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POINTED WATER VAPOR RADIOMETER CORRECTIONS FOR ACCURATE GLOBAL POSITIONING SYSTEM SURVEYING

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Abstract. Delay of the Global Positioning System (GPS) signal due to atmospheric water vapor is a major source of error in GPS surveying. Improved vertical accuracy is important for sea level and polar isostasy measurements, geodesy, normal fault motion, subsidence, earthquake studies, air and ground-based gravimetry, ice dynamics, and volcanology. We conducted a GPS survey using water vapor radiometers (WVRs) pointed toward GPS satellites to correct for azimuthal variations in water vapor. We report 2.6 mm vertical precision on a 50-km baseline for 19 solution days. Kalman filter or least-square corrections to the same data do not account for azimuthal distribution of water vapor and are degraded by 70%.

Introduction

Correction for signal delay caused by atmospheric water vapor can improve precision in GPS surveys. Wet delay errors appear to dominate in regional surveys when precise orbits and high-accuracy analysis methods are applied. The most direct, and potentially the most accurate, method for correction of wet delay uses WVRs pointed to each GPS satellite individually, giving the wet correction for each. When this is done, no assumptions about the structure of atmospheric water vapor, such as azimuthal symmetry, are needed in processing the GPS data.

Ware et al [1986] reported 12 mm vertical precision on a 22-km baseline for three days of pointed WVR-corrected GPS surveys. More recently, Tralli et al [1988], Davis et al [1989], Dixon and Kornreich Wolf [1990], Tralli and Lichten [1990], Dixon et al [1991], Lindqwister et al [1991], Bock et al [1993], and Blewitt et al [1993], reported zenith WVR, surface meteorological, Kalman filter, and least-squares wet delay corrections. Vertical precision was 10 mm or more for baselines ranging from several km to nearly 2000 km.

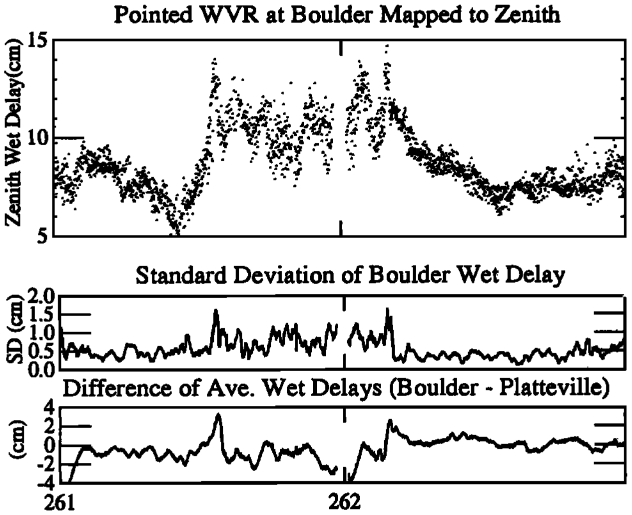
Vertical repeatability, or precision, in these prior studies did not depend on baseline length, indicating that wet delay error was larger than orbit error. Kalman and least-squares results were typically better than zenith WVR results. Combinations of corrections, such as zenith WVR plus Kalman, yielded repeatabilities that were in general worse, and at best equivalent, to Kalman alone. In our study, the combined methods also degraded repeatability. We feel that this weakening of the solution most likely results from estimating too many parameters which are not sufficiently independent in modelling the propagation of the GPS signal.

The discrepancy between our findings using pointed WVR data and studies using zenith WVR data suggest that azimuthal variations in wet delay are significant. An additional reason for the discrepancy between our findings and prior studies may be WVR stability and calibration. Tralli et al [1992] reported that VLBI and GPS estimated zenith wet delays can be biased from WVR-measured wet delays by as much as 2 cm. Rocken et al [1991a] reported up to 3-cm bias among wet delays measured by four different types of WVRs. Similar WVR bias has been seen by Elgered et al [1991] and Kuehn et al [1991]. Using the same data set reported here, however, Rocken et al [1993] report GPS sensing of atmospheric water vapor with sub-mm agreement between GPS-estimated and WVR-measured water vapor. This suggests that WVR bias may have degraded prior results.

Experiment Description

We occupied two sites separated by 50 km at Boulder and Platteville Colorado during fall 1992. This region has a relatively dry, but variable, climate. The wet delay in this location has been seen to vary from 5 cm to nearly 15 cm in only a few hours.

Trimble^{TM} 4000-SST 8-channel dual-frequency phase and C/A code receivers observed at 30-second intervals all GPS satellites with elevation angles above 15 degrees. Radiometrics^{TM} WVRs pointed sequentially to each satellite, taking 8 minutes to observe a typical group of five satellites. Pressure, temperature, and other surface meteorological data were recorded at each site. Typical WVR data are shown in Figure 1.


