Strategies for GPS-Based Estimates of' Troposphere Delay

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1 NTRODUCTI ON

Traditionally used for high precision geodesy, the GPS system has recently emerged as an equally powerful tool in atmospheric studies, in particular, climatology and meteorology. I'here arc several products of Gl%-based systems that arc of interest to climatologists and meteorologist. One of the most useful is the G1'S-based estimate of the amount of Precipit able. Water Vapor (PWV) in the t roposphere. Water vapor is an important variable in the study of climate changes and atmospheric convection (Yuan et al., 1 993), and is of crucial importance for severe weather forecasting and operational numerical weather prediction (kuo et al., 1993).

A grmmct-based GPS system dots not produce estimates of PWV directly. PWV is inferred from a direct estimate of the Total Zenith Delay (TZD), with the help of some ancillary information. The TZD quantifies the atmospheric delay for a GPS signal coming from the zenith direction. It is mapped to the. elevation angle of a particular satellite-receiver link by means of an appropriate mapping function, assuming horizontal symmetry. The TZD can be separated into two components, Zenith Dry Delay (ZDD) and Zenith Wet Delay (ZWD). 'I'he. ZDD is caused by the propagation delay and ray bending due to the dry gases in the troposphere. It can be accurately inferred by using precise measurements of atmospheric pressure at ground level, and removed from the total delay. The remaining ZWD is nearly proportional to the quantity of" PWV integrated along the zenith direction. The total PWV can be extracted from the ZWD to an accuracy of a few percent given measurements of the temperature at ground level. (Bevis et al., 1994, Rocken et al., 1993, Yuan et a]., 1 993). In the absence of pressure or temperature measurements on site, they can be approximated by means of an appropriate climate model. Verification of accuracy of GPS-based estimates of PWV is typically done by comparing it with estimates based on the more established techniques of radiosondes and Water Vapor Radiometers (WVR). Indeed, several recent comparisons demonstrated that GPS can provide Illillillctcl-level accuracy in measuring PWV (Businger et al., 1994, Schenewerk cl al., 1 994, Wolfe and Gutman, 1994, Fang et a].,] 994, Elgered et a]., 1995, Rocken et al., 1995, Chiswell and Businger, 1995, NOAA, 1995). The current level of accuracy of G1'S-based estimates of TZD is believed to be better than 1 cm. The extracted PWV is believed to be 1 -2 mm accurate.

It is well known that water vapor has significant smal]-scale variations in time and space (] .illy and]'cJ'key, 1976). The high temporal and spatial resolution of GPS-based estimates of PWV makes the GPS technology unique in its ability to augment the sparse measurements from the radiosondes network. For, example, the JPL routine processing of GPS data from the IGS network produces estimates of TZD every five minutes. The only other existing technology for PWV retrieval with high temporal resolution is based on Water Vapor Radiometers (WV]<), but their global distribution is extremely sparse due to their high cost. This fact highlights a crucial advantage. in exploiting the vast network of GPS ground receivers, namely, its very low cost.

Another unique advantage of G1'S-based PWV estimates is the potential availability of data from ground receivers in Near Real Time (NRT), allowing for timely assimilation of the estimates into numerical weather prediction schemes. Producing PWV estimates from NRT processing of GPS data poses a challenge, though. Usually, high accuracy estimates arc available after processing data from a relatively large global network of receivers. **in** NRT, only data from a small number of stations is expected and their distribution is unlikely to be global, at least in the near future.

in this paper wc discuss various aspects of the process by which ZWD arc estimated from GPS data and wc describe a very simple estimation strategy for NRT applications.

EVALUATING GPS-BASED ESTI MATES OF ZWD

in order to analyze various estimation strategies for ZWD from GPS data wc set up an experiment by which we compared GPS-based esti mates of PWV with those obtained from a collocated water vapor radiometer. The GPS data used in this experiment was obtained from an 8 channel, dual frequency, TurboRogue GPS receiver that is in continuous operation at a site located at the Jet Propulsion Laboratory. Simultaneous surface pressure and temperature measurements were. obtained from a Paroscientific Model 601613 pressure sensor with a stated accuracy of 0.01% of the nominal atmospheric pressure at the comparison site. Surface temperatures were obtained from a temperature sensor contained within the pressure sensor. The water vapor radiometer used in this comparison was a 3 channel design developed at J}']. (Keihm,1991). During the period of the inter comparison, the WVR operated continuously in a fixed scanning pat [cm. Measurements of the sky brightness temperature were made at a number of elevation angles to allow necessary gain corrections to be made to the W VR signal. PWV estimates used in this comparison were obtained from the WVR measurements made at zenith.

The GPS-based estimates of PWV were obtained by processing the data with the GIPSY/OASIS II software system using the technique of precise-point-positioning (Zumberge et al., 199S). The GPS orbits used in the precise-point-positioning technique were those produced routinely at JPL for the IGS. The measurement interval is five minutes. Pseudorange measurements are carrier-smoothed anti carrier phase measurements are simply decimated to the five minutes mark. The troposphere is modeled as random walk with sigma of approximate] y 1 cm/√hour. Estimates of ZWD arc produces every five minutes.

