10 SMOI FA J4.4 THE WESTFORD WATER VAPOR EXPERIMENT: ACCURACY ISSUES INVOLVING THE USE OF GPS TO MEASURE TOTAL PRECIPITABLE WATER VAPOR

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1. **INTRODUCTION**

The Westford Water Vapor Experiment (WWAVE) was designed to measure the temporal and spatial variability of the total precipitable water vapor (PWV) over an area within approximately 25 km of the Haystack Observatory in Westford, MA. The main experiment was conducted from 15 August to 30 August 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); and 11 Global Positioning System (GPS) receivers, separated by 0.5 to 40 km. 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 antenna as part of a six-station Very Long Baseline Interferometry (VLBI) network that also included antennas in Alaska, Hawaii, Germany, Sweden, and Norway.

PWV is defined as the height of liquid water that would result from condensing all the water vapor in a column from the Earth's 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 greenhouse 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.

The 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 both satellite information and from twice daily radiosonde launches at approximately 70 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 recovery of the PWV by radiosondes is fairly straightforward, however, the radiosonde network is expensive to operate, and there are currently proposals to reduce the number of operational sites. In addition, balloons carrying the sonde packages take about an hour to reach the tropopause and can drift over an area of 100 square km. As a result, radiosonde data do not represent actual vertical water vapor profiles. Finally, with the current network, the horizontal spatial density is too low (70 sites) and the time between launches too long (12 hours) to observe rapid changes of the water vapor with time and position.

GPS has the potential of providing a continuous measurement of the average total precipitable water vapor around a site on a near real-time basis (half-hour). Once installed, a GPS receiver can run automatically, and additional costs are associated primarily with data processing. The type of information provided by GPS can close the 12-hour gap and allow for better spatial distribution in the network**.** It has been shown by Kuo et al., (1996) that when a PWV time series was introduced into the NCAR/Penn State mesoscale model, the accuracy of short-range precipitation forecasts was significantly improved. The assimilation of precipitable water vapor improved the rms errors in the initial moisture analysis--a key component of the forecast model--by 20%. The additional inclusion of surface humidity data further reduced this rms error by as much as 40%.

The analysis of GPS data produces an estimate of zenith wet delay, ZWD. The zenith wet delay is the part of the range delay that can be attributed to the water vapor in the troposphere. PWV is related to ZWD by a factor that is approximately 0.15 (Bevis, 1994). This factor varies by 20% and is a function of the weighted mean temperature of the atmosphere (Davis, 1985). It can be determined to about 2% when it is computed as a function of surface temperature, and to about 1% if data from numerical weather models are used. The zenith wet delay, ZWD, 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 WWAVE experiment was designed to use a geographically smaller array than other groups studying this issue (Rocken, 1995, Dodson, 1995). The 11 GPS receivers used in WWAVE were separated by 0.5 to 40 km. Three of the receivers were located within 1 km of both the WVR and radiosonde launch sites. These closely spaced receivers allowed for an evaluation of the consistency of the GPS determined values of zenith wet delay among GPS receivers/antennas of the same type.

The primary goal of WWAVE was to evaluate the accuracy of the GPS PWV measurement and to analyze

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the issues involved in determining this accuracy. However, an absolute assessment of the GPS PWV measurement is not possible because a measurement technique capable of determining the absolute “true” value of PWV does not exist. This was evidenced in the comparison of the various PWV measurement techniques used during WWAVE. All methods have calibration issues. For example, discrepancies on the order of 10-30 mm of zenith wet delay (1-5 mm of PWV) were seen when PWV measurements obtained by radiosondes launched at Haystack were compared to those obtained from the nearest NWS radiosonde sites (Grey, Maine; Chatham, Massachusetts; and Albany, New York). Possible explanations include differences in geographical locations, humidity sensors used by the different sonde manufacturers (Viz versus Vaisala), and/or processing algorithms. In addition, a comparison of the collocated Haystack radiosonde and WVR estimates of PWV also indicated differences on the order of 10 mm wet zenith delay (1-2 mm of PWV). These differences can possibly be attributed to the retrieval coefficients used to solve for the WVR estimate of PWV, which are based on a fit to three months of NWS sonde data (the Haystack sonde data set was too limited to be used for determining retrieval coefficients). Finally, systematic differences in the GPS determination of PWV were observed that depend on the elevation cutoff used in the GPS analysis. These differences were not specific to the type of GPS antenna or receiver and were 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. This last finding is directly applicable to the real-time determination of PWV using GPS data.

