Developing an Operational, Surface-Based, GPS, Water Vapor Observing System for NOAA: Network Design and Results

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ABSTRACT

The need for a reliable, low-cost observing system to measure water vapor in the atmosphere is incontrovertible. Experiments have shown the potential for using Global Positioning System (GPS) receivers to measure total precipitable water vapor accurately at different locations and times of year and under all weather conditions. The National Oceanic and Atmospheric Administrations's (NOAA) Forecast Systems Laboratory (FSL) and Environmental Technology Laboratory (ETL), in collaboration with the University NAVSTAR Consortium, University of Hawaii, Scripps Institution of Oceanography, and NOAA's National Geodetic Survey (NGS) Laboratory, are addressing this need by developing a ground-based water vapor observing system based on the measurement of GPS signal delays caused by water vapor in the atmosphere. The NOAA GPS Integrated Precipitable Water Vapor (NOAA GPS–IPW) network currently has 35 continuously operating stations and is expected to expand into a 200-station demonstration network by 2004. This paper describes the major accomplishments of the project since its inception in 1994. Results from the analysis of the effect of satellite orbit accuracies on IPW accuracy are discussed. Several comparisons with collocated remote and in situ measurements, including radiosondes and ground- and space-based radiometers are shown. Results from preliminary model runs using the FSL Forecast Research Division's Mesoscale Analysis and Prediction System (MAPS) model are presented. This work shows the feasibility of an operational system using GPS to continuously monitor atmospheric water vapor in near–real time with accuracies ($<$1.5 cm) comparable to radiosondes and water vapor radiometers.

1. Introduction

Water vapor is one of the most important constituents of the atmosphere since it contributes to the transport of moisture and latent heat. The measurement of atmospheric water vapor is vital for weather and climate research as well as 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 limited by the lack of timely water vapor data. At approximately the same time that the first Global Positioning System (GPS) water vapor systems were first being demonstrated, Kuo et al. (1993) showed that accurate, high-resolution measurements of integrated precipitable water vapor (IPW) used in conjunction with vertical profiles of winds can significantly improve the accuracy of short-term cloud and precipitation forecasts. On a global scale, Yuan et al. (1993) looked at the potential of GPS–IPW to help monitor global climate change based on the relationships between temperature, water vapor, and CO_2.

Most of the water vapor in the atmosphere resides in the troposphere, which ranges in depth from about 9 km at the poles to more than 16 km at the equator. The National Weather Service (NWS) primarily uses 12-h, balloon-borne radiosondes to measure water vapor in the troposphere, but there are problems with this technique. These problems include increasing operational costs, infrequent launches, large distances between launch points compared with the spatial variations in water vapor, and performance of the radiosonde moisture sensors currently used by the NWS (Wade 1994, 1995). Alternative ground-based methods of measuring atmospheric water vapor, such as the dual-channel microwave radiometer (Westwater 1978; Westwater et al. 1989) and Raman lidar (Melfi et al. 1989; Goldsmith et al. 1994) overcome the temporal frequency problem, but the high cost of these instruments precludes their large-scale deployment. In addition, these instruments require

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frequent calibration or personal attention, and they do not function well under all weather conditions. Satellite infrared radiometers, on the other hand, are capable of global coverage. They measure brightness temperatures and estimate integrated precipitable water vapor. Accuracies over land are affected by the large variability in the surface brightness temperature and the results are limited to clear-sky conditions.

Past experiments have demonstrated that data from GPS satellites can be used to monitor IPW with millimeter accuracy and subhourly temporal resolution (Rocken et al. 1993; Gutman et al. 1994). Recent work (Businger et al. 1996; Ware et al. 1996) further demonstrates the potential advantages of both ground- and space-based GPS receivers. The major advantages of ground-based GPS instruments include working under virtually all weather conditions, individual systems do not require calibration, and they are relatively inexpensive ($10 000–$20 000 per receiver/antenna).

As a consequence, The National Oceanic and Atmospheric Administration's (NOAA's) Environmental Research Laboratory (ERL) has developed, tested, and is deploying a demonstration network of GPS ground-based receivers to continuously monitor IPW. The data from this network are available with 24-h latency to weather and climate researchers, operational forecasters, modelers, ionospheric scientists, and others interested in a reliable source of high accuracy IPW data.

2. GPS meteorology

The Global Positioning System was originally conceived and developed by the U.S. Department of Defense (DoD) as a military positioning, navigation, and time transfer system. Numerous unanticipated uses of GPS started to emerge even before the system became fully operational in 1994. One of these is GPS meteorology and the monitoring of IPW.

a. Background

Suggestions about the utility of GPS for atmospheric remote sensing appeared in the literature as early as 1990 (Dixon et al. 1990). Based on an approach suggested by Bevis et al. (1992), experiments were conducted in 1993–94 that demonstrated GPS data could be used to continuously monitor IPW from fixed stations on the surface of the earth with millimeter accuracy and subhourly temporal resolution (Gutman et al. 1994; Rocken et al. 1995).

