ABSTRACT
Precipitable Water Vapor (PWV) is a good source to monitor precipitation. It is defined by the amount of water vapor present in atmosphere. Traditionally, radiosondes and microwave radiometers were used to derive PWV. However, these devices have poor temporal resolutions and high operational costs. Therefore, GPS signal delay is now widely used for such purposes. The main aim of this paper is to study relationship between GPS derived PWV and precipitation. We present an analysis which shows that PWV increases before any rainfall event, while it decreases after the rainfall event. We also derive a threshold PWV that detects the occurrence of rainfall, once PWV exceeds the threshold value. PWV and rainfall data of June 2010 and 2011 are used for validation.

Index Terms— Global Positioning System (GPS), GIPSY-OASIS, Precipitable Water Vapor (PWV), Precipitation

1. INTRODUCTION
Water vapor content of atmosphere is an integral factor in the determination of precipitation. As a parcel of air containing water vapor rises in the atmosphere, it reaches a particular height at which, the temperature becomes less than dew point temperature and the air becomes saturated. Any small excess of water vapor beyond this saturation point will cause the excess amount of vapor to condense into liquid water or ice, forming clouds [1]. Further ascent of water vapor can cause growth of clouds which may finally precipitate.

Water vapor is generally referred as Precipitable Water Vapor (PWV). It is defined as the total atmospheric water vapor contained in a vertical column of unit area (measured in mm). Radiosondes and microwave radiometers are classical instruments to measure PWV. However, radiosondes have poor temporal resolution and microwave radiometers have high operational costs [2]. Geostationary and polar orbiting sensors are also used to monitor cloud formation in the earth’s atmosphere.

Several studies have been done to analyze the potential of GPS derived PWV to forecast rainfall. [5] and [6] show PWV derived from GPS has a relationship with the measured rainfall. Although relation between PWV and precipitation is pointed out, rigorous studies are yet to be done in estimating the threshold PWV to indicate precipitation.

2. METHODOLOGY
2.1. Data
In this paper, we use PWV and rainfall measurement values to analyze the relationship between them. For retrieval of PWV, GPS station (NTUS), of International GNSS Service (IGS) Network is chosen. It is located at NTU Earth Observatory of Singapore (1.3455°N 103.6797°E). Data recorded by IGS stations are stored in RINEX format which can be downloaded from FTP site provided by NASA.

Rainfall is recorded by Weather Station (WS) located at the rooftop of university building at Nanyang Technological University Singapore (1.3453°N, 103.6833°E). WS records data at an interval of 1 minute, which are archived in a server.

2.2. Data Processing
GNSS Inferred Positioning SYstem and Orbit Analysis SImulaton Software (GIPSY-OASIS) from NASA is used to process the daily RINEX files downloaded for Singapore site (NTUS). GIPSY-OASIS is run in the Precise Point Positioning (PPP) mode to process the files. The files after being processed give a measure of total Zenith Wet Delay (ZWD) for a particular time. PWV is estimated using Eq. [1]

$$PWV = \frac{\Pi}{\rho_v} \frac{ZWD}{\rho_v},$$

where $\rho_v$ denotes the density of liquid water (1000 kg/m3) and $\Pi$ is the dimensionless factor determined by Eq. [2]

$$\Pi = \frac{10^6}{((\frac{k_1}{T_m}) + k_2)T_m},$$

This research is funded by the Defence Science and Technology Agency (DSTA), Singapore.
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where, $R_v$ is the specific gas constant for water vapor of 461.5181 J/kgK, $k_3$ and $k_2$ are the refractivity constants of $(3.776 \pm 0.14) \times 10^3 K^2/Pa$ and $(17 \pm 10) \times 10^{-2} K/Pa$, respectively. Here, $T_m$ is the water vapor weighted mean temperature, which is usually calculated using Bevis Equation [7] that relates $T_m$ with the surface temperature $T_s$. However, Bevis Equation is derived from radiosonde profile data of temperate regions. In our earlier work [8], we have proposed an equation designed specifically for Singapore. The relation between $T_m$ and $T_s$ for Singapore [8] is given in Eq. 3.

$$T_m = 182.56 + 0.3432 T_s$$  \hspace{1cm} (3)

We process PWV values at an interval of 5 minutes. Rainfall Rate is recorded by WS (mm/hr). The values are stored in the server. The recording is done every minute. MATLAB is used to post process the recorded data.

3. RESULTS AND DISCUSSION

3.1. PWV and Rainfall

The amount of PWV present in air is affected by different factors like temperature, humidity, seasons and also time of the day. We observed some variations in PWV values, when we analyzed for rainy and non-rainy days.

Figure 1 shows the PWV averaged per day per month of Year 2011. The days of a month were first separated into rainy (filled bars from Fig. 1) and non-rainy days (empty bars from Fig. 1), then an average PWV of each category was calculated. From Fig. 1, we see that in average, PWV values for rainy days are higher than the non-rainy days. From this analysis of the year 2011, we can see maximum difference in PWV of rainy and non-rainy days to be of $11.45 \text{ mm}$ in February. Such variation in PWV during rain and no rain conditions, indicates the role of PWV in precipitation.

To investigate the detailed relation between PWV and rainfall, PWV before and after rain event are plotted together. Rain events are first identified, then PWV values are averaged for an hour, 2 hours and 3 hours before and after the rain event and plotted as shown in Fig. 2. For both figures (a and b) of Fig. 2, green lines (with star head and asterisk head) represent the PWV calculated during rain and the lines (with circle head) are the averaged PWVs before and after the rain events. Figure 2(b) shows two rain events, and thus we use different colors and numbering to indicate PWV associated with different rain events.

