

GPS Meteorology: Direct Estimation of the Absolute Value of Precipitable Water

JINGPING DUAN AND MICHAEL BEVIS

Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, Hawaii

PENG FANG AND YEHUDA BOCK

Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California

STEVEN CHISWELL AND STEVEN BUSINGER

Department of Meteorology, University of Hawaii, Honolulu, Hawaii

CHRISTIAN ROCKEN, FREDERICK SOLHEIM, TERESA VAN HOVE, AND RANDOLPH WARE

University NAVSTAR Consortium (UNAVCO), Boulder, Colorado

SIMON MCCLUSKY, THOMAS A. HERRING, AND ROBERT W. KING

Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Manuscript received 24 April 1995, in final form 18 October 1995)

ABSTRACT

A simple approach to estimating vertically integrated atmospheric water vapor, or precipitable water, from Global Positioning System (GPS) radio signals collected by a regional network of ground-based geodetic GPS receivers is illustrated and validated. Standard space geodetic methods are used to estimate the zenith delay caused by the neutral atmosphere, and surface pressure measurements are used to compute the hydrostatic (or "dry") component of this delay. The zenith hydrostatic delay is subtracted from the zenith neutral delay to determine the zenith wet delay, which is then transformed into an estimate of precipitable water. By incorporating a few remote global tracking stations (and thus long baselines) into the geodetic analysis of a regional GPS network, it is possible to resolve the absolute (not merely the relative) value of the zenith neutral delay at each station in the augmented network. This approach eliminates any need for external comparisons with water vapor radiometer observations and delivers a pure GPS solution for precipitable water. Since the neutral delay is decomposed into its hydrostatic and wet components after the geodetic inversion, the geodetic analysis is not complicated by the fact that some GPS stations are equipped with barometers and some are not. This approach is taken to reduce observations collected in the field experiment GPS/STORM and recover precipitable water with an rms error of 1.0–1.5 mm.

1. Introduction

Water vapor plays a crucial role in a variety of atmospheric processes that act over a wide range of spatial and temporal scales. It is widely appreciated that improved monitoring of atmospheric water vapor will lead to more accurate forecasts of precipitation and severe weather and to a better understanding of climate and climate change. Emerging networks of continuously operating Global Positioning System (GPS) receivers invite a new and powerful approach to the re-

mote sensing of atmospheric water vapor (Bevis et al. 1992). The GPS consists of a constellation of satellites that transmit L-band radio signals to large numbers of users engaged in navigation, time transfer, and relative positioning (Hoffman-Wellenhof et al. 1993). These signals are delayed by atmospheric water vapor as they propagate from GPS satellites to ground-based GPS receivers. This "wet delay" is nearly proportional to the quantity of water vapor integrated along the signal path (Hogg et al. 1981; Askne and Nordius 1987). An estimate of the zenith wet delay (the wet delay in the vertical direction) can be transformed with very little additional uncertainty into an estimate of precipitable water (PW) (e.g., Bevis et al. 1994), which is the total quantity of water vapor overlying a point on the earth's surface expressed as the height of an equivalent column of liquid water.

Corresponding author address: Dr. Michael Bevis, School of Ocean and Earth Science Technology, University of Hawaii, 2525 Correa Rd., Honolulu, HI 96822.
E-mail: bevis@soest.hawaii.edu

A small-scale demonstration of GPS meteorology was performed in late 1992 (Rocken et al. 1993). A second and much larger demonstration experiment, named GPS/STORM, was conducted in May 1993. This experiment was analyzed by Rocken et al. (1995) and is reanalyzed here using a different approach. The rapidity with which this meteorological application has been developing reflects the fact that most of the critical algorithms had already been developed by GPS geodesists. The GPS geodesists in turn had learned a great deal about characterizing atmospheric signal delays from geodesists and astronomers engaged in very long baseline interferometry (VLBI), most of whom made extensive use of water vapor radiometers (WVRs) (e.g., Resch 1984; Elgered et al. 1991). GPS meteorology requires no major hardware innovations. All that is necessary to render a geodetic GPS station useful for meteorology is to record surface pressure and temperature. The recovery of PW estimates from a GPS network can be viewed as postprocessing of a more or less conventional geodetic analysis. Rocken et al. (1995) and this paper demonstrate that GPS meteorology has already developed to the point that it yields PW estimates of immediate meteorological utility.

Rocken et al. (1993, 1995) obtained their best results by using GPS to estimate the relative values of PW among the GPS stations and using a WVR to measure the absolute value of PW at a reference station, thereby determining the correction necessary to transform relative PW estimates into absolute PW estimates at every station in the network. Our emphasis is on estimating the absolute value of PW directly without incorporating WVR observations in the reduction of the GPS observations. Our immediate goal is to show that it is possible to obtain a pure GPS solution for PW with accuracy at least as good as that obtained previously with the hybrid GPS-WVR technique.

For a general overview of GPS meteorology and its geodetic heritage see Bevis et al. (1992). In this paper we review only those concepts central to our theme of estimating absolute rather than relative PW. Table 1 is provided for the reader's convenience.

2. Geodetic modeling of neutral atmospheric delay

In GPS geodesy the relative positions of GPS satellites and GPS receivers are gauged either by timing the flight of radio signals (codes) that propagate from satellites to receivers or, over an extended period of time, by modeling the phase history of the associated carrier waves (e.g., Hoffman-Wellenhop et al. 1993). Both measurements are complicated by the presence of the earth's atmosphere. One of the tasks of geodetic GPS processing software is to model or calibrate these propagation effects. Atmospheric delays are caused by the ionosphere and by the neutral atmosphere. The ionospheric delay is dispersive (frequency dependent) and can be determined by observing both of the frequencies

TABLE 1. Abbreviations and symbols used in this paper.