The experiment spanned the months of August and October, 1995. Wc will describe here results from 18 days during August. W VR measurements from the rest of the month were excluded due to the existence of clouds. WVR measurements were available again for most of October but the result of the comparisons is similar.

When considering the results below, it must be remembered that there arc inherent limitations to the accuracy of both WVR and GPS-based estimates of PWV. A simple analysis of major error sources (Runge, 1995) has estimated that the uncertainty in GPS-based estimates of PWV is approximately 1.1mm for PWV values in the range of 20 mm. Similarly, due to uncertainties in instrument calibrations and retrieval algorithms, the accuracy of WVR measurements of PWV is currently limited to 1 to 1.6 mm,

EFFECTS OF ELEVATION ANGLE CUTOFF

In this experiment we tested the effect Of the GPS receiver elevation angle cutoff' on the quality Of the ZWD estimates. The results are summarized in 1 'igure 1. We found that the standard cutoff of 15 degrees gave rise to a significant bias between the GPS-based estimates Of ZWD and PWV and the WVR-based estimate.s. This bias was reduced dramatically when the elevation angle cutoff was reduced to 7 degrees. An illustration of' the different estimates during the first three days in August is presented in Figure 2. Similar behavior was observed with the October data.

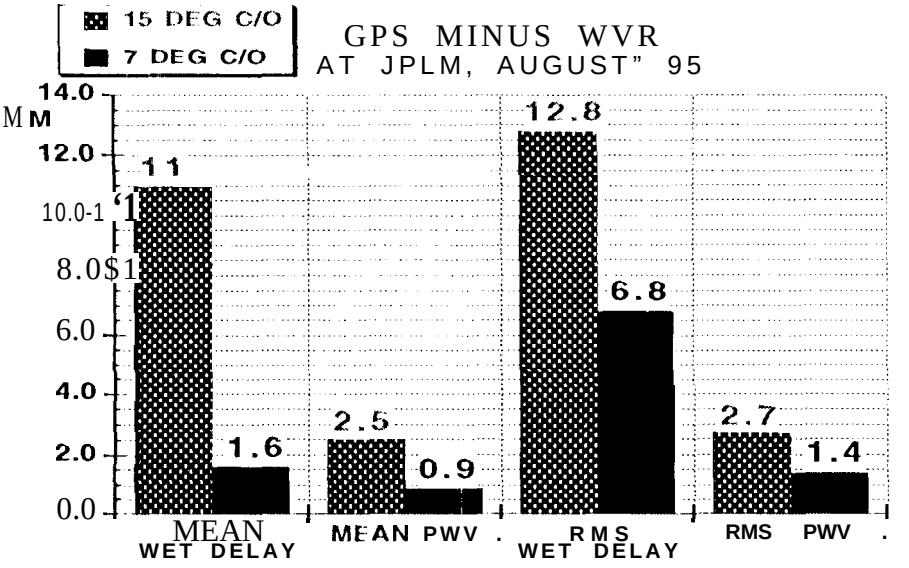

Fig 1. Effects of elevation angle cutoff on difference between GPS-based estimates of ZWD and WVR estimate. Statistics were based on 18 days in Auguts 1995.

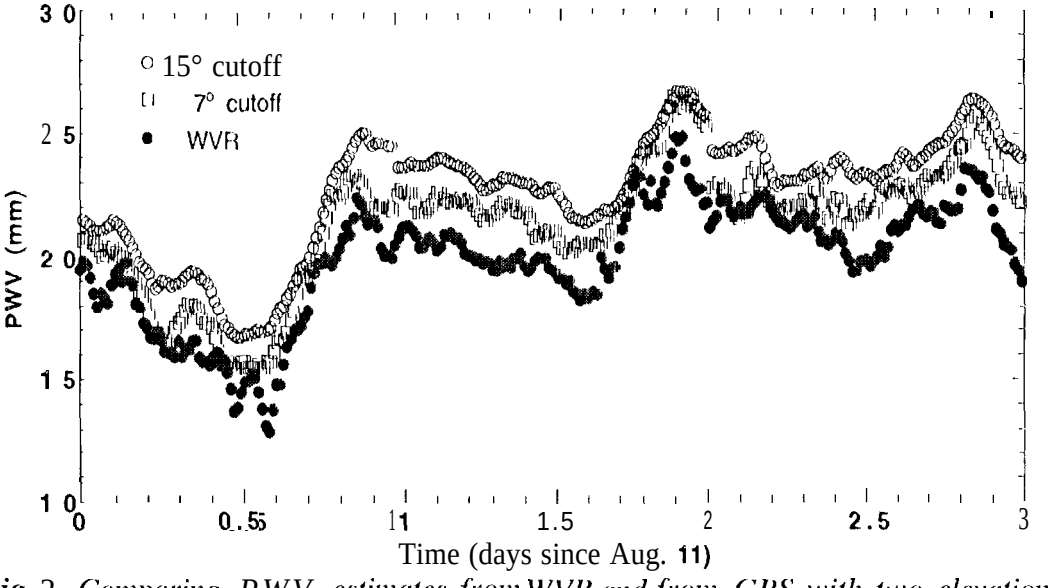

Fig 2. Comparing PWV estimates from WVR and from GPS with two elevation angle cutoffs for three cloys in A uguts, 1995, at the JPLM site.

