Development of a Water Vapor Tomography System Using Low Cost L1 GPS Receivers

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Abstract

A system of low cost Global Positioning System (GPS) stations is being developed to measure the three-dimensional (3-D) structure of tropospheric water vapor over a small ground network. The concept is to deploy 20 GPS stations in a network spanning 10 km to 20 km. For each of the 20 stations, we will measure the integrated water vapor from the GPS antenna to each of the GPS satellites in view. These slant water vapor (SWV) observations will enhance current precipitable water vapor (PWV) measurements by providing information on the spatial variability of water vapor above the network. In addition, they will be used as input for a tomographic estimation of the water vapor field. During the first year of this project, the primary focus has been in the development and testing of the prototype GPS station. Each station consists of a GPS receiver, a low multi-path GPS antenna, data communication capability through a 900-MHz radio modem equipped with Time Division Multiple Access (TDMA) technology, and a solar-charged battery for power. Eight of these GPS stations have been built. These instruments were tested near Platteville, Colorado, from August to September of 1998. This field deployment was used to verify the quality of the observations, to develop and test analysis software, and to evaluate SWV observations. We provide an overview of the system, present preliminary observations, and outline future tasks. A 20-station system will be deployed at the Cloud and Radiation Testbed (CART) facility in Lamont, Oklahoma, for the Water Vapor Intensive Observation Period (IOP) in the fall of 1999. Applications of the data obtained from this network include their use in comparison with other water vapor instruments at the CART site (lidars, radiosondes, profiling radiometers, etc.), as well as validating water vapor fields in single-column modeling (SCM) parameterizations.

Introduction and Overview

The GPS accurately and reliably measures total column water vapor (Rocken et al. 1993; Rocken et al. 1995), also called PWV. Applications for GPS-derived PWV measurements include their assimilation into short-term weather forecasts (Kuo et al. 1993; Kuo and Guo 1996), long-term climate monitoring of total column water vapor, use in SCM parameterizations, and as a calibration measurement for water vapor profiling instruments.

PWV measurements are derived by estimating the delay on a GPS signal as it propagates from the transmitting GPS satellite to an individual GPS antenna on the ground (Bevis et al. 1994). The delay can be related to atmospheric properties through the refractivity equation (Campen et al. 1961; Hogg et al. 1981). Example PWV measurements from Lamont, Oklahoma, are shown in Figure 1.

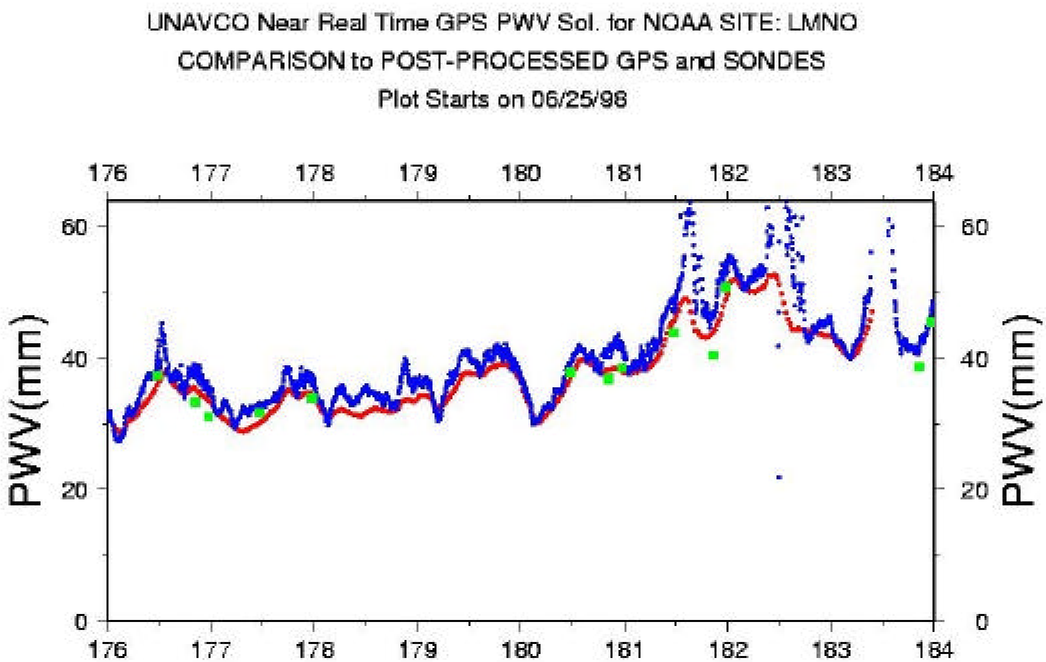

Figure 1. PWV observations from the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site. GPS-derived PWV measurements are shown in red, water vapor radiometer (WVR) observations are shown in blue, and RAOBS are shown in green. WVR and RAOBS measurements agree with the GPS observations to better than 2 mm root mean square (rms), with a bias of less than one mm. In addition to these PWV measurements, we have begun computing SWV values that contain information on the spatial variability of water vapor in the atmosphere.

