# Measurements of Precipitable Water Vapor by GPS, Radiosondes, and a Microwave Water Vapor Radiometer

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## BIOGRAPHY

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## ABSTRACT

Results from the Westford WAter Vapor Experiment (WWAVE) will be discussed. This experiment was designed to measure the temporal and spatial variability of the total precipitable water vapor (PWV) over an area of roughly 25 km radius around the Haystack Observatory in Westford, MA. The main experiment was conducted from August 15 to August 30, 1995, and a variety of techniques were used to measure the water vapor, including radiosondes launched two to three times daily from the Westford site; a water vapor radiometer (WVR) located at the site; and eleven GPS receivers arranged within a 25 km radius around the site (with three receivers located within one km of each other at the site). Surface meteorological monitoring units were collocated at eight of the GPS sites. In addition, estimates of the precipitable water vapor were obtained with the Westford VLBI antenna as part of a 6-station network which included antennas in Alaska, Hawaii, Germany, Sweden, and Norway.

Discrepancies on the order of 10-30 mm of zenith wet delay (1-5 mm of PWV) are seen in the measurements of precipitable water vapor by the Haystack radiosonde launches as compared to those from the nearby NWS radiosonde sites (Grey, Maine, Chatham, Massachusetts, and Albany, New York). Possible explanations are differences in geographical locations, in humidity sensors, and/or in the processing algorithms. A comparison of the collocated Haystack WVR and radiosonde estimates of the precipitable water vapor also indicates differences on the order of 10 mm zenith delay (1-2 mm of PWV). Finally, systematic differences in the GPS determination of PWV are observed that depend on the elevation cutoff used in the GPS analysis. These differences are not related to the type of GPS antenna and receiver, and are not seen at all sites. The discrepancies are consistent with the effects of near field scattering seen in geodetic GPS measurements and indicate that GPS antenna mounts should be considered in designing water vapor retrieval systems based on GPS.

## INTRODUCTION

The Westford Water Vapor Experiment (WWAVE) was designed to investigate the use of the Global Positioning System (GPS) to determine total precipitable water vapor (PWV). PWV is defined as the height of liquid water that would result from condensing all the water vapor in a column from the surface to the top of the atmosphere. Such information can be used in climate and weather research. Water vapor is one of the most important green house gases. Long-term changes in the amount of water vapor in the atmosphere need to be monitored to help detect and predict changes in the earth's climate.

PWV measurement can also be used to improve weather forecasting. Atmospheric water vapor is a critical component in the formation of clouds,

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precipitation, and severe weather. Currently, the National Weather Service (NWS) obtains information on the water vapor distribution from satellite information and from twice daily radiosonde launches at 93 sites around the continental U.S. The recovery of the PWV by satellites is complicated over land (not oceans) because of the variable surface temperature. The radiosonde network is expensive to operate, and there are currently proposals to reduce the number of operational sites in the US. Furthermore, the balloons carrying the sonde packages take about an hour to reach the tropopause, and thus the data are not available on rapid time scales. In addition, although the radiosondes provide information on the water vapor profile, the horizontal spatial density is too low and time between launches too high to observe rapid changes of the water vapor with time and position. GPS can provide a continuous measurement on a near real-time basis (half-hour) of the average total precipitable water vapor around a site. Once installed, a GPS receiver can run automatically, and additional costs are associated primarily with data processing. The type of information provided by GPS could both close the 12 hour gap and allow for better spatial distribution in the network.

GPS data are used to estimate the zenith tropospheric delay from measurements of the delay to each GPS satellite in view from a ground station. Typically six to nine GPS satellites are in view at any given time over the continental U.S. A network of GPS receivers is required to determine both the GPS orbits and the additional biases introduced by the satellite clocks, the receiver clocks, and the receiver biases. The analysis of GPS data produces an estimate of zenith wet delay (ZWD). The zenith wet delay is that part of the range delay that can be attributed to the water vapor in the troposphere. PWV is related to ZWD by a factor $\Pi$ that is approximately 0.15 (Bevis et al., 1994) and varies by 20%. The factor $\Pi$ is a function of the weighted mean temperature of the atmosphere (Davis et al., 1985) and can be determined to about 2% when it is computed as a function of surface temperature, or 1% if data from numerical weather models are used. The zenith wet delay in the Westford, Massachusetts area ranges from near 0 to approximately 40 cm, corresponding to a PWV of 0 to 6 cm. The data presented in this paper are given in terms of zenith wet delay (ZWD).

