Toward an Operational Water Vapor Remote Sensing System Using the Global Positioning System

S. I. Gutman,[a] R. B. Chadwick,[b] and D. W. Wolf[c]
National Oceanic and Atmospheric Administration
Boulder, Colorado

A. Simon
Cooperative Institute for Research in Environmental Science
Boulder, Colorado

T. Van Hove and C. Rocken
University Navstar Consortium
Boulder, Colorado

Background

Water vapor is one of the most important constituents of the free atmosphere since it is the principal mechanism by which moisture and latent heat are transported and cause “weather.” The measurement of atmospheric water vapor is essential for weather and climate research as well as for operational weather forecasting. An important goal in modern weather prediction is to improve the accuracy of short-term cloud and precipitation forecasts, but our ability to do so is severely limited by the lack of timely water vapor data.

Most of the water vapor in the atmosphere resides in the troposphere, which ranges from an altitude of approximately 9 kilometers at the poles to more than 16 kilometers at the equator. The National Weather Service primarily uses balloon-borne radiosondes, launched at 12-hour intervals at approximately 100 sites in the United States, to measure water vapor in the troposphere, but there are several problems with this technique: increasing operational costs; infrequent launches; large distances between launching points compared with the lateral scale of variations in water vapor; and data not acquired at the assumed (reported) point of acquisition.

Alternative methods of measuring atmospheric water vapor, such as the dual-channel microwave radiometer (Westwater 1978; Westwater et al. 1989) overcome the temporal frequency problem, but the high cost of these instruments precludes large-scale deployment. In addition, most microwave radiometers require frequent calibration and do not function well under all weather conditions.

Recent experiments have demonstrated that data from Global Positioning System (GPS) satellites can be used to monitor precipitable water vapor with millimeter accuracy and sub-hourly temporal resolution (Rocken et al. 1993). Major advantages of GPS-based systems include the following: they work under virtually all weather conditions; individual systems do not have to be calibrated; and they are relatively inexpensive. At approximately the same time that the first GPS water vapor systems were being demonstrated, Kuo et al. (1993) showed that accurate, high resolution measurements of precipitable water vapor (PWV) used in conjunction with frequent, closely spaced vertical profiles of winds (such as produced by networks of wind profiling radars), can significantly improve the accuracy of short-term cloud and precipitation forecasts.

As a consequence, the National Oceanic and Atmospheric Administration’s (NOAA) Environmental Research Laboratory, in collaboration with University Corporation for Atmospheric Research’s (UCAR) University Navstar Consortium (UNAVCO) and the University of Hawaii at Manoa, plans to develop, test, and deploy a network of real-time GPS PWV systems in the near future. The data from this network will be available to weather and climate researchers, operational forecasters, numerical weather

(a) Forecast Systems Laboratory—Systems Technology Associates, Inc.
(b) Forecast Systems Laboratory.
(c) Environmental Technology Laboratory.

modelers, ionospheric scientists, and others interested in a reliable source of highly accurate GPS data over a large geographic area.

Overview

The influence of moisture on the propagation of signals from GPS satellites has been discussed by many authors including Brunner and Welsch (1993). The usefulness of GPS for climate studies was suggested by Yuan et al. (1993), and the potential of GPS as a meteorological remote sensing tool was first discussed by Bevis et al. (1992, 1994).

To measure the quantity of PWV in the atmosphere using GPS, it is necessary to estimate the effect that propagation delays caused by both the ionosphere and the neutral atmosphere are having on the GPS signal. This process is accomplished by separating the errors introduced into the calculation of apparent position by system-related and geometric factors from those caused by the passage of the GPS signal through the atmosphere.