To accurately measure IPW in the atmosphere using GPS, one must first separate the propagation delays caused by the neutral atmosphere from other sources of positioning error and then attribute the correct portion of the neutral delay to the total quantity of water vapor in the atmosphere. After data processing has identified these and other sources of positioning error, including satellite orbit inaccuracies, clock errors, receiver biases, signal multipath, and deliberate modification of the signal by DoD, the remaining error in position can be attributed to the transmission of microwave signals through the ionosphere (a propagating medium), and the troposphere (an electrically neutral medium). Since the velocity of radio waves in a propagating medium depends on frequency and electron density, the effects of the ionosphere can be eliminated (or determined) using dual-frequency GPS receivers. The remaining errors in position are associated with delays caused by the passage of the radio signals through the neutral atmosphere.

Assuming no obstructions, approximately four to eight randomly distributed GPS satellites are always visible above any point on the surface of the earth. Because these satellites are not directly overhead, a mapping function is applied to convert off-zenith measurements of signal delay to what would be observed if all satellites were directly overhead. The zenith-scaled values are averaged to generate one estimate of the zenith tropospheric delay (ZTD) for each observing period, typically 30 min. This technique assumes that the atmosphere through which the GPS signals travel is azimuthally isotropic. While this assumption is only an approximation, it has turned out to be a fairly good one under most conditions since most of the water vapor resides in the planetary boundary layer close to the surface. Nonetheless, ZTD measurements provide no information about the horizontal or vertical variability of the signal delays. A great deal of information about the moisture structure of the atmosphere is potentially available in the observation as techniques are developed to assimilate them into numerical weather prediction models.

The ZTD depends only on the refractive index, which, in the atmosphere, is a function of temperature, pressure, and water vapor. This delay has two components: a dry or zenith hydrostatic delay (ZHD) caused by the weight of the atmosphere and a zenith wet delay (ZWD) caused by the dipole moment of water vapor refractivity. Since the hydrostatic delay can be derived from a direct measurement of surface pressure, the signal delay caused by the vertically integrated column of water vapor overlying the GPS antenna can be estimated by subtracting ZHD from ZTD. The ZWD is related to IPW through a dimensionless quantity that is a function of the bulk constituents of the atmosphere, the vertical distribution of water vapor, and the mean weighted temperature (T_m) of the atmosphere (Bevis et al. 1992; Businger et al. 1996). The ZHD accounts for approximately 90%–100% of the ZTD, and the ZWD contributes about 0%–10% (in exactly the same proportion as the dry to wet constituents of the atmosphere). The variability in the ZTD is dominated by the wet delay, which is related to the quantity and distribution of water vapor in the atmosphere.

In practice, the accuracy of GPS water vapor estimates appears to be limited by the accuracy with which the ZTD can be measured. A comparison between in-

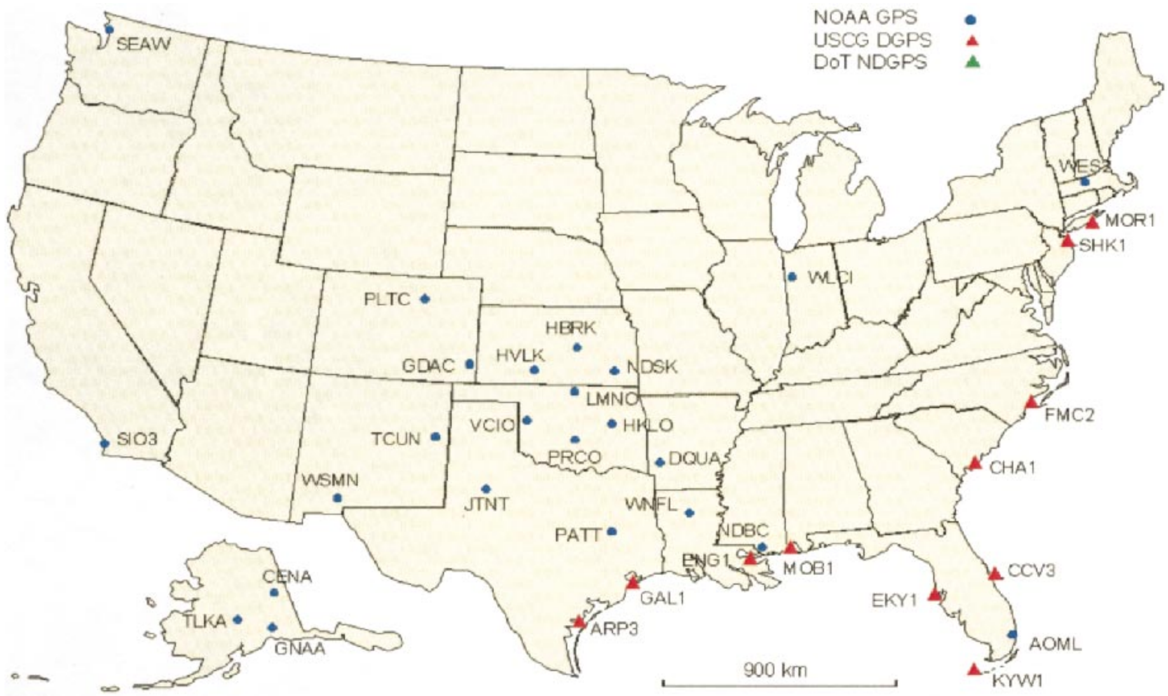

FIG. 1. NOAA GPS–IPW network map (see Table 1 for site key).