Accompanying the bias in ZWD between GPS estimates with different elevation angle cutoffs was a bias in the estimated geodetic height of the station. This bias can be observed from Figure 3, depicting the daily geodetic height estimate over the whole month of August with the two elevation angle cutoff values. The mean bias is 2.5 cm.

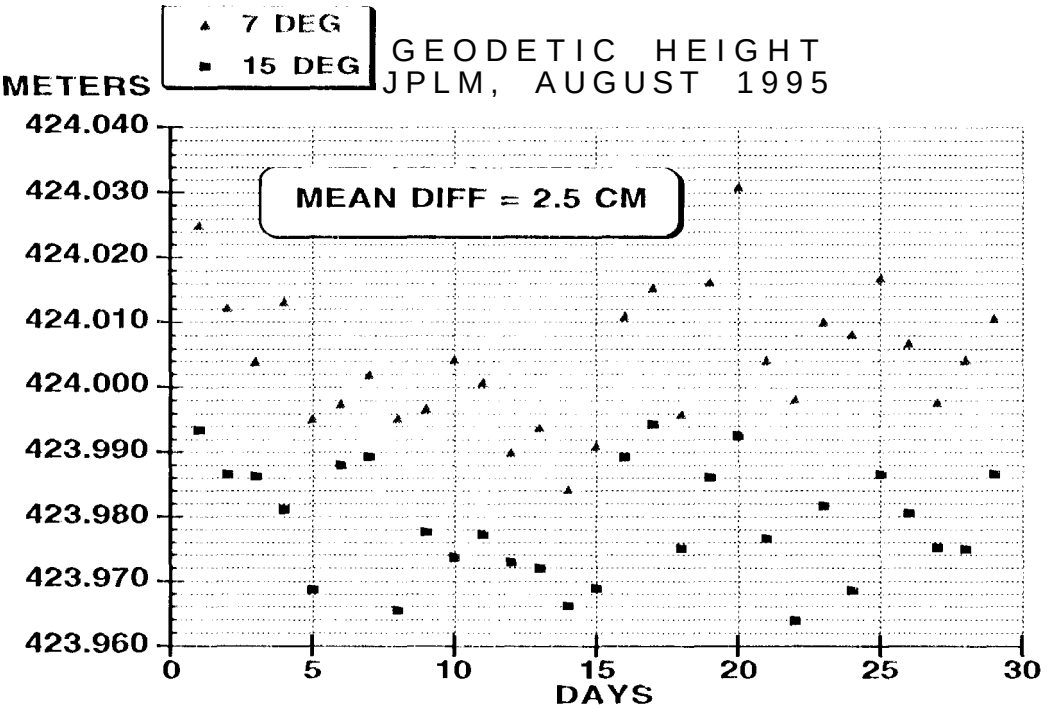

Fig. 3. Estimated geodetic height of JPLM with two elevation angle cutoff values.

Although WVR estimates were not available there, we compared GPS-based estimates of ZWD with the two elevation angle cutoffs for several other sites during January, 1996. We found that the size of the bias between the estimates varies from site to site and it can often be insignificant (less than 5 mm) for many. The largest bias was found at 1 '01<" 1', a relatively wet site. (See Figure 4.)

We hypothesize that the improvement in ZWD estimates at lower elevation angle cutoff, as observed at JPLM during August and October, 1995, is due to the reduction in the correlation between ZWD and station height. More experimentation is required in order to establish that this phenomena is not site/receiver dependent.

in general, lowering the elevation angle cutoff did not have a detrimental effect on station position repeatabilities over a month. It suggest that carrier phase multipath may not be very damaging at 7 degrees elevation.

