The Westford Water Vapor Experiment: Use of GPS to Determine Total Precipitable Water Vapor

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BIOGRAPHY

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ABSTRACT

The Westford WAter Vapor Experiment (WWAVE) was designed to measure the temporal and spatial variability of the total precipitable water vapor over an area within a 25 km radius of the Haystack Observatory in Westford, MA. The main experiment was conducted from August 15 to August 30, 1995, and a variety of different techniques were used to measure the water vapor, including: radiosondes, launched two to three times daily from one location; a water vapor radiometer (WVR); eleven GPS receivers separated by 0.5 to 35 km (with 3 receivers located within 1 km of each other at the central location); and 8 surface meteorological monitoring units. In addition, this campaign coincided with the CONT95 VLBI experiment. Thus water vapor retrieval from VLBI is also available for comparison against the other techniques. This paper will focus on the comparison of the total precipitable water vapor measured by radiosondes, water vapor radiometers, and GPS, and will specifically address the accuracy issues of the GPS derived estimate of this quantity.

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, 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 Π that is approximately 0.15 (Bevis et al., 1994) and varies by 20%. The factor Π 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.

The primary goal of WWAVE was to estimate the total precipitable water vapor from GPS data and to evaluate the accuracy of these estimates. 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. In order to evaluate the accuracy of the GPS measurement of PWV, GPS estimates were compared to those from water vapor radiometers (WVRs) and radiosondes. In addition, different types of GPS receivers and antennas were compared. Finally, three Allen Osborne Associates Turbo Rogue GPS receivers with Dorne Margolin choke ring antennas were sited approximately 1 km apart at the central Westford location. The three GPS antennas, referred to in this paper as WFRD, WES2, and MHR0, were spaced closely with the intent of measuring the variations in the PWV estimate that could be attributed to multipath or to instrumental differences rather than real differences in the PWV.

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 trailor. 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. In addition, the GPS processing software (GIPSY/OASIS) (Webb and Zumberge, 1995) was updated with the Niell tropospheric mapping function (Niell, 1996) described later in this paper. The focus of the work presented here is on the accuracy of the GPS measurements of PWV. 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 and a WVR. In addition, the consistency of the GPS determined value of zenith wet delay among different GPS receivers/antennas was studied by analyzing the data from three receivers located within 1 km of each other. WWAVE used improved P-code GPS receivers, specific antennas to reduce site multipath, and GPS software optimized for tropospheric estimation.

THE GPS MEASUREMENT

GPS was designed as a navigation system. Each satellite carries an atomic clock and knows its own position in earth center earth fixed coordinates. A simple description of how this system works is given here. The GPS satellite broadcasts a signal at two frequencies (L1 = 1575.42 MHz and L2 = 1227.6 MHz). A single receiver on the ground receives a coded signal from the GPS satellite from which it can obtain the time the GPS signal left the satellite plus the orbital position of the satellite at that time. For one satellite, assuming that the GPS signal traveled at the speed of light, the knowledge of the difference in time between when the GPS signal was sent from the satellite and when it was received on the ground, allows the calculation of the receiver's location somewhere on the surface of a hypothetical sphere. To have the receiver's position pinpointed in three-dimensional space, at least three GPS satellites must be in view. A fourth satellite is needed to compute a clock offset to the receiver's clock. With the fully implemented GPS system of 24 satellites, there are always at least six satellites in view over the Continental U.S., and there can be as many as eleven, depending on user location and orbit inclination.

Obviously, this simple description neglects a number of additional factors that must be accounted for if precise positioning is required. First, the GPS signal does not travel at the speed of light, but rather at a slower speed corresponding to the group velocity of the wave. The group velocity is less than the speed of light in both the ionosphere and the troposphere. In the ionosphere, the index of refraction depends both on the frequency of the wave and on the total electron content. In the troposphere, the index of refraction depends on the pressure, temperature, and humidity. Because the ionospheric group delay is dispersive (dependent on frequency) use of a dual frequency GPS receiver allows for direct calculation of the ionospheric term. In addition to the atmospheric delays, other factors must be taken into account, including: signal multipath (the type of antenna used plays a factor in multipath reduction), the receiver location, the satellite's true orbit (since the broadcast orbit is not very accurate), satellite clock offsets, and receiver clock offsets. To determine very precise GPS orbits, the effects of the gravitational potential, special relativistic shifts, and Doppler shifts must all be accounted for.