WWAVE consisted of a one month campaign using a network of ground-based GPS receivers to recover the total precipitable water vapor at individual stations. The 11 GPS sites are within 25 km of the Haystack Observatory which is located in Westford, MA. The primary goal of WWAVE was to estimate the total precipitable water vapor from GPS data and to evaluate the accuracy of these estimates. In order to evaluate the accuracy of the GPS measurement of ZWD, GPS estimates were compared to those from water vapor radiometers (WVRs), very long baseline interferometry (VLBI), and radiosondes. Initial WWAVE results have been discussed in Coster, et al., 1996 and Niell, et al., 1996. This paper includes the initial comparisons of the VLBI zenith wet delay estimates at Westford, as well as a more complete analysis of the NWS radiosonde data.

A secondary goal of WWAVE was to examine the effect of different types of GPS receivers, and GPS antennas and antenna mounts, on the retrieval process of PWV. To this end, different types of GPS receivers and antennas were compared during this campaign. An analysis of the effect of different elevation cutoffs of GPS data used in solving for the PWV is presented.

## BACKGROUND

Since 1992, a combined group of scientists from UNAVCO, North Carolina State University (now at the University of Hawaii), and MIT have been investigating the use of GPS for the determination of total precipitable water vapor (Bevis et al., 1992, Rocken et al., 1993, Bevis et al., 1994, Rocken et al., 1995). Earlier work by Coster et al., 1990, indicated that GPS data could be used to recover the tropospheric path delay. Initial results from these experiments have been encouraging, although it is clear that issues remain in the area of data processing, real-time development, and accuracy determination. Several other groups have begun to look at these problems, including Dodson and Shardlow, 1995, who used a network of receivers located in the United Kingdom, Germany, Spain, Sweden, Finland, and the Netherlands.

In the GPS/STORM experiment (Rocken et al., 1995) data were collected from six GPS receivers for a one month period in 1993 at sites in Colorado, Oklahoma, and Kansas. Four of these sites were also equipped with water vapor radiometers (WVR's). All of the GPS receivers used in GPS/STORM were Trimble™ 4000 SST 8 channel dual frequency phase and C/A code receivers. Most of their antennas were mounted 3 m high atop stable fence posts. One was mounted atop a trailer. A 15 degree elevation cutoff was used throughout the analysis of the GPS/STORM data. Because of this, the specific tropospheric mapping function used was not significant. Data were analyzed with the UNAVCO version of the GPS Bernaese V.3.4 software using GPS satellite orbits generated by the Center for Orbit Determination in Europe (CODE) in Berne, Switzerland. The analysis of this data indicated that water vapor can be monitored with an accuracy of 1-2mm of PWV (6-12 mm of zenith wet delay) over a 900 km 6 receiver network. In the conclusion, it was suggested that better GPS antennas could be installed at the site to reduce multipath. In addition, a feasibility study was suggested to consider the operation of near real-time GPS meteorological monitoring networks. Finally, note that DoD anti-spoofing (AS) was not on during the GPS/STORM experiment. AS was on during WWAVE.

WWAVE was designed to use a geographically smaller array than the above groups. The GPS/STORM experiment had receivers scattered over several states, while WWAVE focused on a network of receivers spaced within 25 km radius of the central Westford location. The majority of antennas used during WWAVE were Dorne Margolin choke ring antennas. These antennas were designed to minimize the multipath problem, and their use allowed the inclusion of GPS data down to 5 degrees in elevation. Two of the antennas used were the Ashtech 700718B, which is one of the standard surveying antennas that comes with the Ashtech Z12 system.

The GPS processing software (GIPSY/OASIS) (Webb and Zumberge, 1995) was updated with the Niell tropospheric mapping function (Niell, 1996). The focus of the work presented here is on the accuracy of the GPS estimates of PWV as compared to other water vapor retrieval estimates. The issues examined concern the consistency of the GPS determined value of the zenith wet delay (ZWD) as compared to ZWD's derived from radiosondes, VLBI, and a WVR. WWAVE used improved P-code GPS receivers, specific antennas to reduce site multipath, and GPS software optimized for tropospheric estimation.

The measurement theory of GPS, radiosondes, and water vapor radiometers has been described in detail in an earlier WWAVE paper (Coster, et al., 1996), and by several other authors (Rocken et al., 1995, Davis, et al., 1985, Elgered, G, 1993). Retrieval of the zenith wet delay from VLBI data is discussed in Herring, et al., 1990. For the sake of brevity, the theory will not be presented here.

In this paper, the GPS estimates of the zenith wet delay were computed using JPL's GIPSY/OASIS software (Webb and Zumberge, 1995) and the JPL determined precise orbits were used. These orbits are predicted to be accurate to 20 centimeters (Lichten, et al.,1995), although recent modifications have improved the orbits to 10-15 cm (Lichten,1996).