Quantity	Abbreviation	Symbol
Zenith wet delay	ZWD	Z_w
Zenith hydrostatic delay	ZHD	Z_h
Zenith neutral delay	ZND	Z_n
Zenith delay (nonspecific)	Z	Z
Satellite elevation angle		θ
Wet mapping function		$m_w(\theta)$
Hydrostatic mapping function		$m_h(\theta)$
Neutral mapping function		$m_n(\theta)$
Mapping function (nonspecific)		$m(\theta)$
Precipitable water	PW	PW

transmitted by GPS satellites (L1 at 1.575 GHz and L2 at 1.228 GHz) and exploiting the known dispersion relations for the ionosphere (e.g., Spilker 1980). Ionospheric delays affecting observations recorded by a dual frequency GPS receiver can be eliminated without reference to observations recorded by other GPS receivers in the same network. The delay due to the neutral atmosphere, which we shall refer to as the neutral delay, is not dispersive and cannot be estimated or calibrated in this way. It is possible, however, to parameterize the neutral delays affecting each station in a network of GPS receivers and to estimate these parameters jointly as part of the overall geodetic inversion for the relative geometry of the network and the precise orbits of the satellites (e.g., Hoffman-Wellenhop et al. 1993).

The neutral delay accumulated along a path through the atmosphere is smallest when the path is oriented in the zenith direction. For slanted paths the delay increases approximately inversely with the sine of the elevation angle. GPS and VLBI analysts typically model the delay along a path of arbitrary orientation as the product of the zenith delay and a "mapping function," which describes the dependence on path orientation. These functions can take into account the curvature of the earth and are dependent primarily on the profile of temperature and water vapor through the troposphere, effects that become important at the low elevation angles ($\sim 5^\circ$) used for VLBI observations (see Davis et al. 1985). Unlike the large, highly directional antennas used for VLBI, GPS antennas are small and omnidirectional, making them susceptible to ground reflections (multipathing) at low elevations. Hence, most analysts process only those observations collected from satellites with elevation angles greater than 15° . Above 15° , and with an azimuthally symmetric atmosphere, the mapping function can be represented as a function only of elevation angle. The simplest atmospheric delay models have the form

$$D = Zm(\theta), \tag{1}$$

where D is the delay accumulated along the signal path with elevation angle θ , Z is the zenith delay, $m(\theta)$ is

the mapping function, and $m(\theta) \approx \csc(\theta)$. For this class of models, a particular mapping function is adopted a priori and signal delays are totally specified by the (time varying) zenith delay parameter. GPS data processing software allows the analyst to introduce zenith delay parameters for each station in a GPS network and estimate these "nuisance" parameters along with parameters of geodetic interest. The physical basis for estimating the zenith delay parameter Z is that a GPS receiver is typically tracking 4–8 GPS satellites simultaneously and so senses the value of D for multiple values of θ , thus overdetermining the value of Z . The simplest approach for retrieving the zenith delay from GPS data is to assume that it remains constant for one or more time intervals, and to estimate these values more or less independently. A more sophisticated approach utilizes the fact that the temporal variation of the zenith delay has exploitable statistical properties. The zenith delay is unlikely to change by a large amount over a short period of time (e.g., 10 min). In fact, the zenith delay can be viewed as a stochastic process, and the process parameters can be estimated using a Kalman filter, or a related class of optimal filters based on the state-space, time-domain formulation (Treuhaft and Lanyi 1987; Lichten and Border 1987; Tralli et al. 1988; Dixon and Kornreich Wolf 1990; Herring et al. 1990). In our analysis we adopt a hybrid approach, using a batch least squares estimator but parameterizing the zenith delay by a linear spline with knots at 30-min intervals. By treating the knots as a Gauss–Markov process, we are able to gain most of the advantages of a sequential estimator with less computational burden.

The delay due to the neutral atmosphere can be decomposed into the "hydrostatic delay" associated with the induced dipole moment of the atmosphere and the "wet delay" associated with the permanent dipole moment of water vapor (Saastamoinen 1972; Davis et al. 1985). The zenith hydrostatic delay (ZHD) has a typical magnitude of about 2.3 m at sea level. (We follow the usual practice of stating delays in terms of the equivalent excess pathlengths.) Given surface pressure measurements accurate to 0.3 mb or better, it is usually possible to predict the ZHD to better than 1 mm (Elgered et al. 1991). The zenith wet delay (ZWD) can vary from a few millimeters in very arid conditions to more than 350 mm in very humid conditions. It is not possible to predict the wet delay with any useful degree of accuracy from surface measurements of pressure, temperature, and humidity. It is possible to estimate the wet delay using ground-based WVRs (Resch 1984; Tralli et al. 1988; Elgered et al. 1991; Dixon and Kornreich Wolf 1990). Given the expense of WVRs and the difficulty of calibrating them with sufficient accuracy, most geodesists prefer either to estimate the neutral delay from the GPS observations or to measure the hydrostatic component of the neutral delay, using barometers, and estimate the remaining wet delay during in-

version of the GPS observations. One advantage of decomposing the neutral delay in this way is that it enables the delay models to incorporate separate hydrostatic and wet mapping functions, thereby taking better account of the differing scale heights of the wet and hydrostatic components of the neutral atmosphere. In this case, Eq. (1) is generalized thus

$$D = Z_w m_w(\theta) + Z_h m_h(\theta), \quad (2)$$

where Z_w is the ZWD, Z_h is the ZHD, $m_w(\theta)$ is the wet mapping function, and $m_h(\theta)$ is the hydrostatic mapping function. This approach is highly advantageous in the context of VLBI, in which radio sources are tracked to elevation angles as low as 5°. Above 15°, however, the wet and dry mapping functions differ only very slightly, and it is reasonable to lump the wet and hydrostatic delays together and use a single mapping function, thereby parameterizing the problem solely in terms of the zenith neutral delay (ZND) (Tralli and Lichten 1990). Thus,

$$D = Z_n m_n(\theta), \quad (3)$$

where $m_n(\theta)$ is the neutral mapping function, and the ZND (Z_n) is simply

$$Z_n = Z_w + Z_h. \quad (4)$$

We adopt this approach. Once the ZND parameters have been estimated during the geodetic inversion, it is possible to estimate the ZWD by subtracting the ZHD from the ZND—that is, $Z_w = Z_n - Z_h$, where the ZHD is derived from surface pressure readings.