The following are the significant system and geometric sources in error in this process:

- Calculation and/or reporting of the orbits of the Navstar satellites. This problem is mitigated in post-processing by using precise satellite orbits provided by available services such as the National Aeronautics and Space Administration's Jet Propulsion Laboratory (NASA JPL) and the National Oceanic and Atmospheric Administration's National Geodetic Survey (NOAA NGS). In the case of a real-time GPS PWV system, precise orbits will have to be predicted or calculated "on-the-fly" using data acquired by the network of GPS PWV systems.
- Deliberate degradation or modification of the satellite signal (called Selective Availability and Anti-spoofing) by the Department of Defense. This error is minimized by "differential surveying" or measuring the signals from the GPS satellites at two or more receivers simultaneously.
- Errors in the clocks onboard the satellites. These errors are also corrected for by differential surveying.
- Errors in the clock in the GPS receiver and differences between the clocks in different receivers. These errors are reduced by using high-quality geodetic surveying receivers and/or high accuracy external clocks.
- Objects that block or reflect the GPS signal. Such objects result in "cycle slips" that must be identified and eliminated before data processing. Errors caused by the reflection of a GPS signal from nearby objects into the GPS antenna are called "multipath" errors that can be minimized by antenna designs and careful siting of GPS systems.

Once these effects have been accounted for, most of the remaining range delay errors are associated with the transmission of microwave signals through the ionosphere (a propagating medium) and the troposphere (a neutral medium) where most of the water vapor in the atmosphere is concentrated.

- Ionospheric refraction causes range delays that may be corrected for by receiving two carrier frequencies simultaneously to correct for the dispersive characteristics of the ionosphere.
- Range delays in the neutral atmosphere, referred to as the total tropospheric delay (TD), consist of a hydrostatic or "dry" delay and a "wet delay" as follows:

$$TD = drydelay \tag{1}$$

The dry delay can be derived from measurements of the surface pressure, while the wet delay (usually expressed in terms of a "zenith wet delay" - ZWD) is associated with the vertically integrated column of water vapor overlying the GPS receiver. Zenith wet delay is related to PWV through a dimensionless constant of proportionality, Π, that is a function of the bulk constituents of the atmosphere and the vertical distribution of water vapor and temperature according to Equation (2).

$$PWV = \Pi * ZWD \tag{2}$$

Depending on the location of the GPS receiver, local weather conditions, and season, Π may vary as much as 10% (Bevis et al. 1994).

Field Experiments

Experience with GPS PWV systems comes primarily from the UNAVCO-North Carolina State University (NCSU)

GPS/STORM (Storm-Scale Observations Regional Measurement Program) experiment during the spring of 1993, and the NOAA-UNAVCO GPS-WISP (Winter Icing and Storms Program) 94 experiment in January-February, 1994. These experiments are described below.

GPS/Storm

As previously discussed, the technique used to measure the zenith wet delay with GPS is inherently differential. In the case of the GPS/STORM experiment, UNAVCO/NCSU established a reference station at Platteville, Colorado, and five remote field sites at NOAA wind profiler sites in Oklahoma and Kansas and one at the Department of Energy's Southern Great Plains Cloud and Radiation Testbed (SGP CART) facility near the NOAA wind profiler at Lamont, Oklahoma (Figure 1).

Trimble Navigation model 4000 SSE Geodetic Survey dual frequency P Code GPS receivers were deployed for approximately one month at the above locations. At wind