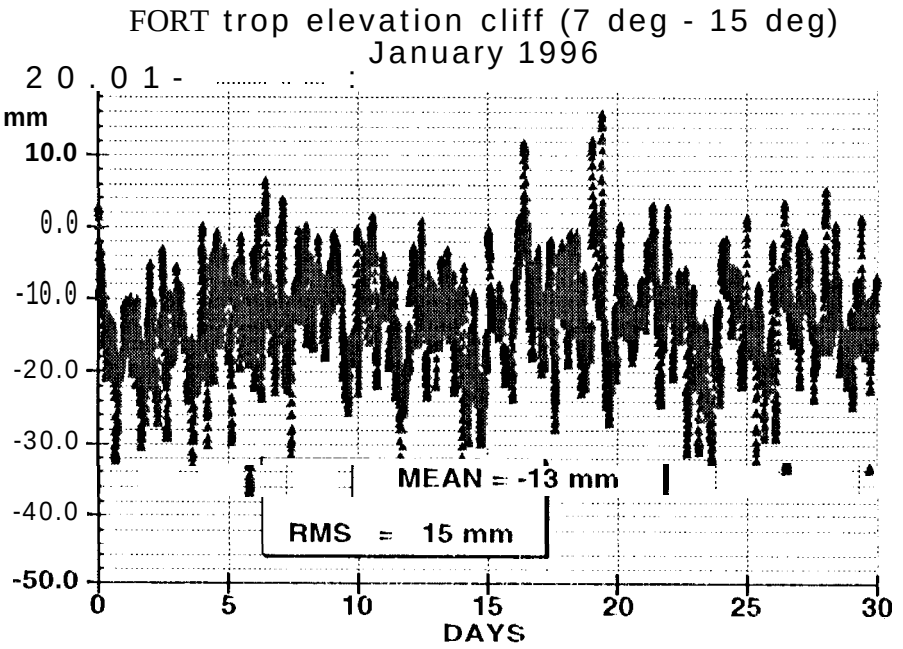

Fig. 4. Difference in ZWD estimates obtained with elevation angle cutoff values of 15 degrees [111(17 degrees.

EFFECTS OF GPS YAW ATTITUDE MISMODELING

GPS satellites display a rather complicated yaw attitude behavior during crossing of the 1 'arth shadow (Bar-Sever et al., 1996, Bar-Sever, 1 996). Mismodeling this behavior is especiall y harmful in precise-point-positioning. In {his experiment wc estimated ZWD at various sites t wice. Once with the new yaw attitude model (Ilar-Sever, 1996) and once with the old yaw attitude model (the basic ROCK model) that is still in use in many geodetic software systems.

Assuming now that the TZD estimates obtained with the ncw yaw model are "truth", and subtracting these estimates from estimates obtained with the ROCK yaw model, there are many cases where the differences significantly exceed 1 cm. Figure 5 depicts two examples: for FORT and BRMU. TZD values for Ill< Ml] (after subtracting the mean), estimated without the yaw model, are also presented in Figure 1 in order to demonstrate that the peaks in the error figure are indeed associated with anomalous features in the estimated value. Ail the peaks in Figure 1 correspond to epochs of observing an eclipsing satellite during its yaw maneuver. These errors may be unacceptably large for some applicat ions. (1 'rrors in TZD arc equivalent to errors in ZWD.)