3. Transforming wet delay parameters into precipitable water estimates

Having estimated the ZWD history at a given GPS receiver, it is possible to transform this time series into an estimate of the PW (Bevis et al. 1994) using the relationship

$$PW = \Pi Z_w, \quad (5)$$

where the constant of proportionality Π is a function of various physical constants and a weighted "mean temperature" of the atmosphere defined (Davis et al. 1985) by

$$T_m = \frac{\int (P_v/T) dz}{\int (P_v/T^2) dz}, \quad (6)$$

where P_v is the partial pressure of water vapor, T is temperature, and the integrations occur along a vertical path through the atmosphere. The time-varying parameter T_m can be estimated using measurements of surface temperature (Bevis et al. 1992) or numerical weather models (Bevis et al. 1994) with such accuracy that very

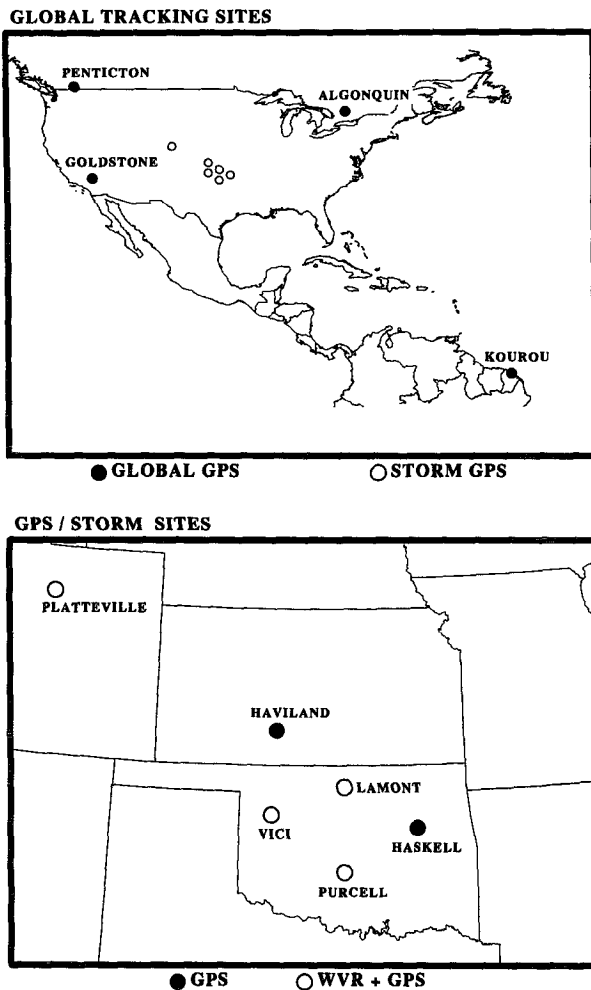


FIG. 1. (top) Regional map showing the six stations of the field experiment GPS/STORM and four outlying global GPS tracking sites used in subsequent data analysis to introduce long baselines into the network. (bottom) Detailed site map for the field experiment GPS/STORM. Dual frequency geodetic GPS receivers were set up at four sites in Oklahoma and one in Kansas, and GPS observations were obtained in addition from a permanent station in Platteville, Colorado. At four of these sites water vapor radiometer (WVR) observations were collected in the immediate vicinity of the GPS receivers. The WVRs at Lamont and Platteville were part of a permanent installation, while those at Purcell and Vici were deployed for the experiment. All six GPS receivers were Trimble 4000 SSE dual-frequency P-code systems. The WVR at Platteville was constructed and is maintained by the Wave Propagation Laboratory in Boulder, Colorado. The other WVRs were commercial instruments manufactured by Radiometrics, Inc. of Boulder, Colorado. Precise barometers were located at each of the six sites.

little noise is introduced during the transformation [Eq. (5)]. That is, the uncertainty in the PW estimate derives almost entirely from the uncertainty in the earlier estimate of ZWD.

The transformation of ZWD into PW [Eq. (5)] assumes that the wet delay is entirely due to water vapor and that liquid water and ice do not contribute signifi-

cantly to the wet delay. Largely theoretical arguments indicate that thick, dense clouds could cause delays as large as 7.5 mm, leading to an error of 1 mm in our estimates of PW (Elgered 1993). Similar arguments indicate that the delay associated with liquid water in the form of raindrops is smaller and can be disregarded altogether. Large quantities of wet snow in the air column may prove problematic (J. Davis 1995, personal communication), though this situation occurs only infrequently.

