

Near real-time GPS sensing of atmospheric water vapor

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Abstract. We describe sensing of atmospheric column water vapor in near real-time using the Global Positioning System (GPS). We use predicted GPS orbits for automated computation of vertical column water vapor within 30 minutes of GPS data collection. Based on a 4 month comparison, near real-time GPS column water vapor agrees with radiosondes and radiometers within 2 mm rms. Our near real-time column water vapor data are posted hourly at www.unavco.ucar.edu. They are available for assimilation in numerical weather models and for other applications.

Introduction

Water vapor is a highly variable atmospheric constituent. It is fundamental to the transfer of energy in the atmosphere and in the formation and propagation of weather. Yet water vapor remains one of the most poorly characterized meteorological parameters. Improved knowledge of its distribution is needed for a variety of atmospheric research applications and for improved weather forecasting.

An opportunity to address this need is presented by the 24 satellite GPS constellation that fills the atmosphere with microwave signals based on atomic clocks. GPS signals are delayed by water vapor, dry air, hydrometeors and other particulates [Niell, 1996; Solheim *et al.*, 1997]. The delay due to water vapor offers an opportunity for sensing water vapor with GPS [Bevis *et al.*, 1992, 1994; Rocken *et al.*, 1993, 1995; Businger *et al.*, 1996; Duan *et al.*,

1996] and promises improvements in short-term forecasting [Kuo *et al.*, 1993, 1996, McPherson *et al.*, 1997].

To use column water vapor for weather forecasting it must be available close to real-time. This requires GPS data and high-accuracy orbit availability in real-time. Since May, 1996 we have begun to analyze GPS data from the NOAA Forecast Systems Laboratory (FSL) GPS network in near real-time (Figure 1). We describe the data, the processing technique, and comparisons of real-time and post-processed GPS with radiosonde and radiometer sensed column water vapor.

Data collection

We are obtaining near real-time GPS tracking data from a 16 station network in the central U.S. (Figure 1). Fifteen of the stations are operated by FSL [Gutman *et al.*, 1994], most of them located at wind profiling (radar) sites. One station is operated in Yellowstone National Park, Wyoming, by the University of Utah. All stations use dual frequency Trimble™ SSE or SSI GPS receivers. The FSL sites transmit 30 sec GPS data, and 6 min surface meteorological data to the FSL data hub in Boulder, Colorado, every 30 min. The Yellowstone site transmits GPS data to Boulder every 30 sec via satellite link. This site is operated primarily to monitor geodetic deformation of the volcanic caldera and does not provide surface meteorological data.

The real-time GPS network extends more than 1,500 km from the Mississippi Gulf coast to Yellowstone. A network of this size

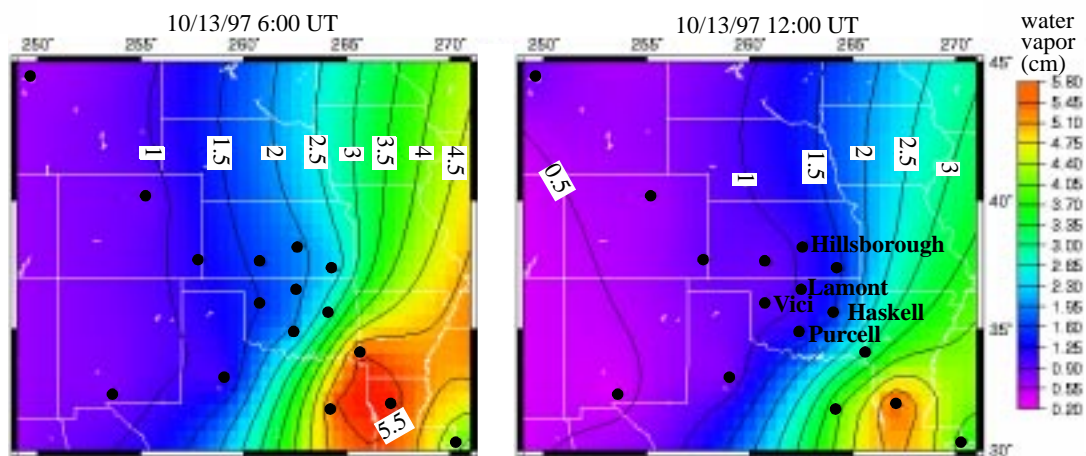


Figure 1. Example of column water vapor maps available in real-time at www.unavco.ucar.edu. The maps were produced using data from 16 central United States GPS sites identified by black dots. GMT software [Smith and Wessel, 1990] was used for interpolation, contouring and plotting. Interpolated and extrapolated values far from the GPS sites are artifacts of the interpolation software. Sites used for comparisons of GPS, radiosonde and radiometer measurements of column water vapor are labeled in the right-hand panel. Shown is an example of a strong drop in column water vapor near the Texas-Arkansas border during 6 hours.

can provide absolute column water vapor data without including additional global GPS stations [Rocken *et al.*, 1993].