**THE EXPERIMENT**

The Westford Water Vapor Experiment (WWAVE) took place from 8 August to 12 September 1995. The main dates for WWAVE were chosen to coincide with the NASA sponsored VLBI campaign which took place from 15 - 29 August 1995. Five types of data were collected: surface meteorological, radiosonde, water vapor radiometer (WVR), very long baseline interferometry (VLBI), and GPS data. The surface meteorological data consisted of either surface pressure, temperature, and humidity measurements, or simply surface pressure measurements. The surface pressure data were used to separate the GPS estimate of the tropospheric wet delay from the total tropospheric delay. The radiosonde launches consisted of balloons carrying Vaisala sonde packages with pressure, temperature, and humidity sensors. The radiosondes were launched twice daily from the Haystack Observatory parking lot, a location close to three of the GPS receivers and also the location of the WVR. Radiosonde data were also collected from the twice daily launches by the National Weather Service at Chatham, MA, Grey, ME, and Albany, NY. The National Weather Service uses Viz sonde packages. Finally, a single additional launch (also using a Vaisala sonde package) from the Phillips Lab on the Hanscom AFB near Lincoln Laboratory was used to verify the data processing of the Haystack radiosonde data. The WVR was positioned approximately 200 meters from the northernmost of the three Westford GPS sites (MHR0) and approximately 625 m from the radiosonde launch site.

The water vapor radiometer data were collected continuously from 8 August through 12 September 1995. A radiosonde was launched twice daily from the Haystack Observatory parking lot starting 15 August and continuing through 29 August. The GPS data collection period began 15 August and extended through 5 September 1995.

Table 1 gives the details of the various GPS receivers used in the WWAVE experiment and of their corresponding weather stations.

TABLE 1. Westford Water Vapor Experiment: GPS Receivers

| SITE | LOCATION | RECEIVER | ANTENNA |
|---|---|---|---|
| MHR0<br>* | Millstone Radar<br>Pole on Roof<br>Westford, MA | A.O.A.<br>Turbo Rogue | Dorne-Margolin<br>w. choke ring |
| WES2<br>* | Westford Antenna<br>10 m Tower<br>Westford, MA | A.O.A.<br>Turbo Rogue | Dorne-Margolin<br>w. choke ring |
| G420<br>** | Lincoln Lab<br>Pole on<br>Flat Roof<br>Hanscom AFB | A.O.A.<br>Turbo Rogue | Dorne-Margolin<br>w.choke ring |
| WFRD<br>* | Ground Mount<br>Westford, MA | A.O.A.<br>Turbo Rogue | Dorne-Margolin<br>w. choke ring |
| AEN0<br>*** | Tripod on<br>Peaked Roof<br>Harvard, MA | A.O.A.<br>Turbo Rogue | Dorne-Margolin<br>w. choke ring |
| ULWL<br>** | University of Lowell<br>Tripod on Flat Roof<br>Lowell, MA | Ashtech<br>Z-12 | Ashtech<br>700936B<br>Dorne-Margolin<br>choke ring<br>& radome |
| NVT0 | Nashoba Tech<br>High School<br>Westford, MA<br>Tripod on<br>Flat Roof | Ashtech<br>Z-12 | Ashtech<br>700936B<br>Dorne-Margolin<br>choke ring<br>& radome |
| SGJ0<br>*** | Pepperell, MA<br>Tripod on<br>Peaked Roof | A.O.A.<br>Turbo Rogue | Dorne-Margolin<br>with choke ring |
| JIM1 | Dunstable, MA<br>Ham Radio<br>Tower | Ashtech<br>Z-12 | Ashtech<br>700718B<br>Surveying<br>Antenna |
| FIRE | Groton, MA<br>Fire Tower | Ashtech<br>Z-12 | Ashtech<br>700718B<br>Surveying<br>Antenna |
| TAC0<br>* | Nashua, NH<br>Tripod on<br>Peaked Roof | A.O.A.<br>Turbo Rogue | Dorne-Margolin<br>with choke ring |

* Rainwise Weather Station
**Vaisala Weather Station,***Paroscientific Barometer

The relative positions of the various GPS receivers are indicated in the map shown in Figure 1.