4. Sensitivity to absolute versus relative zenith delay

For GPS networks with interstation spacings of less than several hundred kilometers, a significant problem is encountered in retrieving PW histories from GPS observations. The ZND or ZWD parameters inferred across the network contain large but highly correlated errors (Rothacher 1992; Rocken et al. 1993). The problem arises because receivers at each end of a short baseline observe satellites at similar elevation angles. Consider the difference in the delays (ΔD) associated with GPS signals propagating from a single GPS satellite to two GPS receivers (i and j):

$$\Delta D = Z_i m(\theta_i) - Z_j m(\theta_j), \quad (7)$$

where Z_i and Z_j are the zenith delays at receivers i and j , $m(\theta)$ is the mapping function, and θ_i and θ_j are the elevation angles of the satellite as viewed from receivers i and j . Clearly, as stations i and j get closer together

$$\Delta D \rightarrow (Z_i - Z_j)m(\theta_i), \text{ as } \theta_j \rightarrow \theta_i, \quad (8)$$

and the differential delay is sensitive only to the differential or relative zenith delay, not to the absolute values of the zenith delays Z_i and Z_j .

In this case, one may infer relative ZWD or PW values across the network but not the absolute values. Rocken et al. (1993) solved this problem by recognizing that the PW solutions obtained at each epoch are correct except for an unknown bias that is common to all stations. This bias can be determined at one site by using a collocated WVR to provide an absolute estimate of PW, and the bias can then be removed from the PW estimates at every other station in the GPS network. This technique has become known as "WVR-levering." (GPS-derived PW values are "levered up the PW axis" until the value at a reference station matches that obtained using a collocated WVR.)

We demonstrate here the alternate, pure GPS approach not requiring WVR observations. (This approach was originally advocated by Bevis et al. (1992) on the basis of the previously demonstrated ability of VLBI and GPS geodesists to resolve the absolute values of atmospheric delay parameters.) Remote stations (more than 500 km distant) are included in the geodetic inversion, so that the absolute (and not just relative) values of the ZWD parameters can be estimated directly. Continuously operating GPS stations of the

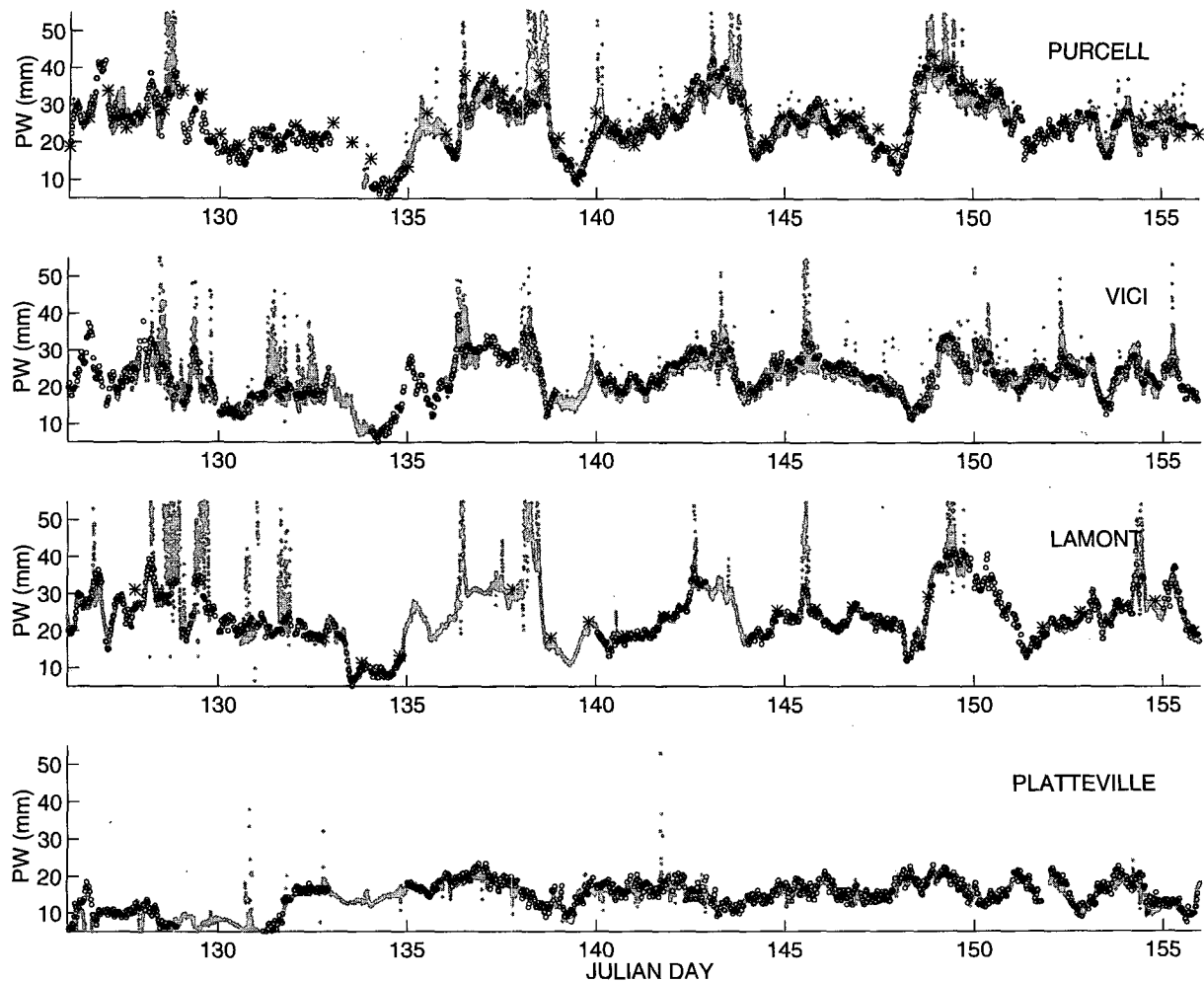


FIG. 2. A comparison of GPS (open circles) and WVR (small gray dots) estimates of PW at four stations in the GPS/STORM network for the entire 30-day period of the experiment. The GPS estimates are knots at 30-min intervals, in a linear spline representing PW over the span of observations. The WVR PW estimates (from Rocken et al. 1995) represent line of sight estimates, acquired at 1–2-min intervals, at various elevations and azimuths, and mapped to the zenith direction. See Fig. 1 for the locations of the sites.

global GPS tracking network can be used for this purpose. To implement this approach we depart from our previous practice (Rocken et al. 1993, 1995) of decomposing the neutral delays in the model used during geodetic inversion so as to estimate the ZWD histories directly. Since precise surface pressure measurements are not available for most global tracking sites, it is not possible to determine the hydrostatic delays at these sites. Accordingly we estimate neutral delays at all stations in the network and then subtract off the hydrostatic delays subsequently for those sites that are equipped with precise barometers.