Radiosonde data and water vapor radiometer data were provided by the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program. Radiosondes are released twice daily at Vici, Purcell, and Haskell, Oklahoma and Hillsborough, Kansas and more frequently at Lamont, Oklahoma. Radiometers are operated continuously at these sites and data are provided at 5 min intervals. We interpolated 30 min GPS sensed column water vapor to the radiosonde release times, and averaged six of the 5 min radiometer data points to match the 30 min GPS data.

The radiometers, manufactured by Radiometrics Corporation and operated by ARM, are described by Ware *et al.* [1993, 1997]. We excluded radiometer data degraded by moisture on the radiometer windows and radiosonde data that were flagged as not reliable.

Real-time data analysis

We retrieve real-time GPS data hourly and use Bernese 4.0 software [Beutler *et al.*, 1996] to estimate vertical column water vapor. Station coordinates are held fixed and satellite positions are also assumed known. Signal delay due to the dry atmosphere is removed using surface barometric pressure measurements and a mapping function [Niell, 1996]. Vertical zenith wet delay is estimated every 30 minutes for each station in the network under the assumption that the delay is azimuthally isotropic and changes approximately as the cosecant of the satellite elevation angle. The zenith wet delay is converted to zenith column water vapor using the linear relationship, published by Bevis *et al.* [1994].

We use predicted GPS satellite orbits computed at the University of Berne, Switzerland, for real-time analysis. These orbits become available every day at 15:00 UT. They are estimated from the International GPS Service (IGS) global network data [Zumberge *et al.*, 1994] collected from 0:00 to 24:00 UT during the previous day. The Berne group computes satellite positions from previous day data, and then integrates the equations of motion for each GPS satellite to predict orbits two days ahead. Thus, the predicted GPS orbits that we use for near real-time processing are 39 hr old just before downloading at 15:00 UT, and 15 hr old just after downloading. Predicted orbits degrade in time primarily because of unpredictable non-conservative drag forces. Their accuracy ranges from ~0.1 m rms at zero hr to ~1.5 m at 48 hr. The average accuracy of predicted orbits with 15 to 39 hr age is ~0.4 m rms.

Data from each GPS satellite are weighted according to the goodness of fit to previous day global tracking data, provided by the group in Berne. However, satellite maneuvers are unpredictable and can cause large orbit errors. Our real-time analysis detects and eliminates such errors prior to column water vapor estimation, based on the goodness of fit to the hourly data from the FSL GPS network.

Bernese 4.0 uses a batched least squares algorithm which stores the normal equations for each processed time interval. We process the real-time data in hourly observation windows, store the normal equations, and then stack the normal equations from the sequence of the last 24 solutions. This processing mode enforces continuity between the hourly segments and it is nearly equivalent to processing 24 hr of observations, but requires significantly less computer

time. We invert the data from the 16 station network in about 20 min, including data translation and preparation of contour maps and plots for hourly publishing, on one HP K200™ workstation central processor unit (CPU). Thus, our current procedures allow us to post column water vapor data on the Internet within about 30 min of real-time. This process can be streamlined to reduce processing time to less than 10 min. It is also possible to compute column water vapor more frequently.

Results and discussion

We estimate column water vapor in near real-time using GPS data from each site every 30 min. Figure 2 shows an example of a near real time water vapor time series that is updated hourly. Our GPS estimations represent averages of integrated water vapor along all GPS ray paths above an elevation cut-off angle of 15°. Since most water vapor is concentrated in the lowest 3 km of the atmosphere all observations fall within a circular cone of 3 km height and ~11 km radius at the top. Thus we estimate 30 min averages of the vertical column water vapor within a 400 km³ volume.

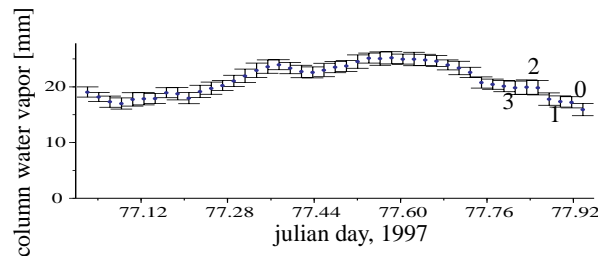


Figure 2. Near real-time GPS column water vapor estimates and their formal errors for one day. The numbers to the right mark the solutions that we define as 0,1,2,3, etc. hour latency results.

