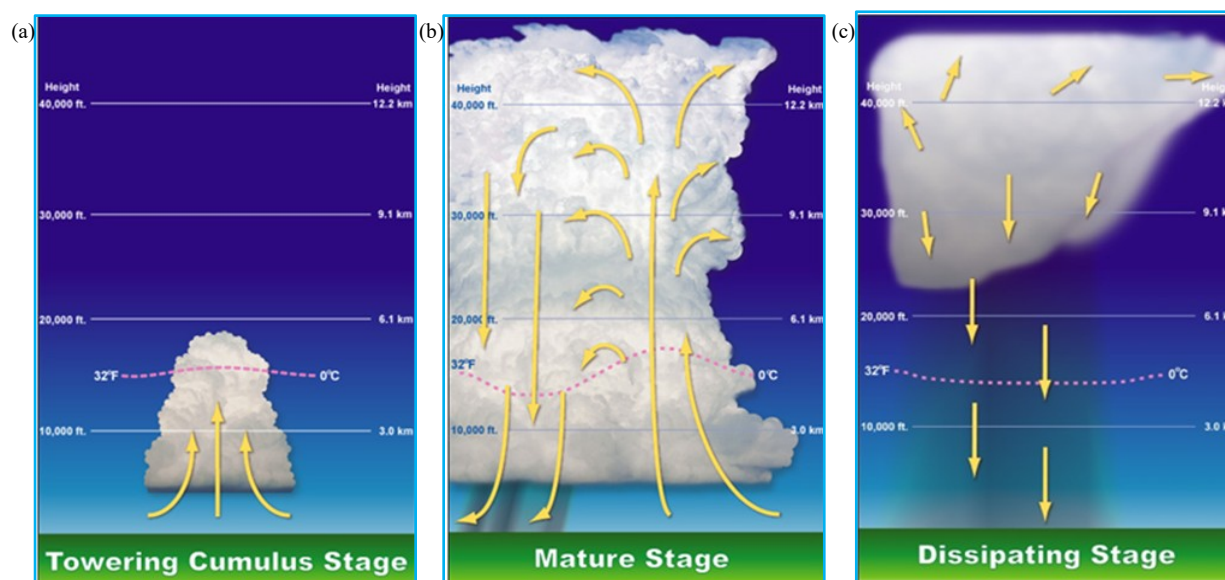
TABLE 2

Estimated T_m from Table 2 and RSRW

Date/Time (UTC)	T_m (°K) (Nearest RSRW)	T_m from Surface Temperature (°K)					RSRWPW (mm)	GPSPW (mm)
		Bevis	Mendes	Solbrig	Schueler	IMD		
1 st Aug, 2007	0000	287.99	286.92	287.89	286.47	281.64	287.57	55.14
	1200	286.43	286.84	287.81	286.39	281.58	287.49	65.26
27 th Jul, 2009	0000	289.30	288.36	289.47	288.01	282.94	289.11	70.06
	1200	292.99	292.97	294.52	292.94	287.08	294.02	69.07
21 st Aug, 2009	0000	291.84	284.76	285.52	284.16	279.71	285.26	45.23
	1200	285.46	286.20	287.10	285.70	281.00	286.80	57.66

the mapping functions are different for hydrostatic and the wet parts. These mapping functions were usually developed based on the assumption that the atmosphere is azimuthally isotropic. Many mapping functions have been developed based on the use of different input parameters, *e.g.*, meteorological data or site coordinates. For example Chao's (1972) mapping functions use one each for M_h and M_w , make no reference to meteorological conditions, whereas the hydrostatic mapping function derived by Davis *et al.* (1985) incorporates surface temperature,

pressure and relative humidity, the height of the tropopause and the tropospheric temperature lapse rate. Similarly in new Niell's mapping function (NMFs) (Niell, 1996), the delays are modelled separately for the hydrostatic and wet components. Nearly all of the mapping functions that have been suggested in the literature assume no azimuthal variation in path delay (Bevis *et al.*, 1992). The assumption of azimuthal symmetry at 15° elevation typically produce a rms variations of 7 mm, but this effect may go 5 times when the local troposphere has large