GPS-derived PWV observations provide the total column water vapor above a station, but provide no information of the water vapor profile. It is now possible to measure the total amount of water vapor between a receiving GPS antenna and each of the GPS satellites observed by a station. This observation is known as an SWV observation (Ware et al. 1997). At any instant in time, there are up to 12 GPS satellites spaced throughout the sky above a GPS station. By measuring the SWV to each satellite, variations in the water vapor structure can be observed. A dense network of GPS stations (spaced in 1-km or smaller intervals) can produce a collection of SWV observations to retrieve detailed information on the water vapor structure above the network. As part of the ARM Water Vapor IOP scheduled for fall 1999, we plan to locate up to 20 GPS stations around the SGP Lamont facility. These stations will provide data for assimilation into numerical weather models, and a tomographic inversion of the water vapor field above the network.

GPS Network Design and Development

In collaboration with the University NAVSTAR Consortium (UNAVCO), a low-cost GPS station has been developed for monitoring solid earth and small-scale atmospheric processes. Twenty of these stations will be deployed in a network around the SGP facility in late 1999. Each station includes an L1 carrier phase GPS receiver and antenna for data collection. The data are transmitted in real time back to a central processing computer through a 900-MHz radio modem equipped with TDMA technology. The station is powered through a combination of solar power and battery backup. The total cost of each station is approximately $3500. This is significantly less than the $15 to $20K for a dual frequency station similar to the ones currently used for other GPS atmospheric applications. The low cost of this new GPS station allows for more instruments to be deployed, and a higher resolution of atmospheric features.

Because the GPS receivers used in these stations track only the L1 carrier phase, the observations will be corrupted by the ionosphere. This error will be minimized by using ionospheric models to remove large-scale errors, and by keeping the total diameter of the network small (approximately 10 km).

Each GPS station will transmit its data stream to a central collection computer. This computer will simultaneously log data from all the GPS stations through the master TDMA modem. The data will then be processed using the Bernese GPS Software V4.0 (Beutler et al. 1996) to obtain SWV observations. From there, the SWV observations will either be directly assimilated into a numerical weather model, or used for a tomographic inversion of the water vapor field.

Platteville Experiment and Results

Eight of these L1 GPS stations were operated in Platteville, Colorado, from August through September of 1998. The purpose of this deployment was to test the systems for robustness, equipment operation, and installation problems. Overall, the stations worked well. There were very few problems with data gaps, and the observations were of high quality. Sky plots of atmospheric water vapor variability are shown in Figure 2.

GPS and WVR SWV Comparisons

In May 1996, a pointed WVR was operated adjacent to a GPS receiver in Platteville, Colorado. The data from the GPS station were processed to obtain SWV observations, while the WVR was configured so that it would sample the sky following the current GPS satellite configuration. The GPS station computed SWV observations every 30 seconds, while the WVR would point to each GPS satellite in view every 8 minutes. Comparison of the GPS and WVR observations offers a validation of how well the GPS instrument is able to measure spatial variability in the atmospheric water vapor structure. Figure 3 shows the comparisons of SWV (mapped to the zenith to reflect PWV variations).