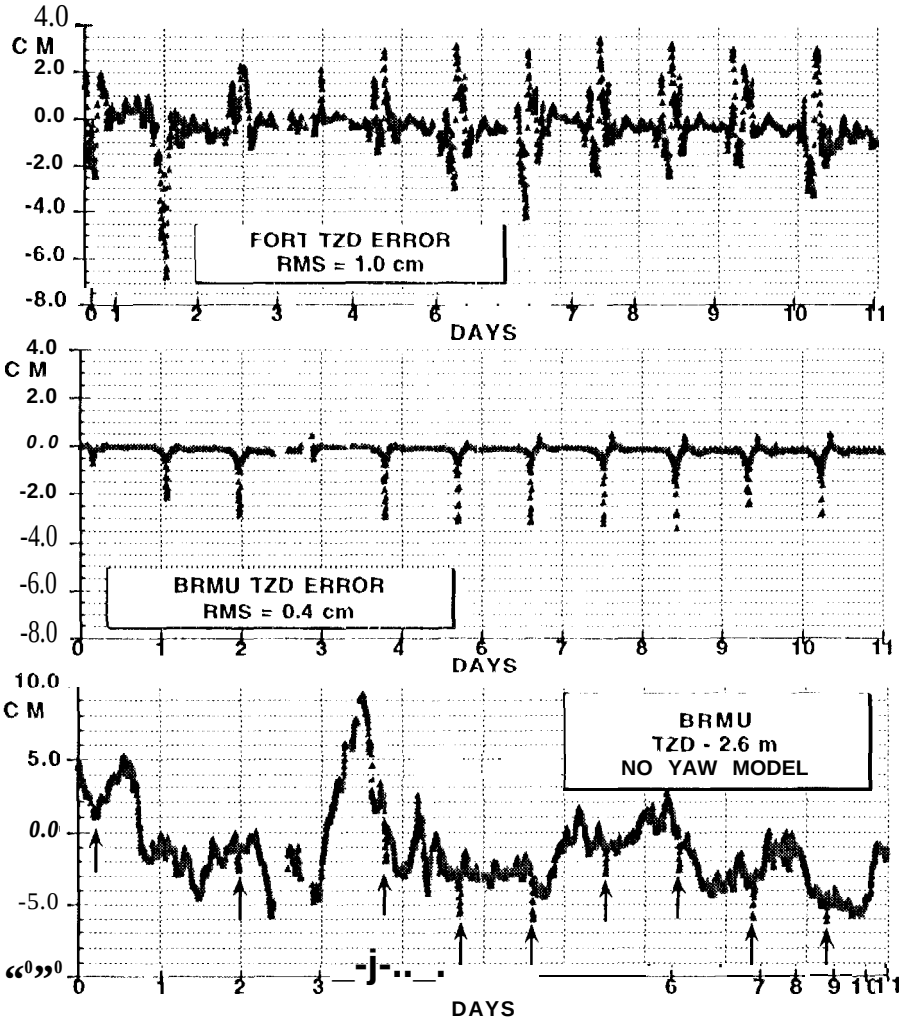

Fig. 5. Effects of omitting the GPS yaw model on estimates of total troposphere zenith delay (TZD) for FORT and BRMU. Estimates of TZD with the full yaw model (with estimated yaw rates) are considered truth. Top: TZD errors for FORT. Middle: TZD errors for BRMU. Bottom: estimated TZD for BRMU after a mean of 2.6 m was taken out and when GPS yaw model was not used. The arrows indicate the anomalous features of the estimates that correspond to the peaks in the error middle figure.

EXTRACTING A SIGNAL FROM THE POST-FIT RESIDUALS

It is a common notion that some tropospheric signal is still present in the carrier phase post-fit residuals. In order to test this notion and its utility for ZWD retrieval, pint-fit residuals from receiver-transmitter links with elevation angles greater than 60 degrees were added to the estimated ZWD. If more than one link exists at an epoch, the residuals from all the links were averaged. Crude editing was used to exclude residuals larger than 8 mm. The "corrected" ZWD estimates were then compared to the WVR estimates. This experiment was carried out for the 15 degrees elevation cutoff case (that had a large bias wrt the WVR estimates) and for the 7 degrees elevation cutoff case. The results are summarized in Figure 6. (Epochs for which no corrections were available were removed from the statistics.)

When residuals corrections were applied, the biases wrt the WVR estimates decreased in both cases, more so for the 15 degrees elevation cutoff case. But in both cases the RMS increased. For the 15 degrees elevation cutoff case. the bias decreased for each individual day out of the 18 days in August. In the 7 degrees elevation cutoff case the. bias decreased on most individual days, These results support the notion that there is tropospheric signs] in the carrier phase post-fit residuals but it also demonstrate that there is quit a bit of noise there. The noise level in the correction may be reduced perhaps, with a more sophisticated editing scheme, but there is no doubt that there is not enough signal in the post-fit residuals to offset the large bias in the estimates. Low elevation angle residuals, though, could be more useful in correcting line-of-sight wet delay because they are expected to contain larger tropospheric signal, in proportion to the larger air mass the signal traverses.

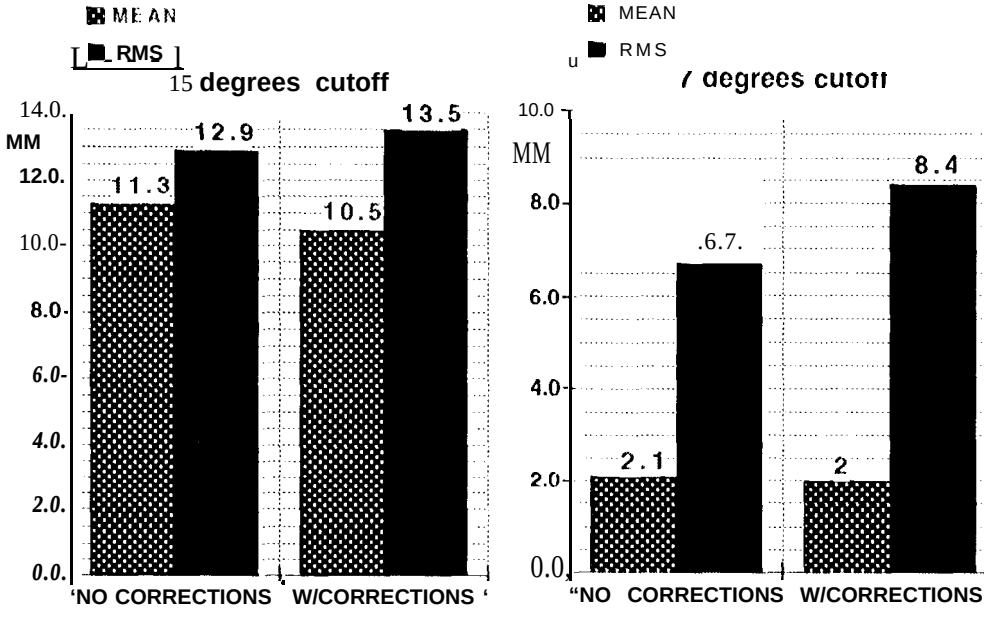

Fig 6. Effects of adding "zenith" residuals to ZWD estimates on the difference between the GPS-based estimates and the WVR estimates.