Figs. 3(a-c). Three stages of thunder storms.<http://en.wikipedia.org/wiki/Thunderstorm>)

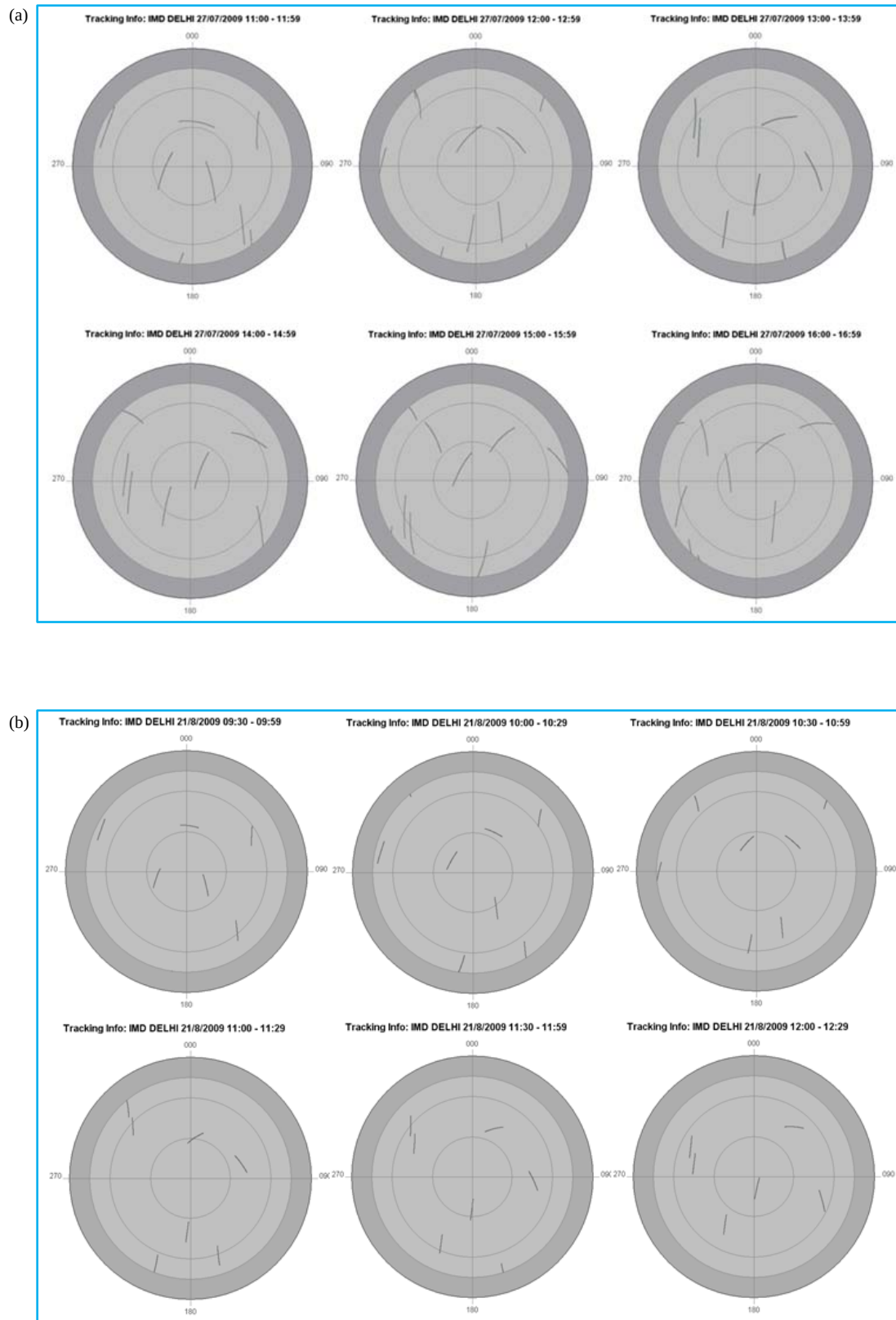
lateral temperature, pressure or humidity gradients usually accompany strong frontal weather systems (Bevis *et al.*, 1992). Fig. 2(c) shows the 21st August, 0500 UTC MODIS (Aqua) 11 μm image. Fig. 2(d) shows the variation of brightness temperature (BT) of 11 μm IR channel in MODIS from Aravalli region (Western India) to New Delhi. Along this line it is observed that the BT decreases and at some point there is a sudden dip in BT of the order of 8° K - A frontal surface separating a shallow, warm moist layer from a deeper, hot and dry layer. Some asymmetry also found in temperature and humidity gradient in east-west direction on 21st August, 2009. It is worth to note that the presence of dry line is favourable conditions for the formation of thunderstorm.

