GPS Water Vapor Projects Within the ARM Southern Great Plains Region

J. Braun, T. Van Hove, S. Y. Ha, and C. Rocken
GPS Science and Technology Program
University Corporation for Atmospheric Research
Boulder, Colorado

Abstract

The U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program has a need for an improved capability to measure and characterize the four-dimensional distribution of water vapor within the atmosphere. Applications for this type of data include their use in radiation transfer studies, cloud-resolving and single-column models, and for the establishment of an extended time series of water vapor observations. The University Corporation for Atmospheric Research's (UCAR) GPS Science and Technology (GST) Program is working with ARM to leverage the substantial investment in Global Positioning System (GPS) infrastructure within the Southern Great Plains (SGP) region to improve ARM's ability to monitor the water vapor in the area. Over the past year there has been progress on multiple fronts. This includes network installation and operation, a refinement in data analysis techniques, observation validation, and in the application of these observations to characterize the state of the atmosphere. Fifteen SuomiNet stations have been installed in the past year by the ARM Program and the University of Oklahoma. These data are now routinely being processed at UCAR/GST to produce precipitable water (PW) estimates at each of the SuomiNet-equipped extended facilities. In addition, a new direct mapping function has been implemented, which provides PW estimates that are less dependent on changes in elevation mask and have better agreement with other water vapor sensors within the ARM instrument suite. The sensing of slant water vapor (SWV), which is water vapor along the line of site path between a transmitting satellite and a ground-based GPS receiver, is a new technology that has been recently refined. A comparison of 37 days of SWV from a GPS receiver and a microwave radiometer located at the ARM Central Facility (CF) has been conducted. This comparison produced a data set with 1.3 mm root mean square (rms) agreement. Operation and analysis of the 24-station GPS network within a 40-square-kilometer area around the CF continues. Within the past year the estimates of the four-dimensional water vapor field have been improved through the determination of absolute water vapor density profiles and the incorporation of profile information to improve vertical resolution. Finally, an observing system simulation experiment (OSSE) has been conducted for a network of GPS stations in the SGP area. The results from the OSSE indicate that measurements of PW and SWV can improve the retrieval of water vapor within the entire SGP region and improve short-term forecasts.

GPS Networks in the SGP Region

The SGP contains almost 50 GPS stations whose primary purpose is atmospheric monitoring. The ARM SGP area is shown in the left panel of Figure 1 as the dashed rectangle. GPS stations installed and operated by National Oceanic and Atmospheric Administration-Forecast Systems Laboratory are shown as black diamonds. The blue diamonds are SuomiNet (Ware et al. 2000) stations that were installed in 2001 through a cooperative agreement between ARM, the University of Oklahoma, and UCAR/GST. These data are routinely processed to produce half-hour PW estimates at UCAR/GST and displayed on the web (www.gst.ucar.edu/gpsrg/ realtime). They are also available via the Internet as NetCDF files, and will be submitted to the ARM archive next year. The ARM CF, shown as the red star within the larger SGP region, has a network of 24 single-frequency GPS stations located within a 40-square-kilometer area (6.5 km x 6.5 km) around the CF. The data from this network (shown on the right figure) are processed to compute SWV. These data are combined in fifteen-minute batches to estimate the three-dimensional water vapor field above the network.

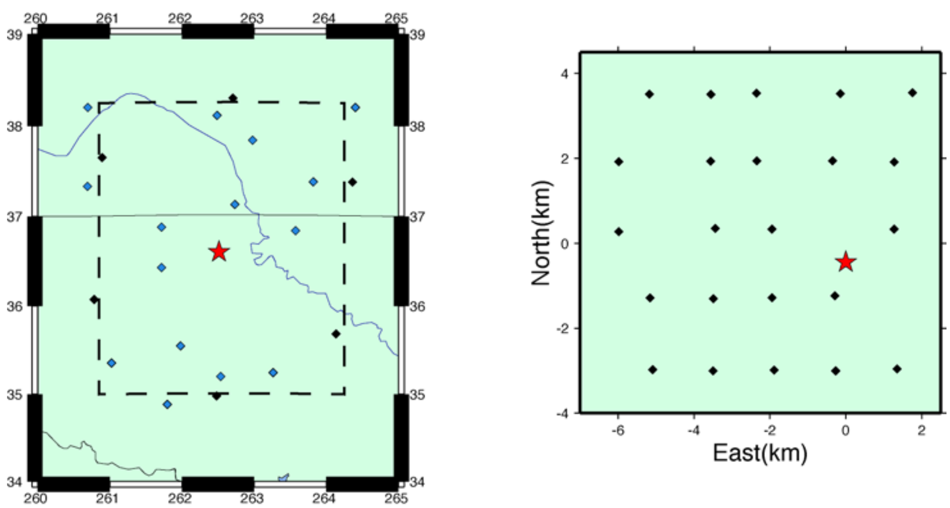

Figure 1. GPS networks in the SGP region.

