Measurement Of Integrated Water Vapor Over Bangalore Using Ground Based GPS Data

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ABSTRACT

This paper describes the estimation of daily Integrated Water Vapor (IWV) using ground-based GPS at Bangalore, India. The GPS data was analysed using GAMIT-10.07 to derive total zenith delay (TZD). The IWV was derived from TZD after deducting hydrostatic delay component using empirical models established for Bangalore based on atmospheric parameters and ray-tracing techniques. The GPS derived IWV was compared with radiosonde observations. Even though the day-to-day variations in GPS derived IWV compares well with that derived from Radiosonde, a significant bias of ~12% was observed in the absolute values. The bias was attributed to the overestimation in some other error components in GAMIT processing as well as the uncertainty in Radiosonde measurements.

INTRODUCTION

The main source of atmospheric humidity observation was the radiosonde until the emergence of space-based remote sensing. Sparse spatial distribution of Radiosonde observations, limits the ability of the horizontal structure of small-scale weather features and the satellite based water vapor measurements over land is far more difficult because of the large heterogeneity of land surface features. Most of the satellite-based measurements of atmospheric water vapor prove to be more useful over the oceanic regions. A local network of GPS receivers is an effective alternative for water vapor remote sensing over land surface [5]. This recently developed technique proves to be very effective in measuring Integrated Water Vapor (IWV), as clouds and precipitation do not significantly affect the propagating GPS signals at 19 and 24 cm wavelengths. Rocken *et al*. ([12], [13]) demonstrated ground based GPS system for measuring IWV with rms accuracy of 1-2 mm. However, most of the studies were conducted over mid-latitude locations where the average IWV is < 20 kg/m^2. This points the importance of IWV measurements using GPS over tropical region where the atmospheric water vapor content is relatively large.

This paper attempts an estimate of IWV from ground based GPS observation from Bangalore located in southern part of Indian peninsula and examine the accuracy of IWV derived from GPS observations by comparing it with the Radiosonde data. The GPS data collected from the IGS (International GPS service) station located at Indian Institute of Sciences (IISC) campus, Bangalore, along with eight other IGS stations were downloaded from the IGS website *http://www.ngs.noaa.gov/CORS/Data.html.* The GPS data analysis software GAMIT 10.07 was used to process the GPS data.

METHODOLOGY

Retrieval of Zenith Delays From GPS Data

GPS based IWV measurements are based on the refraction effect of microwave signals by polar air molecules mainly water vapor as it passes through the neutral atmosphere. Most of the neutral gas molecules are non-polar and also cause refraction to microwave. The delay in zenith direction caused by non-polar gas molecules, called Hydrostatic Zenith Delay (HZD), which is a function of hydrostatic pressure and temperature; and Wet Zenith Delay (WZD) caused by water molecules is linearly related to the integral of water vapor (in kg/m^2) along the zenith ray path. In GPS based water vapor estimation, the WZD is obtained after subtracting HZD, from GPS derived TZD.

GPS Data Analysis:

The IGS station network in Indian subcontinent is very poor. The selection of these IGS stations was based on an optimization studies in which, different groups (combinations) of IGS stations located in and around Bangalore station were considered. The best stations were chosen on the basis of the post fit normalized RMS value of the double differencing (< 0.25) and the post fit RMS value to and by the satellite (< 5), obtained from the GAMIT processing and also on basis of the fact that the input GPS data is from the same satellite for all these stations. The daily GPS

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phase observations in the Receiver-Independent Exchange (RINEX) format at 30 seconds sampling rate are collected for Bangalore and other eight IGS stations (Fig. 1). The GAMIT software solves the phase data for TZD and other parameters using a constrained batch least square inversion procedure [10]. The least square adjustment to solve for the TZD parameters in two hourly bins results in the sampling of the GPS data at the rate of 2 hours centered around odd hours [8]. The two hourly bins considered in the IWV retrieval in the study matches fairly with the radiosonde ascend duration, which often requires more than an hour or so to complete the vertical ascend up to 7 mb pressure level. In the present analysis mapping function developed by Arthur Niell [11] of MIT's Haystack observatory was employed. To avoid the error due to multipath a lower cutoff value about 15^{o} is fixed for the minimum elevation angle.