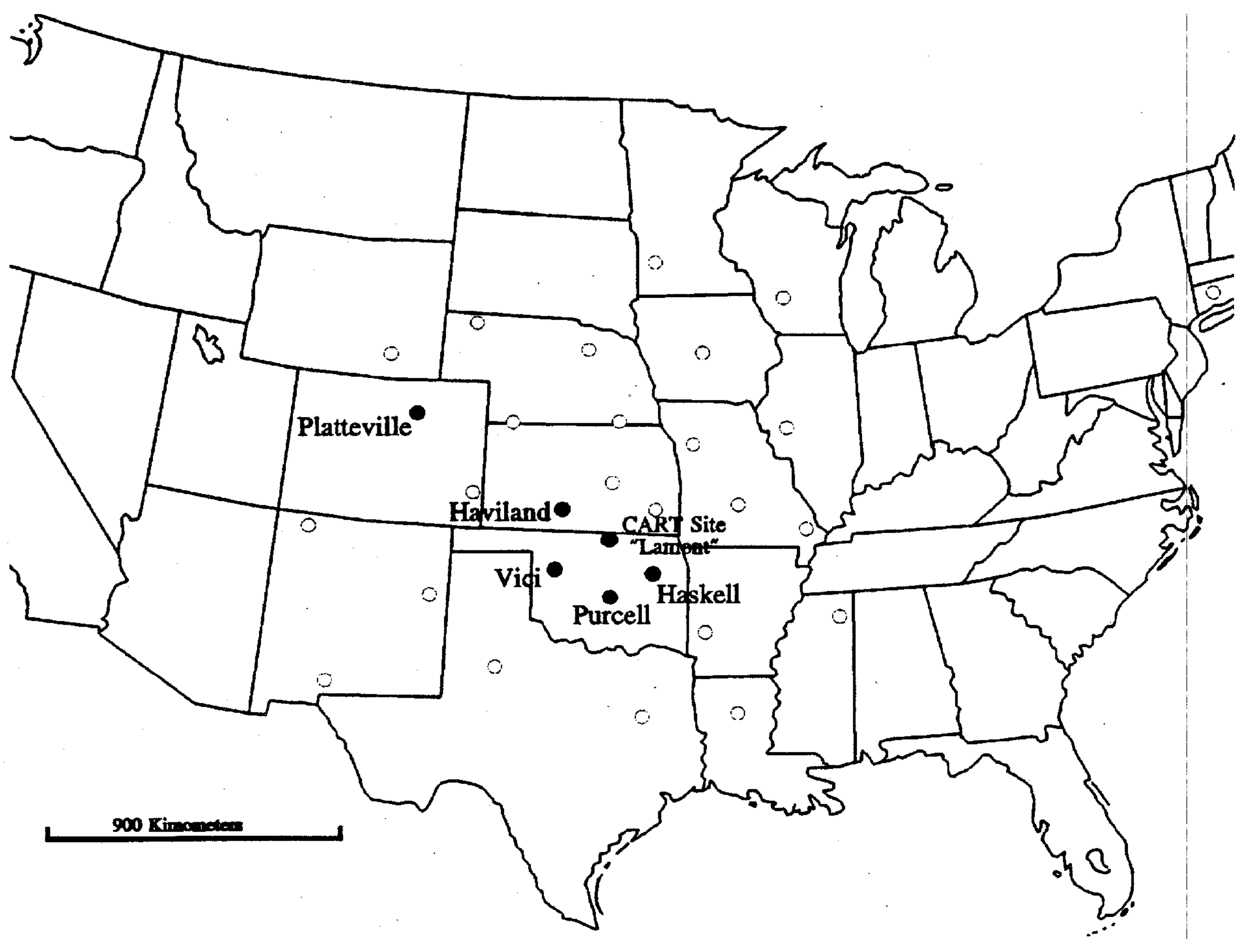

Figure 1. Network of GPS PWV systems deployed during GPS/STORM experiment.

profiler sites, GPS antennas were mounted on stable fence posts approximately 3 meters above the ground and away from extraneous sources of electromagnetic interference. Data were logged for 22 hours each day and automatically downloaded to a PC at the site at the completion of the acquisition period. When it was confirmed that data had been successfully transferred from the receiver to the PC, the data files on the receiver were manually deleted to conserve limited memory. Data were then transmitted to UNAVCO over the phonelines at the convenience of the experimenters. Real-time data acquisition was not required since the data would be processed retrospectively and processing requires improved satellite orbits that are generally available 1 to 2 weeks after the satellite pass. UNAVCO/NCSU used Bernese version 3.3 software (Rothacher 1992), a data processing package developed by the University of Bern, Switzerland, for precise geodetic surveying, to calculate the ZWD.