dependent ZTD measurements made by similar GPS receivers and antennas over short baselines (<10 km) indicates that standard deviations of less than 6 mm delay can be routinely achieved (Westwater et al. 1998). A 6.5-mm error in ZTD corresponds to an error of about 1 mm in IPW. Since modern surface meteorological sensors can easily provide pressure and temperature measurements with accuracies of less than 0.5 mb and 1°C, errors in estimating the ZHD from surface pressure measurements, or the function that maps ZWD into IPW (calculated from the surface temperature), will almost always be small in comparison. For example a 1-mb error in surface pressure results in approximately 0.37-mm error in IPW, and a 2-K error in measuring surface temperature, which corresponds to less than 1-K error in T_m, has a very small (<0.05 mm) impact on IPW accuracy.

b. Early experiments

Two field experiments preceded the development of the NOAA GPS Integrated Precipitable Water Vapor (GPS–IPW) network: GPS/STORM in the spring of 1993, conducted by the University NAVSTAR Consortium (UNAVCO) and North Carolina State University (Rocken 1995), and the GPS–Winter Icing and Storms Project experiment (GPS–WISP94), conducted by NOAA and UNAVCO in January–February 1994 (Gutman et al. 1994).

GPS/STORM evaluated techniques for calculating and validating IPW estimates derived from a network of GPS receivers under actual field conditions. Rocken et al. (1995) compared GPS and Water Vapor Radiometer (WVR) IPW data and found good agreement (<0.2-cm bias) with very little scatter (better than 0.2-cm rms) during periods of relatively high and variable IPW. GPS–WISP94 was conducted during a period of low IPW in eastern Colorado and addressed some of the scientific and engineering issues associated with developing an operational GPS–IPW network. Both experiments showed that GPS is a cost-effective and reliable means of continuously monitoring IPW under dry (<0.25 cm) and moist (>4.0 cm) conditions with accuracies comparable to calibrated WVRs and radiosondes.

3. Development of the GPS–IPW network

The Forecast Systems Laboratory's Demonstration Division (FSL/DD) developed and has operated the NOAA Profiler Network (NPN), formally the Wind Profiler Demonstration Network (Chadwick 1988), over the past 11 years. This network (Fig. 1) consists of thirty-two 404-MHz wind profiler sites, 14 with surface meteorological packages called profiler surface observing systems (PSOS) and 7 with Radio Acoustic Sounding System temperature profilers. Forecast Systems Laboratory's Demonstration Division also operates three 449-MHz wind profilers in Alaska. Dedicated telephone lines communicate these data from the profiler sites to Boulder, Colorado, every 6 min. The findings of Kuo et al. (1993) on the improvement of precipitation forecasts by combining wind profiles with IPW in numerical models was a main factor for developing GPS–IPW in the NPN Program Office. The cost and time needed to develop the GPS–IPW network has been reduced significantly using the resources and infrastructure of the NPN. Lessons learned from the GPS/STORM and GPS–WISP94 experiments are incorporated into the design of GPS–IPW systems. A GPS–IPW antenna is shown in Fig. 2a. The GPS receivers used are commercially available, dual frequency, 18-channel, geodetic-quality units rack mounted with their own uninterruptible power supply. The GPS antenna is mounted about 2.5 m above the ground on a corner steel fence post set in 0.9 m of concrete. Because NOAA/ERL GPS antennas are not formally monumented as per geodetic survey standards, questions arise about the stability of these sites and their usefulness for geodetic surveying as well as IPW monitoring. Site stability can be monitored by calculating the mean of the differences between the average daily site position (x, y, z) and the predetermined fixed-site position over many days. This calculation was done over a 177-day period at several NOAA sites and compared to the stability of a formally monumented site operated by National Geodetic Survey as part of the Continuously Operating Reference Station (CORS) network for high-accuracy geodetic work. Results of this comparison indicate no significant differences in the stability or higher-frequency antenna movement at the NOAA sites. Comparisons of GPS–IPW measurements to other water vapor measurement techniques, shown later in this paper, also support the fact that the stability (or lack thereof) of the current NOAA antenna installations do not adversely affect the long-term accuracy of GPS measurements of IPW. The ultimate importance of this is that it is relatively easy to establish a GPS–IPW monitoring site and that the addition of surface meteorological sensors at existing CORS sites should facilitate global coverage (over land) in a timely and cost-effective manner.

