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SENSING ATMOSPHERIC WATER VAPOR WITH THE GLOBAL POSITIONING SYSTEM

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Abstract. Global Positioning System (GPS) receivers, water vapor radiometers (WVRs), and surface meteorological equipment were operated at both ends of a 50-km baseline in Colorado to measure the precipitable water vapor (PWV) and wet delay in the line-of-sight to GPS satellites. Using high precision orbits, WVR-measured and GPS-inferred PWV differences between the two sites usually agreed to better than 1 mm. Using less precise on-line broadcast orbits increased the discrepancy by 30%. Data simulations show that GPS measurements can provide mm-level separate PWV estimates for the two sites, as opposed to just their difference, if baselines exceed 500 km and the highest accuracy GPS orbits are used.

Introduction

Water vapor plays a major role in atmospheric processes ranging from global climate change to micrometeorology. The distribution of water vapor is highly variable in space and time. Atmospheric scientists use surface, balloon-borne, and remote sensing instruments to measure water vapor. Measurement of surface water vapor is of limited use because of its high spatial variability.

Radiosonde observations provide water vapor profiles. Their cost limits the spacing of release sites and restricts use to typically two daily launches per site. Thus, spatial and temporal resolution of water vapor from radiosondes is inadequate [Anthes, 1983], and limitations of water vapor data are a major source of error in short-term (<24 hour) forecasts of precipitation.

Ground-based WVRs measure water vapor radiative brightness temperatures which are converted into PWV using retrieval coefficients [Hogg et al., 1983]. Retrieval coefficients are calculated by regression analysis of radiosonde data, and depend on climate and weather. Ground based WVRs provide high temporal and poor spatial resolution because only a few of these instruments are in use today. On the other hand, space-based down-looking WVRs perform well over oceans, poorly over land, and provide high spatial and poor temporal resolution.

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Atmospheric water vapor can also be measured using GPS [Dixon and Kornreich Wolf, 1990; Bevis et al., 1992]. PWV ranges from 0 - 60 mm. We show that GPS can estimate PWV with mm accuracy every 30 minutes. PWV measurements of this accuracy and frequency are useful for meteorology and hold promise to aid in the estimation of vertical water vapor profiles [Kuo et al., 1993]. Because of rapid developments in GPS technology, water vapor monitoring GPS networks may become cost-effective. GPS receivers spaced at 50-500 km could provide 30-minute water vapor data that could be assimilated into numerical weather forecasts.

Experiment Description

We collected data from Sep. 17 to Nov. 28, 1992, at both ends of a 50-km baseline between Boulder and Platteville, Colorado. Trimble™ 4000SST 8-channel dual-frequency phase and C/A code receivers observed all GPS satellites above 15 degrees elevation at 30-second intervals. Radiometrics™ 23.8 and 31.4 GHz WVRs automatically pointed sequentially towards the satellites, using elevation and azimuth computed from broadcast GPS ephemerides. A typical five-satellite scenario required 8 minutes to observe the line-of-sight wet delay in the direction of all satellites.

Data Analysis

WVR Data. Our WVR software converted observed sky brightness temperatures into wet delay for each WVR observation. Data were time tagged and stored with the GPS satellite number, elevation, and azimuth. Wet delay can be related to integrated water vapor through the equation,

$$\text{Wet Delay} = K \times \text{Integrated Water Vapor}$$

Zenith integrated water vapor is equivalent to PWV. The dimensionless value of K is approximately 6.5 [Bevis et al., 1992]. Thus, 6.5 cm wet delay is caused by 1 cm PWV. This approximation may cause a 5% error in the WVR-GPS comparison. WVR corrections were linearly interpolated to the time of GPS measurements and applied to GPS phase observations. In the following sections, we will refer to wet delay when discussing atmospheric effects on GPS, and we will refer to PWV as the meteorological quantity of interest. Wet delay scaled to zenith ranged from 45 - 150 mm during our experiment, corresponding to a PWV range of 7 - 23 mm.