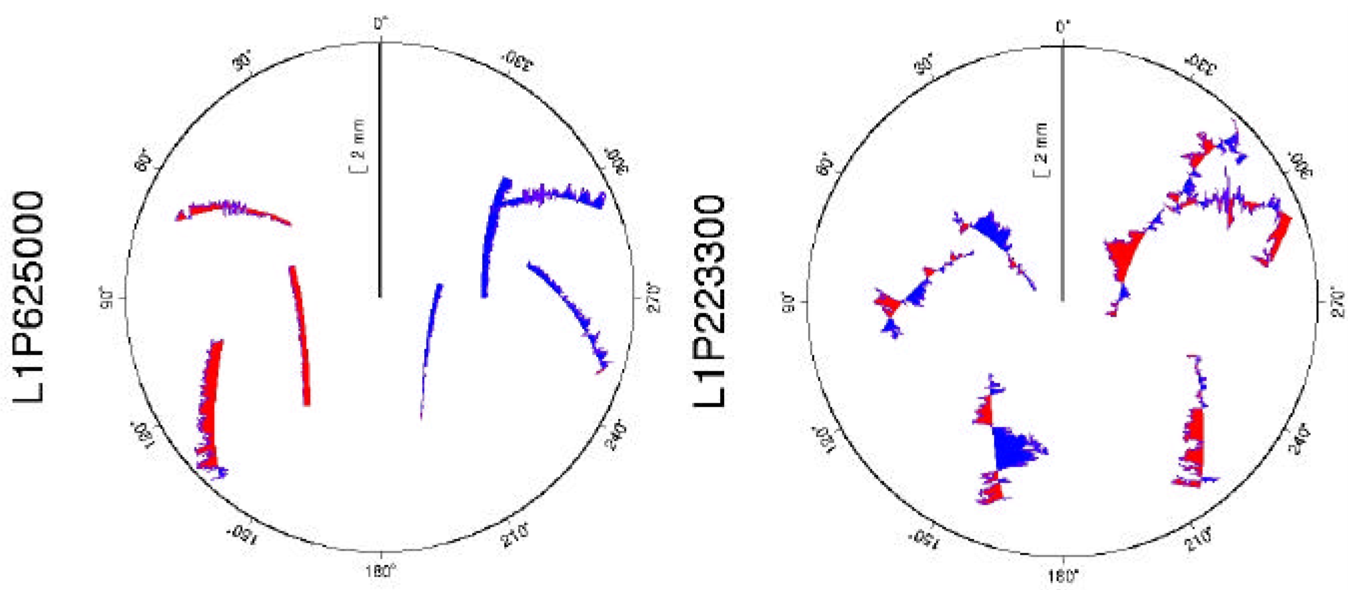

Figure 2. Variability in SWV for two different stations in Platteville. Each plot represents a different 4-hour time window. The SWV observations are plotted using a sky plot in the direction of the seven satellites in view during the 4-hour time window. The satellite track is drawn in polar coordinates (ρ,θ) by using the satellite elevation as the radius (ρ), and the azimuth as the angle (θ). Positive SWV relative to the mean is plotted as red, and negative SWV relative to the mean is plotted as blue. A satellite directly above the station would appear in the center of each circle; a satellite on the eastern horizon would appear on the right of each circle. The left panel shows a gradient with more water vapor in the southwest and less vapor in the northeast. The panel on the right shows a patchy distribution of water vapor.

Summary

In the first year of a 3-year project to measure the spatial and temporal water vapor structure above a network of GPS stations, there were two significant accomplishments. First, a GPS station was designed and tested for use in the project. The cost of an individual GPS station is approximately $3500. Each of these instruments will be deployed in a network around the SGP facility in Lamont, Oklahoma, during the Water Vapor IOP in the fall of 1999. It has been determined that the data from these stations is of high enough quality to allow for the detection of variability in the SWV between a receiving GPS antenna and the transmitting GPS satellite. Second, GPS-derived SWV measurements have been compared with observations from a pointing WVR. These two independent measurements show agreement in water vapor structure, and offer validation that the GPS observations accurately measure atmospheric features. During the next year, the focus of the project will turn to the deployment of the network in Lamont and the application of the SWV observations. This includes their assimilation into the MM5 (National Center for Atmospheric Research/Pennsylvania State University Mesoscale Model) numerical weather model and their input into a tomographic inversion of the observations to determine the 3-D water vapor structures above the network.