In this paper, the GPS estimates of the zenith wet delay were computed using JPL’s GIPSY/OASIS software (Webb, et al., 1995), and the JPL determined precise orbits and corresponding satellite clocks were used. These orbits are predicted to be accurate to better than 20 centimeters (Lichten, et al., 1995). Recent improvements to the software and analysis have led to orbits accurate at the 10-15 centimeter level (Lichten, 1996).

2. THE EXPERIMENT

The Westford Water Vapor Experiment (WWAVE) took place from 8 August to 12 September 1995. These dates were chosen to coincide with the NASA sponsored CONT95 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. 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 with choke ring
WES2 *	Westford Antenna 10 m Tower Westford, MA	A.O.A. Turbo Rogue	Dorne-Margolin with choke ring
G420 **	Lincoln Lab Pole on Flat Roof Hanscom AFB, MA	A.O.A. Turbo Rogue	Dorne-Margolin with choke ring
WFRD *	Ground Mount Westford, MA	A.O.A. Turbo Rogue	Dorne-Margolin with choke ring
AEN0 ***	Tripod on Peaked Roof Harvard, MA	A.O.A. Turbo Rogue	Dorne-Margolin with 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 Tripod on Flat Roof Westford, MA	Ashtech Z-12	Ashtech 700936B Dorne-Margolin choke ring & radome
SGJ0 ***	Tripod on Peaked Roof Pepperell, MA	A.O.A. Turbo Rogue	Dorne-Margolin with choke ring
JIM1	Ham Radio Tower Dunstable, MA	Ashtech Z-12	Ashtech 700718B Surveying Antenna
FIRE	Groton, MA Pepperell, MA	Ashtech Z-12	Ashtech 700718B Surveying Antenna
TAC0 *	Tripod on Peaked Roof Nashua, NH	A.O.A. Turbo Rogue	Dorne-Margolin with choke ring

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

3. EXPERIMENTAL RESULTS

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

Estimates of the ZWD from the WVR and from the MHR0 GPS receiver during the experiment are shown in Figure 1. 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).

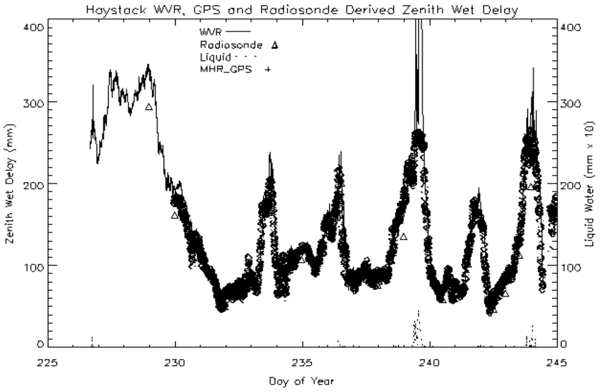

Figure 1. Estimates of Zenith Wet Delay by WVR, radiosonde, and GPS.

The average difference between WVR and 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 GPS and radiosonde estimated ZWD was +12 mm with a standard deviation of 14 mm.

3.2 Comparison of Radiosonde, WVR, and VLBI Estimates of Zenith Wet Delay

Estimates of the ZWD from a partial segment of the VLBI campaign (Ryan, 1996) are shown in Figure 2. The GPS estimates of ZWD were not plotted here since visually they cannot be separated from the VLBI estimates.