GPS Data. Virtually all current high-accuracy GPS analysis software includes techniques to estimate atmospheric delay parameters. While geodetic applications estimate station coor-

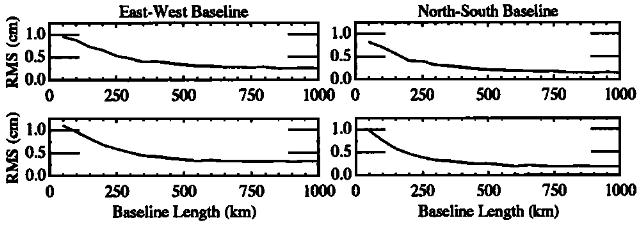

Fig. 1. Data simulation results for estimation of PWV at both ends of a GPS baseline. The rms error of PWV as computed for east-west (left panels) and north-south (right panels) vs. baseline length is shown. Estimated PWV at one end of a baseline was compared to actual WVR measurements included in the simulations. Pointed WVR measurements from days 298 (top panels) and 299 (bottom panels) were used. Simulations, assuming perfect satellite orbits, show that 2-mm PWV accuracy can be achieved for large station separation only. North-south oriented baselines appear slightly better suited for GPS estimation of PWV than east-west baselines.

dinates, satellite orbits, and zenith delay simultaneously, our application of GPS to atmospheric sensing focuses on estimating zenith delay parameters. Estimation is simplified if good a priori station coordinates and satellite orbits are known. In our study, this was achieved by computing the average station position for the entire experiment and by using precise satellite orbits determined from global GPS tracking networks.

Total tropospheric delay of the GPS signal is the sum of wet delay, caused by water vapor, and dry delay, caused by other atmospheric constituents. Dry delay was calculated from surface pressure measurements using the Saastamoinen [1972] model.

Two methods of zenith wet delay estimation are most widely used in high-accuracy GPS analysis: (a) least squares estimation, typically determining one parameter per station per specified time interval; and, (b) estimation as a stochastic process using a Kalman filter [Tralli et al., 1990]. In both methods the estimation is based on the assumption that the atmosphere above a GPS antenna is azimuthally isotropic, and wet delay along a line with elevation angle e is related to zenith wet delay (e=90 degrees) by the mapping function:

$$\text{Wet Delay} = \frac{\text{Zenith Wet Delay}}{\sin(e)}$$

This mapping function is sufficiently accurate for estimating wet delay above 15 degrees elevation. Dry delay corrections were mapped to e using the Saastamoinen mapping function.

We processed the GPS data with the Bernese software version 3.3 [Rothacher, 1992]. The Bernese GPS software package is designed for high-accuracy geodetic work and GPS satellite orbit improvements. In this study, we used broadcast orbits, PGGA orbits [Bock et al., 1991], and CODE orbits [Beutler et al., 1993], for the estimation of zenith wet delay and thus PWV.

Phase data from the two ends of the baseline were combined in single differences. A single difference is the difference between measurements of the phase from one satellite as received at the same time at the two ends of a baseline. Single differences are formed in GPS to eliminate satellite clock errors, especially Selective Availability (S/A) clock dithering errors [Rocken and Meertens, 1991]. The single difference files were pre-processed to fix carrier phase cycle slips. These cleaned files were used to estimate zenith wet delay for the Boulder site. We applied the total tropospheric delay correction (dry delay from surface pressure plus wet delay from the WVR) at Platteville. At Boulder we applied dry delay corrections only, and estimated zenith wet delay from the GPS data. GPS estimates of zenith wet delay, converted to PWV, are therefore directly comparable to WVR measurements of PWV at the Boulder site.

Zenith wet delay was not estimated simultaneously at Platteville and Boulder because it is not possible to reliably determine absolute PWV at both ends of a short 50-km baseline. Data simulations show that absolute estimation of PWV at both ends of a baseline to better than 2 mm requires site separation of more than 500 km (Figure 1). The reason is that GPS satellite elevation angles are nearly identical at both ends of short baselines, and thus the zenith wet delay parameters for the two ends are highly correlated. Figure 1 was computed for the "best-case" of perfectly known orbits and dry delays. Even under these circumstances, and for baselines up to 1000 km, we were unable to estimate absolute PWV at both sites to better than 1.5 mm rms.

