# Measurement of Water Vapor by GPS, WVR, and Radiosonde

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ABSTRACT

During the CONT95 VLBI campaign, measurements of the atmosphere delay due to water vapor were made at Haystack Observatory using radiosondes, GPS, and a water vapor radiometer (WVR). The goals were to evaluate the accuracy with which precipitable water in the atmosphere could be measured with GPS and to investigate the distribution of water vapor, both spatial and temporal, around the Westford VLBI antenna during CONT95. Initial analysis of the GPS, radiosonde, and WVR data reveals that the comparison is limited by systematic errors in each of the instruments. These errors reach 40 mm of zenith wet delay for the radiosondes, 15 mm for the GPS, and 6 mm for the WVR. Such large errors within each technique must be reduced before accuracies of 1 mm of precipitable water vapor (~6 mm of zenith wet delay) can be claimed.

OBSERVATIONS

In the last two weeks of August, 1995, measurements of water vapor delay in the atmosphere were made with eleven GPS systems distributed over a region within ~25 km of Haystack Observatory. Radiosondes were launched twice daily from the parking lot near the Haystack telescope, and a microwave water vapor radiometer was operated continuously on a tower approximately 625 m away.

Three of the GPS sites were within 1 km of each other at the Observatory, one near the WVR (MHR0), the second next to the Westford VLBI telescope (WES2), and the third 500 m further south (WFRD). All three were AOA 8-channel TurboRogue receivers attached to Dorne-Margolin antennas with choke rings. Four other TurboRogue systems occupied sites five to 25 km from the Observatory.

Two of the systems consisted of an Ashtech Z-12 receiver connected to the Ashtech version of the Dorne-Margolin with choke ring antenna; these were "protected" with the radome obtained from Ashtech. Two other Ashtech Z-12 receivers were used, but the associated antenna was in each case a Model 700718B antenna. One of these, FIRE, was mounted atop a fire tower 5 km west of the Observatory.

The WVR was a Radiometrics Corp. Model 1100™ dual frequency radiometer. The retrieval coefficients were calculated from VIZ radiosonde data from the NWS sites at Albany, NY (ALB), Chatham, MA (CHH), and Portland, ME (PWM). Data for the months of 1995 June-August, up to the time observations began at Haystack, were used.

Vaisala RS-80 radiosondes were launched from Haystack Observatory at 1200 and 2300 UT on all days and additionally at 1800 UT on some days. Winds were not measured. The raw data were captured at one second intervals, and the temperature and pressure were checked with independent measurements. For comparison, additional radiosonde data were obtained from the three nearest National Weather Service sites, approximately 150 km from Haystack uniformly spaced in azimuth.

Barometric pressure was measured at seven sites. Paroscientific Digi-quartz™ barometers were used at AEN0 and SGJ0 and were used to calibrate the other barometers. Comparison of the measurements at the seven sites showed that, during this two week period, the pressure at any site could be calculated from another with an accuracy of 0.1 mb based on the height difference, resulting in negligible error in the calculation of the apriori hydrostatic zenith delay.

RESULTS

*Water Vapor Radiometer*

The zenith wet delays (ZWD) measured by the WVR for the comparison period, 1995 August 18 through September 1, are shown in Figure 1.

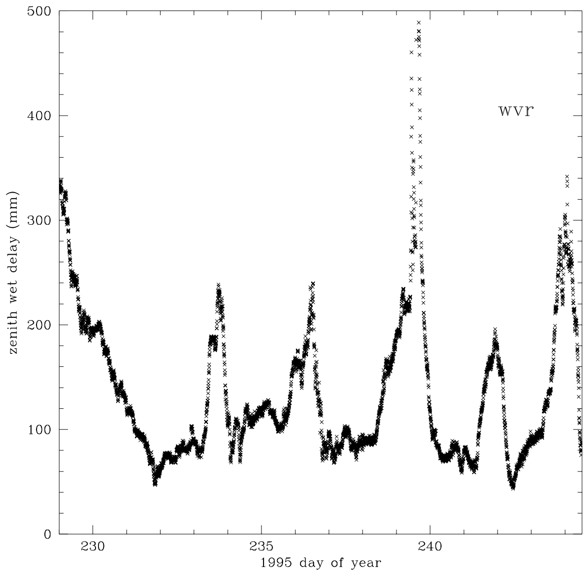


Figure 1. Zenith wet delay (mm) as measured by WVR at Haystack Observatory.