8. Error due to satellite positions

In above, we have discussed all possible error sources and if this has been taken into consideration, the observed PW is still much less than the expected one. If one accepts that GPS PW can be one of a tool for a real time forecaster then the questions arises whether the initial 46 mm of PW would give 76 mm of rainfall? If it is so, then most of the monsoon days the PW is above 45 mm and many occasions the PW reaches 60 to 62 mm without any rainfall. In the first two events the PW reached its peak value of 70 and 69 mm before the intense rainfall. However, in third events it is not so. This means that the GPS measurements still does not representing the actual atmosphere completely. If so under what situations?

Now consider the situation as in Figs. 3(a-c). Assume that the GPS antenna is at the center of towering cumulus

cloud [Fig. 3(a)], so that the atmosphere is symmetric with respect of GPS receiver on the ground. Now for a 6 km towering cloud, to capture it by GPS receiver, there should be at least one GPS satellite in the Zenith Direction. Or if the towering cumulus extends ~ 3 to 4 km radius in the horizontal and 6 km in the vertical then, any GPS satellites between 90 to 60 degree elevations can represent the cloud fully. If the cloud extends up to 24 km (12 km radius) in the horizontal direction then satellites up to 30 degree elevation can track the clouds. Below 30 degree elevations satellite signals pass through only part of the thunderstorm and do not depict the atmosphere in the Zenith properly. In the same way during mature stage [Fig. 3(b)], the thunder cloud reach up to height of 18 km, to perceive this by GPS satellites at 30 degree elevation, the cloud should extend up to 44 to 45 km or radius of 22 km in the horizontal direction. For 60 degree elevation, the thunder cloud should extend at least 30 km (15 km radius) in the horizontal direction. However in tropics quite often small scale thunder clouds or squalls do not have large horizontal coverage. During dissipating stage also the base of the cloud [Fig. 3(c)] is at a height of 6 km, most of the low elevation GPS signals reach the antenna without seeing the cloud. Thus non availability of GPS satellite in near zenith direction always underestimates PW over GPS station. Figs. 4(a&b) show the satellite elevation and azimuth angle on 27th July, 2009 and 21st August, 2009. If we compare the satellite image of 27th July 2009 [Figs. 2(a&b)], it is evident that almost all GPS signal pass through the thunder clouds before it reach GPS antenna since the cloud is sufficiently large dimension and the atmosphere is symmetric with respect to GPS antenna. On the other in event 3, the cloud dimension is very



Figs. 4(a&b). Satellite elevation and azimuth angle on (a) 27th July, 2009 (hourly sky plots) and (b) 21st August, 2009 (half hourly). Plot center is zenith and right center the eastern horizon relative to satellite ground tracks. The value of PW depends upon number of satellite signals passes through the cloud