Each GPS receiver was collocated with a barometer accurate to better than 0.5 mb to estimate the dry delay, and a thermometer. The reference station at Platteville was located next to a dual frequency water vapor radiometer (WVR) operated by NOAA Environmental Research Laboratories Environmental Technology Laboratory (NOAA ERL/ETL).

The WVR provides an independent measurement of precipitable water vapor in the atmosphere at the reference station, as well as an objective method of resolving the uncertainty between the observed ZWD for a specific constellation of GPS satellites and the tropospheric water vapor responsible for that delay. Once this relationship is derived, it can be applied to all remote stations observing the same constellation of satellites. The accuracy of this technique (better than 2 mm rms over distances greater than 600 kilometers) has been verified, and measurements exceeding 900 km have been demonstrated (Rocken et al., in press).

The value of this technique is that one reference station equipped with a GPS PWV system (GPS receiver, barometer, and thermometer) and a WVR can provide differential corrections for an unlimited number of remote stations equipped only with a GPS PWV system as long as the same constellation of GPS satellites is visible.

Figure 2 shows some of the data acquired during GPS/STORM. In this plot, the GPS data are represented by the darker points, while WVR data acquired by Dick-type WVR (manufactured by Radiometrics™ of Boulder, Colorado) deployed at Vici, Purcell, and Lamont, are represented by the fine points.

The large dots are PWV estimates interpolated from the network of National Weather Service (NWS) radiosondes and do not represent collocated measurements. Large, mesoscale features are clearly evident traversing the network; smaller synoptic-scale features representing local variations in moisture are also seen. The build-up of moisture on day 148 at Haskell coincides with thunderstorm activity in the Tulsa, Oklahoma, area at about 1600 GMT.

GPS-WISP 94

The purpose of the GPS-WISP 94 was to investigate some of the scientific and engineering issues involved in developing an operational GPS PWV system. These include hardware and software configurations; data acquisition parameters; precision and accuracy of GPS PWV estimates compared with WVR and radiosonde derived values; reliability of various system components (GPS, WVR, pressure sensors, radiosondes, etc.); and measurement independence (i.e., differences in the values of PWV at one station calculated simultaneously using the reference stations at two different locations).

GPS-WISP 94 was carried out between January 25 and February 25, 1994, during the 1994 Winter Icing and Storms Project, to take advantage of the meteorological data acquired during that campaign. Three NOAA GPS systems identical to those deployed during GPS/STORM were installed at Platteville, at Erie, and at the Denver Weather Service Forecast Office (WSFO) at Stapleton Airport (Figure 3). Each site was collocated with ETL WVRs; Platteville and Stapleton had frequent radiosonde launches during the experiment.

Data were acquired continuously between 0000 GMT and 2330 GMT using a 30-second sampling period. At 2330 GMT, GPS data were automatically downloaded from the GPS receiver to the PC at each site. When this transfer was accomplished successfully, the data files on the GPS receivers were deleted to save memory.

Data were transmitted on command to the Profiler Control Center in Boulder over the phone lines; merged with pressure, temperature and WVR data at ETL; and