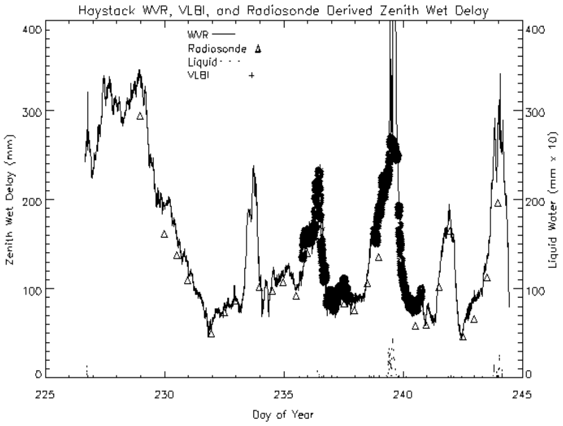

Figure 2. Estimates of Zenith Wet Delay by WVR, radiosonde, and VLBI.

The statistical analysis of the four data sets, VLBI, GPS, WVR, and radiosonde, shows that VLBI estimates of ZWD are, on average, larger than the estimates of all the other measuring techniques. These results are summarized in Table 2. The average difference between VLBI and WVR estimated zenith wet delays (excluding the time periods associated with rain) was +3 mm. The average difference between VLBI and GPS estimates of ZWD was +8mm, and the average difference between VLBI and radiosonde estimates was +24 mm.

TABLE 2
Average Difference and Standard Deviation in the Zenith Wet Delay
Estimated by WVR, Radiosondes, 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)

The difference between GPS and WVR estimates of ZWD is illustrated in Figure 3. The data in this figure show that, aside from an average offset of 4.4 mm between GPS and WVR estimates of ZWD, there are no obvious departures from a linear fit between the two data sets.

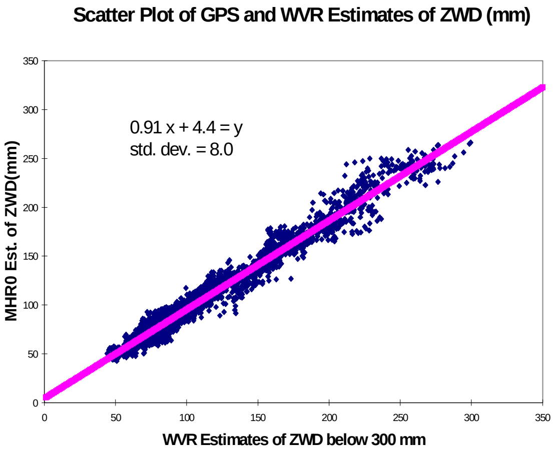

Figure 3. Scatter Plot of the WVR and GPS Estimates of Zenith Wet Delay.

Figure 4 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.

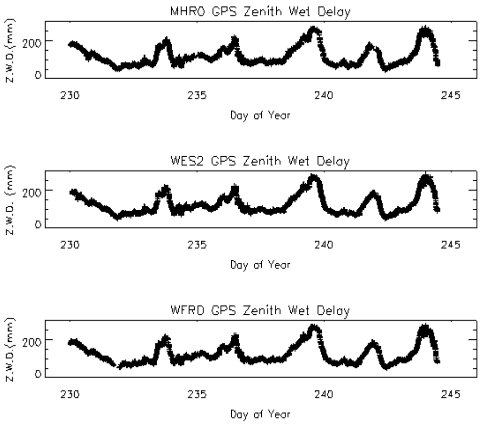

Figure 4. GPS estimates of the Zenith Wet Delay for three sites from Day 230 to Day 244, 1995.

The average differences between the zenith wet delays at the three sites are given in Table 3. 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 systematic errors associated with the electromagnetic environment of the antenna.

TABLE 3
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

It is doubtful that errors in pressure caused the average difference in PWV estimates at the three sites. Pressure gradients observed during the WWAVE experiment were shown to be, on average, negligible based on a comparison of the barometer differences from the various 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 on two occasions during WWAVE against a Paroscientific barometer, which has an advertised accuracy of better than 0.1 mb.