5. Results from GPS/STORM

GPS/STORM observations were collected at six stations in Oklahoma, Kansas, and Colorado (Fig. 1) for 22 h a day over a 30-day period in May 1993. Water

vapor radiometers (WVRs) were available at four of these sites, and precisely calibrated barometers at all six. The analysis of the WVR observations is described in Rocken et al. (1995).

We analyzed the GPS data from GPS/STORM using the software package GAMIT (King and Bock 1994). To introduce long baselines (large elevation angle differences), we incorporated data from four stations in North and South America (Fig. 1). In our analysis we combined our 10-station daily solutions with similar solutions generated for 32 globally distributed stations at the Scripps Orbit and Permanent Array Facility (Bock et al. 1992), using the techniques discussed in Feigl et al. (1993). This step provided precise (sub-centimeter) geocentric positions for the six GPS/STORM stations with respect to the International Terrestrial Reference Frame, realized by the positions of the global tracking stations (Boucher et al. 1993). The

daily GAMIT solutions were then repeated, tightly constraining the positions of all ten stations. We modeled the neutral delay using ZND parameters at 30-min intervals with the Gauss–Markov constraints on the ZND parameters set sufficiently loose that the constraints had little effect on the estimates. Finally, we recovered ZWD histories for the six GPS/STORM sites by subtracting the ZHD computed from surface pressure, and used Eq. (5) to convert these to PW.

Figure 2 and Table 2 show the comparison between GPS-derived PW and WVR-derived PW estimates during the 30-day experiment for the four stations with collocated instruments. The root-mean-square differences between the two sets of estimates vary between 1.15 and 1.45 mm, slightly better than those previously obtained by Rocken et al. (1995) using the WVR lever. The biases between the series are negligible. Figures 3 and 4 show with finer resolution the comparison for station Purcell over a representative 14-day period. The brief periods of extremely high scatter in the WVR PW estimates are caused by wetting of the WVR’s window by rainfall or dew, which renders the PW estimates meaningless. Except for the rain spikes, the differences between the GPS and WVR estimates (Fig. 4) show no strong temporal patterns that might indicate systematic errors in either set of measurements. Also shown in Fig. 3 are PW estimates derived twice daily from a radiosonde. We attribute the relatively large differences between the radiosonde estimates and those derived from GPS and WVRs to the distance between the balloon launch point and the GPS–WVR station (28 km) and to the downwind drift of the ascending radiosonde.

6. Discussion

Figures 3 and 4 illustrate a significant advantage of estimating PW from GPS observations without using collocated WVRs in the GPS analysis. The measurements of PW provided by WVRs are virtually useless during brief but not rare episodes in which these instruments are wetted by rainfall or heavy dew. This shortcoming of WVRs greatly complicates their use as external reference systems for solving time-varying biases associated with relative PW solutions. The pure GPS approach demonstrated here is more robust as well as simpler to implement than the hybrid GPS–WVR approach.

Although it is preferable that WVRs are not used in the derivation of PW from GPS observations, WVR observations remain very useful in that they provide a basis for external comparison. During our first attempts to process the GPS/STORM data we found that the WVR PW and GPS PW time series tracked each other nicely but were offset by several millimeters. This led us to discover a small but significant bug in the mapping function module with GAMIT. On fixing this error in the code, the bias between the WVR and GPS time series disappeared. If GPS networks analyzed for PW

TABLE 2. The weighted rms difference between PW solutions derived from GPS and PW solutions derived from WVR observations, for all stations in the GPS/STORM network with collocated GPS receivers and WVRs. The weighting procedure was designed to accommodate the difference in the intervals of the WVR (1–2 min) and GPS (30 min) estimates, and to manage objectively the problem of wildly varying and physically meaningless WVR estimates during brief periods in which a WVR was wetted by rainfall or by dew (Fig. 3). We fit the WVR estimates to a linear spline with knots coincident with the knots of the GPS spline. We then assigned to each smoothed WVR value an uncertainty equal to the rms scatter (about the linear spline) of the original WVR estimates within 15 min of the epoch of the knot. These uncertainties were used to weight the comparison between the GPS and WVR estimates for PW. Also shown are the weighted mean differences, or biases, which are very small.

Station name	Weighted rms difference GPS PW vs WVR PW (mm)	Bias (mm)	Number of paired observations used
Vici	1.15	0.10	1003
Platteville	1.26	0.00	1143
Purcell	1.30	0.01	868
Lamont	1.45	0.13	851

contain at least one station with a collocated WVR, the comparison between the WVR and GPS time series at that station could provide a basis for controlling the quality of the network solution. This would be particularly attractive in a nearly real-time setting.