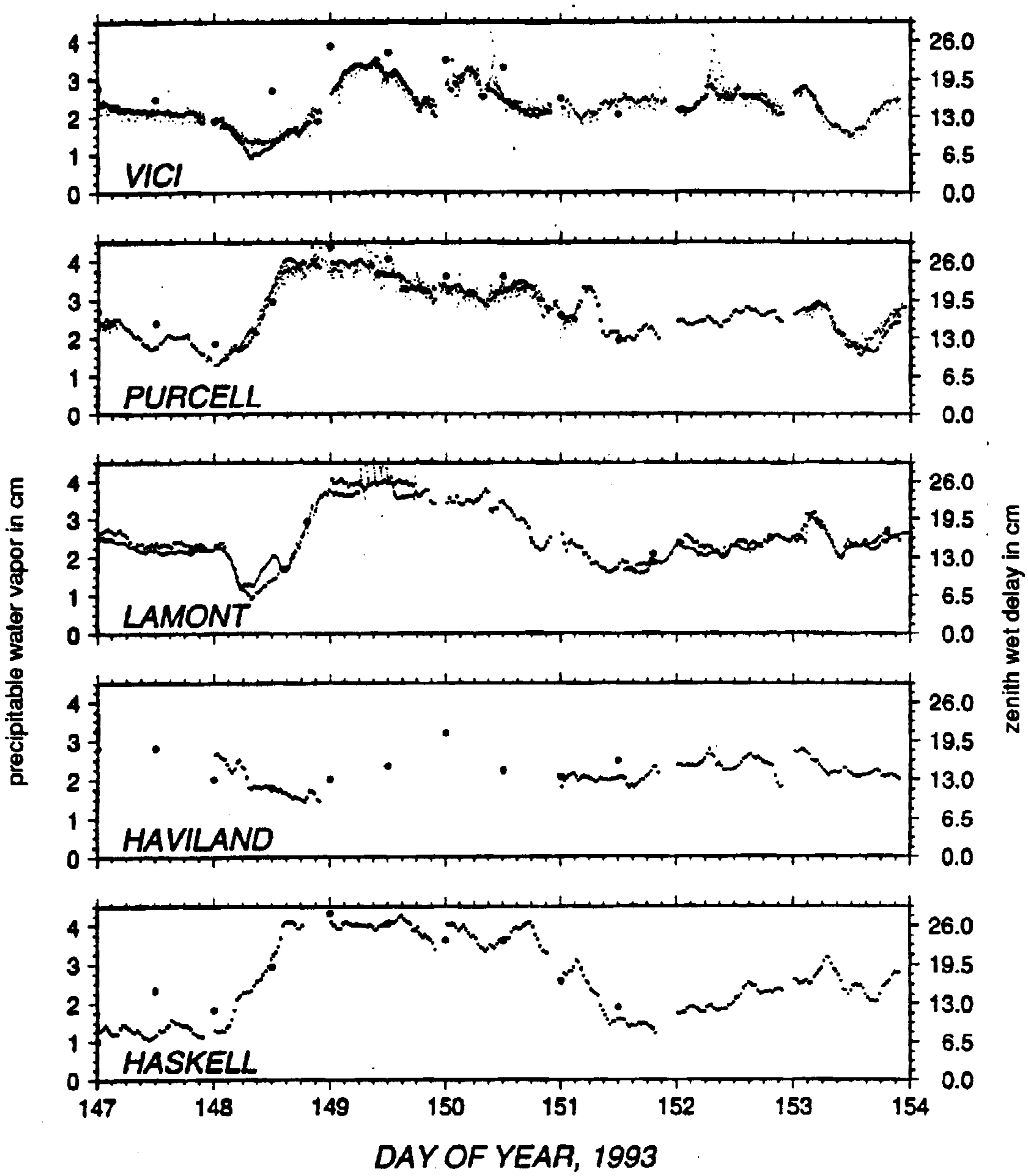

Figure 2. Precipitable water vapor data from GPS, WVR, and radiosondes acquired in a 7-day period during a GPS/STORM experiment in 1993. Dark points are GPS-derived PWV estimates; fine points are WVR measurements; large dots are interpolated from the NWS radiosonde network.)