To date, the Environmental Technology Laboratory and FSL have 35 GPS–IPW instrumented sites (Fig. 1). Nineteen of the 35 sites are NOAA NPN sites (Table 1a), 5 sites are located at other sister NOAA facilities (Table 1b), and 11 are part of the U.S. Coast Guard (USCG) differential GPS (DGPS) and Department of Transportation (DoT) navigational DGPS sites (NDGPS, Table 1c). Examples of non-NPN sites are illustrated in Figs. 2c,d, and some details of the different site configurations are explained in section 4d of this paper. As seen in Tables 1a–c, many of the GPS–IPW sites are located in close proximity to Atmospheric Radiation Monitoring (ARM) Cloud and Radiation Testbed (CART) radiosonde and WVR sites and/or NWS radiosonde sites. These sites provide a continuous source of data for comparison and quality control. Results of some of these comparisons are discussed below.

4. Network and system evaluation

One of the main goals of the GPS–IPW project is to provide IPW data with sufficient accuracy for operational weather forecasts. Several issues had to be addressed in order to meet this goal. 1) How does the accuracy and timeliness of GPS satellite orbits affect IPW? 2) How accurate is GPS–IPW compared to radiosondes and other remote sensing techniques? 3) What is the impact of GPS–IPW measurements on numerical weather prediction models and forecast accuracy? 4) Is it possible to completely automate GPS data processing?

a. GPS satellite orbit accuracy

Three different geodetic software packages were used to process GPS signal delays and produce IPW for initial comparisons of the effect of satellite orbit accuracies: Bernese (Rothacher 1992), developed by University of Bern (UB); GPS at Massachusetts Institute of Technology (GAMIT) (King and Bock 1996), developed by MIT and Scripps Institution of Oceanography (SIO); and Page3 (Mader et al. 1994), developed by NOAA's National Ocean Service Geophysical Laboratory (NOS/GL) in Silver Spring, Maryland. The same GPS dataset collected by FSL was distributed to all three agencies for independent processing. Table 2 outlines the organizations, orbits, software, IPW processing, and wet delay mapping techniques used in this evaluation. Variable wet delay mapping (π) is the technique described earlier that converts ZWD into IPW. Note that processing by NOS/GL included a constant wet mapping value of 6.5.

Because of the need for high-accuracy GPS satellite orbits for geodesy and geophysics (or the measurement of water vapor from GPS signal delays), an organization known as the International GPS Service for Geodynamics (IGS) was established to calculate high quality orbits for all GPS satellites and provide related geodetic and satellite tracking information to the GPS community. Three types of GPS satellite orbits are currently available from IGS centers, each with different accuracy and availability. Precise orbits are the most accurate (12–15 cm) and take 1–2 weeks to produce. Rapid orbits, have somewhat lower accuracy (25 cm), but are available within 24 h. In the past couple of years, real-time needs have pushed the development of predicted or forecast satellite orbits. These orbits are the least accurate of the three but are available in near–real time. Only precise and rapid orbits are analyzed in this paper as they relate to IPW accuracies.

Comparisons of the three different geodetic software packages using precise orbits show that there are no significant differences between UB and SIO (Fig. 3). The NGS data have a comparable trend, but the standard deviations were much larger. We believe this result is due primarily to the lack of a variable wet delay mapping function (Table 2). Precise versus rapid orbits are shown only for SIO processing (Fig. 4). Similar com-