The quality of real-time column water vapor is determined by comparison with radiosonde, water vapor radiometer, and post-processed GPS data. Post-processed results are computed in 24-hour batches using accurate GPS orbits provided by the University of Berne 4 days after data collection. Figure 3 shows an example of the compared data, where a sharp dip in column water vapor at Lamont from 40 mm to 10 mm during 5 hours is clearly resolved.

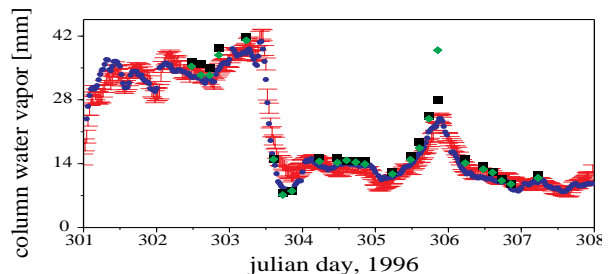


Figure 3. Seven day comparison of real-time GPS (read vertical error bars), post-processed GPS (blue dots), radiosonde (black squares) and radiometer data (green diamonds).

Comparisons of 4 months of data are summarized in Table 1. The average column water vapor for the five sites during this period was 14 mm. The near real-time column water vapor data agrees with radiosonde and radiometer data during this period within 2.1 and 1.9 mm rms respectively. Near real-time and post-processed GPS results during the same period agree to 1.7 mm rms. Radiometers and the radiosondes agree for the same period to 1.5 mm rms (not shown in table). Post-processed GPS results using 5 to 10 cm quality orbits agree with the radiosondes to 1.3 mm rms (not shown in table).

Table 1: Comparison of near real-time GPS column water vapor estimates with post-processed GPS estimates, radiosondes, and radiometers during a four month period. Approximately 5,000 post-processed, 190 (470 at Lamont) radiosonde, and 4,000 radiometer comparisons are included for each site.

	Comparison results (rms \pm bias in mm)		
	Post-process	Radio-sonde	Radio-meter
Hillsborough	1.5 0.0	1.7 -0.1	1.7 0.9
Haskell	1.8 0.0	2.5 0.3	2.4 1.3
Lamont	1.6 0.0	2.1 -0.6	2.2 -1.0
Purcell	1.8 -0.1	2.1 -0.8	1.7 0.1
Vici	1.7 -0.2	1.9 0.0	1.7 -0.8
average	1.7 -0.1	2.1 -0.2	1.9 -0.1

The rms values in Table 1 and those quoted above are computed relative to zero without bias removal. Some sites appear to be affected by significant biases. At Lamont and Purcell radiosonde measurements of column water vapor are 0.6 and 0.8 mm respectively higher than real-time GPS. The largest radiometer bias is seen at Haskell where the radiometer reports on average 1.3 mm less column water vapor than GPS. The source of these biases is not understood.

Improving real-time accuracy

While post-processed GPS results agree with radiometers and radiosondes to 1.3 mm rms, real-time results agree presently to only 2 mm rms. Therefore we examined possible ways to improve the accuracy of real-time column water vapor data by comparing post-processed column water vapor with results obtained in three different real-time analysis modes during a ten day test period. The first mode was the routine hourly real-time analysis described above. For the second mode we applied the same analysis but used more accurate post-processed orbits, instead of the predicted orbits. Finally, for the third mode, we used the better orbits and changed the analysis to resolve the correct initial number of GPS carrier wavelengths at signal lock-on (ambiguities) for each hourly data segment [Blewitt, 1989].

Comparisons of the results as a function of latency for the three processing modes are shown in Figure 4. As labeled in Figure 2, we define latency as the elapsed time from the end of an hourly obser-

vation window to the start of the analysis. We find: (1) better results can be obtained if better orbits are used; (2) ambiguity resolution, if possible, further improves the quality of the results; and (3) results improve with increasing latency, especially when ambiguities are not resolved.