NEAR REAL TIME ESTIMATION STRATEGIES

To serve as useful input to numerical weather prediction models, the GPS-based estimates of PWV would need to be available within several hours after the data have been collected. In contrast, GPS-based PWV estimates described in the previous sections were produced using precise GPS orbits and clock obtained by processing data from a global network of ~30 GPS receivers and are available 2-4 days after data has been collected. Therefore, it is currently not possible to use precise GPS orbits and clocks as the basis for a system to provide near real time PWV estimates. For this reason, we have investigated the use of "predicted" GPS orbits as an alternative. It should be clear that the results cannot be as accurate as those obtained with precise orbits and clock. The minimal level of accuracy demanded from the NRT PWV is application-dependent and has not been established yet. In this study, rather arbitrarily, we set the accuracy goal at 2 mm RMS for PWV (approximately 12 mm RMS for ZWD).

The predicted GPS orbits used in this study were obtained by fitting an orbit to four consecutive days of precise daily solutions, adjusting for 6 epoch state parameters and eight additional empirical parameters. The solution was then extrapolated forward using the satellite's dynamics. Orbit error increase quadratically, in this scheme, up to a level of two meters RMS after two days.

Because of SA satellite clocks cannot be extrapolated. Hence the need to estimate them (or difference them out). This requires the simultaneous processing of at least two ground stations. We have found that under certain circumstances no more stations are needed. This forms the simplest scheme for NRT retrieval of ZWD.

When one of the station's clock is held as a reference it is possible to solve for the other station clock as well as ZWD for both stations and all observed GPS clocks with a technique equivalent to double differencing. This technique imposes some constraints on the selection of the second station (one of the stations is considered the target of the ZWD estimate. The other is brought in to provide clock resolution. Its ZWD may or, may not, be desired). The two stations should not be too far apart. If they are, they will fail to form enough double differences. They should also not be too close. If they are, the normal equations will tend to be singular and troposphere at the two stations will be strongly correlated. We have found that separation of 200 km - 1 000 km usually work well (Figure 7).

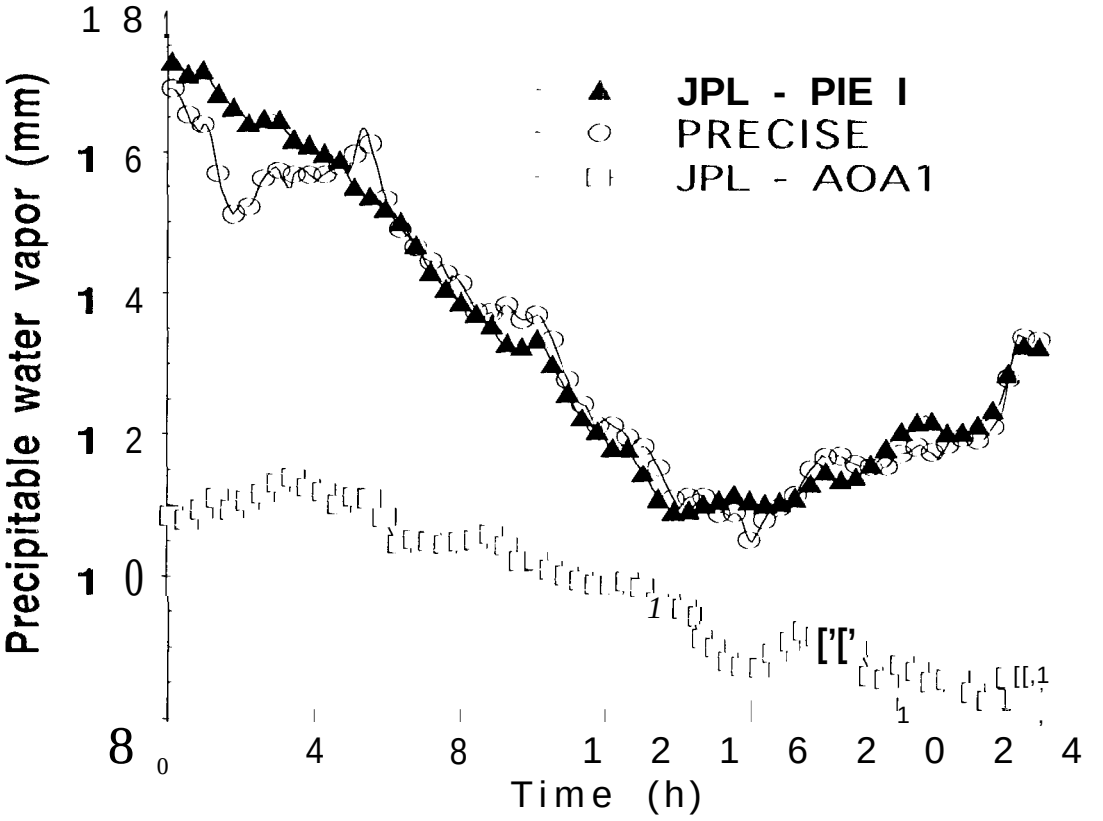

Fig 7. The effect of site separation on the accuracy of GPS-based PWV estimates. The JPL-PIE1 distance is ~1000 km while the JPL-AOA1 distance is ~60 km. The "precise" results are those obtained using post-processed GPS orbits and clocks rather than predicted orbits.