GPS RECEIVER LOCATIONS

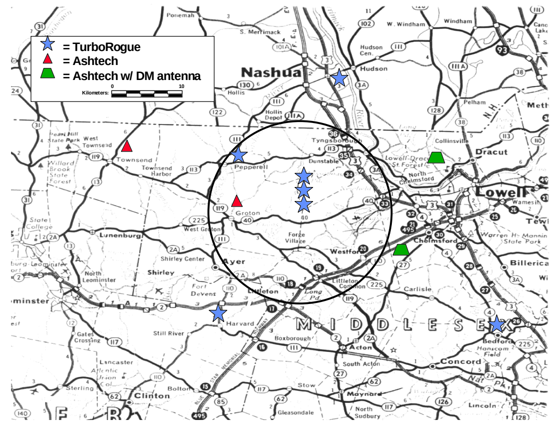


*Figure 1. Map showing location of the GPS Receiver Sites.*

The GPS data used for comparison to the VLBI, WVR, and radiosonde data were taken from one of the closest GPS sites: MHRO, which is represented by the top of the three stars in the center of Figure 1. The WVR at the Firepond facility, the Haystack radiosonde launches, and the Westford antenna used for VLBI measurements, were also located near the position of the top of these three stars in the center of the circle. The GPS derived positions in the WGS-84 coordinate frame for ten of the GPS sites are given in Table 2. These positions were derived using an average of the GPS data over the fifteen days of the main experiment (day 230-244). The positions have a precision on the order of 5 mm. Approximate positions are also listed for the Westford VLBI antenna, the WVR ,and the radiosonde launch site at the Haystack Observatory. Note the difference in heights between the different stations.

TABLE 2. WGS-84 Positions of GPS Sites and of the WVR, VLBI, and Radiosonde Launch Sites

| WGS-84 | Latitude (deg) | E. Longitude (deg) | Height (m) |
|---|---|---|---|
| MHR0 | 42.61789573 | 288.50885365 | 112.768 |
| WFRD | 42.60815900 | 288.50598577 | 56.438 |
| WES2 | 42.61333773 | 288.50667395 | 85.235 |
| AEN0 | 42.52873272 | 288.44481112 | 99.059 |
| G420 | 42.45949781 | 288.73484282 | 54.813 |
| JIM1 | 42.63978280 | 288.31232957 | 86.057 |
| FIRE | 42.61008779 | 288.44235602 | 146.367 |
| SGJ0 | 42.66578305 | 288.44378072 | 42.994 |
| ULWL | 42.65452079 | 288.67408204 | 23.453 |
| NVT0 | 42.57103698 | 288.59034549 | 65.387 |
| VLBI* Westford | 42.62 | 28.5 | 116 |
| WVR* | 42.618 | 288.51 | 107 |
| Haystack Radio-sonde* | 42.623 | 288.51 | 92 |

***** approximate positions

**DATA ANALYSIS**

This section will focus primarily on the comparisons of different kinds of data. First, a comparison was made between the zenith wet delays measured by the Haystack radiosonde launches and those measured by the three closest NWS radiosonde sites in Grey, ME, Chatham, MA, and Albany, NY. Following this, a comparison between the Haystack radiosonde derived zenith wet delays and the WVR determined zenith wet delays will be shown for the 15 day period of the main experiment. To this comparison, the estimated zenith wet delay associated with the nearest GPS site to both the WVR location and to the Haystack radiosonde launch site will be added. Finally the VLBI estimates of zenith wet delay are compared to those from the WVR, GPS, and Haystack radiosonde. This analysis of the different data sets allows for an assessment of the accuracies offered by the different kinds of techniques used to measure precipitable water vapor. The data analysis section ends with an examination of the effect on the determination of zenith wet delay when different elevation cutoffs are used in the GPS data processing.

**Comparison of the Haystack Radiosonde and the NWS Radiosonde Zenith Wet Delay**

Figure 2 shows the comparison of the zenith wet delay calculated from the Haystack radiosonde data and the NWS radiosonde data from Chatham, MA, Grey, ME, and Albany, NY. The zenith wet delays were calculated using an atmospheric delay raytrace program developed by J. Davis, T. Herring, and A. Niell (Niell, 1996). This program computes the zenith wet delay from the pressure, temperature, and relative humidity. What is clearly evident in Figure 2 is that the Haystack estimates of the zenith wet delay are consistently lower than the other three NWS sites. On average, the difference between the Haystack estimate and the estimates from the other three sites is 33 mm in zenith wet delay. Since Haystack is in the center of the region (east of Albany, NY and west of Chatham, MA and Grey, ME), the consistently lower value measured for the zenith wet delay raised a flag.