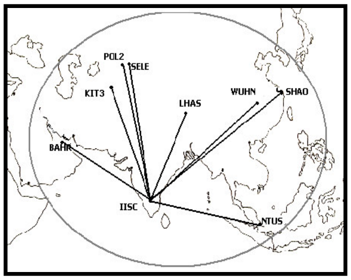

Fig. 1: The network of IGS ground-based GPS stations

To deduce the WZD from the GPS analyzed TZD data we have to have an estimate of HZD. The HZD is a function of hydrostatic pressure [2],[3]. Using Three years (1995-97) of radiosonde data a Linear relationships between surface parameters and hydrostatic components of TZD were sought to model the range error with surface pressure (P_s) expressed in millibar (mb) in a simple linear form as [14]

$$\text{HZD} = 2.26 \times 10^{-3} \times P\text{s} \tag{1}$$

The model predictions were compared against the true range error estimated by ray-tracing using the daily radiosonde data from Bangalore, its regression analysis, provided a correlation coefficient of 0.57. The normalized mean of absolute difference between observed and estimated values were found be about ± 8 mm for HZD.

ESTIMATION OF WEIGHTED MEAN TEMPERATURE - T_m

In the retrieval of IWV from WZD, effect of temperature is to be taken into account. However, effect of temperature and water vapor partial pressure are interrelated. Therefore, the vertical profiles of temperature are taken into account through a term called weighted mean temperature (T_m). Many authors attempted to estimate this term using vertical profiles of water vapor partial pressure and temperature of the atmosphere to retrieve the IWV from GPS measurements. Askne and Nordius [1] attempted to relate the IWV and WZD through a linear relation given as:

$$\text{IWV} = \Pi \times \text{WZD} \tag{2}$$

Where, Π is the proportionality constant. Liou *et al.* [9] related Π with the atmospheric parameters through T_m as:

$$\Pi = \frac{10^8}{\rho_{H_2O}\, R_v \left[(k_3/T_m) + k_2'\right]} \tag{3}$$

T_m in (3) is estimated following the expression as [6]

$$T_m = \frac{\int \left(e(z)/T(z)\right) dz}{\int \left(e(z)/T^2(z)\right) dz} \tag{4}$$

where e in millibars (mb), T_m and T are in Kelvin (K). The vertical distribution of water vapor pressure acts as a weighting factor in the definition of T_m. As most of the water vapor (~80%) in the atmosphere is confined to lower altitude, < 3 Km, T_m should be well correlated with the surface temperature T_s. Bevis *et al.* [2] proposed a linear relation between for T_m and T_s of the form

$$T_m = 70.2 + 0.72\, T_s \tag{5}$$

Above equation was obtained from different sites in United States with a latitude range of 27^{o} to 65^{o}. No equivalent model is currently available for a tropical location like Indian subcontinent. An empirical model for T_m was developed based on radiosonde measurements over India. Radiosonde data from eight IMD stations (covering 8^{o}N to 32^{o}N) over Indian subcontinent are used for this purpose. The T_m estimated for different T_s conditions are presented in a scatter plot shown in Fig. 2. A linear relationship was established between the two following regression analysis. This yielded an empirical relation with correlation coefficient = 0.9, in the form

$$T_m = 62.57 + 0.75 \times T_s \tag{6}$$

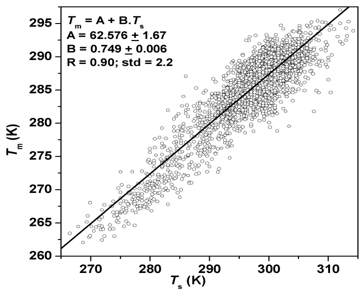

Fig. 2: T_m model for Indian subcontinent (General Model).

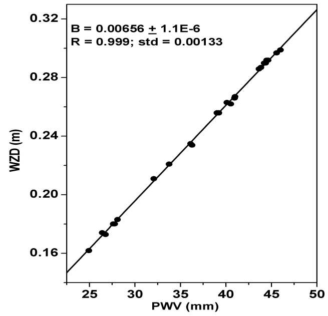

Fig 3: Local Model for retrieving WZD

The typical value of Π is ~ 0.15 [9]. However, it varies from place to place and season to season. It was found in our analysis for Bangalore, that mean value of Π is about ~ 0.162 with month-to-month variation ranging from ~ 0.161 to 0.164 corresponding to the variation of 282 K to 287 K in T_s. This showed that annual variation of Π for Bangalore is very less, about 0.0033.