If one assumes roughly 0.05 mm of ZWD per meter near the surface of the earth, the difference in height between WFRD and MHR0 (56 m) could partially account for the average difference in their measured ZWD. The difference in the heights of the three stations alone would require corrections of –1.4 mm, -1.4 mm, and –2.8 mm for the three rows of Table 3, given a uniform distribution of water vapor up to a height of 3000 m and an average ZWD of 150 mm.

The observed ZWD differences in Table 3 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 the discrepancy in the average ZWD differences between the sites. The WFRD site is located in a fairly flat grass covered field. 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. One could therefore anticipate slightly “drier” readings of PWV at the MHR0 site, which is consistent with the data in Table 3.

It is also likely 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° elevation cutoff. 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.

3.3. Evidence of Small Scale Variations in the Observed Zenith Wet Delay (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.

The wave-like structures can be observed in the GPS estimated ZWD data from the three closely located sites at the Millstone/Haystack complex shown in Figure 12 between 244.25 and 244.37. A clear separation of ZWD estimates can be observed at the three sites between 244.25 and 244.37.

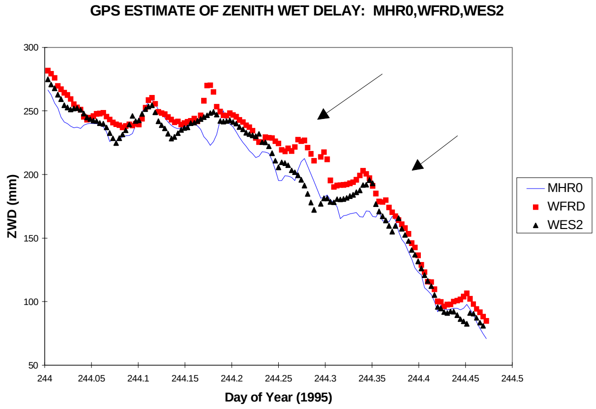

Figure 5. Anomalous Zenith Wet Delay estimates between the three closely located GPS sites: MHR0, WES2, and WFRD on Day 244.

Figure 6 shows the difference between the GPS estimated ZWD at MHR0 and the WVR estimate of ZWD during this same time period on Day 244. The WVR determined liquid water vapor content is also shown and is scaled according to the information given on the right-hand axis of the graph. Note that the same wave-like structure in the ZWD is observed in the WVR data. This suggests that this was a real phenomenon rather than some obscure artifact of the GPS data processing.

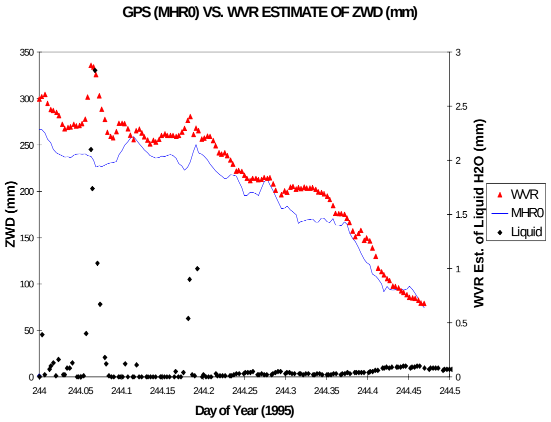

Figure 6. GPS estimates of Zenith Wet Delay versus WVR estimates of ZWD on Day 244.

4. 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 used for these accuracy comparisons were all taken with A.O.A. Turbo Rogue GPS receivers using Dorne-Margolin choke ring antennas. Additional GPS data was analyzed using Ashtech Z-12 receivers and either Dorne-Margolin choke ring antennas or their surveying antenna, the 700718B. An elevation cutoff of 5 degrees was used in all of the data processing for instrument comparison. These values of PWV accuracy are consistent with the results of GPS/STORM (Rocken, 1995) even though they used an elevation cutoff of 15 degrees and different receivers and antennas. Furthermore, D.O.D.'s anti-spoofing (AS) had not been turned on during GPS/STORM, while it had been during WWAVE. The precision of the GPS measurement of ZWD is better than 6 mm (1 mm of PWV) as shown by the agreement of three closely spaced GPS systems.