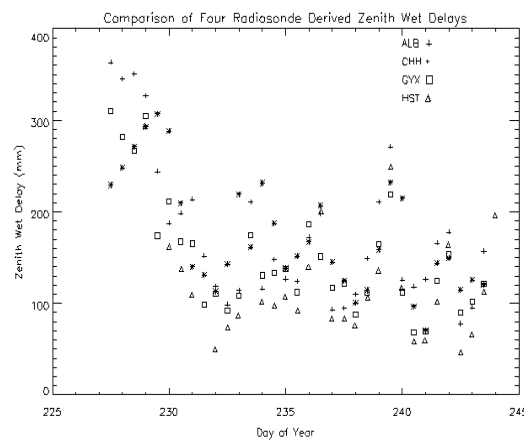


*Figure 2. Comparison of zenith wet delays obtained by NWS radiosondes flown from Albany, NY, Chatham, MA, and Grey, ME and by the Haystack radiosondes.*

TABLE 3. The average differences in ZWD between the Albany, Chatham, Grey and Haystack radiosondes.

| | Average Difference in ZWD (mm) | Std. Dev.of the Diff. in ZWD (mm) |
|---|---|---|
| ALB-HST | 35 (6 PWV) | 27 (4 PWV) |
| CHH-HST | 46 (8 PWV) | 41 (7 PWV) |
| GYX-HST | 19 (3 PWV) | 24 (4 PWV) |

The Chatham (CHH) and Grey (GYX)

measurements of zenith wet delay might be expected to be slightly larger than the Haystack (HST) values since these sites are located near the ocean and are at lower altitudes. However, the consistently larger average value of precipitable water vapor seen at Albany (ALB) was surprising. Closer evaluation of these discrepancies indicated that the differences could be partly attributed to the different type of sondes and data processing algorithms used. The VIZ sondes of the National Weather Service (NWS) use hygristors to measure the humidity, and it is known that hygristors are less accurate in regions of very high or very low humidity. In fact, the NWS does not report relative humidities below 20% RH (Westwater, et al., 1989, Wade, 1994). The Vaisala sondes used during the Haystack launches typically measure drier than the Viz sondes. The NWS is in the process of converting over to Vaisala sondes. To verify our data processing, a Haystack Vaisala sonde data set was compared with a data set from another Vaisala sonde flown simultaneously from Phillips Laboratory on Hanscom AFB 25 km away (Jackson and Caudill, 1996). The resulting humidity profiles agreed to 3% from 1000 to 50 mb except for a feature from 800 to 700 mb which differed by 10% (Niell, et al, 1996b).

**Comparison of the Haystack Radiosonde and the WVR Zenith Wet Delay**

Figure 3 shows both the WVR estimates of the zenith wet delay and the Haystack radiosonde estimates. The liquid water scale is given on the right hand abscissa. Evidence of rain is apparent in the small peaks in the liquid water on day 239 and day 244.

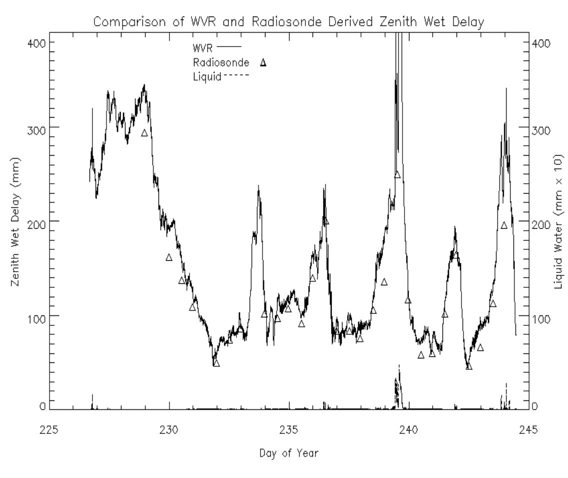


*Figure 3. Difference between the WVR and Haystack radiosonde estimates of the zenith wet delay.*

Excluding the two data points associated with rain (evident in the above graph near the end of day 239 and on day 244), the average difference between the estimated zenith wet delays obtained from the WVR and from the Haystack radiosonde launches is 18.3 mm with a standard deviation of 12.5 mm. Liquid water on the WVR in the ray path direction (for example, on the cover of the unit) may cause erroneous readings of the path delay.

The average measured difference between the Haystack Radiosonde estimate and the WVR estimate of the zenith wet delay is equivalent to about 3 mm of difference in precipitable water vapor. It is worth noting that the retrieval coefficients used for the WVR used in WWAVE were derived using an average of three months of NWS radiosonde data (presumably VIZ sondes) for this time period from previous years. The WVR retrieval coefficients should be re-estimated using the Haystack radiosonde data or other sets of data taken with Vaisala sondes. Unfortunately, retrieval coefficients based on the Haystack Vaisala data alone would have large uncertainties due to the small amount of data available to use in the estimation.

**Comparison of Radiosonde, WVR, and GPS Zenith Wet Delay**

Figure 4 shows estimates of the ZWD from the WVR and from the MHR0 GPS receiver during the experiment. MHR0 is the receiver located closest both to the WVR location (about 200 m away and 6 m higher) and to the Haystack parking lot where the radiosondes were launched (about 625 m away and 20 m higher). Table 2 gives the locations of these three sites.