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, although recent modifications have improved the orbits to 10-15 cm (Lichten,1996).

Tropospheric Range Delay

The excess path length due to travel in the troposphere, Δr_{trop}, at zenith, is defined to be:

$$\Delta r_{trop}(90^o) = 10^{-6} \int_{r_s}^{r_a} N(r)\, dr \qquad 1)$$

where the refractivity, N, is related to the index of refraction, n, by $N = 10^6(n-1)$, r_s is the geodetic radius of the earth's surface, and r_a is the geodetic radius of the top of the neutral atmosphere (Mendes and Langley, 1995). By looking only at the zenith delay, the geometric delay term, Δr_{geo} , that accounts for the difference between the refracted and rectilinear ray paths can be neglected. Normally this term would need to be included in eqn. 1.

The refractivity of a parcel of air is given by the empirical formula (Thayer, 1974):

$$N = k_1\left(\frac{p_d}{T}\right)Z_d^{-1} + \left[k_2\left(\frac{p_v}{T}\right) + k_3\left(\frac{p_v}{T^2}\right)\right]Z_w^{-1}, \qquad 2)$$

where T is the temperature in Kelvin, p_d is the partial pressure of the dry air, p_v is the partial pressure of water vapor in millibars, k_1 ,k_2 ,k_3 are empirically determined constants, Z_d is the compressibilitity factor for dry air, and Z_w is the compressibility factor for wet air. The first and second terms of this equation arise from electronic transitions of the induced dipole type for dry air molecules and water vapor, respectively. The third term arises from the permanent dipole rotational transitions of water vapor. The dry component of refractivity can be rewritten in terms of the total pressure as (Davis et al., 1985):

$$\mathrm{N} = k_1 R_d \rho + \left[k_2{}'\left(\frac{\mathrm{p_v}}{\mathrm{T}}\right) + k_3\left(\frac{\mathrm{p_v}}{\mathrm{T}^2}\right)\right]\mathrm{Z_w}^{-1} \qquad 3)$$

$$\text{where } k_2{}' = \left(k_2 - k_1\frac{M_w}{M_d}\right).$$

The above definition of the refractivity can be used to define a “hydrostatic” and a “wet” component of the tropospheric path delay at zenith, $\Delta r_{trop,hydro.}(90^o)$ and $\Delta r_{trop,,wet}(90^o)$. A mapping function can then be used to compute the correction needed to convert the zenith delay term to one associated with the line of sight,

$$\Delta r_{trop}(el) = \Delta r_{trop}(90^o)M(el) \qquad 4)$$

However, the use of separate mapping functions for the "hydrostatic" and "wet" component of the excess path length is physically more correct and produces better estimates:

$$\Delta r_{trop}(el) = \Delta r_{trop,hydro}(90^o)\,M_{hydro}(el) + \Delta r_{trop,wet}(90^o)\,M_{wet}(el). \qquad 5)$$

Niell, 1996, has generated a global hydrostatic mapping function, $M_{hydro}(el)$, which has as inputs only the height above sea level, the latitude of the station, and the day-of-year. He also generated a wet mapping function, $M_{wet}(el)$, which is a function only of latitude. The separation of the wet from the hydrostatic term of tropospheric delay requires accurate surface barometric pressure readings. A pressure error of 0.5 mb in the surface pressure measurement used to calculate the “hydrostatic term” of the tropospheric delay causes a 1 mm error in the zenith wet delay (Rocken et al., 1995).

OTHER INSTRUMENTS

WWAVE relied on a number of other instruments to obtain PWV information. These other techniques are described briefly.

Surface Meteorology

The separation of the wet from the hydrostatic term of tropospheric delay requires accurate surface barometric pressure readings. Pressure sensors accurate to 0.5 mb were required for proper calibration of the WWAVE experiment.. Two Paroscientific Barometers were used to calibrate the other barometers used in WWAVE listed in Table 1.