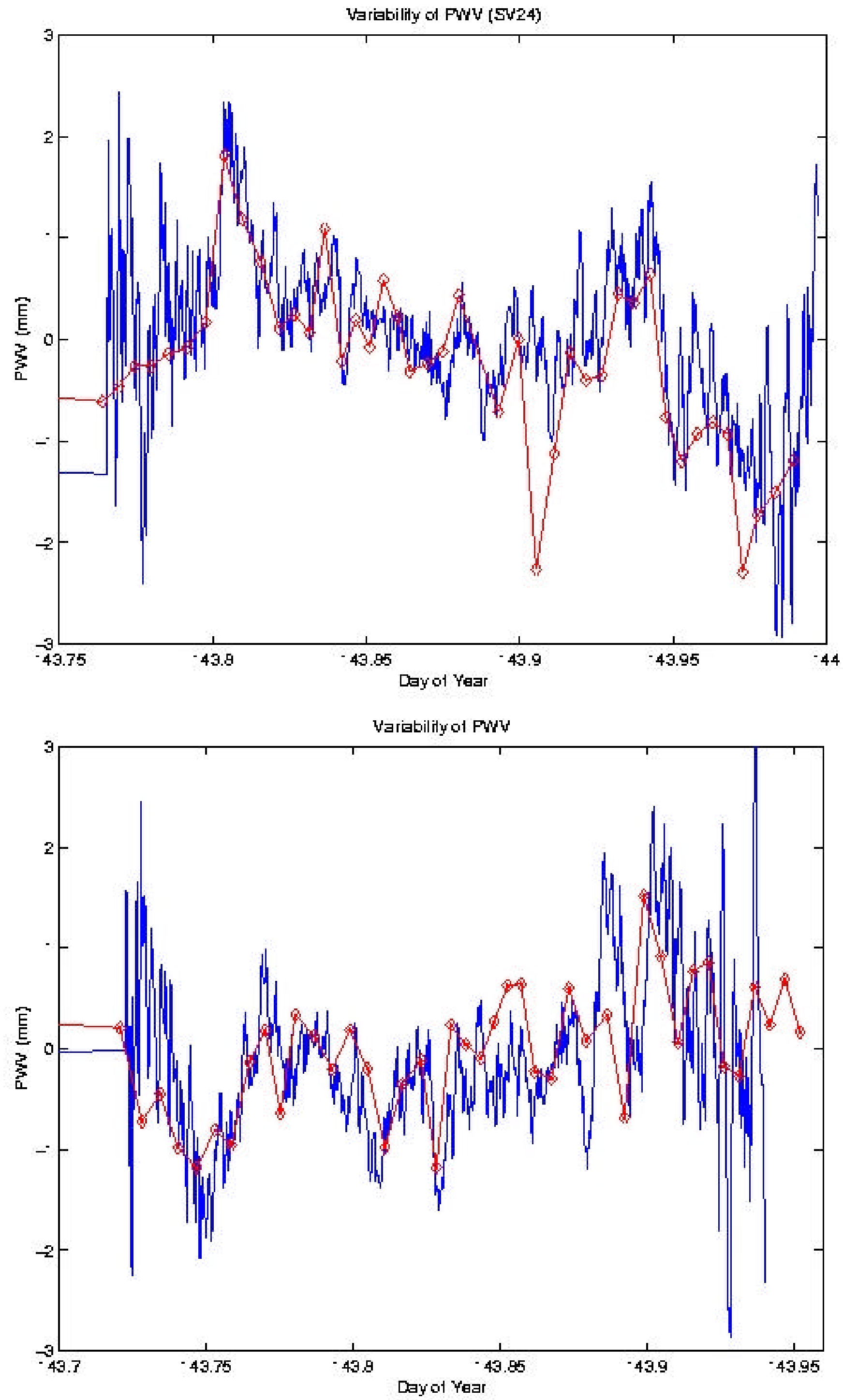

Figure 3. Variations of SWV, mapped to zenith, measured by GPS and WVR. The blue lines are GPS-derived variations at 30-second intervals. The red lines are WVR variations at approximately 8-minute intervals. These variations illustrate spatial and temporal variability of the atmospheric PWV above a GPS station. The total SWV is computed by scaling the PWV at that time to the elevation angle of the satellite plus these residuals.

References

Beutler, G., E. Brockman, S. Frankhauser, W. Gurtner, J. Johnson, L. Mervart, M. Rothacher, S. Schaer, T. Springer, and R. Weber, 1996: *Bernese GPS Software Version 4.0*. University of Berne, September 1996.

Bevis, M., S. Businger, S. Chiswell, T. Herring, R. Anthes, C. Rocken, and R. Ware, 1994: GPS meteorology: mapping zenith wet delays onto precipitable water vapor. *Journal of Applied Meteorology*, **33**, 379-386.

Campen, C., R. Cunningham, and V. Plank, 1961: Electromagnetic wave propagation in the lower atmosphere. In *Handbook of Geophysics*, New York Macmillan, Ch. 13, 5-11.

Hogg, D., F. Guiraud, and M. Decker, 1981: Measurement of excess radio transmission length on earth-space paths. *Astron. Astrophys*., **95**, 304-307.

Kuo, Y.-Y., and Y.-R. Guo, 1996: Variational assimilation of precipitable water using a nonhydrostatic mesoscale adjoint model Part 1: Moisture retrieval and sensitivity experiments. *Monthly Weather Review*, **124**, 122-147.

Kuo, Y.-H., Y.-R. Guo, and E. Westwater, 1993: Assimilation of precipitable water measurements into a mesoscale numerical weather model. *Monthly Weather Review*, **121**, 1215-1238.

Rocken, C., T. Vanhove, 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 Ocean Technology*, **12**, 468-478.

Rocken, C., R. Ware, T. Van Hove, F. Solheim, C. Alber, and J. Johnson, 1993: Sensing atmospheric water vapor with the global positioning system. *Geophysical Research Letters*, **20**, 2631-2634.

Ware, R., C. Alber, C. Rocken, and F. Solheim, 1997: Sensing integrated water vapor along GPS ray paths. *Geophysical Research Letters*, **24**, 417-420.