The degradation in the quality of the predicted orbit causes, in turn, a degradation in the quality of the ZWD estimated (Figure 8). It is desired, therefore, that the prediction period be minimized. If orbit errors are potentially too large, a third station can be brought in. The three-station differential solution has enough data strength to adjust the GPS orbit. Moderate baselines between all three stations should be maintained for best results. (Figure 9.)

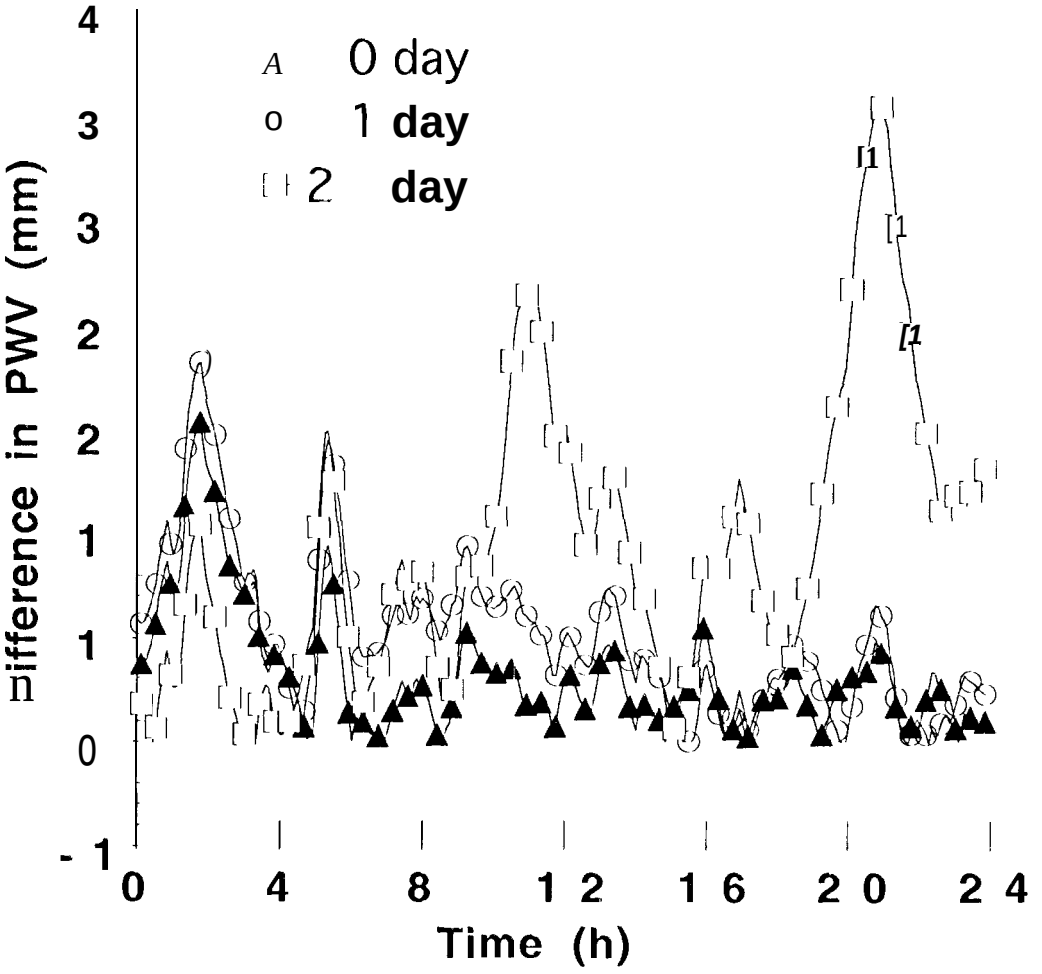

Fig 8. The effect of GPS orbit prediction period on the accuracy of the PWV estimates. The "0 day" graph corresponds to estimates obtained with precise GPS orbits and clocks and no prediction. The "1 day" graph corresponds to estimates obtained using GPS orbits predicted 24 hours, over these 24 hours. The "2 day" graph corresponds to estimates obtained using GPS orbits predicted 48 hours, over the last 24 hours.

in NRT applications data will arrive at the processing center in small batches. If the batch length is too short there will not be enough data to resolve the ZWD properly, given the temporal correlation of the troposphere delay model. In our test, a minimum of three hours was required to resolve the ZWD reasonably well (Figure 10). Processing short batches is possible with proper initialization of the covariance matrix with the covariance of the previous batch.