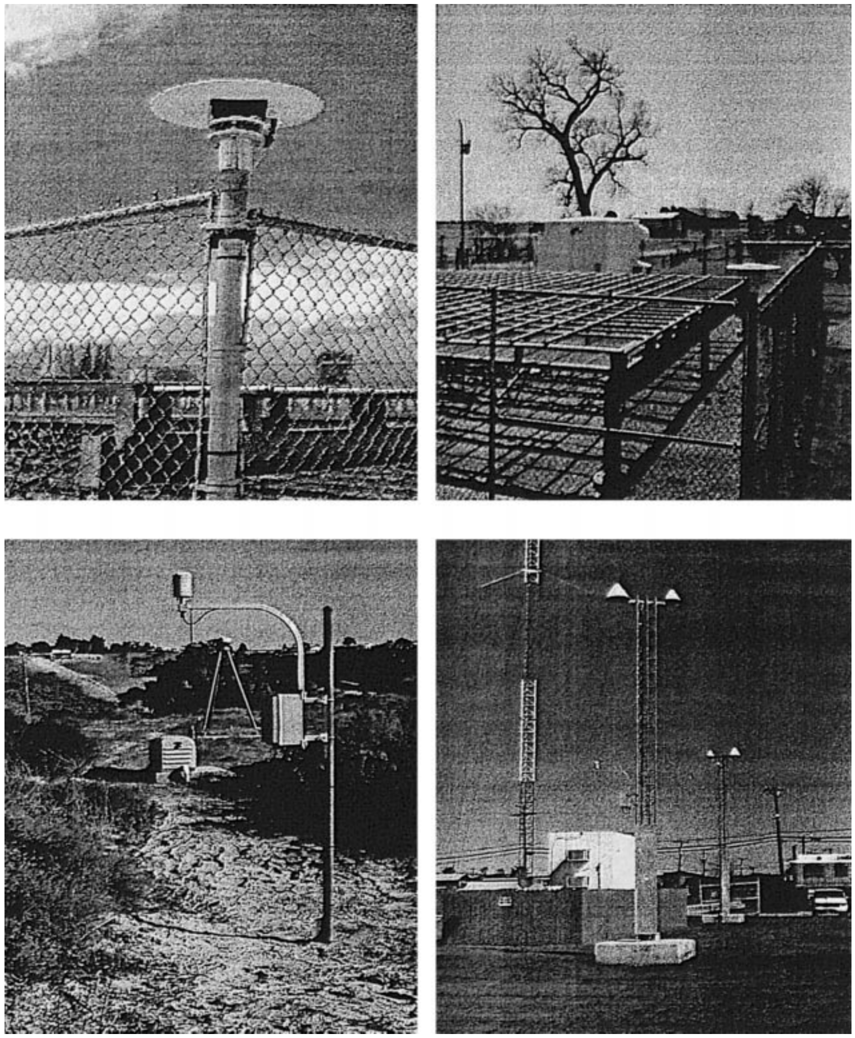

FIG. 2. GPS–IPW sites: (a) close-up of GPS antenna, PLTC; (b) NPN GPS–IPW site, LMNO; (c) GPS–IPW sister NOAA site, SIO3; (d) GPS–IPW DoT NDGPS site, ARP3.

parisons of Bernese and Page3 processing, using precise orbits, to SIO rapid orbits show more variability. We believe this variability is due to the differences in processing software (not discussed in this paper). Figure 5 shows the comparison of the SIO precise IPW data with the radiosonde IPW. The offset between the GPS and the radiosonde has been attributed to the fact that early in the development of the GPS–IPW, the satellites were only tracked down to 15° above the horizon. This was done to eliminate the potential for noisy data caused by multipath at low elevation angles. Studies since have shown that tracking GPS satellites down to 7° improves the agreement, although data still need to be checked for increased multipath.

These studies show that IPW measurements using rapid orbits are well within the accuracy requirement of 1 mm when compared to radiosonde data. Currently, real-time orbits are not of sufficient accuracy, with a 2-mm mean difference compared to radiosondes and a significantly larger standard deviation.

The results described above were used in determining which geodetic processing software to incorporate into the GPS–IPW design. Since there were no significant differences found between IPW calculated using Bernese or GAMIT geodetic software, additional factors were considered including cost and perceived ease of use. FSL has acquired, installed, and implemented GAMIT (whose development was partially funded by the United States government) on a workstation operating under Solaris 2.5.

b. GPS IPW accuracies

Initial development of the GPS technique by Bevis et al. (1992) relied on at least one collocated WVR as an independent reference. Called the ''levered'' tech-

TABLE 1a. NOAA GPS–IPW network NOAA profiler network sites.

Site Id/No.	Location	Lat (°N)	Long (°W)	Elev (m)	Date online
CENA 1	Central, AK	65.5	−144.68	272	24 Sep 1997
DQUA 2	DeQueen, AR	34.06	−94.17	195	17 Dec 1996
GDAC 3	Granada, CO	37.46	−102.1	1155	17 Oct 1996
GNAA 4	Glennallen, AK	62.11	−145.97	573	17 Jul 1997
HBRK 5	Hillsboro, KS	38.18	−97.17	447	5 Jul 1996
HKLO 6	Haskell, OK	35.4	−95.51	218	19 Apr 1995
HVLK 7	Haviland, KS	37.39	−99.05	648	29 May 1996
JTNT 8	Jayton, TX	33.01	−100.58	707	22 May 1996
LMNO 9	Lamont, OK	36.41	−97.28	306	22 Nov 1994
NDSK 10	Neodesha, KS	37.22	−95.38	255	6 Sep 1996
PATT 11	Palestine, TX	31.46	−95.42	119	23 May 1997
PLTC 12	Platteville, CO	40.1	−104.43	1524	3 Nov 1994
PRCO 13	Purcell, OK	34.58	−97.31	331	28 Nov 1995
TCUN 14	Tucumcari, NM	35.05	−103.36	1241	23 Nov 1997
TLKA 15	Talkeetna, AK	62.31	−150.42	151	21 Jul 1997
VCIO 16	Vici, OK	36.04	−99.13	648	13 Apr 1995
WLCI 17	Wolcott, IN	40.81	−87.05	212	12 Sep 1998
WNFL 18	Winnfield, LA	31.53	−92.46	93	23 May 1997
WSMN 19	White Sands, NM	32.24	−106.2	1224	28 Apr 1995

TABLE 1b. NOAA GPS-IPW network sister NOAA sites.

