

# GPS Slant Path Residuals for Rainfall Detection

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**Abstract**— In this paper, Global Positioning System (GPS) derived slant path residual values are studied with respect to a rainfall event. Slant path residuals can be defined as the difference between the slant path wet delay at a particular elevation angle and the zenith wet delay projected to that elevation angle. The slant path residual values are corrected for multipath using multipath stacking algorithm. The corrected residuals show a good correlation with a rainfall event. It is observed that the standard deviation (SD) of the residuals is higher during a rainy time period. The slant path residuals can be used as an added feature in the existing algorithms to improve the rainfall prediction results.

## I. INTRODUCTION

Global Positioning System (GPS) derived precipitable water vapor (PWV) is a good predictor of a rainfall event. It has been used in many rainfall detection and prediction algorithms [1], [2]. Recently, zenith total delay (ZTD) values have been studied from a rainfall detection point of view [3]. Most of these algorithms use PWV values which are an average of the multiple slant path water vapor and/or the wet delay values in zenith direction (ZWD). Different from the literature, in this paper, we study the usefulness of the GPS slant path residuals for rainfall prediction.

$$STD(e) = MF_h(e) \cdot ZHD + MF_w(e) \cdot ZWD + R \quad (1)$$

The slant total delay ( $STD$ ) is simply expressed as shown by eq. (1). Here,  $MF_h$  and  $MF_w$  are the hydrostatic and wet mapping functions to map the zenith delay to a particular elevation angle ( $e$ ) and vice-versa.  $ZHD$  is the zenith hydrostatic and  $R$  represents the residual values. Here,  $R$  can be described as the difference between the delays at a particular elevation angle and the zenith delay values mapped to that angle. Out of the two delays, the wet delay is highly variable in nature. Therefore, day-to-day variations in residuals can be useful in explaining the variations in moisture content of atmosphere. A positive  $R$  indicates that the slant path has higher water vapor content compared to the zenith and a negative  $R$  indicates that the slant path has lower water vapor content compared to the zenith. Therefore, a map of residual values can show the overall picture of the water vapor concentration at

different slant paths. However, residual values have some errors due to multipath effects which must be removed prior to using the residual values. Multipath Stacking Algorithm (MPS) can be used to remove the multipath effects from the residual values [4].

## II. DATASETS AND DATA PROCESSING

### A. GPS Data

Residual values are calculated for an International GNSS Service (IGS) GPS station located at Singapore (1.34°N, 103.67°E, station Id: NTUS). GIPSY-OASIS software v6.4 is used for the processing of the residual values. Satellite cut-off angle of 10° is used for the processing. The residual values are processed for every 5-min. A number of residual values are recorded every 5 min, which depends on the number of satellites visible within the GPS cone at the given time. The number ranges from 5 to 12. The residual values are reported in units of  $cm$ . Residual values from day-of-year (DOY) 151, 152, 153, and 154 from year 2012 are used for the analysis in this paper.

### B. Weather Station Data

Rain data recorded by a weather station co-located with the IGS-GPS station (NTUS) are used in this paper. Rain is measured by a tipping bucket installed in the weather station with a resolution of 0.2 mm/min. Rain data from DOY 151, 152, 153, and 154 are used for further analysis.

## III. RESULTS AND DISCUSSION

The residual values are processed for all four days from year

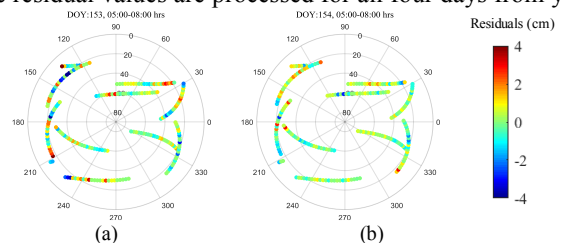


Fig. 1. Corrected residuals ( $cm$ ) from 05:00-08:00 hrs for (a) DOY:153 and (b) DOY:154. The values on the circumference of the plots represent the azimuth angles and the values at different radii represent the elevation angles of the satellites visible at the given time frame. The center of the plot is 90° elevation angle (zenith direction). The color bar shows the different values of residuals in  $cm$ .