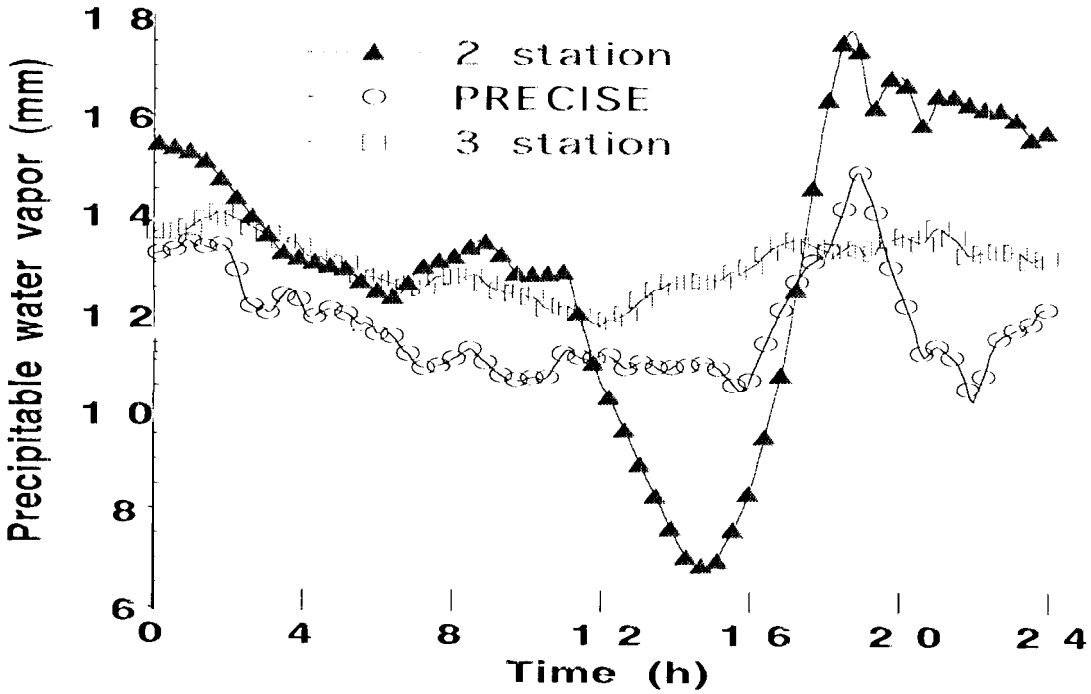

Fig 9. The effect of adding data form a third GPS receiver and adjusting the GPS orbits when estimating PWV values. The two station case used JPL and Pietown, and the three station case added data from LEX1.

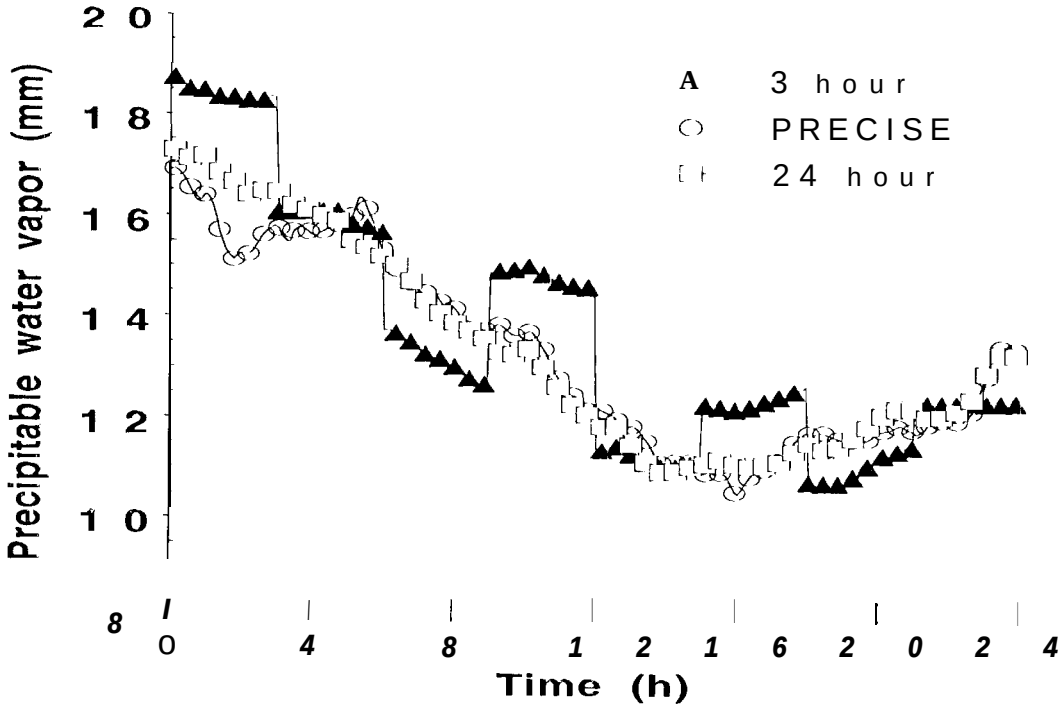

Fig 10. The effect of decreasing the span of the data on the accuracy of GPS-based estimates of PWV. These results were obtained from data recorded at the JPL and Pietown sites.

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