During the geodetic analysis of a GPS network, it is possible to estimate the total neutral delay affecting each station, or, if surface pressure measurements are available, to strip off the hydrostatic component and estimate only the remaining wet component of delay. To optimize PW retrievals from relatively small regional networks like GPS/STORM, it is desirable to incorporate a few distant global tracking stations in order to introduce some very long baselines. The geodetic analysis of such augmented networks is most conveniently framed in terms of the neutral delay, since most global tracking stations are not equipped with barometers. Accordingly, we have chosen to estimate neutral delay at all stations, whether or not they are equipped with barometers, and subsequently to estimate and remove the hydrostatic component of delay at all stations equipped with barometers, thereby isolating the wet delay and thus PW. This strategy allows us to treat all stations in precisely the same way during the course of the geodetic analysis. The practical significance of this is that any global tracking station can be used to augment a meteorological GPS network, not just those global tracking stations equipped with accurate barometers. Barometers are needed only at those sites where PW is wanted. This approach works because observations acquired below 15° elevation are not used in current GPS analyses, and above 15° there is very little difference between the hydrostatic and wet mapping functions. Although we do not need barometers at

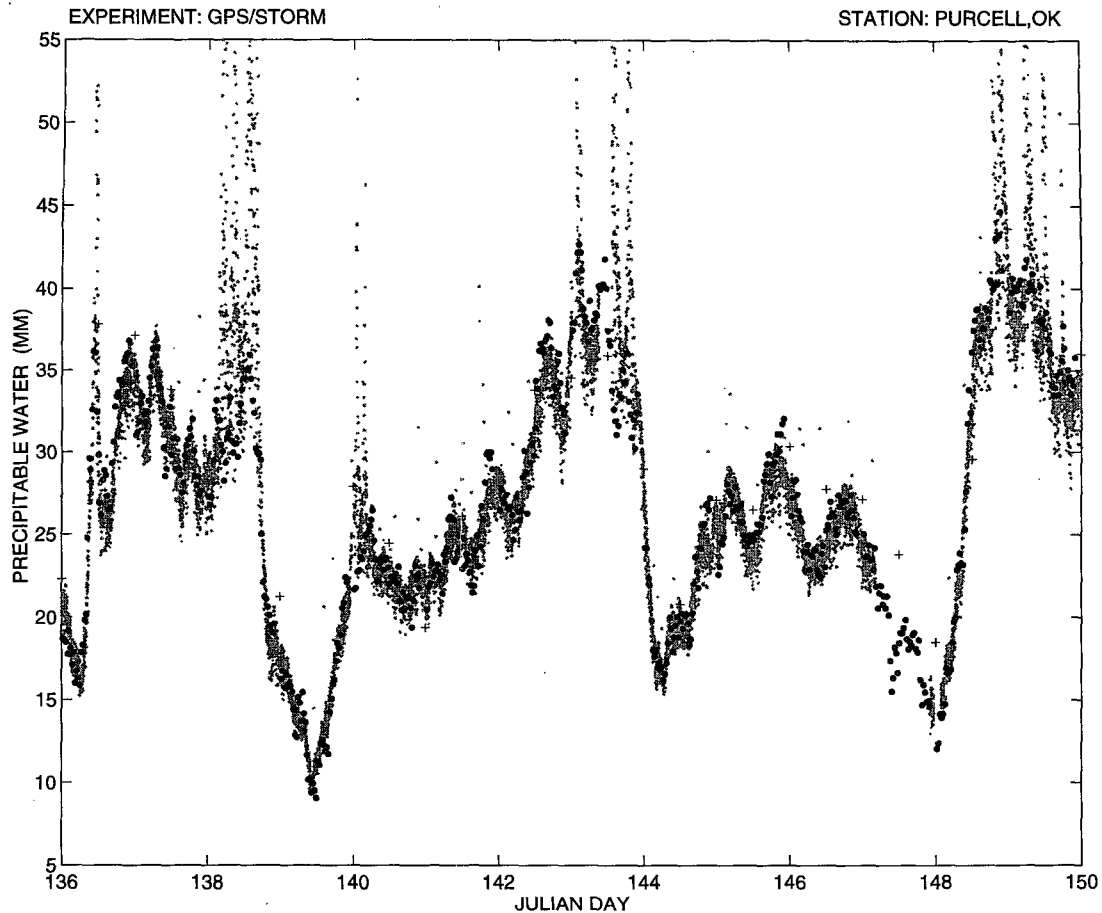


FIG. 3. A comparison of PW estimates derived from GPS (solid circles) and WVR (small gray dots) observations for a 14-day period at Purcell. The GPS receiver and the WVR were located only a few meters apart. Also shown are PW estimates derived twice daily from a radiosonde balloon (crosses) launched 28 km from the GPS receiver and WVR. At most times the vertical scatter in the WVR solutions reflects the magnitude of lateral gradients in PW. However, the brief periods of extremely high scatter in the WVR PW estimates are caused by wetting of the WVR's window by rainfall, which renders the PW estimates meaningless.

global tracking stations in order to use them to retrieve PW from regional GPS networks, if the International GPS Service (IGS) does equip its tracking stations with accurate barometers then this global tracking network could also generate useful measurements of PW.

The WVR rain spikes in Fig. 3 are known to have been associated with thunderstorms. Notice the sharp rise in PW that precedes each thunderstorm. Moisture-flux convergence has long been recognized as essential to convection (e.g., Kuo 1965; Charba 1979), thus, no variable is more critical to quantitative precipitation forecasting than water vapor. By tracking short-term changes in PW associated with moisture-flux convergence and destabilizing midtropospheric intrusions of dry air (not detected by surface measurements), time series PW data constitute a useful new tool for short-term forecasting of thunderstorm activity (Chiswell et al. 1996, submitted to *Mon. Wea. Rev.*). In combination with other data sources, such as Doppler radar and

radiosondes, earth-based GPS receivers can provide valuable input to numerical weather forecasting models. The applications of GPS PW measurements in weather analysis and forecasting are discussed further in Chiswell et al. (1996, submitted to *Mon. Wea. Rev.*). Businger et al. (1996) discuss possible synergy between earth-based GPS data and data collected by satellite-based nadir-pointing radiometers and refractivity profiles derived by space-based GPS receivers (Melbourne et al. 1994; Ware et al. 1996).