Radiosondes appear to have problems related to their humidity sensors, as discussed in Wade et al., (1994) and Coster et al., 1996. Radiosondes also cannot provide frequent average measurements of water vapor in a period of rapidly changing weather. Water vapor radiometers have operational problems during rain 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, antenna, and receiver used may affect the GPS determination 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 as satellite and receiver clock biases. High quality low elevation data are 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. It is worth noting that with some receivers, this effect is worse than others. The impact of the mount, radome, antenna, and receiver on the GPS determination of PWV is an area in need of more investigation.

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6. REFERENCES

Bevis, M., S. Businger, S. Chiswell, T. A. Herring, R. A. Anthes, C. Rocken, and R. H. Ware, 1994, GPS Meteorology: Mapping Zenith Wet Delays onto Precipitable Water, Journal of Applied Meteorology, 33, 379-386.

Coster, A.J., A.E. Niell, F.S. Solheim, V.B. Mendes, P.C. Toor, K.P. Buchmann, and C.A. Upham (1996). "Measurements of Precipitable Water Vapor by GPS, Radiosondes, and a Microwave Water Vapor Radiometer," Proceedings of ION GPS-96, the 9th International Technical Meeting of the Satellite Division of The Institute of Navigation, Kansas City, MO, U.S.A., 17-20 September 1996; pp. 625-634.

Davis, J. L., T. A. Herring, I. I. Shapiro, A. E. E. Rogers, and G. Elgered, 1985, Geodesy by radio Interferometry: Effects of atmospheric modeling errors on estimates of baseline length, Radio Science, 20, 1593-1607.

Dodson, A., P. Shardlow, 1995: The Global Positioning System as a Passive Integrated Atmospheric Water Vapour Sensing Device, SPIE, 2582, 166-177.

Kuo, Y.-H., X. Zou, Y.-R. Guo, 1996, "Variational Assimilation of Precipitable Water Using a Nonhydrostatic Mesoscale Adjoint Model. Part I: Moisture Retrieval and Sensitivity Experiments," *Monthly Weather Review*, 124, pp.122-147.

Lichten, S. M., Y.E. Bar-Sever, W. I. Bertiger, M. Heflin, K. Hurst, R. J. Muellerschoen, S. C. Wu, T. P. Yunck, and J. Zumberge, "Gipsy-Oasis II: A High Precision GPS Data Processing System and General Satellite Orbit Analysis Tool," Technology 2005, Proceedings of NASA Technology Transfer Conference, Chicago, IL (24-26 Oct. 1995).

Lichten, S. M., 1996, personal communication.

Niell, A. E., 1996, personal communication.

Rocken, C. R., T. Van Hove, J. Johnson, F. Solheim, R. Ware, M. Bevis, S. Chiswell, and S. Businger, 1995, GPS/STORM - GPS Sensing of Atmospheric Water Vapor for Meteorology, Journal of Atmospheric and Oceanic Technology, 12, 468-478.

Ryan, J., 1996, personal communication.

Wade, C. G. , 1994, An Evaluation of Problems Affecting the Measurement of Low Relative Humidity on the United States Radiosonde, Journal of Atmospheric and Oceanic Technology, 11, 687-700.

Webb, F. H. and J. F. Zumberge, 1995, An Introduction to GIPSY/OASIS-II, JPL D-11088, California Institute of Technology, Pasadena, California, July 17, 1995.

Zumberge, J. F., Heflin, M. B., Jefferson, D. C., Watkins, M. M., and Webb, F.H., " Precise Point Positioning for the Efficient and Robust Analysis of GPS Data from Large Networks," J. Geophys. Res. Vol. 102, No. B3, pp. 5005-5017, March, 1997.

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