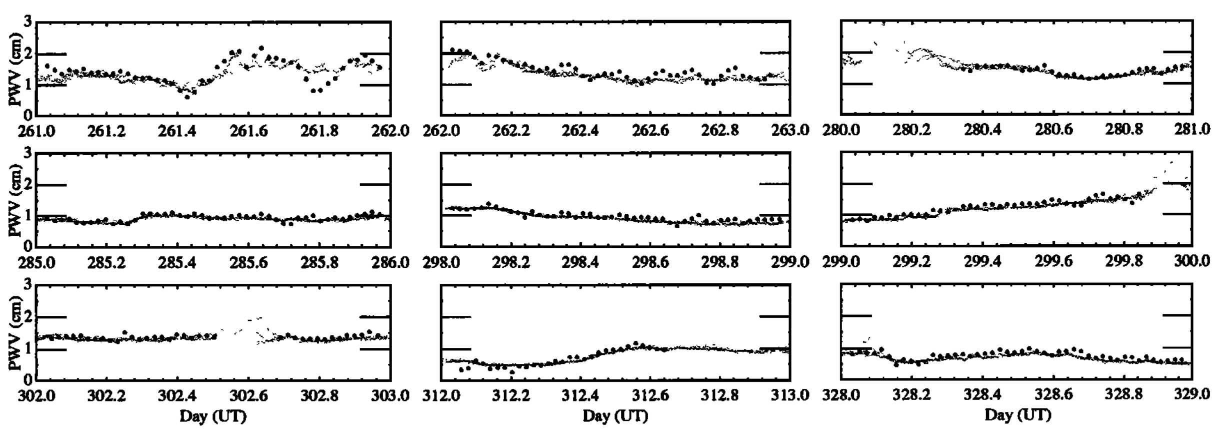

Fig. 2. Comparison of 30-minute pointed WVR and GPS sensed PWV for 9 example days. Small dots are pointed WVR data, circles are GPS estimates. Large scatter in the WVR measurements (i.e. day 280 or 302) is caused by strong azimuthal PWV variations, and is often accompanied by rain events. During rain, WVR data are not valid and were not used. However, GPS estimates of PWV are valid during rain.

Results

Comparison of typical WVR-measured and GPS-inferred PWV are shown in Figure 2. Table 1 summarizes the comparison between WVR data and GPS estimates for the entire experiment. Results computed with CODE orbits yield an overall rms difference between WVR and GPS PWV of 0.81 mm. Results are 0.85 mm for PGGA orbits and 1.00 mm for broadcast orbits.

If broadcast orbits are not significantly degraded in the future due to higher levels of S/A, broadcast orbit results may have value in weather forecasting since these orbits are continually transmitted by the GPS satellites. Precise orbits are currently available with a delay of one to two weeks.

Discussion of Errors

The comparison presented here is affected by: (a) the GPS errors due to orbit, multipath, and phase noise; and, (b) WVR errors at both ends of the baseline; and, (c) pressure sensor errors.

Orbit Errors. CODE and PGGA orbits have errors of 0.01 ppm or less. Thus they contribute no more than a 0.5 mm error in the horizontal components of the 50-km test baseline. GPS survey errors are 2 to 3 times larger in the vertical than in the horizontal. Thus, we attribute up to 1.5 mm to orbit errors. As a result of vertical dilution of precision [Spilker, 1980], GPS vertical baseline errors are typically 3 times as large as the tropospheric errors causing them. Following this argument, orbit errors contribute no more than 0.5 mm of the observed difference between GPS and WVR zenith wet delay (or less than 0.1 mm in PWV difference).

Multipath errors. These errors, caused by signal reflections from objects near the GPS antennas, are harder to quantify. We believe that multipath is a limiting error source in GPS sensing of PWV. Figure 3 shows 5 days of 30-minute differences between GPS-inferred and WVR-measured PWV. Error patterns repeating in sidereal time are typical for multipath errors [Georgiadou and Kleusberg, 1988]. Judging from the magnitude of the repeated patterns, multipath may be responsible for most of the 1 mm PWV differences.

Phase noise errors. We processed the ionosphere-corrected linear combination of the two GPS carriers [Spilker, 1980]. Phase noise of this linear combination is about 3 mm. Because of the large number of observations that are used for estimating each 30-minute zenith wet delay parameter (roughly 300 phase observations per 30 minutes, assuming 5 observed GPS satellites and a sampling rate of 30 seconds), the contribution of phase noise is negligible.