Site Id/No.	Location	Lat (°N)	Long (°W)	Elev (m)	Date online
AOML 20	Miami, FL	25.74	−80.17	26	20 Nov 1997
NDBC 21	Stennis, MS	30.36	−89.61	6	26 Jun 1996
SEAW 22	Sand Point, WA	47.68	−122.26	21	16 Dec 1997
SIO3 23	La Jolla, CA	32.86	−117.25	71	19 Dec 1997
WES2 24	Westford, MA	42.61	−71.49	103	1 May 1997

TABLE 1c. NOAA GPS–IPW network USCG DGPS/DoT NDGPS sites.

Site Id/No.	Location	Lat (°N)	Long (°W)	Elev (m)	Date online
ARP3 25	Aransas Pass, TX	27.84	−97.06	4	2 Mar 1998
CCV1 26	Cape Canaveral, FL	28.46	−80.54	4	3 Aug 1998
CHA1 27	Charleston, SC	32.76	−79.84	3	21 Jul 1998
EKY1 28	Egmont Key, FL	27.6	−82.76	3	16 Apr 1998
ENG1 29	English Turn, LA	29.88	−89.94	4	2 Feb 1998
FMC2 30	Fort Macon, NC	34.7	−76.68	3	29 Jul 1998
GAL1 31	Galveston, TX	29.33	−94.74	4	4 Mar 1998
KYW1 32	Key West, FL	24.58	−81.65	3	23 Jan 1998
MOR1 33	East Moriches, NY	40.79	−72.75	3	15 Nov 1998
MOB1 34	Mobile Point, AL	30.23	−88.02	5	3 Feb 1998
SHK1 35	Sandy Hook, NJ	40.47	−74.01	5	27 Apr 1998

Atmospheric Radiation Monitoring Sites: 5, 6, 7, 9, 13, 16. National Weather Service Offices: 12, 13, 21, 22 (Denver, CO; Norman, OK; Slidell, LA; Seattle, WA, respectively).

TABLE 2. GPS water vapor processing tools and techniques.

Organization	Orbit	GPS processing package	IPW processing technique	Variable wet delay mapping?
UNAVCO	CODE (precise)	Bernese	Absolute	Yes
UNAVCO	CODE (precise)	Bernese	Levered	Yes
NOS/GL	NGS (precise)	Page3	Absolute	No
UH/SIO	SIO (precise)	GAMIT	Absolute	Yes
UH/SIO	SIO (rapid)	GAMIT	Absolute	Yes

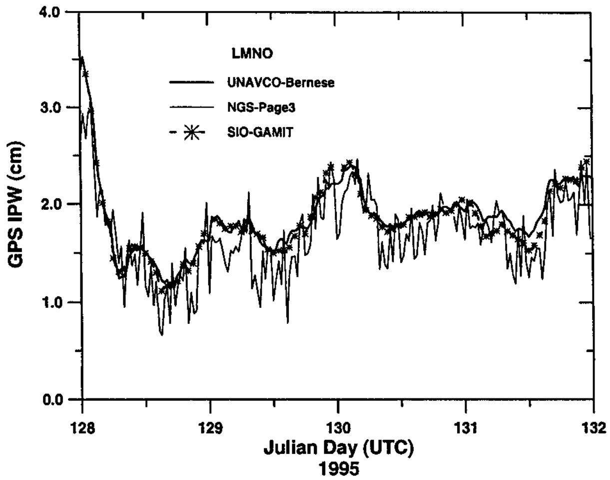

FIG. 3. Time series of SIO–GAMIT, NGS-Page3, UNAVCO–Bernese IPW calculations using precise orbits: LMNO, 8–12 May 1995.

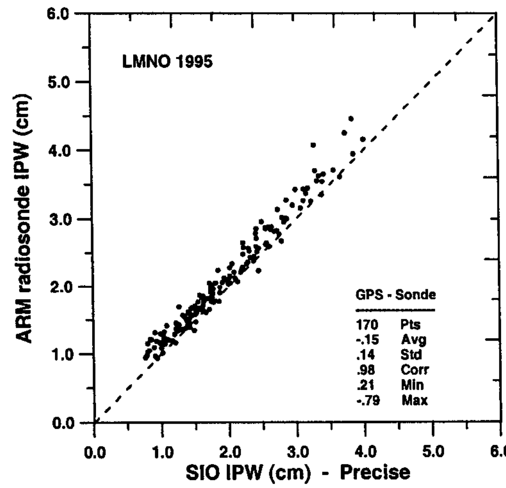

FIG. 5. SIO–GAMIT IPW using precise orbits vs radiosonde IPW: LMNO, 18 Apr–17 May 1995.

nique, a WVR at a reference site provided an independent measurement of precipitable water vapor in the atmosphere and thus an objective method of resolving the uncertainty between the observed signal delay caused by the water vapor in the atmosphere and the absolute quantity of water vapor in the troposphere responsible for that delay. Researchers at the University of Hawaii and SIO, in collaboration with UNAVCO, developed a method of calculating IPW independently of the WVR. This technique, called the ''absolute'' method (Duan et al. 1996), requires that the location of one GPS receiver be known to a high accuracy and this station be located at least 1000 km away from the receiver being used to measure water vapor. Despite the slight offset seen in Fig. 6, an artifact of the WVR calibration, comparisons confirm that the absolute method is as accurate as the levered method, thereby, eliminating the requirement for a WVR. This also allows one to determine the accuracy of the GPS independently of the WVR.