Validation of SWV

SWV is the integrated water vapor along the path between a GPS receiver and a GPS satellite (Braun et al. 2001). Unlike PW, SWV provides information on the spatial variability of water vapor in the atmosphere surrounding a GPS station. The observation can be divided into an isotropic and nonisotropic component. A convenient description of this is: $SWV(\theta) = m(\theta)*PW + S$, where $m(\theta)$ is the mapping function that relates water vapor at zenith to elevation angle θ, PW is the isotropic component, and S is the nonisotropic component. A validation study was conducted at the ARM CF where SWV was measured using both GPS and a pointing Microwave Radiometer (MWR), which continuously measured SWV in the direction of all GPS satellites above the horizon. Examples of results are shown in Figure 2. The top panel shows the nonisotropic component (S) as measured by the GPS (red) and MWR (black) for individual satellite tracks. The bottom panel shows the total amount of water vapor (isotropic + noniosotropic) for the same satellite track, scaled to the equivalent zenith value.

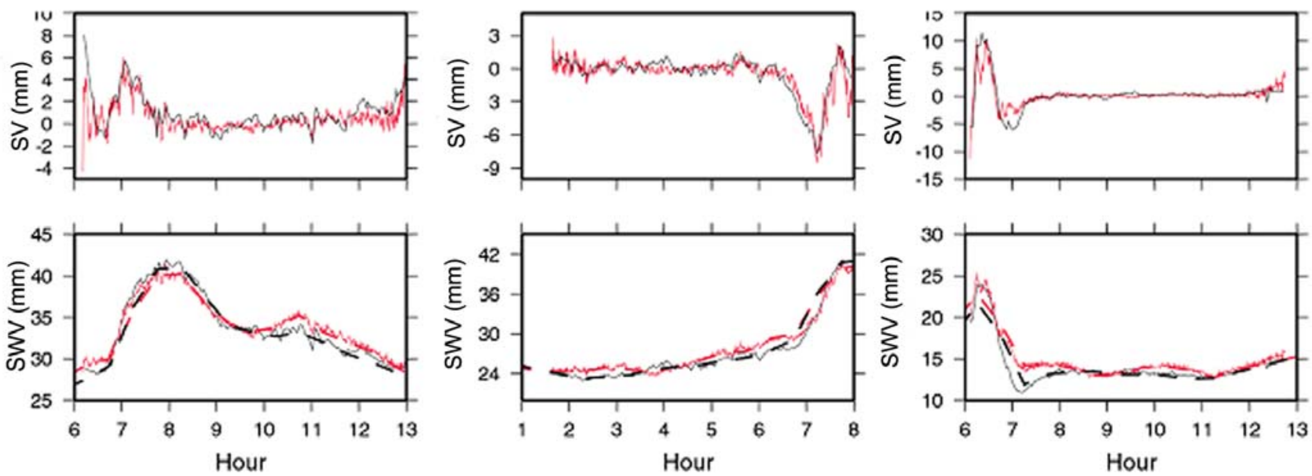

Figure 2. Comparisons of GPS and MWR SWV observations.

PW is shown as the thicker dashed lines (GPS-red and MWR-black) in the bottom panel to illustrate the magnitude of S with respect to PW. The rms agreement of the two instruments was 1.3 mm for 37 days of observations spanning a wide range of atmospheric conditions. These results are being compiled into a manuscript for review.

Direct Mapping to Improve PW

The accurate and absolute determination of PW provides a constraint for testing and validation of Line-by-Line Radiative Transfer Models. Results from the ARM WVIOP3 experiment revealed that GPS PW results varied as a function of elevation cutoff angle when the Niell mapping function was used in the analysis. The scatter plot on the left in Figure 3 shows GPS PW results using a 7-degree elevation mask against results using a 12-degree mask for: (1) a Niell mapping function (blue) and (2) a direct mapping function (Rocken et al. 2001) using the AVN numerical weather model (red). The Niell results show a scale change in the PW estimates based on elevation mask, while the AVN direct mapping