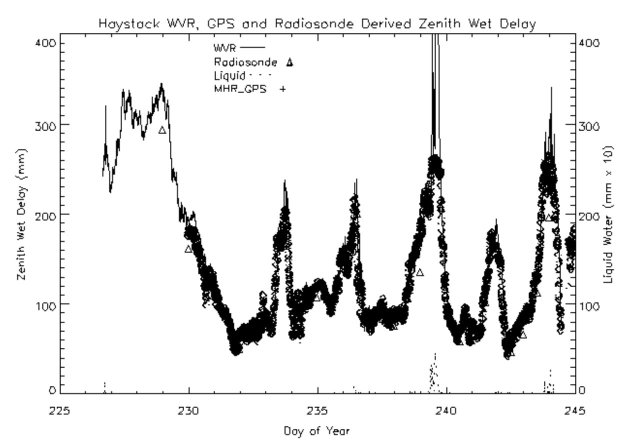


*Figure 4. Estimates of ZWD by WVR, radiosonde, and GPS.*

The average difference between the WVR and the GPS estimated zenith wet delays (again excluding time periods associated with rain) was 6 mm with a standard deviation of 9 mm. Time periods associated with rain were defined to be those with a measured delay due to liquid water greater than 0.3 mm. The average difference between the GPS and the radiosonde estimated ZWD was 12 mm with a standard deviation of 14 mm.

**Comparison of Radiosonde, WVR, and VLBI estimates of Zenith Wet Delay**

Figure 5 shows estimates of the ZWD from a partial segment of the VLBI campaign (Ryan, 1996). The position of the the Westford antenna used in the VLBI campaign is given in Table 2. The GPS estimates of ZWD were not plotted here since visually they can not be separated from the VLBI estimates.

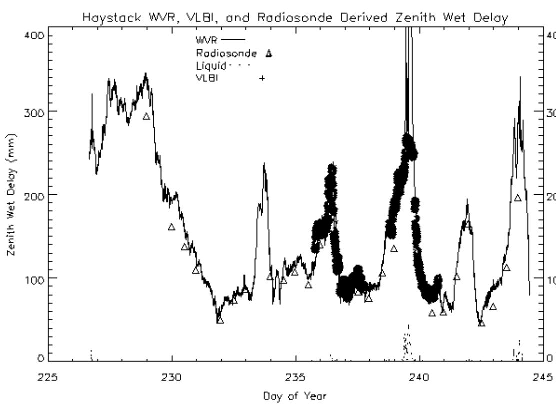


*Figure 5. Estimates of ZWD by WVR, radiosonde, and VLBI.*

The statistical analysis of the four data sets, VLBI, GPS, WVR, and radiosonde, show that the VLBI estimates of ZWD are, on average, larger than the estimates of all the other measuring techniques. These results are summarized in Table 4. The average difference between the VLBI and WVR estimated zenith wet delays (excluding the time periods associated with rain) was 3 mm. The average difference between the GPS and VLBI estimate of ZWD was 8 mm, and the average difference between the VLBI and radiosonde estimates was 24 mm.

TABLE 4. Average difference and standard deviation in the ZWD estimated by WVR, VLBI, radiosonde, and GPS

| | Ave. Diff. In ZWD (mm) | Std. Dev. in Diff. Of ZWD (mm) |
|---|---|---|
| WVR - GPS | 6 (1 PWV) | 9 (1.5 PWV) |
| GPS - Radiosonde | 12 (2 PWV) | 14 (2 PWV) |
| WVR - Radiosonde | 18 (3 PWV) | 13 (2 PWV) |
| VLBI - GPS | 8 (1.5 PWV) | 10 (1.5 PWV) |
| VLBI - WVR | 3 (0.5 PWV) | 9 (1.5 PWV) |
| VLBI - Radiosonde | 24 (4 PWV) | 11 (2 PWV) |

**Elevation Cutoff Dependence**

One of the goals of WWAVE was to examine the effect of different types of antennas and antenna mounts on the retrieval of PWV. The retrieval of PWV, especially in a near-real time scenario, depends on the separation of the tropospheric delay term from other estimated quantities, such satellite and receiver clock biases. In addition, the delay due to the ionosphere must be correctly determined. High quality low elevation data is extremely useful in determining all of the unknown quantities in the GPS data, however with the advent of anti-spoofing, the deliberate policy of the D.O.D. to corrupt the GPS performance, the signal-to-noise ratios of the low elevation data have been significantly degraded. With some receivers, this effect is worse than others.