In order to evaluate the accuracy of GPS IPW, data were acquired from ARM radiosonde and WVR sites encompassing the spring and fall 1995 Intensive Operational Periods (IOPs). These ARM sites are located typically within 1 km of the nearest NPN/GPS–IPW site. Minimal quality control was done on these data to check for obvious outliers and to eliminate them from the comparison. Radiosonde IPW data were calculated by integrating the moisture profile. ARM radiosonde data for these comparisons represent one flight per day at 1730 UTC for HBRK, HKLO, VCIO, PRCO during non-IOP periods and seven flights per day (0230, 0530, 0830, 1130, 1430, 2030, 2330 UTC) for IOPs. At LMNO five flights (0530, 1130, 1430, 1730, 2030 UTC) were made on non-IOP days, increased to seven flights for IOPs.

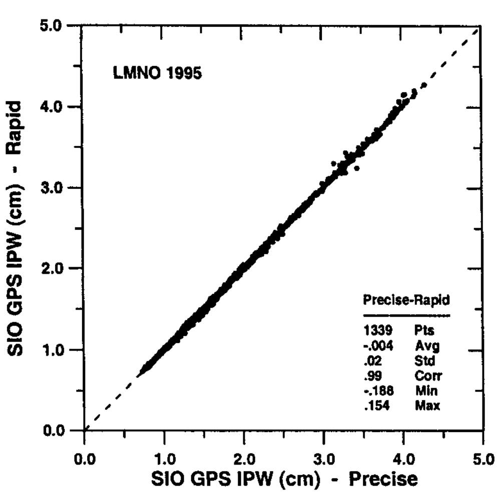

FIG. 4. Precise vs rapid orbit IPW comparison using SIO–GAMIT: LMNO, 18 Apr–17 May 1995.

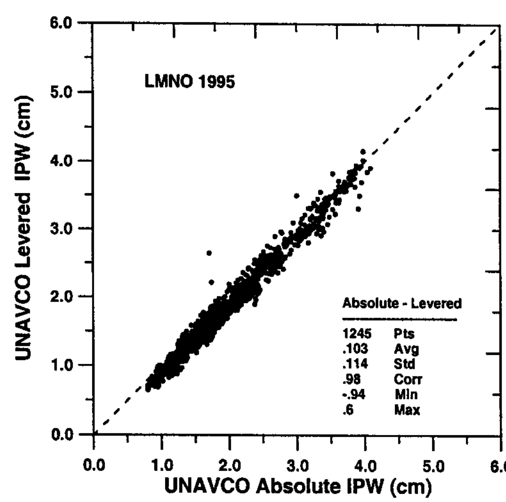

FIG. 6. UNAVCO–Bernese GPS absolute IPW vs levered IPW comparison: LMNO, 18 Apr–17 May 1995

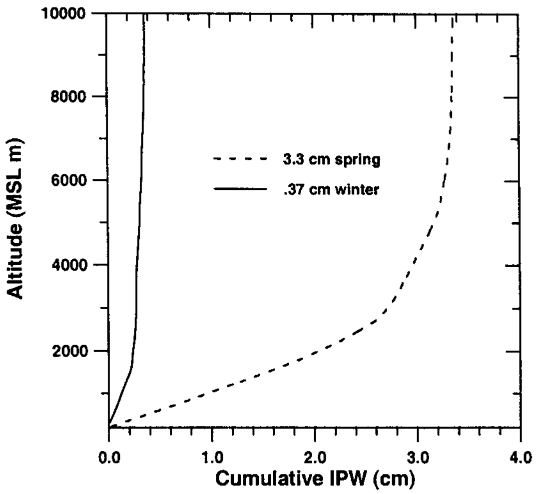

FIG. 7. Cumulative IPW profiles for a winter and spring case: LMNO.

Flights not reaching a maximum altitude corresponding to 300 mb (~9 km) were eliminated from the comparisons. This is based on the assumption that more than 95% of the IPW is confined to the lowest 8–10 km of the atmosphere. Figure 7 shows examples of dry wintertime (<0.5 cm) and wet springtime (>3.0 cm) moisture profiles, which confirms this assumption for most conditions expected in these data. Note that 90% of the moisture is actually contained in the lowest 4–5 km above the surface for both cases. The 5-min WVR data were averaged to 30 min and then matched in time to the GPS–IPW data. Both the WVR and GPS IPW data were then matched to the closest radiosonde launch time (±15 min) for comparison.

There are inherent differences in the measurement techniques of the GPS, radiosondes, and WVR systems.