Radiosonde

Vaisala RS-80 Radiosondes were launched two or three times a day during daylight hours from a launch site about 1 km north of the WVR. The following specifications were provided by Vaisala. The Vaisala sondes measure the humidity with a thin film capacitor. Vaisala quotes a measuring range of 0 to 100% RH, where RH stands for relative humidity, with a resolution of 1% and a 1 s time lag. The humidity sensors have a reproducibility of better than 3% RH and a calibration repeatability of 2% RH. The pressure is measured with a capacitive aneroid sensor, with a measuring range from 1060 hPa to 3hPa (mb), a resolution of 0.1 hPa, and an accuracy of 0.5 hPa both in the reproducibility and in the repeatability of calibration. The temperature is measured with a capacitive bead, which has a measuring range from +60^o C to - 90^o C, a resolution of 0.1^o C, a reproducibility better than 0.4^o C, and a repeatability of 0.2^o C.

Water Vapor Radiometers

A ground based water vapor radiometer (WVR) is an instrument that scans the sky and measures the brightness temperature (radiation energy) of all water vapor along the line of sight. For WWAVE, a Radiometrics^{TM} Corporation WVR-1100 portable water vapor radiometer was used. It operates at two frequencies. One channel is at 23.8 GHz the other is at 31.4 GHz. The 23.8 GHz channel is dominated by water vapor but contains some cloud liquid signal, and the 31.4 GHz channel is dominated by cloud liquid but contains some vapor signal. The contributions can be separated algebraically.

The WVR measures the sky brightness temperatures at the two frequencies and converts the measurements to atmospheric opacities. The WVR is calibrated using tipping curve measurements [Elgered, 1993], an ambient blackbody target, and a noise diode. The radiometer output at each operating frequency is related to the atmospheric brightness temperature T_b which in turn is related to the absolute absorption τ (in nepers) by

$$T_b = 2.75e^{-\tau} + T_{mr}(1-e^{-\tau}), \qquad 6)$$

where T_{mr} is the mean radiating temperature of the atmosphere and 2.75 is the cosmic background brightness temperature (both in kelvins). The absorption at each frequency is derived from the measured T_b by

$$\tau_i = \ln\left\{\frac{T_{mr} - 2.75}{T_{mr} - T_i}\right\}, \qquad 7)$$

where τ_i (i=1,2) is the opacity at each of the two frequencies, and 2.75 is equal to the cosmic background radiation in Kelvin.

Finally, PWV is derived from the absorptions at the two frequencies by

$$PWV = c_0 + c_1\tau_1 + c_2\tau_2 , \qquad 8)$$

where c_0, c_1,and c_2 are the values of the retrieval coefficients. The T_{mr} and retrieval coefficients were computed by linear regression analysis of the previous years radiosonde data for July, August, and September from the NWS sites of Chatham, MA, Grey, ME, and Albany, NY. This analysis assumes a model for the molecular absorption of water vapor. Errors can be introduced in the retrieval algorithms, in the absorption models for water vapor emission at the WVR frequencies, and/or in the calibration uncertainties of the radiometer. S. J. Keihm, 1995, estimates that one can expect PWV retrieval biases of 1mm in PWV for dry conditions (6.5 mm zenith wet delay) and 2.5 mm of PWV (16-20 mm zenith wet delay) for very humid conditions.

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 *	Millstone Radar Pole on Roof Westford, MA	A.O.A. Turbo Rogue	Dorne-Margolin w. choke ring
WES2 *	Westford Antenna 10 m Tower Westford, MA	A.O.A. Turbo Rogue	Dorne-Margolin w. choke ring
G420 **	Lincoln Lab Pole on Flat Roof Hanscom AFB	A.O.A. Turbo Rogue	Dorne-Margolin w.choke ring
WFRD *	Ground Mount Westford, MA	A.O.A. Turbo Rogue	Dorne-Margolin w. choke ring
AEN0 ***	Tripod on Peaked Roof Harvard, MA	A.O.A. Turbo Rogue	Dorne-Margolin w. choke ring
ULWL **	University of Lowell Tripod on Flat Roof Lowell, MA	Ashtech Z-12	Ashtech 700936B Dorne-Margolin choke ring & radome
NVT0	Nashoba Tech High School Westford, MA Tripod on	Ashtech Z-12	Ashtech 700936B Dorne-Margolin

	Flat Roof		choke ring & radome
SGJ0 ***	Pepperell, MA Tripod on Peaked Roof	A.O.A. Turbo Rogue	Dorne-Margolin with choke ring
JIM1	Dunstable, MA Ham Radio Tower	Ashtech Z-12	Ashtech 700718B Navigation Antenna
FIRE	Groton, MA Fire Tower	Ashtech Z-12	Ashtech 700718B Navigation Antenna
TAC0 *	Nashua, MA Tripod on Peaked Roof	A.O.A. Turbo Rogue	Dorne-Margolin 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.