Pointed WVR at Boulder Mapped to Zenith

Standard Deviation of Boulder Wet Delay

Difference of Ave. Wet Delays (Boulder - Platteville)

Fig. 1. Pointed WVR data for Julian days 261-262 (UT). Azimuthal variation in wet delay is indicated by scatter in the pointed WVR data. The standard deviation reflects this scatter, not the error, of the pointed WVR-measured wet delay.

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Data Analysis

We used modified Bernese software [Beutler et al, 1987], including Kalman and least-squares atmospheric delay estimation options. The Bernese software is designed for high-accuracy geodetic work and GPS orbit improvements. CODE [Beutler et al, 1993] precision orbits were used.

GPS phase data from Boulder and Platteville were combined in single differences. Single differences are the phase difference from one satellite received at two sites. They are formed to eliminate satellite clock errors, in particular, errors due to clock dithering [Rocken and Meertens, 1991b]. The single differences were pre-processed to fix carrier cycle slips. Phase ambiguities were successfully determined in 90% of the solutions. We computed Boulder coordinates, holding Platteville fixed, and applied pointed WVR, zenith WVR, Kalman, hourly least-square, and model [Saastamoinen, 1972] corrections.

The zenith WVR correction is included to demonstrate the effect when azimuthal wet delay asymmetries are not corrected using pointed WVR data. It should be noted, however, that it is not data taken in the zenith direction, but is obtained by averaging the pointed data taken over a 20-minute window centered on the time of the GPS data to which the correction is applied.

We calculated dry delays (resulting from atmospheric constituents other than water vapor) using the Saastamoinen model. The WVR-corrected results include dry delay correction based on Boulder and Platteville surface pressure data. The model results are based on constant total (dry and wet) atmospheric delay, depending on site altitude and assuming 15 C surface temperature and 50% humidity. They are presented as an indication of uncorrected atmospheric error for this particular data set.

We used the least-squares option to estimate a hourly zenith delay correction to the model, effectively giving a variable total delay. The Kalman option models the total delay as a random walk stochastic process, giving a correction to the constant model delay on 30-second intervals. We used a power spectral density of 4 x 10^{-8} m^2/s. Rothacher [1992] describes this option in greater detail.

It rained for varying, but typically short, periods on 8 of the 19 solution days. WVR data collected during rainy periods when liquid water was present on the WVR windows were inaccurate and wet delays during short rainy periods were interpolated.

Results and Discussion

Vertical precision, weighted by formal GPS solution errors, and offsets are shown in Figure 2 and are listed in Table 1. Offsets are relative to the pointed WVR solution, but it should be noted that this choice of reference is arbitrary. Each solution-day included at least 20 hours of data.

Pointed WVR solution precision is 2.6 mm rms. Precision of solutions not using pointed WVR data is degraded by 70% or more. In particular, the zenith-mapped WVR solution is degraded by over 100%, indicating that azimuthal variations in wet delay significantly degrade precision.

North and east results are listed in Table 2. All of the correction methods gave horizontal results that agree within their respective rms errors. However, offsets as large as 0.8 mm between pointed WVR and Kalman or least-squares results are seen. Note that the precision in the east-west solution is degraded by 65% when pointed WVR data are not used. This result may be attributed to atmospheric water vapor distributions that are corrected using pointed WVR data.

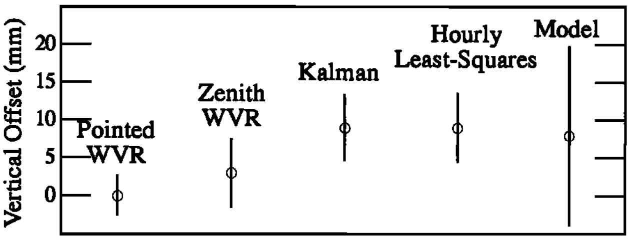

Fig. 2. Boulder-Platteville vertical offsets and repeatability. The offset is arbitrarily chosen relative to the pointed WVR solution.

Error Discussion

The precision and accuracy of pointed WVR-corrected GPS surveys are influenced by WVR calibration and stability, WVR retrieval coefficients, GPS orbits, multipath, receiver drift, and pressure sensors.

WVR Calibration and Stability. The Radiometrics™ WVRs observe sky brightness temperatures at 23.8 and 31.4 GHz which are converted into wet delay. The WVRs are calibrated using tipping curve measurements [Elgered, 1993], an ambient blackbody target, and a noise diode. Tipping curves were performed twice daily during data acquisition, taking sky brightness measurements at elevation angles of 45, 60, and 90 degrees in the east, north, west, and south directions. Tipping curves that were not sufficiently linear were ignored.

Table 1: Vertical precision, and offsets from the pointed WVR solution.

Solution Method	RMS Precision (mm)	Offset (mm)
Pointed WVR	2.6	0
Zenith WVR	5.4	3.1
Kalman	4.4	9.7
Hourly Least-Squares	4.6	9.2
Model	11.8	8.4

Table 2: North and east precision, and offsets from pointed WVR solutions.