GPS data were acquired for day of year (DOY) 230 through 244. Unfortunately this was during a period of drought, but the range of daily variation of ZWD was not abnormally low. The rain on DOY 239, which is indicated by the extremely high values of ZWD, was light and serves to emphasize the limitation of the WVR in rainy conditions. For the purpose of evaluating different techniques for measuring water vapor, the dry conditions were fortunate since the WVR estimates of ZWD are not useful in the presence of rain or other conditions that cause liquid water to be present in the optics of the radiometer.

The expected uncertainty in the WVR measurements ranges from 6 mm at ~100 mm of ZWD to 20 mm at ~300 mm (Elgered et al, 1993; Solheim, 1996 (private communication)). Determination of the retrieval coefficients from the NWS radiosonde data may introduce an additional error in the comparison because of the differences in radiosonde results noted in the next section. A test by P. Jarlemark (1996, private communication) indicates that this may be as large as 6 mm of ZWD for a total ZWD of 200 mm.

*Radiosonde*

Vaisala radiosondes were used because they were readily available near the Observatory and because they were also being used by another group at Lincoln Laboratory, the site of one of the GPS systems. However, this choice proved fortuitous in pointing out the discrepancy in measurements between sondes of different manufacturers in addition to differences that are documented for high and low relative humidities (Wade and Schwartz, 1993; Wade 1994). The ZWDs calculated by raytracing the radiosonde profiles for Haystack and for the NWS sites are shown in Figure 2.

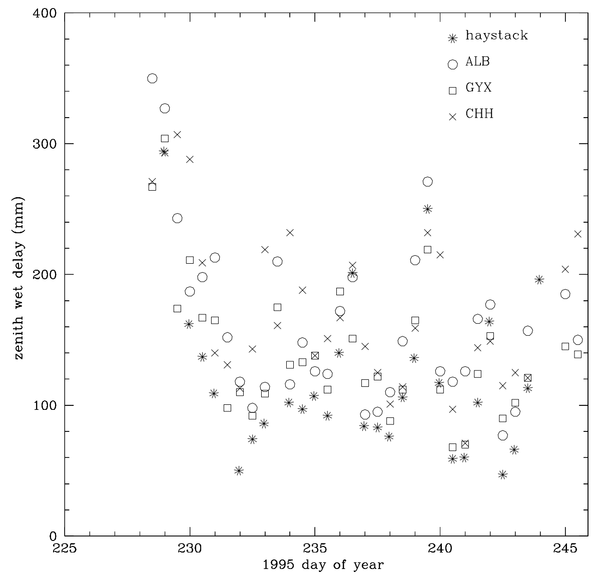


Figure 2. Zenith wet delay for radiosondes launched nearly simultaneously at four sites. Vaisala RS-80 sondes were used at Haystack Observatory VIZ sondes were launched and analyzed by the NWS at ALB, CHH, and GYX.

The Vaisala ZWD values appear systematically low with respect to the NWS results for ZWDs less than 200 mm. The differences averaged over the entire observation period are given in Table 1. In the third column the zenith wet delay differences have been converted to precipitable water vapor differences using a factor of ~1/6.15.

Table 1. The average and standard deviation of the zenith wet delays calculated from the NWS VIZ sondes relative to the Vaisala RS-80 sondes launched at Haystack Observatory.

| | ZWD difference (mm) | PWV difference (mm) |
|---|---|---|
| ALB-HST | 39 (26) | 6 (4) |
| CHH-HST | 50 (44) | 8 (7) |
| GYX-HST | 21 (26) | 3 (4) |

In the United States the primary source of radiosonde data is the National Weather Service (NWS). In recent years the principal sonde used by the NWS has been manufactured by VIZ Corporation. Because of linearity problems with the sensor, combined with errors in the treatment of the data by the NWS (Wade, 1994), the reported relative humidity does not go below ~15%. For the comparisons reported here only the data above the boundary layer are affected by this problem and thus the contribution to the difference in ZWD is negligible. Of more concern is the difference seen in the relative humidity mid-range. Fortunately on August 25 at 1200 UT (DOY 237.5) the same model of Vaisala sonde was launched at Lincoln Laboratory, ~25 km from Haystack, simultaneously with the Haystack and NWS sondes. The relative humidity as a function of pressure for the five sondes is shown in Figure 3.