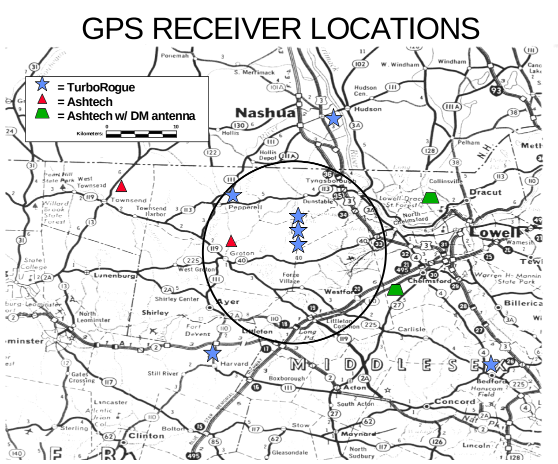

Figure 1. Map showing location of the GPS Receiver Sites

A primary goal of this paper is to assess the accuracy of the GPS estimates of the zenith wet delay (which can be converted to precipitable water vapor). Therefore, the majority of the GPS data presented in this paper were taken from the three closely related GPS sites: WES2, WFRD, and MHRO, which are represented by the three stars in the center of Figure 1. The WVR at the Firepond facility and the Haystack radiosonde launches were also located near the position of the top of these three stars in the center of the circle. A final plot showing the differences in GPS measured precipitable water vapor from different sites will compare data from AEN0 (represented by the star located to the furthest west in Figure 1) to data from the G420, the GPS receiver at MIT Lincoln Laboratory on Hanscom AFB (represented by the star to the furthest east on the map).

The GPS derived positions in the WGS-84 coordinate frame for the WES2, WFRD, MHRO, AEN0, and G420 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 WVR and the radiosonde launch site at the Haystack Observatory. Note the difference in heights between the different stations. Note again that AEN0 is the station furthest to the west and G420 is the station furthest to the east.

TABLE 2. WGS-84 Positions of Primary GPS Sites and of the WVR 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
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 data from the three closely spaced GPS sites will be compared for the 15 day time period. This analysis of all 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.

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 is 36 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.

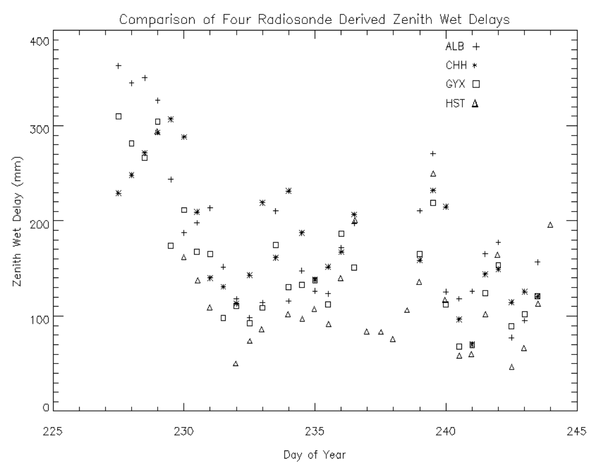

Figure 2. Comparison of zenith wet delays obtained by NWS radiosondes flown from Albany, NY, Chatham, MA, and Grey, ME and by the Haystack radiosondes.

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	39.0 (6.0 PWV)	25.6 (3.9 PWV)
CHH-HST	50.0 (7.7 PWV)	44.3 (6.8 PWV)
GYX-HST	20.5 (3.2 PWV)	26.4 (4.1 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 weather service 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%.

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.

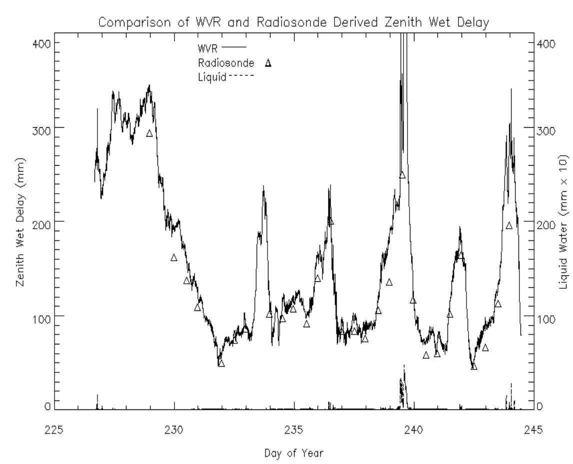

Figure 3. Difference between the WVR and Haystack radiosonde estimates of the zenith wet delay.