Solution Method	RMS Precision (mm)		Offset (mm)	
	North	East	North	East
Pointed WVR	1.5	0.6	0	0
Zenith WVR	1.5	1.4	-0.1	-0.9
Kalman	1.4	1.0	0.8	0.5
Hourly Least-Squares	1.4	1.0	0.8	0.5
Model	1.3	1.1	0.9	0.5

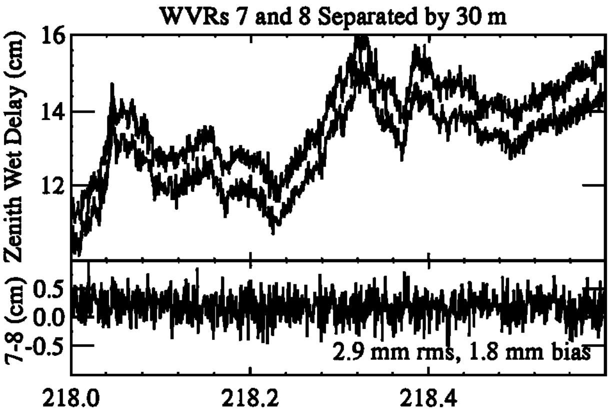

Fig. 3. Zenith wet delay observations by the two Radiometrics™ WVRs used at Boulder and Platteville, separated by 30 m. The trace for WVR 8 is shifted upward by 1 cm to show detail. The difference of the two is shown in the lower plot.

Additional calibration of one of the WVRs using a liquid nitrogen target showed 0.3 K accuracy in brightness temperature. Furthermore, simultaneous zenith wet delay observations for over 12 hours in Boulder by the two WVRs separated by 30 m showed an rms difference of 2.9 mm with a relative bias of 1.8 mm. Data from this comparison are shown in Figure 3.

We expect the high frequency variations to average out and we attribute the relative bias to calibration error. The combined calibration error for the two WVRs is therefore less than 0.4 K, or 2 mm in wet delay. Multiplying by three to account for vertical dilution of precision [Spilker, 1978], the vertical error from WVR calibration is less than 6 mm.

Retrieval Coefficients. WVR measurements of sky brightness temperatures are converted to wet delay using retrieval coefficients which, in general, depend on the integrated atmospheric water vapor and cloud cover [Elgered, 1993]. We generated constant retrieval coefficients using Denver radiosonde data and a program, which we modified, developed at JPL by S. Keihm. We investigated the effects of site dependent retrieval coefficients for Boulder and Platteville and found that retrieval coefficient variability tended to cancel since we are differencing between the two sites.

GPS Orbits. CODE orbits are typically accurate to 0.01 ppm. Thus, orbit uncertainty would contribute no more than 0.5 mm error to our 50-km horizontal baseline components. Vertical components are usually degraded by a factor of two to three compared to horizontal. Therefore, orbit uncertainty contributes no more than 1.5 mm to our vertical precision.

Multipath. Multipath error is caused by reflections from objects near the GPS antenna and can be amplified when satellite geometry is weak [Genrich and Bock, 1992]. Multipath is reduced by averaging [Georgiadou and Kleusberg, 1987]. We estimate that multipath errors contribute less than 1 mm for the daily solutions presented here.

Receiver Drift. Receiver phase noise is insignificant after averaging. However, errors related to receiver drift may be significant. Our preliminary laboratory tests using a single GPS antenna connected to two receivers suggest that the vertical solution may depend on changes in the temperature difference between the two receivers. Since the Boulder receiver was located in an air conditioned building and the Platteville receiver was located in a shed with no air conditioning, diurnal changes in the temperature difference of the two receivers may have been 20 C or more. We estimate that this error contributes 1.5 mm or less to vertical precision and bias.

Pressure Sensors. We estimate calibration uncertainty of 1 mb for the Boulder and Platteville pressure sensors. Combining the two as independent errors gives 1.4 mb, which converts to 8 mm vertical bias (vertical dilution of precision of three included).

The sum of all our estimated variable errors is 2.3 mm, including GPS orbits (1.5 mm), multipath (1 mm), and receiver drift (1.5 mm). The bias between our various vertical solutions is as large as 10 mm. We attribute most of the bias to 8 mm pressure sensor calibrations uncertainty, and the remainder to WVR calibration (6 mm), orbits (1.5 mm), and receiver drift (1.5 mm).

Conclusions

We have demonstrated 2.6 mm vertical precision for a 50-km baseline measurement using GPS with pointed WVR corrections. Kalman and least-square corrections to the same data do not account for azimuthal distribution of water vapor and are degraded by 70%. Pointed WVRs provide the most direct and potentially the most accurate wet delay correction method. Further improvements in the precision and accuracy of pointed WVR corrected GPS surveys may be possible using improved pressure sensors, receiver drift stabilization or correction, P-code receivers to improve ambiguity resolution, and more accurate GPS orbits.

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