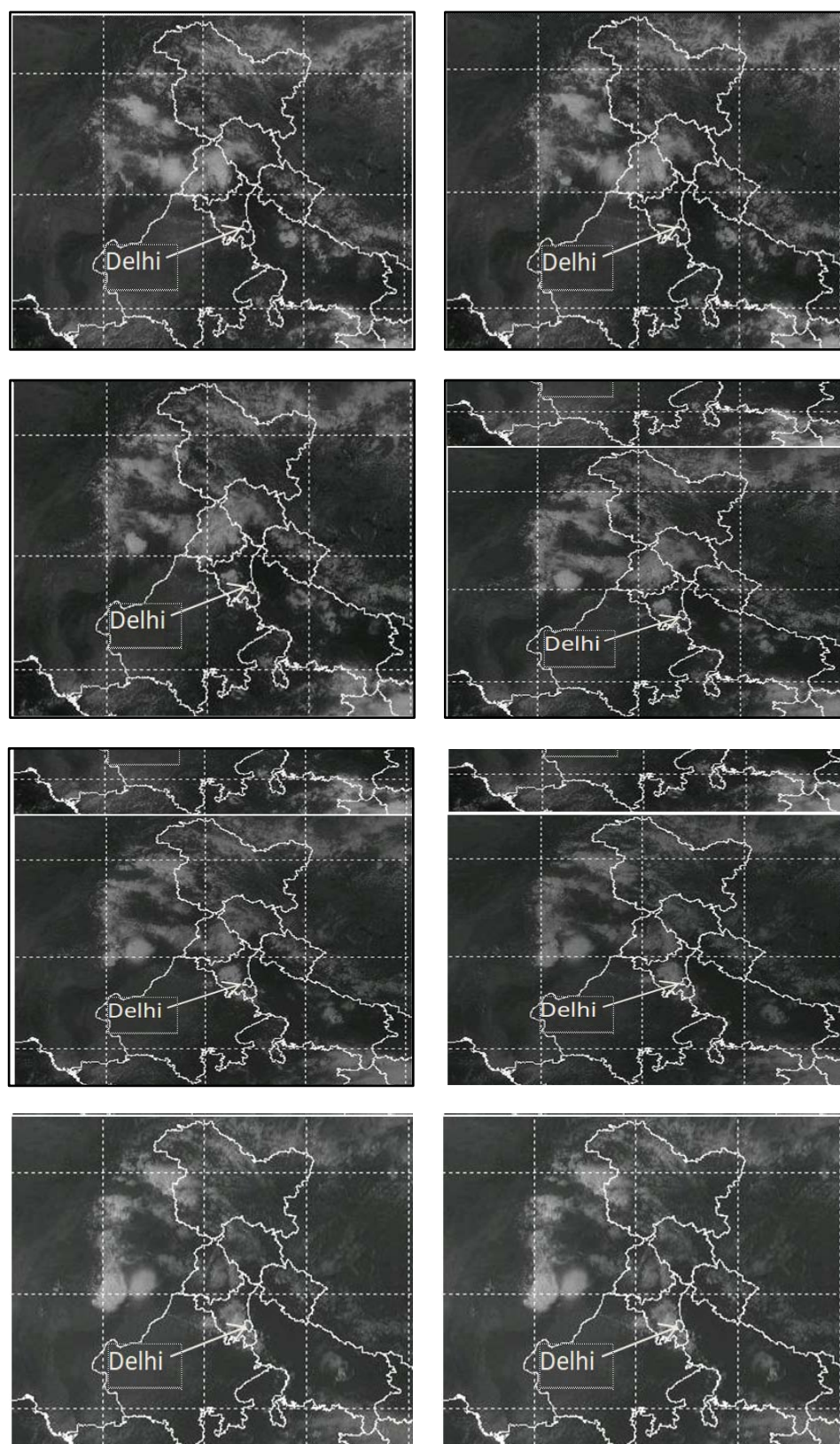
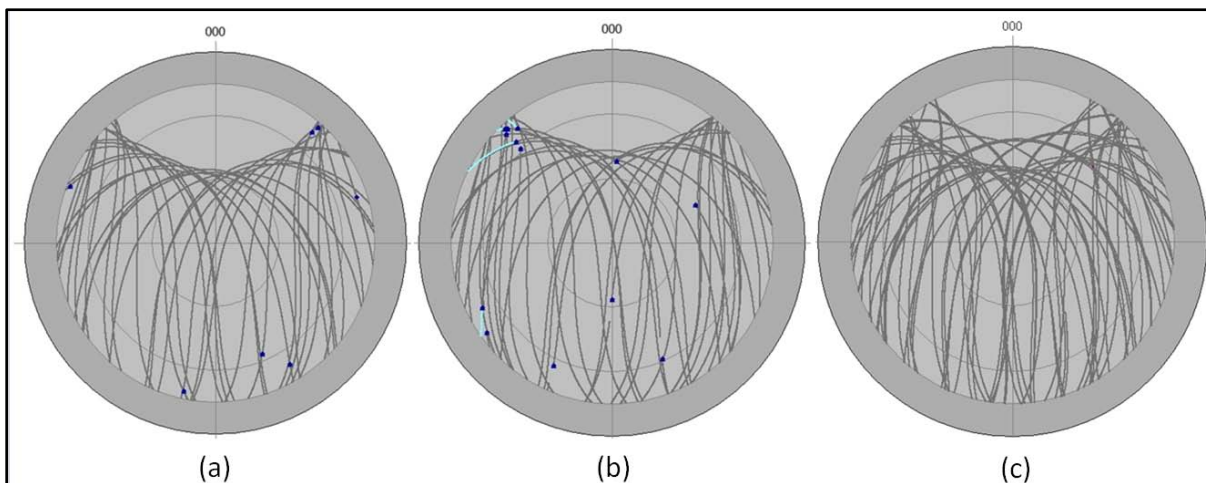