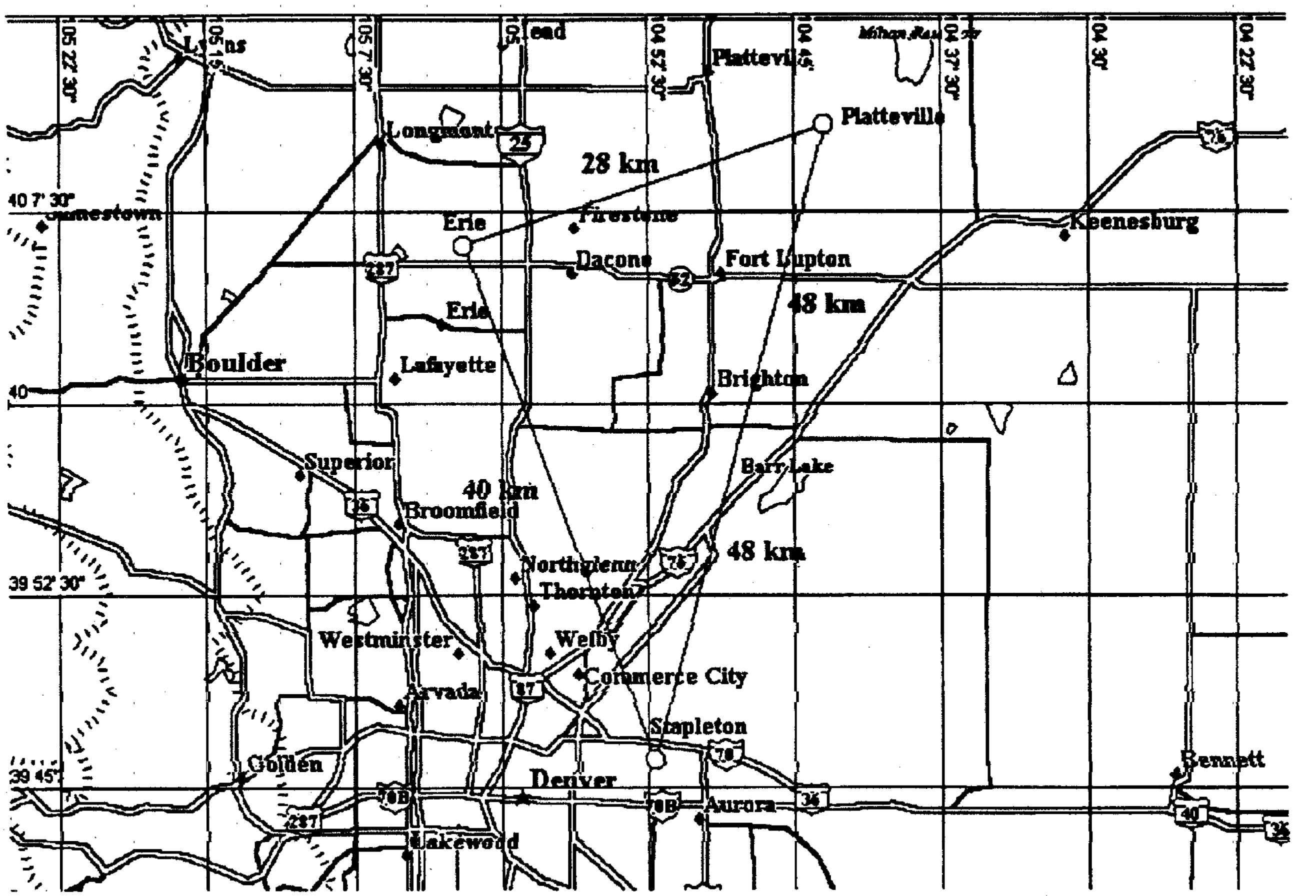

Figure 3. Network of GPS PWV systems deployed during GPS WISP-94.

transferred to UNAVCO over the Internet for data processing. Once again, UNAVCO used Bernese software to process the data after improved Center for Orbit Determination in Europe (CODE) orbits for the GPS constellation had been received from the University of Bern (Van Hove and Rocken 1994).

Figure 4 is a plot of the data acquired during one week of the experiment. After all data were corrected and all problems (described below) resolved, the differences between the WVR- and GPS-derived PWV measurements for all the data were 0.53 mm ±0.13 mm rms (Van Hove and Rocken 1994). Of the 705 hours of data possible, 100% were recovered from Platteville, 97% from Stapleton, and 92% from Erie.

Problems encountered during GPS-WISP 94 include the following: PC clock drift timing problems interfered with the download of data from the GPS receiver to the PC; firmware problems with the GPS receiver caused memory errors and loss of data; firmware problems with the GPS receiver caused it not to record data when it was operating on backup power; discontinuities in the data caused by the loss-of-lock on the GPS satellites, in turn, caused data processing problems; and errors in the calibration of the WVR retrieval coefficients caused 1-2 millimeter offsets in the data acquired at Erie and Platteville relative to Stapleton.