We have demonstrated that GPS networks can estimate PW with a temporal resolution of 30 min or better and with an accuracy better than 1.5 mm. Both this analysis, and that of Rocken et al. (1995), were achieved by postprocessing. This enabled us to incorporate precise orbit solutions generated by analysis of global tracking data collected throughout each GPS day. With no further technical development, it is clear that GPS can play a useful role in water vapor clima-

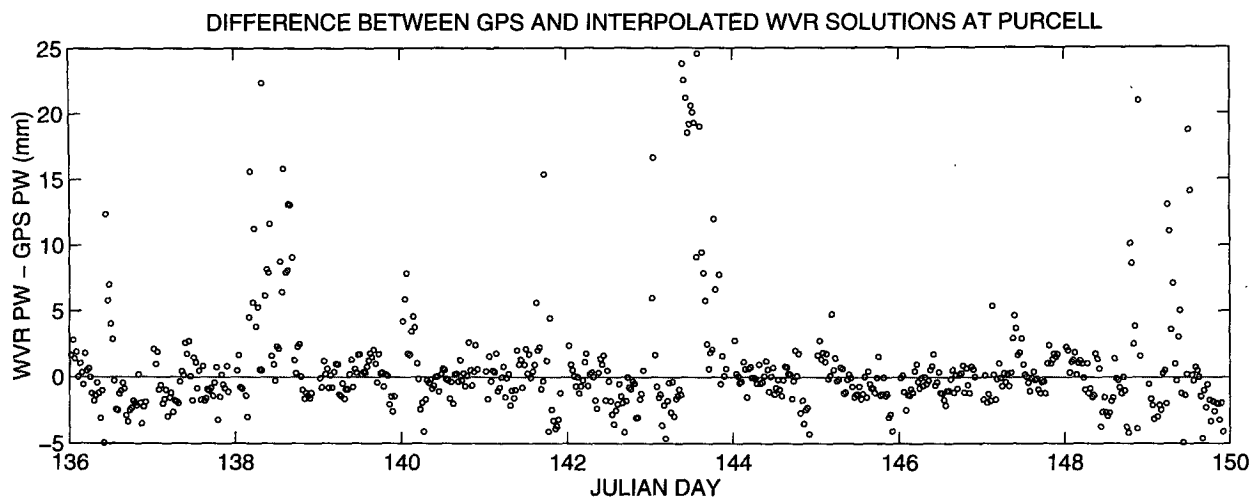


FIG. 4. The difference between PW estimates derived from GPS and WVR observations for the 14-day period at Purcell shown in Fig. 3. Since the WVR measurements were much more frequent than the GPS observations, the residuals were formed by comparing the GPS values and a piecewise linear approximation to the WVR data evaluated at the times of the GPS solutions, as described in Table 2.

tology (IPCC 1992). By modifying our algorithms and procedures so as to assimilate GPS observations in nearly real time and incorporate precise orbit predictions, it will be possible for GPS to play a useful role in operational weather analysis and prediction. The rapid emergence of continental-scale GPS networks, therefore, represents an opportunity for the meteorological community to appreciably enhance its ability to resolve the distribution of atmospheric water vapor.

Predicted orbits are less accurate than orbital solutions obtained post facto, and since errors in predicted orbits grow with the age of the prediction (i.e., the time span of extrapolation), the major issue related to nearly real-time applications will be the accuracy of the GPS PW solution as a function of solution latency and time of day. At present the IGS downloads the global tracking network just once a day; therefore, real-time meteorological GPS networks would have to be analyzed with predicted orbits extrapolated as much as 24 h. It may prove desirable to download and analyze the global tracking network more than once a day in order to optimize the value of GPS PW measurements for operational weather analysis and prediction.

Acknowledgments. This research was supported by the National Science Foundation under Grants ATM-9207111 and ATM-9496335. We would like to thank James Johnson, Jim Normandeau, John Braun, and Chris Alber of UNAVCO and Russ Chadwick and Seth Gutman of the NOAA Wind Profiler Group for logistical support. We thank James Lijegren and the AMR project for support at the CART site and for the WVR data from Lamont. Ed Westwater and Michael Falls from NOAA/ETL kindly provided retrieval coefficients and WVR data from Platteville. Radiometrics Inc. of Boulder, Colorado, loaned us two WVR's for

GPS/STORM. Paroscientific, Inc. loaned us a precise barometer for calibration purposes. We thank two anonymous reviewers for useful comments and suggestions. This is School of Earth and Ocean Science and Technology contribution number 4060.