Fig. 5. Kalpana 30 minutes visible Image on 21st August. From top left 0800 UTC and the bottom right is 1130 UTC. Convective cloud starts developing since 0800 UTC onwards and entering Delhi from north of northwest direction



Figs. 6(a-c). GPS Satellite elevation and azimuth angle (sky plots) at (a) Delhi (b) Chennai and (c) skyplot of GPS & GLONASS over Delhi. Plot center is zenith and right center the eastern horizon relative to satellite ground tracks. At lower latitude (Latitude of Chennai $\sim 13^\circ$) the GPS satellite coverage is relatively higher as compared to higher latitude (Delhi $\sim 28^\circ$). So, GPS PW measurement is more biased at higher latitude. However the error could be minimised by the inclusion of other constellation such as GLONASS and GALILEO. In Fig. (c) after adding GLONASS constellation

narrow (Fig. 5) most of the GPS signals reaching the antenna without seeing the cloud. This can be evident from the sky plot [Fig. 4(b)]. One may also notice in the sky plots [(Fig. 6(a)], below 60 degree elevation towards north of the plot center between 315-040 degree azimuth, no satellites covering this region, thus GPS signals does not detect presence of clouds in these regions. This is due to inclination of GPS orbital plane with respect to equatorial plane of earth. In radar meteorology there is a “cone of silence” directly above the radar, in which radar does not detect any object that comes under cone region. Similarly GPS measurements do have blind region that does not detect presence of any thunder clouds. In first two events this zone does not have any effect in PW measurements because the clouds were extended both horizontally and vertically over large region, thus all GPS signals pass through clouds before reaching the antenna. On the other hand for event 3, the thunder clouds develops and enter the GPS site from north north-westerly direction and thus most of the satellite signals reach the GPS antenna without seeing the cloud [Fig. 4(b)]. This is evident from Kalpana satellite image (Fig. 5) and from surface wind measurement [Fig. 2(e)]. So this might be another reason for error in PW computations. Thus If a system develops to the north of GPS site and if there is no satellite or less number of satellite in the northern side then the measured PW will always be less. On the other hand if a system develops to the south of GPS site then many satellite signals sees the cloud and thus gives relatively higher PW. This can be clear if we examine the PW time series [Fig. 1(g)] in which PW increased from 46.5 mm to 47.7 mm after the event. The error due to non