In an attempt to examine this issue, the retrieval of GPS-determined ZWD as a function of elevation was compared for ten different sites during the WWAVE experiment: WES2, WFRD, MHR0, SGJ0, G430, AEN0, FIRE, ULWL, NVT0, and JIM1. With the exception of FIRE, ULWL, NVT0, and JIM1, all of the data examined were taken with A.O.A. Turbo Rogue receivers and Dorne-Margolin choke ring antennas. The FIRE and JIM1 sites used an Ashtech Z-12 receiver and the standard Ashtech surveying antenna, the 700718B. The NVT0 and ULWL sites used an Ashtech Z-12 antenna with a Dorne-Margolin choke ring antenna and a radome.

Estimates of the ZWD for each site were determined using elevation cutoffs of 5, 10, 15, 20, 25, and 30 degrees. The elevation cutoff merely represents the elevation at which GPS data were excluded from the estimation procedure for ZWD. Once these estimates were obtained, the average difference between the ZWD estimate for the elevation cutoff being examined and the ZWD estimate for that site using a 5 degree cutoff was computed, i.e., ZWD(elcutoff) - ZWD(5°). This difference for all of the GPS sites is plotted in Figure 6 as a function of elevation cutoff. The data in Figure 6 represent the averaged difference over a 24 hour period during WWAVE. The 5° elevation cutoff represents the zero point, since everything is being referred back to the ZWD estimate at 5° elevation. The best antennas and antenna configuration should show little or no dependence on elevation cutoff.

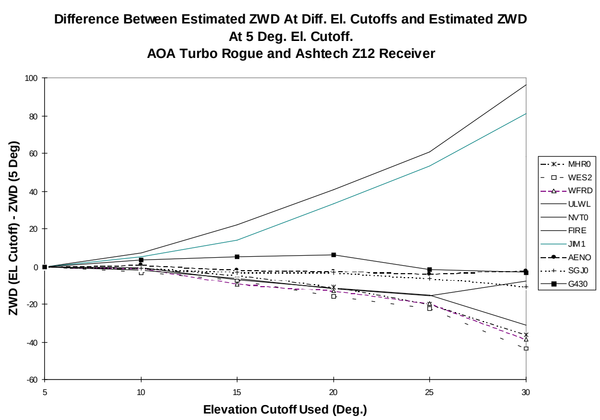


*Figure 6. Elevation Cutoff comparison between sites.*

What is extremely evident in Figure 6 is that two of the sites, FIRE and JIM1, show a clear dependence on elevation cutoff. These sites both use an Ashtech Z12 receiver with an Ashtech 700718B antenna. The FIRE antenna was mounted above a flat metal roof on a building atop the Groton fire tower. The antenna at the JIM1 site was located on top of a 13 m amateur radio tower. Both sites suffer the same elevation dependence at all elevations. This suggest that the extreme elevation dependence (80 mm in ZWD difference) is dominated by the antenna and not the mount. This standard surveying antenna does not have the multi-path rejection capability offered by the Dorne-Margolin choke ring antenna.

Figure 7 shows the performance of GPS receivers at the ULWL and NVT0 sites. Both of these sites used the Ashtech Z-12 receiver with a Dorne-Margolin choke ring antenna with a radome. The difference between the 5° and 10° cutoff is minimal. The two sites are separated by almost 10 km, so it is worth noting that the dependence on elevation cutoff is almost identical up until the 25° elevation cutoff point. This may be partially attributed to the radome. The Ashtech Dorne-Margolin antennas have radomes which have been shown to influence the determination of PWV as a function of elevation (Niell, et al., 1996).

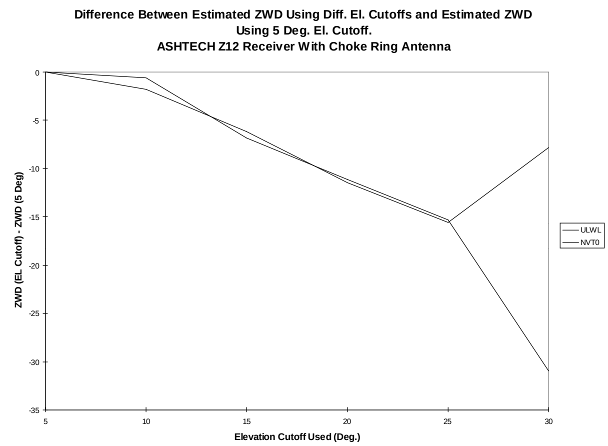


*Figure 7. Elevation Cutoff comparison with the Ashtech Z12 receivers with the Dorne Margolin choke ring antennas with radome.*

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Figure 8 shows the elevation cutoff dependence of the six sites equipped AOA Turbo Rogue GPS receivers and Dorne-Margolin antennas. These sites were WES2, WFRD, MHR0, AEN0, SGJ0, and G420. There is a clear division illustrated in Figure 8. Three of the sites show little or no elevation cutoff dependence, AEN0, SGJ0, and G420, while the other three sites show a dependence on elevation cutoff on the order of 36 mm in ZWD (6 mm in PWV). Two of the best sites, AENO and SGJ0, had antennas that were standard tripod/tribach mounts and were installed on the peak of roofs. The other site that showed good performance was at G420. Here the antenna was mounted on a wooden platform about 30 cm above a flat rubberized roof.