![Figure 1: Average PWV per day per month for Rainy and Non-rainy days (2011)](Image)

From Fig. 2(a and b), we can clearly see that PWV before rainfall has a tendency to increase. Precipitation is generally observed after PWV values reach a peak. Similarly, when we observe PWV after the rain event, we observe a fall in PWV values. In Fig. 2(b), for rain event 1, we can see that after the rainfall event, PWV value decreases but it starts to increase again because of the rain event 2. Thus, a particular behavior of PWV before and after rainfall can be observed. And increment in PWV values can be taken as an indicator of rain in near time.
3.2. Threshold PWV

From the previous section, we observe a clear relation between PWV and the occurrence of rainfall. We discussed that an increment in PWV indicates rain. In this section, we derive a threshold value in PWV that indicates the occurrence of rain. Threshold PWV value must be defined in such a way that, when PWV at any instant of time exceeds this threshold value, it must indicate rain. We choose the month of June 2010 and June 2011 to conduct the experiment.

Table 1: Average PWV per month

<table>
<thead>
<tr>
<th>Month</th>
<th>Rainy Days</th>
<th>Non Rainy Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 2010</td>
<td>55 mm</td>
<td>43.26 mm</td>
</tr>
<tr>
<td>June 2011</td>
<td>52.38 mm</td>
<td>44.7 mm</td>
</tr>
<tr>
<td>Avg of 2010 and 2011</td>
<td>53.7 mm</td>
<td>44 mm</td>
</tr>
</tbody>
</table>

Table 1 shows the average PWV values for 2010 and 2011. Since, the threshold value must be the base value and PWV values exceeding this threshold must indicate rain, it is likely to choose the average of rainy day 53.7 mm or more as the threshold.

![Figure 3: CDF of PWV for Rainy and Non-Rainy days of June 2011](http://www.nea.gov.sg/training-knowledge/publications/annual-weather-review-2011)

Figure 3 shows the Cumulative Distribution Function (CDF) plot of PWV for June 2011. For this month if the threshold is chosen to be 53.7 mm (broken lines in Fig.3), then from the CDF of non-rainy days, we see that 50% of time, PWV value is higher than the chosen threshold. But we want the PWV values of non-rainy days to be lower than the threshold values for most of the time (excluding some exceptions), so that we can correlate the increment of PWV values beyond threshold limit with rainfall event. So, a higher value of 58 mm (solid line in Fig 3) is chosen (from the plot) as threshold. At 58 mm, for non-rainy days, PWV values exceed the threshold value less than 2% of time. And for rainy days, at 58 mm, the PWV values are higher than the chosen threshold value for 40% of time. Results using this threshold limit, is presented in the next session.

3.3. PWV and Rainfall with Threshold PWV

We choose two cases corresponding to June 16, 2010 and June 5, 2011 to study the relation between PWV and rainfall with respect to chosen threshold PWV. These particular cases are chosen from Annual Weather Review published by National Environment Agency (NEA) that marks them as heavy rainfall days.

Figure 4 shows the rainfall and PWV plot for these two days. The blue (continuous) line represents the GPS-PWV available every 5 minutes. The magenta stars represent the average PWV of an hour, 2 hours and 3 hours before the rainfall event. The green lines indicate rainfall rate and red line is the threshold PWV representing 58 mm.

![Figure 4: Study of rainfall and PWV with respect to threshold PWV (Heavy Rain event)](http://www.nea.gov.sg/training-knowledge/publications/annual-weather-review-2011)

Figure 4 clearly shows an occurrence of rain event when the PWV value exceeds the threshold. The deviation of PWV from the threshold PWV before rain event are also calculated. We see that for a maximum deviation of 3.8731 mm on June 16, 2010 a total rainfall of 12.66 mm is recorded. On the other hand, a deviation of 5.4068 mm corresponds to a total rainfall of 47.8 mm on June 5, 2011.

Similarly, Fig.5 shows a case of a light rainfall event. The total rainfall recorded on June 13, 2010 (Fig.5(a)) is just 0.6

mm and deviation of PWV from the threshold is also less, 1.64 mm. Figure 5(b) shows two cases of light rain. The first one has a maximum PWV deviation of 0.8 mm and corresponds to rain of 0.2 mm. The second rain event of 3.8 mm corresponds to a deviation of 3.04 mm in PWV. From these examples of heavy and light rainfall events, we can conclude that a higher deviation in PWV values indicates the occurrence of a heavy rainfall, and lower deviation in PWV indicates otherwise.

Fig. 5: Study of rainfall and PWV with respect to threshold PWV (Light Rain event)

4. CONCLUSION

This paper discusses the relation of PWV with precipitation. Based on the data of June 2010 and June 2011, a threshold PWV value has been derived to indicate precipitation. It has been concluded that increment of PWV beyond the threshold value indicates rain. Results have been presented that show higher rainfall for larger deviation of PWV from the threshold value. The threshold value can be improved by taking more data into consideration and by considering effects of different seasons. Studies are yet to be done to come up with more concrete threshold which can be generalized for different months. Moreover, PWV is not the only factor to determine rain. We also plan to use ground-based sky cameras to detect and classify clouds, and also to estimate the cloud-base height. These observations can further validate the results obtained for the threshold PWV.

5. REFERENCES