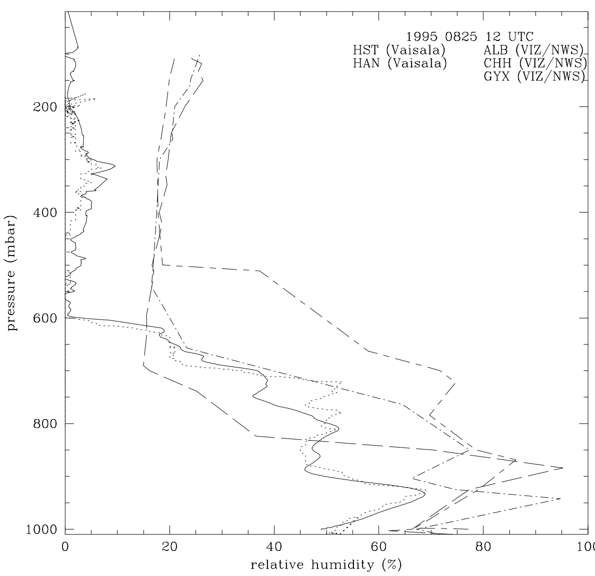


Figure 3. The relative humidity - pressure relation for radiosondes launched 1995 August 25 1200 UT (DOY 237.5) for the three NWS sites (VIZ sondes) nearest Haystack Observatory and for Vaisala sondes launched at Haystack Observatory and at Lincoln Laboratory, ~25 km away. HST (solid) and HAN (dots) are Vaisala RS-80 sondes from Haystack Observatory and Lincoln Laboratory, respectively. ALB (long dash), CHH (dot-dash) and GYX (- --) are VIZ sondes launched and analyzed by the NWS

In addition to the failure of the NWS/VIZ sondes to report the very low relative humidity (RH) above 600 mb level, there is a difference of about 20% through the boundary layer. This is not likely to be a local phenomena since the NWS sondes are uniformly spaced around the Haystack/LL sites, and the two Vaisala sites are separated by almost 20% of the distance to the NWS sites. Wade (1996, private communication) reports that there is evidence that the Vaisala sondes report RH ~4% low in mid- to high RH conditions, but the discrepancy observed here is much larger. England, Schmidlin, and Johansson (1993) flew Vaisala, VIZ and AIR sondes attached to the same balloon. They observed a larger difference (25% - 30%) at low humidity (above ~8000 m altitude), but a difference of only ~10% relative humidity above 80%.

Although radiosondes are considered the standard of accuracy of PWV measurements by the NWS, the large systematic differences between sonde results must be included in the uncertainty of the accuracy of measurements of ZWD.

*GPS*

Two types of GPS antenna were used, but perhaps more importantly, the antennas were mounted in significantly different environments, including tripod on a flat roof, tripod on the peaked roof of a wood house, steel tower, small pole over metal roof, and concrete pillar with metal support (FLINN monument). An important result from this measurement campaign is illustrated in Figure 4 which shows the dependence of the estimated height of four of the antennas on the minimum elevation of data included in the solution. These results were obtained using point-positioning with the GIPSY-OASIS II software. The ionosphere-corrected phases observables were used, and receiver clock, site position, and troposphere zenith wet delay were estimated. The zenith hydrostatic delay was calculated from the pressure at each site and mapped to the line-of-sight using NMFH (Niell, 1996). NMFW was used for the ZWD partials.

If the estimated height is not independent of the minimum elevation, an unknown bias will affect all solutions because of the changing satellite coverage with time (Elósegui et al, 1995). Similarly, the estimated ZWD will be affected temporally as changes occur in the minimum elevation of the satellites in view during the (effective) sample interval of the atmosphere estimate.

FIRE used an Ashtech 700718B antenna which was mounted above a flat metal roof; the other 7018B was located atop a 13 m amateur radio tower and suffered the same elevation dependence at all elevations (within 1.5 times the formal height uncertainty of ~3 mm at 5° and 14 mm at 30°), suggesting that the extreme elevation dependence (200 mm total height change) is dominated by the antenna and not by the mount. Of more serious concern are the different elevation dependencies exhibited by the Dorne-Margolin choke-ring antennas. The three illustrated in Figure 4 represent three types of mounting.