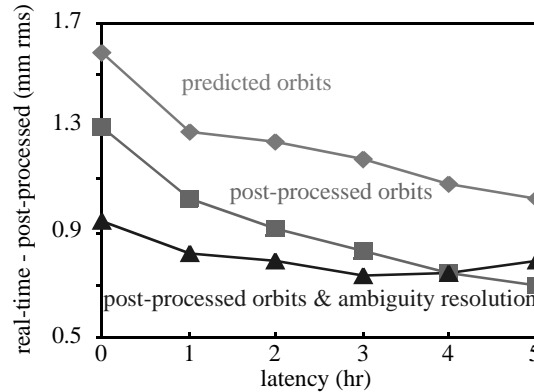


Figure 4. Comparisons of post-processed and near-real-time column water vapor data as a function of result latency for three different real-time processing test modes.

Ambiguity resolution results in more precise tropospheric estimates because fewer parameters have to be estimated once the ambiguities are fixed to their correct integer values. Increasing latency improves the results because added normal equation files generally reduce formal uncertainties of the column water vapor values estimated by least squares. This can be seen in Figure 2 where the formal errors of the 0-hr latency solutions are slightly larger than the errors with several hour latency. Data from hr N provide additional information for hr N-1 solutions, and thus contribute to improving the 1, 2, 3, ..., hr latency results.

In summary, we found that better real-time results can be achieved with improved predicted GPS orbits. Presently predicted GPS orbits are not sufficiently accurate to allow reliable integer ambiguity resolution in real-time for the FSL network. Orbit error effects scale with station spacing and ambiguity resolution should be applied for denser GPS networks with shorter baselines to achieve improved real-time GPS results. The easiest way to obtain better results is to wait and include a few hours of additional data in the processing. This however, is not acceptable for weather forecasting applications where the most recent 0-hr latency results are of greatest value.

Related applications

Real-time GPS estimation of column water vapor has applications beyond weather forecasting. GPS is an all-weather system that could be used to supplement the Geostationary Operational Environmental Satellite (GOES) and other satellite observations that are degraded in cloudy regions. GPS column water vapor can also be used for calibration and validation of satellite radiometers.

Average global atmospheric column water vapor is expected to rise due to increasing atmospheric CO₂ concentrations [Yuan *et al.*, 1993]. GPS column water vapor that is available close to real-time

can be included in operational numerical weather models that provide the primary input for climate studies. Thus real-time analysis is valuable for climate monitoring applications of GPS column water vapor.

Measurements of slant water vapor with GPS networks [Ware *et al.*, 1997] could potentially be applied to water vapor tomography, prediction of convection, and related aviation wind shear hazard. These applications are also most valuable if conducted close to real-time.

We have recently begun to apply real-time GPS analysis to the estimation of ionospheric total electron content (TEC). TEC models, similar to those determined for the column water vapor, are generated and can be applied to correct GPS observations with lower-cost single frequency receivers and for ionospheric research and monitoring [Ho *et al.*, 1996].

Real-time maps of GPS derived column water vapor as shown in Figure 1 can also be used to compute tropospheric delay corrections for real-time kinematic GPS surveying and potentially improve survey accuracies [E. Cannon, *personal communication*, 1997].

Conclusions

We have demonstrated automated computation of near real-time GPS sensed column water vapor with 2 mm rms radiosonde and radiometer agreement and less than 1 hr latency. Real-time column water vapor improvement to about 1.5 mm rms agreement with radiosondes is possible if carrier phase ambiguities are resolved.

Because real-time GPS column water vapor is accurate, works in all weather, and has high temporal resolution it promises to be complementary to other atmospheric observing systems such as radiosondes, GOES, and other satellites. Scientists at the National Center for Atmospheric Research (NCAR) and at FSL are currently studying the impact of GPS column water vapor by assimilating it into numerical weather models. Evaluation of these assimilation studies is needed to determine the accuracy, latency, and spatial and temporal resolution required for improved weather prediction.

Dense dual-frequency GPS networks for crustal deformation monitoring are currently installed in Japan (950 stations) and in southern California (250 stations). In addition, a growing number of GPS sites are operated world wide for a variety of reasons. The growing GPS infrastructure, using real-time GPS data analysis and integrated water vapor assimilation techniques, has the potential to significantly improve weather and precipitation forecasting in the near future.

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References

Beutler, G., E. Brockman, S. Frankhauser, W. Gurtner, J. Johnson, L. Mervart, M. Rothacher, S. Schaer, T. Springer, and R. Weber, Bernese GPS

Software Version 4.0, *Univ. Berne*, September, 1996.