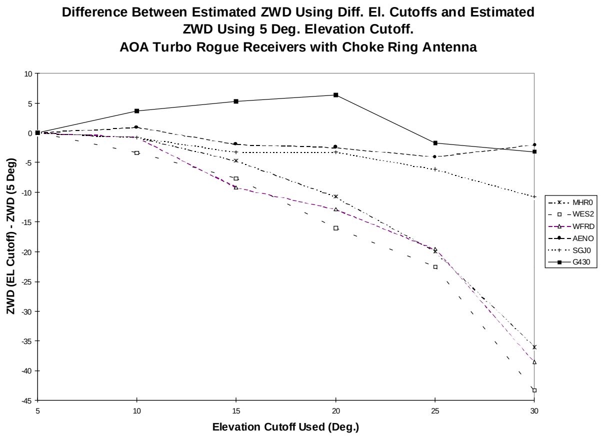


*Figure 8. Elevation Cutoff comparison AOA Turbo Rogue GPS receivers with Dorne-Margolin antennas.*

The antennas at WES2, WFRD, and MHR0 sites were mounted in various configurations. WFRD was located in a fairly flat open field. The antenna for WFRD was mounted in an aluminum ring with the bottom of the choke rings 96 mm above the surface of a 0.76 m diameter concrete pillar. The surface is ~1m above the ground and is inlaid with a plate 0.46 m in diameter which contains the geodetic reference mark for the WFRD site. The antenna for WES2 is mounted on top of a 10 m steel tower. The MHR0 antenna is mounted on the roof of the main Millstone Radar building, surrounded by a parking lot. The MHR0 antenna is supported by a crossed pair of sheet metal plates on a 6 inch square attached to a pole of approximately 2 m slightly offset from the peak of the Millstone Radar building roof. Clearly, the effect of the antenna mount on PWV estimation is an area in need of more investigation.

It is interesting to note that the two Ashtech Z12 receivers with the Dorne Margolin antennas show a similar elevation dependence as the three “bad” A.O.A. Turbo Rogue sites shown in Figure 8. This dependence is shown in Figure 9.

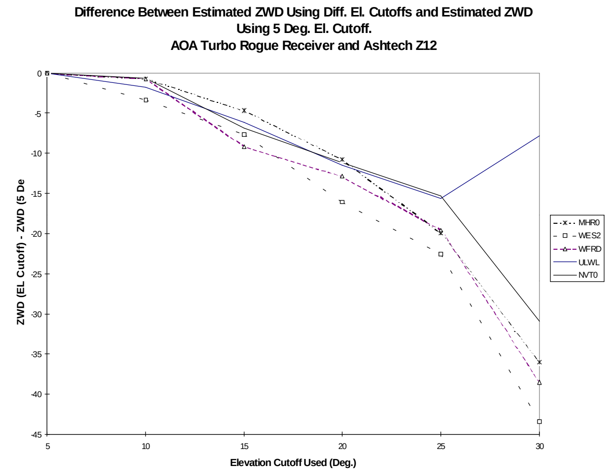


*Figure 9. Elevation Cutoff comparison AOA Turbo Rogue GPS receivers and Ashtech Z12 GPS receivers with Dorne-Margolin antennas.*

## CONCLUSIONS

Based on the analysis of the WWAVE data set, GPS estimates of zenith wet delay agree with measurements by WVR, VLBI, and radiosondes to within 6-12 mm corresponding to 1-2 mm of PWV. The GPS data used for comparison with the WVR, VLBI, and radiosonde data sets were taken with an A.O.A. Turbo Rogue GPS receiver with a Dorne Margolin choke ring antenna at the MHR0 site. An elevation cutoff of 5 degrees was used in all of the data processing. These values of PWV accuracy are consistent with the results of GPS/STORM (Rocken, 1995). Radiosondes appear to have problems related to their humidity sensors, as indicated in this paper and as discussed by Wade, 1994. Radiosondes also can not provide frequent average measurements of water vapor in a period of rapidly changing weather. Water vapor radiometers have operational problems during rain storms and may have accuracy restrictions based on their dependence on the radiosonde data to determine their retrieval coefficients. On the other hand, it is important to note that the type of mount, radome, and the antenna used may affect the GPS determination of PWV. The impact of the mounts, antennas, and radomes, on the GPS determination of PWV, is an area in need of more investigation.

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