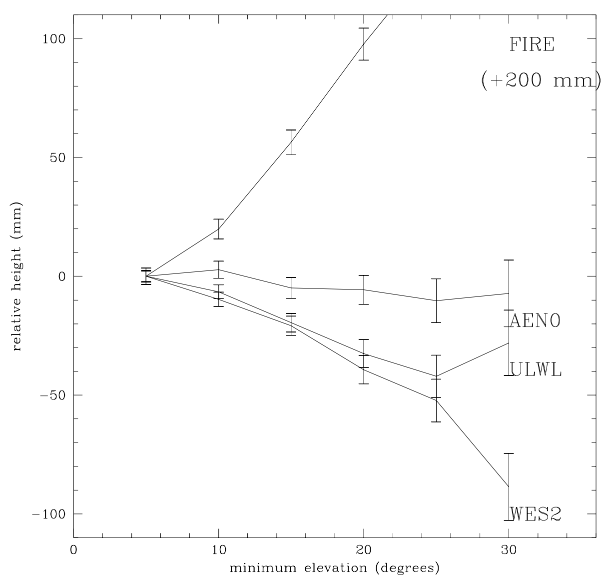


Figure 4. The dependence of estimated antenna height on minimum elevation of included data for four sites. FIRE is an Ashtech 7018B, and the other three are Dorne-Margolin antennas with choke rings. AEN0 and WES2 are manufactured by AOA. ULWL is manufactured by Ashtech and was covered by the radome available from Ashtech.

WES2 is attached to a metal supporting beam located on the top of a 10 m steel tower. AEN0 has a standard tripod/tribrach mount, but it was installed on the peak of the roof of a wood house. ULWL was also mounted on a standard tripod/tribrach but on a flat, rock-covered roof; in addition this antenna was covered by the radome available from Ashtech for the choke-ring antenna, which also has an effect on the height as a function of elevation (Niell et al, 1996). Elósegui et al (1995) demonstrated that the immediate environment of the antenna can have a significant effect on the estimated position and ZWD, and this is evident in Figure 4. The change in ZWD is approximately -0.4 times the change in height. Thus for any period during which the minimum visible satellite elevation was at least 30°, the zenith wet delay at WES2 would differ from that estimated with satellites visible to 5° by as much as 35 mm. This can be seen in Figure 5 in which the ZWD estimates for 5° have been subtracted from the 15° estimates for site WES2 for DOY 236. The average difference in ZWD between the two elevation cutoffs represents a bias of over 1 mm of PWV, and there are changes in difference of over 6 mm of PWV in less than an hour. By contrast, for AEN0, which exhibited the least change in height with change in elevation cutoff, the mean difference in ZWD for 15°-5° minimum elevation was 1.9 mm with a standard deviation of only 3.9 mm. This supports the contention that reducing the elevation dependence will improve the repeatability.

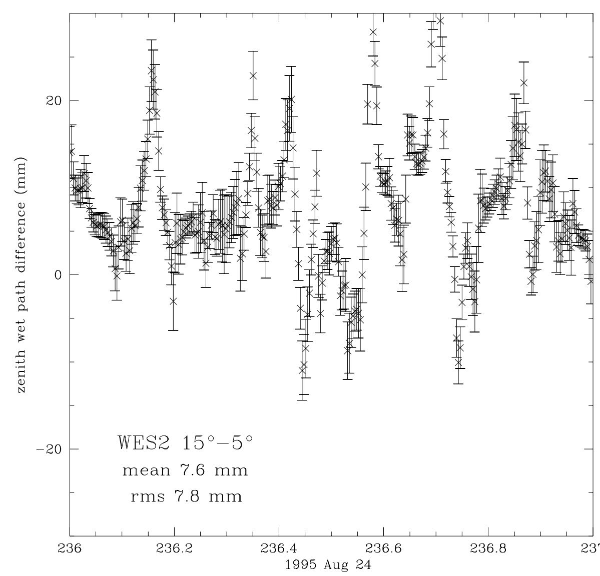


Figure 5. The difference in ZWD estimates for site WES2 between 15° and 5° minimum elevation solutions for DOY 236.

Although not shown, sites with similar mounts are found to have elevation dependencies that are similar. Thus it might be possible to find an environment, such as for AEN0, that would minimize the elevation dependence of the estimated parameters.