- Bevis, M., S. Businger, T. Herring, C. Rocken, R. Anthes and R. Ware, GPS Meteorology: Remote Sensing of Atmospheric Water Vapor Using GPS, *J. Geophys. Res.*, 97, 15,787-15,801, 1992.
- Bevis, M., S. Businger, S. Chiswell, T. Herring, R. Anthes, C. Rocken, and R. Ware, GPS Meteorology: Mapping Zenith Wet Delays onto Precipitable Water, *J. Appl. Meteorol.*, 33, 379-386, 1994.
- Blewitt, G., Carrier Phase Ambiguity Resolution for the Global Positioning System Applied to Geodetic Baselines up to 2000 km, *J. Geophys. Res.*, 94, 10187-10203, 1989.
- Businger, S., S. Chiswell, M. Bevis, J. Duan, R. Anthes, C. Rocken, R. Ware, T. Van Hove, and F. Solheim, The Promise of GPS in Atmospheric Monitoring, *Bull. Am. Meteorol. Soc.*, 77, 5-18, 1996.
- Duan, J., M. Bevis, P. Fang, Y. Bock, S. Chiswell, S. Businger, C. Rocken, F. Solheim, T. Van Hove, R. Ware, S. McClusky, T. A. Herring, and R. W. King, GPS Meteorology: Direct Estimation of the Absolute Value of Precipitable Water, *J. Appl. Meteorol.*, 35, 830-838, 1996.
- Gutman, S., R. Chadwick, D. Wolfe, A. Simon, T. Van Hove, and C. Rocken, Toward an Operational Water Vapor Remote Sensing System Using GPS, *FSL Forum*, September 1994.
- Ho, C., A. Mannucci, U. Lindquister, X. Pi, and B. Tsurutani, Global ionosphere perturbations monitored by the worldwide GPS network, *Geophys. Res. Lett.*, 23, 3219-3222, 1996.
- Kuo, Y.-H., Y.-R. Guo, and E. Westwater, Assimilation of Precipitable Water Measurements into a Mesoscale Numerical Model, *Mon. Wea. Rev.* 121, 1215-1238, 1993.
- Kuo, Y.-H., X. Zou, and Y.-R. Guo, Variational Assimilation of Precipitable Water Using a Nonhydrostatic Mesoscale Adjoint Model, *Mon. Wea. Rev.*, 124, 122-147, 1996.
- McPherson, R., E. Kalnay, and S. Lord, The Potential Role of GPS Observations in Operational Numerical Weather Prediction, *Proc. Nat. Res. Council Workshop on GPS in Geoscience* (in press), 1997.
- Niell, A., Global Mapping Functions for the Atmosphere Delay at Radio Wavelengths, *J. Geophys. Res.*, 101, 3227-3246, 1996.
- Rocken, C., R. Ware, T. Van Hove, F. Solheim, C. Alber, and J. Johnson, Sensing Atmospheric Water Vapor with GPS, *Geophys. Res. Lett.*, 20, 2631-2634, 1993.
- Rocken, C., T. Van Hove, J. Johnson, F. Solheim, R. Ware, M. Bevis, S. Chiswell, and S. Businger, GPS Sensing of Atmospheric Water Vapor for Meteorology, *J. Atm. Ocean. Tech.*, 12, 468-478, 1995.
- Smith, W.H.F and P. Wessel, Gridding with continuous curvature splines in tension, *Geophysics*, 55, 293-305, 1990.
- Solheim, F., J. Vivekanandan, R. Ware, and C. Rocken, Propagation delays induced in GPS signals by dry air, water vapor, hydrometeors and other particulates, submitted to *J. Geophys. Res.* 1997.
- Ware, R., C. Rocken, F. Solheim, T. Van Hove, C. Alber, and J. Johnson, Pointed Water Vapor Radiometer Corrections for Accurate GPS Surveying, *Geophys. Res. Lett.*, 20, 2635-2638, 1993.
- Ware, R., C. Alber, C. Rocken, and F. Solheim, Sensing Integrated Water Vapor along GPS Ray Paths, *Geophys. Res. Lett.*, 24, 417-420, 1997.
- Yuan L., R. A. Anthes, R.H. Ware, C. Rocken, W. Bonner, M. Bevis and S. Businger, Sensing Climate Change Using the Global Positioning System, *J. Geophys. Res.*, 98, D8, 14,925-14,937, 1993.
- Zumberge, J., R. Neilan, G. Beutler, and J. Kouba, The International GPS Service for Geodynamics - Benefits to Users, *Proc.: Inst. Nav.*, 7th *Tech. Meet.*, Sept., 1994.

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