Table 1. GPS minus WVR estimated PWV at Boulder as computed with CODE, PGGA, and broadcast orbits. Results with bias and with bias removed are shown.

orbit	bias (mm)	rms with bias (mm)	rms no bias (mm)	hours of data
CODE	-0.39	0.81	0.66	613.5
PGGA	-0.42	0.85	0.70	416.5
Broadcast	-0.27	1.00	0.89	614.5

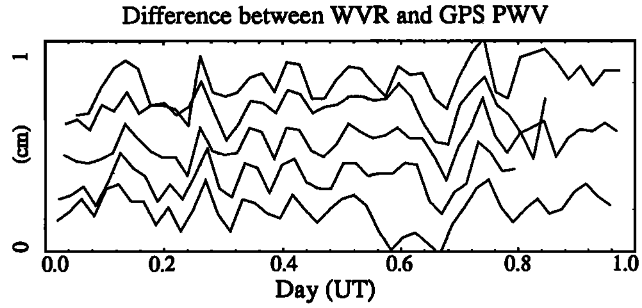

Fig. 3. 30-minute differences between WVR and GPS sensed PWV are shown from top to bottom for days 294, 295, 298, 299 and 306. Data are plotted in sidereal time and traces are arbitrarily offset. We attribute the coherence between the traces to GPS phase multipath.

WVR Errors. Side-by-side comparison of the two Radiometrics™ WVRs showed a 1.8 mm zenith wet delay bias due to instrumental calibration errors [Ware et al., 1993]. Thus, WVR errors contribute about 0.3 mm to the GPS-WVR PWV comparison error budget. Additional WVR errors result from the two assumptions that (a) the K-factor of "6.5" is correct, and, (b) the same retrieval coefficients apply to Boulder and Platteville. Our attempts to vary K as a function of surface temperature [Bevis et al., 1992] did not improve WVR-GPS agreement.

WVR data were not used during rain events because rain drops on the WVR window introduce unrealistically large delay corrections. We did, however, use data collected during times with large azimuthal wet delay variations. The Bernese software assumes that the atmosphere is azimuthally homogenous. This contributes to the discrepancy between GPS and WVR results.

Pressure Sensor Errors. Barometric pressure measurement errors affect the GPS-WVR comparison because dry delay errors will be absorbed in the GPS wet delay estimates. A pressure error of 1 mb causes a 2 mm zenith wet delay error. We estimate 1 mb calibration uncertainty in the pressure sensors at our sites. Pressure errors can therefore cause as much as a 3 mm error in zenith wet delay (0.5 mm PWV). We believe this may cause much of the bias in Table 1.

To summarize our error discussion, we expect that multipath is a major contributor to short-period variations in the GPS-WVR PWV results. We attribute the 0.4 mm bias to pressure sensor (0.5 mm) and WVR (0.3 mm) calibration errors.

Discussion and Conclusion

We have shown that GPS can be used to determine PWV with sub-mm accuracy. In this study, PWV was estimated relative to a WVR reference site at a distance of 50 km. Results with broadcast orbits indicate that PWV can be determined with GPS in near real time to 1 mm for this 50-km baseline. Data simulations indicate that one WVR within a PWV-monitoring GPS network is required for 1-mm PWV estimation at outlying sites. Absolute PWV estimation without the aid of a WVR may be achieved using an outlying GPS site at a distance of 500 km or more. Estimation over such large distances, using only GPS without the aid of a reference WVR, requires high quality GPS satellite orbits.

We recommend a configuration where one WVR plus a GPS receiver operate in the PWV-monitoring GPS network.

Errors of this WVR will affect GPS PWV estimation at all points of the network, and thus, careful calibration of the reference WVR is of great importance. WVR retrieval coefficients must be known only for the WVR location. GPS estimation of PWV and wet delay is insensitive to retrieval coefficients or rain at outlying sites.

In this study, we used retrieval coefficients calculated from Denver radiosonde observations. A new zenith delay parameter was estimated every 30 minutes. Geodetic coordinates of the Boulder site were estimated simultaneously with the zenith delay. Because we used C/A code GPS receivers, only 90% of the carrier-phase cycle ambiguities were resolved for the 50 km baseline [Blewitt, 1989]. With newly available P-code receivers, we expect to be able to resolve all phase ambiguities.

We believe that the results presented in this study, while very promising, can be improved if we use P-code GPS receivers and improved barometers, reduce site multipath, and optimize GPS software for tropospheric parameter estimation.

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