The precision of GPS measurement of ZWD can be evaluated by comparing results from MHR0, WES2, and WFRD, despite the differences in their supporting structures, since the elevation dependence of the ZWD estimates is very close. The three sites are separated by a maximum of ~1 km and should have very similar amounts of ZWD. The average and standard deviation of the differences between these sites are given in Table 2. The biases and standard deviations between the sites are less than ~1 mm of PWV.

Table 2. The average and standard deviation of the differences in zenith wet delay estimates between the GPS antennas at MHR0, WES2, and WFRD using data down to 5° elevation

| | Avg ZWD diff (mm) | Std.dev (mm). |
|---|---|---|
| WES2-MHR0 | 4.4 | 6.2 |
| WFRD-WES2 | 1.2 | 4.8 |
| WFRD-MHR0 | 5.5 | 6.8 |

## COMPARISON OF TECHNIQUES

The averages of the difference in ZWD over the fifteen common days of observations with the radiosondes, the WVR, and GPS data from MHR0 are given in Table 3 .

Table 3. The average and standard deviation of the differences in zenith wet delay estimates between water vapor radiometer (WVR), the GPS antenna at MHR0 using data down to 5° elevation, and Vaisala RS-80 radiosondes (RS) launched at Haystack Observatory.

| | Avg ZWD diff (mm) | Std.dev (mm). |
|---|---|---|
| WVR - GPS | 6 | 9 |
| GPS - RS | 12 | 14 |
| WVR - RS | 18 | 13 |

In terms of PWV, the WVR registered ~1 mm higher on average than the GPS measurements, and the GPS was ~2 mm higher than the radiosondes. The WVR-GPS difference is well within the predicted uncertainties of the WVR and the unknown bias of the GPS results, and the radiosondes do not differ significantly more than the differences observed between the Haystack and NWS sondes.

As seen in Figure 1, however, expressing the differences as a bias does not address the question of linearity. The Vaisala sondes differ systematically with respect to the NWS VIZ sondes as a function of the total wet delay. A similar problem between the WVR and GPS results can be seen in Figure 6 in which the ZWD estimates agree near 0 and 24 hours but differ near the middle of the day by ~20 mm.

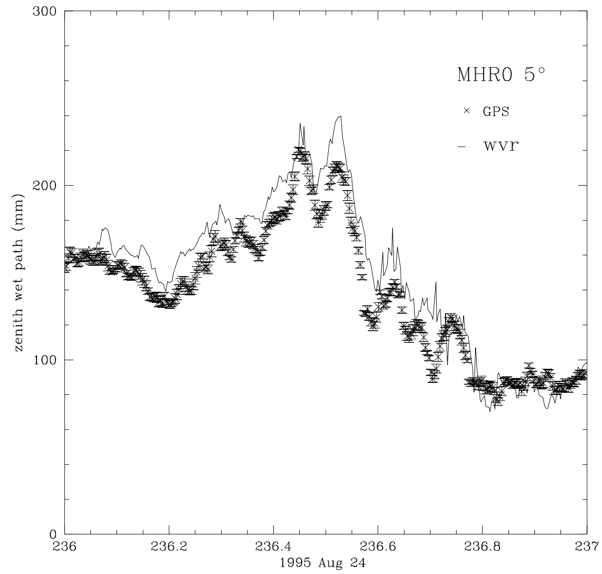


Figure 6. Zenith wet delay measured by WVR and by GPS at MHR0. The sites are separated by ~200 m horizontally and 6 m vertically. The minimum elevation for the GPS estimates is 5°.

## DISCUSSION

Biases of measured PWV greater than 1 mm have been demonstrated for both the radiosondes (Vaisala compared to VIZ) and GPS (for different minimum elevation cutoffs). Comparison of different WVRs in side-by-side tests (Kuehn et al, 1993; Elgered et al, 1993) indicate that the level of agreement is no better than ~1 mm of PWV. Thus there does not appear to be any technique that can claim to measure PWV to better than 1 mm.

Duan et al (1996), in a 14 day campaign to compare WVRs and GPS, find biases of ~0.1 mm of PWV with RMS differences of ~1.2 mm. A minimum elevation of 15° was used in the GPS analysis. Given the results demonstrated above, however, such good agreement must be considered fortuitous.

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