availability of satellite may vary from latitude to latitude because the blind zone is changing with latitude. If we compare the sky plot of Delhi and Chennai [Figs. 6(a&b)] the uncovered zone is relatively less in Chennai which is at lower latitude ($\sim 13^\circ$) than at Delhi which is at higher latitude ($\sim 28^\circ$). This error however can be minimised by incorporating other constellation such as GLONASS, Galileo and COMPASS. Fig. 6(c) shows that, after inclusion of GLONASS with GPS observation, the blind region is reduced considerably. This is because the GLONASS orbital plane is inclined 65 degree whereas GPS orbit is inclined at 55 degree with respect to equatorial plane of the earth.

9. Conclusions

Knowledge about the amount of atmospheric water vapour is important in many areas like nowcasting application, hydrological cycle, NWP and climate modelling etc. Several techniques have been developed and being in use to obtain precipitable water in the atmosphere. However each technology has some advantages and disadvantages and some limitations. Remote sensing of amount water vapour based on ground based GPS systems is an independent method, works under all weather conditions, gives continuous measurement of water vapour at every 10 minutes or less, more accurate, stable and cost effective and requires less maintenance.

Though GPS can be useful to monitor PW changes, but at times does not capture meso scale thunder clouds or

narrow vertical cloud. The wet mapping functions that used to map the wet delay at any angle to the zenith do not represent the localized atmospheric condition particularly for narrow towering thunder clouds. Presence of blind region and non availability of GPS satellite in the vicinity of zenith direction are a major source of error. For the first two events this has no effect, since the thunder clouds have large vertical and horizontal coverage so almost all GPS signals seen the cloud before reaching the GPS antenna. However for the third event GPS does not able to pick up the cloud and measured PW (46.5 mm) was much lower than the expected PW (70 mm). This is mainly due to the fact that very narrow thunder clouds were developed to the north of GPS stations where GPS observation has some blind region below 60 degree elevation and approached the GPS site from north/north westerly direction and large asymmetry components. The blind region is higher at higher latitude and low at lower latitude due to inclination of GPS orbit with respect to equatorial plane. However the blind region can be reduced by incorporating other constellation such as GLONASS, Galileo and compass. Thus inclusion of other constellation with existing GPS can give better estimation of PW. The dip in PW at 1100 UTC for event 2 is attributed to sudden decrease of surface temperature while for event 3 is due to both surface temperature and dynamical pressure. Although the GPS not the 45 mm of PW is sufficient for thunderstorm with heavy rain particularly break monsoon condition

Instead of estimating PW in the Zenith direction, estimation of Slant Wet Delay (SWD) along the signal direction and computing PW in each quadrant or octant (by dividing the atmosphere) would give better understanding of PW distribution and useful for nowcasting. Also fast developing thunderclouds PW estimation should be at every 10 to 15 minutes instead of 30/60 minute since GPS signals are less sensitive to water droplets.

Acknowledgements

Though water vapour is the driving source of all forms of weather events, Peng Fang, SOPAC, USA is the driving source for me to write this paper. His valuable help at crucial time is highly appreciable. I am also thankful to Director General of meteorology, New Delhi, for his continuous encouragement in GPS meteorology and his keen interest to bring more number of GNSS stations over Indian region. At last not least I am very thankful to Shri Vikram Jeetsingh Jasrotia, M/s Elcome Technologies Pvt Ltd., New Delhi, (Leica representative), for his timely help in plotting skyplots of GPS and GLONASS and valuable inputs while writing this paper.

The contents and views expressed in this research paper/article are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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