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.

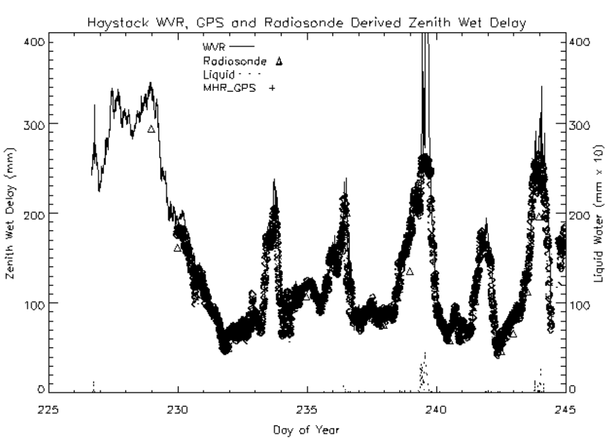

Figure 4. Estimates of ZWD by WVR, radiosonde, and GPS.

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.

TABLE 4. Average difference and standard deviation in the ZWD estimated by WVR, 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)

Comparison of the GPS derived Zenith Wet Delay at three sites for days 230-244

Figure 5 shows the zenith wet delays estimated by the three closely spaced GPS receivers, MHR0, WES2, and WFRD. All of these data were taken with A.O.A. Turbo Rogue GPS receivers with Dorne Margolin antennas with choke rings. Note the nearly identical structure observed by all three sites.

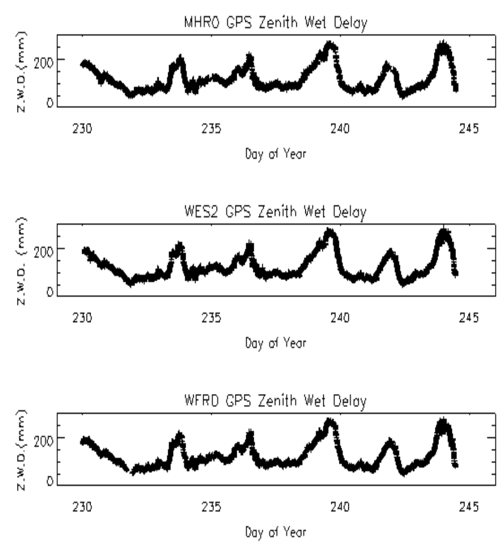

Figure 5. GPS estimates of the Zenith Wet Delay for three sites from day 230 to day 244, 1995.

The average differences between the zenith wet delays at the three sites are given in the Table 5. These differences may be due to some combination of real differences in water vapor at the three sites, error in the barometer value used to remove the hydrostatic components, or in systematic errors associated with the electromagnetic environment of the antenna.

TABLE 5. Average difference between GPS derived zenith wet delay at three sites for days 230-244

	Mean Difference in ZWD (mm)	Std. Dev. of Difference in ZWD (mm)	Height Diff. Of sites (m)
WES2-MHR0	4.4 (0.7 PWV)	6.2 (1.0 PWV)	-27.5
WFRD-WES2	1.2 (0.2 PWV)	4.8 (0.7 PWV)	-28.8
WFRD-MHR0	5.5 (0.8 PWV)	6.8 (1.0 PWV)	-56.3

If one assumes roughly 0.1 mm of ZWD per meter near the surface of the earth, the difference in height between WFRD and MHR0 (56 m) could possibly account for the average difference in their measured ZWD. The observed ZWD differences in Table 5 do increase with height difference but are not consistent with a uniform layer of water vapor (note the differences between WES2-MHR0 and WFRD-WES2). Possible physical differences in the environment, such as the presence of trees around the WES2 site, might account for some of this discrepancy.

Pressure gradients observed during the WWAVE experiment were shown to be, on average, negligible based on a comparison of the barometer differences from the different sites. Pressure measurements from the Rainwise barometer at the MHR0 site were used to compute the pressures at the antennas for MHR0, WES2, and WFRD using the height differences. This barometer was calibrated against a Paroscientific barometer, which has an advertised accuracy of better than 0.1 mb, on two occasions during WWAVE.