REFERENCES

- Askne, J., and H. Nordius, 1987: Estimation of tropospheric delay for microwaves from surface weather data. *Radio Sci.*, **22**, 379–386.
- Bevis, M., S. Businger, T. A. Herring, C. Rocken, R. A. Anthes, and R. H. Ware, 1992: GPS meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System. *J. Geophys. Res.*, **97**, 15 787–15 801.
- , —, S. Chiswell, T. A. Herring, R. Anthes, C. Rocken, and R. H. Ware, 1994: GPS meteorology: Mapping zenith wet delays onto precipitable water. *J. Appl. Meteor.*, **33**, 379–386.
- Bock, Y., J. Zhang, P. Fang, J. F. Genrich, K. Stark, and S. Wdowinski, 1992: One year of daily satellite orbit and polar motion estimation for near real time crustal deformation monitoring. *Developments in Astrometry and Their Impact on Astrophysics and Geodynamics*, I. I. Mueller and B. Kolaczek, Eds., Kluwer Academic Publishers, 279–284.
- Boucher, C., Z. Altamimi, and L. Duhem, 1993: ITRF92 and its associated velocity field. International Earth Rotation Service (IERS) Technical Note 15, 164 pp.
- Businger, S., S. R. Chiswell, M. Bevis, J. Duan, R. Anthes, C. Rocken, R. Ware, T. M. Exner, T. VanHove, and F. Solheim, 1996: The promise of GPS in atmospheric monitoring. *Bull. Amer. Meteor. Soc.*, **77**, 5–18.
- Charba, J. P., 1979: Two to six hour severe local storm probabilities: An operational forecasting system. *Mon. Wea. Rev.*, **107**, 268–282.
- Davis, J. L., T. A. Herring, I. I. Shapiro, A. E. Rogers, and G. Elgered, 1985: Geodesy by radio interferometry: Effects of atmospheric modeling errors on estimates of baseline length. *Radio Sci.*, **20**, 1593–1607.
- Dixon, T. H., and S. Kornreich Wolf, 1990: Some tests of wet tropospheric calibration for the CASA Uno Global Positioning System experiment. *Geophys. Res. Lett.*, **17**, 203–206.

- Elgered, G., 1993: Tropospheric radio-path delay from ground-based microwave radiometry. *Atmospheric Remote Sensing by Microwave Radiometry*, M. A. Janssen, Ed., John Wiley and Sons, 215–258.
- , J. L. Davis, T. A. Herring, and I. I. Shapiro, 1991: Geodesy by radio interferometry: Water vapor radiometry for estimation of the wet delay. *J. Geophys. Res.*, **96**, 6541–6555.
- Feigl, K. L., and Coauthors, 1993: Space geodetic measurement of crustal deformation in central and southern California. *J. Geophys. Res.*, **98**, 21 677–21 712.
- Herring, T. A., 1994: Documentation of the GLOBK software v. 3.2. Mass. Inst. of Technology.
- , J. L. Davis, and I. I. Shapiro, 1990: Geodesy by radio interferometry: The application of Kalman filtering to the analysis of very long baseline interferometry data. *J. Geophys. Res.*, **95**, 12 561–12 581.
- Hofmann-Wellenhof, B., H. Lichtenegger, and J. Collins, 1993: *Global Positioning System: Theory and Practice*. Springer-Verlag, 326 pp.
- Hogg, D. C., F. O. Guiraud, and M. T. Decker, 1981: Measurement of excess transmission length on earth-space paths. *Astron. Astrophys.*, **95**, 304–307.
- IPCC, 1992: *Climate Change 1992*. J. T. Houghton, B. A. Callander and S. K. Varney, Eds., University Cambridge Press, 200 pp.
- King, R. W., and Y. Bock, 1994: Documentation of the GAMIT GPS analysis software v. 9.3. Mass. Inst. of Technology and Scripps Inst. of Oceanography.
- Kuo, H. L., 1965: On the formation and intensification of tropical cyclones through latent heat release by cumulus convection. *J. Atmos. Sci.*, **22**, 40–63.
- Lichten, S. M., and J. S. Border, 1987: Strategies for high precision Global Positioning System orbit determination. *J. Geophys. Res.*, **92**, 12 751–12 762.
- Melbourne, W. G., E. S. Davis, C. B. Duncan, G. A. Hajj, K. R. Hardy, E. R. Kursinski, T. K. Meehan, L. E. Young, and T. P. Yunck, 1994: The application of spaceborne GPS to atmospheric limb sounding and global change monitoring. Jet Propulsion Laboratory Publication 94-18, 147 pp.
- Resch, G. M., 1984: Water vapor radiometry in geodetic applications. *Geodetic Refraction*, F. K. Brunner, Ed., Springer-Verlag, 53–84.
- Rocken, C., R. H. Ware, T. Van Hove, F. Solheim, C. Alber, J. Johnson, M. Bevis, and S. Businger, 1993: Sensing atmospheric water vapor with the Global Positioning System. *Geophys. Res. Lett.*, **20**, 2631–2634.
- , T. Van Hove, J. Johnson, F. Solheim, R. Ware, M. Bevis, S. Chiswell, and S. Businger, 1995: GPS/STORM—GPS sensing of atmospheric water vapor for meteorology. *J. Atmos. Oceanic Technol.*, **12**, 468–478.
- Rothacher, M., 1992: Orbits of Satellite Systems in Geodesy. *Geodaet.-geophys. Arbeit. Schweiz*, **46**, 243 pp.
- Saastamoinen, J., 1972: Atmospheric correction for the troposphere and stratosphere in radio ranging of satellites. *The Use of Artificial Satellites for Geodesy*, *Geophys. Monogr. Ser.* 15, Amer. Geophys. Union, 247–251.
- Spilker, J. J., 1980: GPS signal structure and performance characteristics. Vol. 1, *Global Positioning System*, The Institute of Navigation, 29–54.
- Tralli, D. M., and S. M. Lichten, 1990: Stochastic estimation of tropospheric path delays in Global Positioning System geodetic measurements. *Bull. Geod.*, **64**, 127–159.
- , T. H. Dixon, and S. A. Stephens, 1988: Effect of wet tropospheric path delays on estimation of geodetic baselines in the Gulf of California using the Global Positioning System. *J. Geophys. Res.*, **93**, 6545–6557.
- Truhhaft, R. N., and G. E. Lanyi, 1987: The effects of the dynamic wet troposphere on radio interferometric measurements. *Radio Sci.*, **22**, 251–265.
- Ware, R., and Coauthors, 1996: GPS sounding of the atmosphere from low earth orbit: Preliminary results. *Bull. Amer. Meteor. Soc.*, **77**, 19–40.