The following solutions to these problems have been incorporated into the requirement specifications for an operational GPS PWV system:

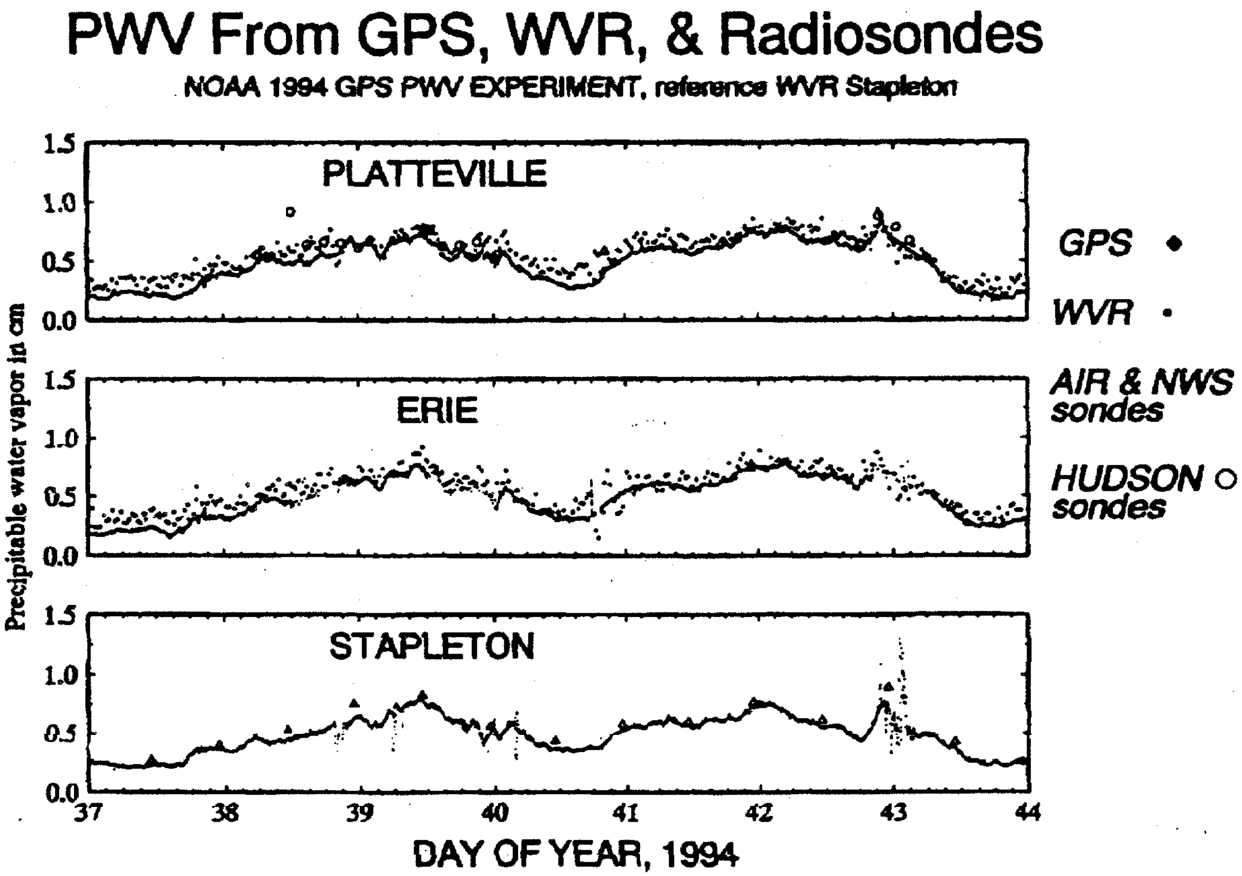

Figure 4. Precipitable water vapor data acquired in a 7-day period during the GPS WISP 94 experiment. (NOAA experiment, reference WVR Stapleton.)