The WFRD site is located in a fairly flat open field. The antenna for WFRD is mounted in an aluminum ring with the bottom of the choke rings 96 mm above the surface of a 0.76 meter diameter concrete pillar. The surface is ~1 meter above the ground and is inlaid with a plate 0.46 meter in diameter which contains the geodetic reference mark for the WFRD site. The antenna for WES2 is mounted on top of a 10 meter steel tower. The tower is surrounded by trees. The MHR0 antenna is mounted on the roof of the main Millstone Radar building, surrounded by a parking lot, with no vegetation close by. The MHR0 antenna is supported by a crossed pair of sheet metal plates on a 6 inch square attached to an approximately 2 m pole slightly offset from the peak of the Millstone Radar building roof.

It is quite possible that some of the differences seen in the estimated zenith wet delay can be attributed to the different antenna mounting configurations used. Niell, et al., 1996 found systematic differences of up to 3 mm in ZWD for Turbo Rogue Dorne Margolin antennas separated by only 15 m when analyzed with a 5^0 elevation cutoffs. The only differences in the receivers and antennas were the mount and the use of a radome. In that study, two antennas were placed on tripods near the WFRD site, while the WFRD antenna was located on a concrete pillar and covered by a radome. Both the radome and the concrete pillar mount were shown to influence estimates of ZWD.

It is interesting to note that on day 239, one of the “rainy”, humid days, the average difference in ZWD between the different sites increased. One would anticipate this difference to increase if there was at least a partial physical explanation for the measured differences in ZWD between the different sites. Between WES2 and MHR0, the average difference in ZWD increased to 5 mm, between WFRD and MHR0, it increased to 7.4 mm, and between WFRD and WES2, it increased to 2.4 mm.

Evidence of Small Scale Variations in PWV

One of the more exciting aspects of using GPS to monitor PWV is the concept that GPS will provide a new window with which to watch the development and propagation of weather fronts. Although no major weather pattern developed during WWAVE, it did rain twice during the experiment: on day 239 and again on day 243 into day 244. The zenith wet delays associated with the beginning of day 244 showed evidence of a wave-like pattern superimposed on the relatively high value of the zenith wet delay. This pattern was evident in the estimated zenith wet delays from all of the GPS sites analyzed that day but not for other days. Figure 6 shows the data from the two most separated sites with A.O.A. Turbo Rogue receivers: GR42, which is the site furthest to the east on Hanscom AFB in Lexington, MA, and AEN0, which is the site located furthest to the west in Harvard, MA (see Figure 1). In the middle third of the day it is clear that the change in water vapor content at GR42 lags that at AEN0, which is consistent with both the general west to east weather pattern in this area and the prevailing westerly winds on that day as seen in NWS radiosonde data.

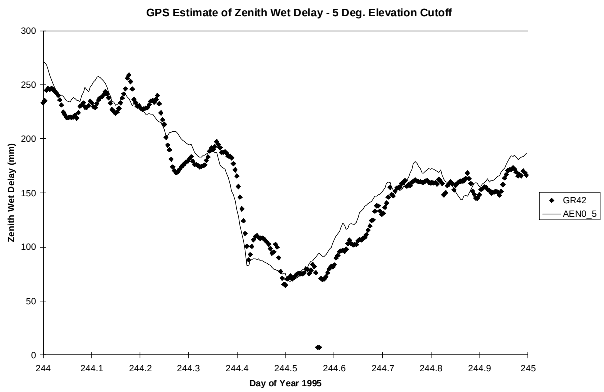

Figure 6. Estimated Zenith Wet Delays from two separated sites.

CONCLUSIONS

Based on the analysis of the WWAVE data set, GPS estimates of zenith wet delay agree with measurements by WVR and radiosondes to within 6-12 mm corresponding to 1-2 mm of PWV. The GPS data presented here were all taken with A.O.A. Turbo Rogue GPS receivers with Dorne Margolin choke ring antennas. Elevation cutoffs of 5 degrees were used in all of the data processing. These values of PWV accuracy are consistent with the results of GPS/STORM (Rocken, 1995). The precision of the GPS measurement of ZWD is better than 6 mm (1mm of PWV) as shown by the agreement of 3 closely spaced GPS systems. Radiosondes appear to have problems related to their humidity sensors, as indicated in this paper and as discussed in 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 determinination of PWV is an area in need of more investigation.

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