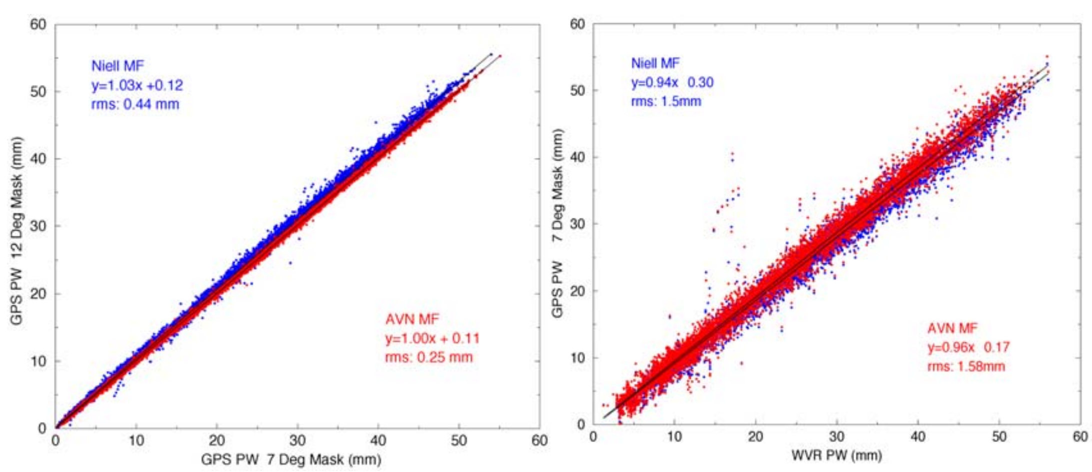

Figure 3. Effects of mapping functions on PW.

results are almost independent of elevation mask. The scatter plot on the right shows a comparison of PW from GPS (located at Lamont, Oklahoma) and a MWR (located at the ARM CF). These results span almost an entire year and indicated that a direct mapping function technique reduces the dependence of GPS PW solutions on elevation mask. This implies that the absolute accuracy of GPS PW has improved.

Small-Scale Tomography Estimates

The panels in Figure 5 illustrate the three-dimensional water vapor density fields that have been retrieved using a tomographic inversion method that combines GPS SWV data and a profile of vapor density from the CART Raman lidar. Each column represents an independent solution using 15 minutes of observations at 120 second sampling. The horizontal extent of the network is approximately 40 square kilometers (6.5 km x 6.5 km); each vertical layer is 410 meters. The GPS data help to determine the variation of water vapor that exists within the column; the Raman lidar helps resolve the vertical profile. Water vapor fields like these can be used to study the planetary boundary layer for features such as dryline convergence and horizontal convective rolls. These could then be used in cloud-resolving models and cloud parameterization studies.

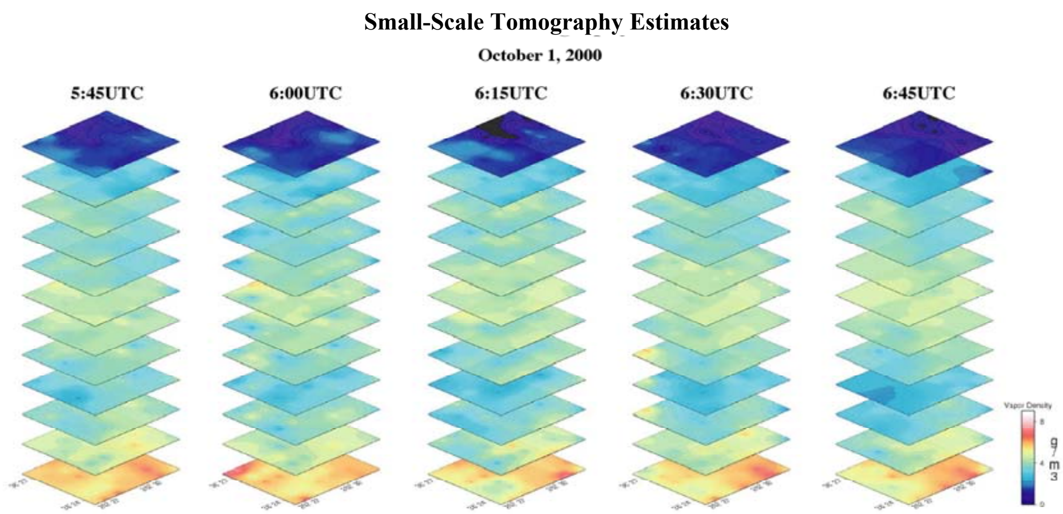

Figure 4. Tomography estimates of water vapor density.