- Eliminate the need for a PC at the site by equipping the GPS receiver with an RS-232 interface and "virtual" control panel.
- Fix the firmware on the receiver to eliminate the memory error problems.
- Provide an uninterruptible power supply in-line with the main power to ensure continuous primary power to the GPS receiver.
- Develop firmware to permit continuous (seamless) data acquisition and data downloading without loss-of-lock on the satellites.
- Establish the reference stations at NWS radiosonde facilities to permit the WVR retrieval coefficients to be routinely checked.

Conclusions

1. GPS is a cost-effective and reliable means of obtaining continuous PWV measurements over land.
2. GPS PWV systems can measure precipitable water vapor in the atmosphere with an accuracy better than a few millimeters (with respect to a radiosonde or water vapor radiometer) over distances of about 1000 kilometers.
3. GPS systems can operate continuously and function reliably under moist (>4.0 centimeter PWV) and dry (<0.25 centimeter PWV) conditions.
4. The accuracy of a GPS PWV estimate appears to be unrelated to the location of the reference station.

5. The greatest impact on the accuracy of remote GPS PWV estimates is the accuracy of the WVR data at the reference station.
6. The greatest impediment to an operational GPS PWV system is the real-time processing of the data. To overcome this situation, improved GPS orbits must be available in real-time or must be calculated “on-the-fly” using the data acquired by the network of GPS PWV systems.

References

Bevis, M., S. Businger, S. R. Chiswell, T. A. Herring, R. A. Anthes, C. Rocken, and R. H. Ware. 1994. GPS Meteorology: Mapping Zenith Wet Delays onto Precipitable Water. *J. Appl. Meteor*. **33**: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.

Brunner, F., and W. Welsch. 1993. Effects of the troposphere on GPS measurements. *GPS World*, pp. 42-51.

Kuo, Y.-H., Y.-R. Guo, and E. R. Westwater. 1993. Assimilation of Precipitable Water Measurements into Mesoscale Numerical Models. *Mon. Wea. Rev.* **121**:1215-1238.

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**(23):2631-2634.

Rocken, C., T. Van Hove, J. Johnson, F. Solheim, R. H. Ware, C. Alber, M. Bevis, S. Businger, and S. Chiswell. GPS Storm - GPS Sensing of Atmospheric Water Vapor for Meteorology. *J. Atmos. Ocean. Techn.*, in press.

Rothacher, M. 1992. Orbits of Satellite Systems in Space Geodesy. *Geodaetischgeophysikalische Arbeiten in der Schweiz.* Ph.D. thesis, U. of Bern, **46**.

Van Hove, T., and C. Rocken. 1994. *WISP-94 NOAA/ ERL - UNAVCO GPS Integrated Water Vapor Experiment, UNAVCO Data Analysis Report*. University Navstar Consortium, Boulder, Colorado.

Yuan, L., R. Anthes, R. H. Ware, C. Rocken, W. Bonner, M. Bevis, and S. Businger. 1993. Sensing Climate Change Using the Global Positioning System. *J. Geophys. Res.* **98**(D8):14,925-14,937.

Westwater, E. R. 1978. The accuracy of water vapor and cloud liquid determination by dual-frequency ground-based radiometry. *Radio Science* **13**:677-685.

Westwater, E. R., M. J. Falls, and I. A. Popo Fotino. 1989. Ground-Based Microwave Radiometric Observations of Precipitable Water Vapor: A Comparison with Ground Truth from Two Radiosonde Observing Systems. *J. Atmos. Ocean. Techn.* **6**:724-730.

Westwater, E. R., J. B. Snider, and M. J. Falls. 1990. Ground-based radiometric observations of atmospheric emission and attenuation at 20.6, 31.65, and 90 GHz: A comparison of measurement and theory. *IEEE Trans. Antennas Propagat.* **38**: 1569-1580.