ESTIMATION OF IWV FROM GPS DATA

One year GPS data for Bangalore were used in this study. The HZD was estimated using the empirical models based on surface pressure measurements (1). This HZD is subtracted from TZD to estimate WZD. From this, IWV is estimated using (2). The parameter Π in (3) was estimated based on Bevis model (5) and the General model developed for Indian Subcontinent, (6). The local model (Fig. 3) was developed exclusively for Bangalore as [14]

$$\mathrm{IWV} = 0.152 \times \mathrm{WZD} \tag{7}$$

The proportionality constant in this case is equivalent to $1/\Pi$. This model is also considered to retrieve IWV.

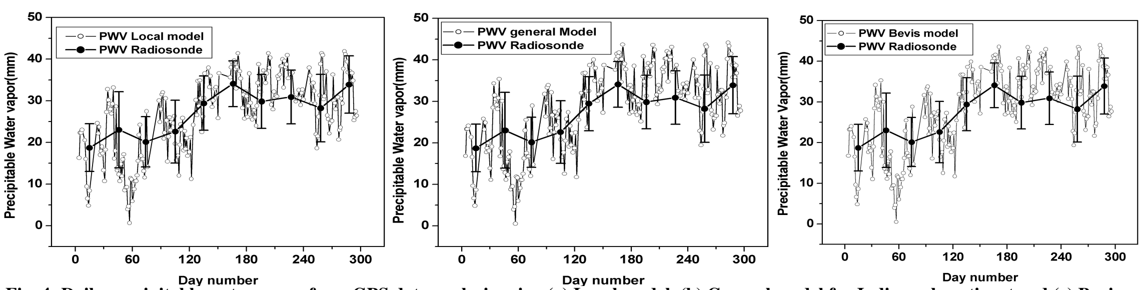

Fig. 4: Daily precipitable water vapor from GPS data analysis using (a) Local model, (b) General model for Indian subcontinent and (c) Bevis model.

Fig. 4 shows the comparison between the daily IWV derived from GPS data analysis employing the above three schemes along with IWV derived from radiosonde ascends at Bangalore for the period January to October of 2002, at 0000 UTC. The daily GPS-IWV in Fig. 4(b) and 4(c) were obtained using the General model for Indian subcontinent and Bevis model, respectively, used to derive the term Π. The daily IWV obtained using the local model (7) in which WZD is directly inverted to IWV is shown in Fig. 4(a). The solid dots in Fig. 4 represent monthly mean of IWV estimated by integrating the altitude profile of water vapor density obtained from radiosonde data, the vertical bars representing the standard deviation or day-to-day variability on water vapor (~ 5 kg/m^2). The IWV estimation by GPS shows large day-to-day variation, which supports the large standard deviation seen with radiosonde estimate. The general trend of IWV derived from GPS measurements was similar to that seen with monthly mean of IWV from radiosonde measurements.

Over Indian subcontinent, the monsoon onsets in first week of June and takes one week or more to propagate over Bangalore and lasts till November. In June and July, the monsoon is very active and associated with abundant precipitation. During this period the moist South-Westerly wind advects lot of water vapor from the oceanic environment to land. This is well depicted in the GPS measurements. Monsoon becomes active again in October – November. These features are also observable in Fig. 4. The deviation of GPS derived IWV is ~5 mm which comes at 15% of change in IWV during the monsoon period where as in December to March periods this is less than 3 mm (12%). The typical error in radiosonde accuracies is quoted as [4]: Barometric pressure about ±2 mb; Temperature about ±0.4 K; and for relative humidity ±4% which may cause an error of 2-3 mm of IWV. This aspect also should be borne in mind when comparing the two estimates of IWV.

The validity of these models was further examined quantitatively by estimating the absolute difference between the GPS derived IWV based on these models and that from radiosonde data on a day-to-day basis. The mean and standard deviation of absolute difference weighted with radiosonde measurements (true) in case of local model are about 6.60 and 4.34, respectively. The corresponding values for General model (5.37 and 3.55) and Bevis model (6.47 and 4.31) are found very close. Though, the difference among the weighted mean differences is less, local model is found superior to other two models. Incorporation of surface temperature parameter through $\prod$ in the retrieval of IWV does not improve the estimate accuracy. Thus to estimate water vapor over tropical region, the simple linear relation between IWV and WZD like local model presented in this study is more apt

CONCLUSION

The dry and wet component of TZD over Bangalore is studied based on ray-tracing technique to three years of daily radiosonde data and the models to predict both components of TZD based on the surface meteorological parameter are developed. This study shows that 1) Bevis model, though developed based on the atmospheric data of mid-latitude, is valid in near tropical region also. 2) The local model that does not use atmospheric temperature variation in the IWV retrieval is found superior to Bevis model and the General model developed for Indian condition.

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