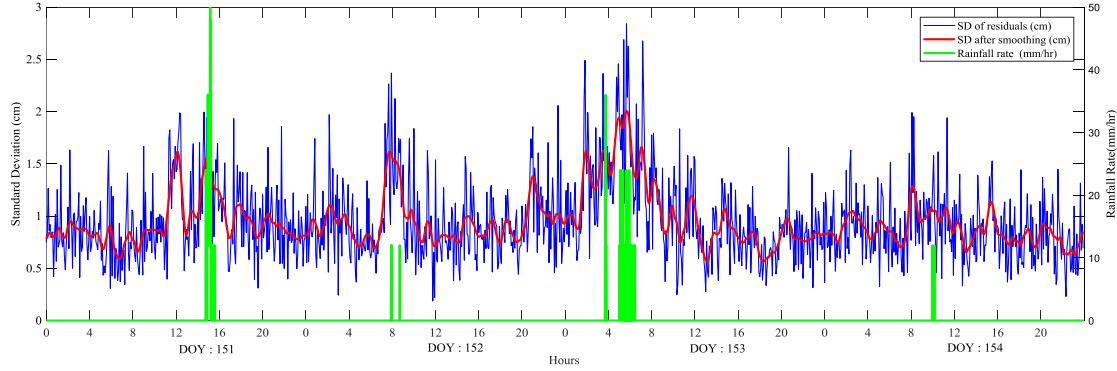


Fig.2. Time series plot of the standard deviation (SD) of residuals (cm) and rainfall rate (mm/hr). The plot shows values for different hours of four days DOY:151, 152, 153, and 154. The plot in blue shows the SD values at every 5 minutes and the plot in red is the moving average of the 5 minutes SD values. The plot in green shows the rainfall rate.

2012. Post processing is done to remove the multipath effects from the residual values using the MPS algorithm. The algorithm is implemented using a MPS map. The map has an average residual values of certain number of observations for a particular elevation and azimuth angle. For this paper, a multipath stacking map with  $1^\circ$  resolution in both elevation and azimuth angles are constructed. Each bin has 7 days averaged residual value. The residual map is updated daily. Once the map is constructed, the actual residual values at a particular elevation and azimuth angle is corrected by subtracting the average residual value from the MPS map at that elevation and azimuth angle. The corrected residual values are then studied with respect to a rainfall event.

#### A. Sky plot observation

Out of the four days, Fig. 1 (a) and (b) show the sky plot of the corrected residual values for the two consecutive days; DOY 153 and 154 respectively for the same period of time (05:00-08:00 hrs). Detailed description about the plots is given in the figure legend. Here it can be observed that the satellite trails for both Fig. 1 (a) and (b) are almost the same as the same time interval is chosen for both days. Satellites have a fixed orbit and revolution time. It is interesting to note that for the same trails the corrected residual values are different for different days. The range of variation of the residuals values observed for DOY 153 is higher compared to the values observed for DOY 154. When the weather station data was checked for the given time period, a rain event was observed for DOY 153 whereas no rain was observed for DOY 154.

#### B. Time series observation

We observed that the variation in residual values might be higher during the rainy hours compared to the non-rainy hours. Therefore, we calculate the standard deviation (SD) of the corrected residual values for every 5 min. The SD is based on 5-12 data (as the number of visible satellites). Fig. 2 shows the time series of the SD of the corrected residuals and rainfall rate for four consecutive days. The different curves are explained in the figure legend. It can be seen that the SD values increase during a rain event. The SD values are higher for a rainy event compared to a non-rainy time period.

A higher SD value indicates a situation where the difference

between the different slant path delays are higher. For a rainy and/or cloudy time frame, few slant paths can pass through the rainy and/or cloudy events where as few slant paths do not, which results in different delays for different paths increasing the SD of the corrected residuals. For a fairly clear sky time frame, all slant paths might experience similar delay, therefore, the SD of the corrected residual are lower compared to the SD corresponding to a rainy time frame.

The SD of the corrected residuals show a promising correlation with the rainfall event. Therefore, SD values can be used as one of the parameters for rainfall prediction in addition to other features as mentioned in [5].

#### IV. CONCLUSION AND FUTURE WORK

The corrected GPS slant path residual values show good correlation with a rainfall event. The SD of the residual values are higher during a rain event compared to a clear sky time period. The corrected residual values can be used as features for rainfall detection and prediction.

In the current work, the residual values were corrected using 7 days of data to remove the multipath effect. As a future work, a statistical analysis will be done to find an optimum number of days to average out the multipath effects. The correlation between slant path residual and rainfall events will be studied in more depth for more number of days and for multiple stations.

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