OSSE

OSSE experiments (Ha et al. 2002) have been performed to determine if a network of GPS stations, all measuring PW and SWV, could have a positive impact on short-range (less than 12 hours) weather prediction. The top row of panels in Figure 5 show the 3-hour total precipitation from a 6-hour forecast using perfect initial conditions (left), no data assimilation (center), and a four-dimensional variational data assimilation (right) using PW and SWV from a network of GPS stations with a separation of 90 km (the network is shown in the right panel). The vertical profiles of horizontal wind and equivalent potential temperature are shown in the bottom panel along the path marked with the red line in the upper

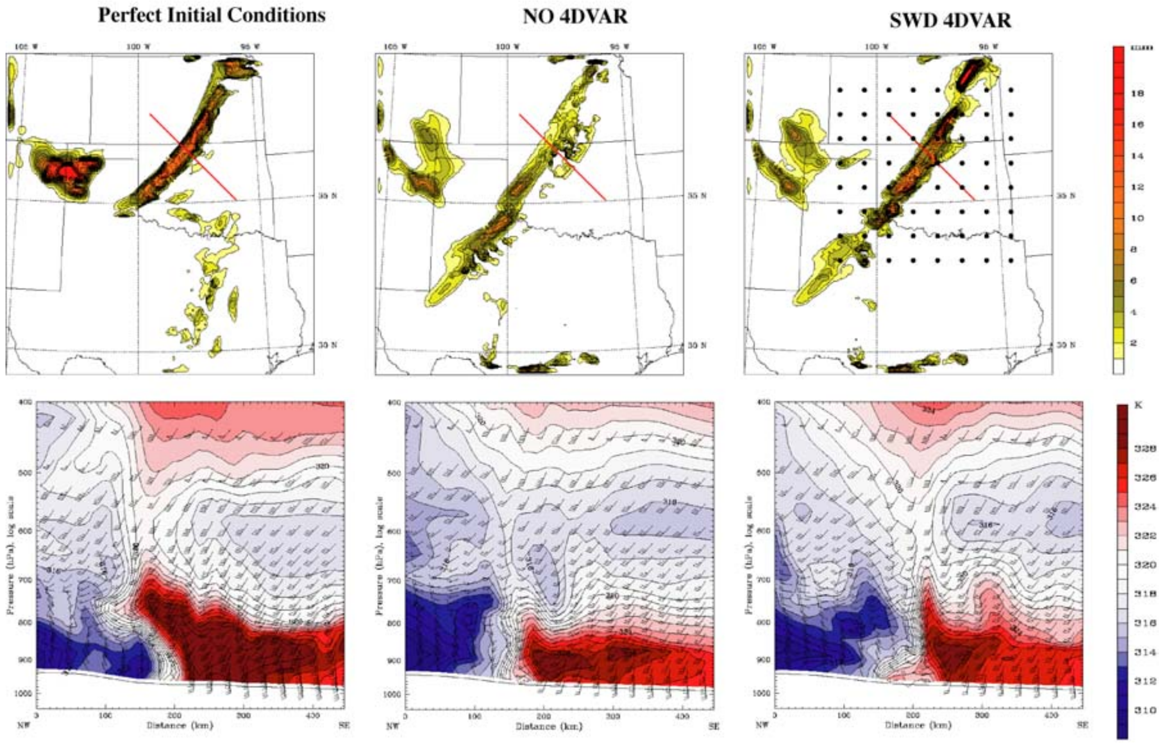

Figure 5. Forecast of three-hour rain (top) and equivalent potential temperature.

plots. These results indicate that a GPS network such as the SuomiNet network could be used in a similar manner to determine the water vapor field in the SGP region for later use in single-column and/or cloud-resolving models.

Future Work

Next year UCAR/GST will continue to operate GPS stations and analyze data from the SGP region. Specific tasks related to the ARM Program will be the submission of GPS PW data from SuomiNet stations into the ARM archive center, continued work on direct mapping techniques to improve the accuracy of GPS PW measurements, the generation of SWV measurements for all stations in the SGP region, and the continued operation of the single-frequency network around the ARM CF to retrieve three-dimensional water vapor density fields. UCAR/GST will also participate in the International H_2O experiment in May and June 2002. We will compare GPS observations to other instruments that will be deployed during the experiment in validation studies.

References

Braun, J., C. Rocken, and R. Ware, 2001: Validation of line-of-sight water vapor measurements with GPS. *Radio Sci*., **36**:459-472.

Ha, S. -Y., Y. -H. Kuo, and Y. -R., Guo, 2002: "Assimilation of ground-based GPS slant-path water vapor measurements and its impact on short-range prediction of pre-frontal squall line: An OSSE Study." In *Proceedings of Third US-Korea Joint Workshop on Storm Scale and Mesoscale Weather Analysis and Prediction*, February 20-22, 2002, Boulder, Colorado.

Rocken, C., S. Sokolovskiy, J. M. Johnson, and D. Hunt, 2001: Improved mapping of tropospheric delays. *J. Atmos. Oceanic Technol*., **18**:1205-1213.

Ware, R. H., D. W. Fulker, S. A. Stein, D. N. Anderson, S. K. Avery, R. D. Clark, K. K. Droegemeir, J. P. Kuettner, J. B. Minster, and S. Sorooshian, 2000: SuomiNet: A real-time national GPS network for atmospheric research and education. *Bull. Amer. Meteor. Soc*., **81**:677-694.