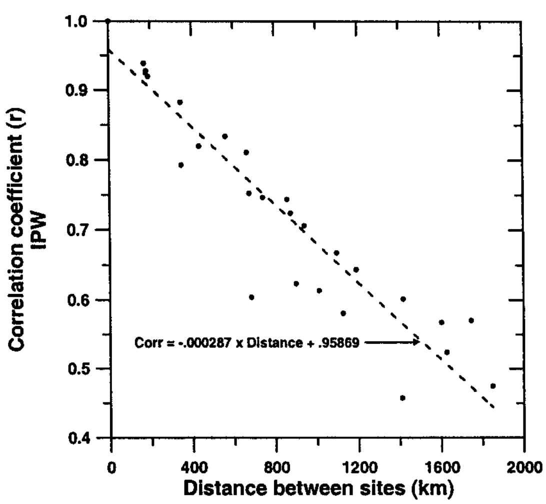

FIG. 8. Correlation of IPW between GPS–IPW sites relative to their separation distance, 1998: LMNO, SIO3, PLTC, NDBC, WNFL, VCIO, GDAC, HBRK, WSMN, HVLK, PRCO, SEAW.

TABLE 3. Water vapor IOP spring 1995: LMNO.

	Radiosonde–WVR differences (cm)	Radiosonde–GPS differences (cm)	WVR–GPS differences (cm)
Mean	−0.26	−0.11	−0.10
Standard deviation	0.19	0.18	0.18
Correlation	0.97	0.98	0.98
Minimum	−0.61	−0.61	−1.07
Maximum	0.87	0.87	1.46
No. of points	535	535	5578

Water vapor measurements from GPS data are in fact a volume average dependent on the orientation of four to eight GPS satellites in view at any particular time and the depth of the moisture. Based on the moisture profiles in Fig. 7 and a GPS satellite tracking cutoff angle of 7°, the GPS views a maximum horizontal distance of 32 km at an altitude of 4 km. In comparison, the WVR is pointed vertically with a beamwidth of 5°, which corresponds to less than 0.5 km at an altitude of 4 km. It should be noted that the method of calibration for the WVR makes an assumption of water vapor horizontal homogeneity (Westwater et al. 1990). Finally, the radiosonde is an in situ sensor drifting with the wind. Assuming a 5 m s^{-1} ascent rate and a 5 m s^{-1} mean wind, the radiosonde package will be 4 km downwind at 4-km altitude. Lilly and Perkey (1976) discusses the spatial variability of moisture in Oklahoma during thunderstorm season showing a moderate to strong correlation for distances on the order of 50 km. This is confirmed by the GPS–WISP94 data where correlations of more than 0.9 exist between Platteville, Erie, and Denver, Colorado. These three sites are separated by 30–50 km. Similar calculations for the GPS–IPW network in 1998 (Fig. 8) indicate a moderate to strong correlation for distances out to 800 km falling off in a linear fashion. It should be noted that frontal passages or significant mesoscale weather events are often associated with strong moisture gradients whose horizontal scales are much less than 50 km (Melfi et al. 1989).

Results from over 30 days of comparisons between the radiosondes, WVRs, and GPS at the four inner-network NPN sites (LMNO, VCIO, HBRK, HKLO) are presented in Tables 3 and 4 for the spring and fall 1995

TABLE 4. Water vapor IOP fall 1995: Lamont, OK.

	Radiosonde vs WVR differences (cm)	Radiosonde vs GPS differences (cm)	WVR vs GPS differences (cm)
Mean	0.185	0.19	0.002
Standard deviation	0.164	0.208	0.191
Correlation	0.97	0.96	0.97
Minimum	−1.23	−0.64	−0.98
Maximum	0.81	1.76	1.47
No. of points	592	592	4552

water vapor IOPs. Note the strong correlations (>0.95) for both periods in all three sets of comparisons. Scatterplots (not shown) show a tendency for increased differences at higher IPW. These differences are comparable to those found for WVR and radiosonde comparisons by Westwater et al. (1989) and are still within accuracies expected for WVR (0.8-mm rms) and radiosonde (1.1-mm rms) IPW measurements. There is a curious difference between the two seasonal comparisons. During the spring period, radiosonde-derived IPW are systematically higher than both the WVR- and GPS-derived values, while for the fall period this difference is reversed with radiosonde data systematically lower. No clear-cut answer has been found for these differences, although water vapor spatial and temporal variability probably plays a role. The fact that these results include four different sites with different WVRs, different radiosonde packages and operators, and different GPS receivers suggests that there may be indeed a seasonal effect.

c. GPS IPW impact on weather forecasts

Two important GPS–IPW project goals include assessing the sensitivity of numerical weather predication models to GPS-integrated precipitable water vapor measurements and determining the impact of these data on weather (especially cloud and precipitation) forecasts. Although current IPW data with an accuracy sufficient for model use are only available with 24-h latency, this is sufficient to test forecast models in a post run fashion. It is also assumed that in the very near future real-time orbit accuracy will improve, thereby improving IPW accuracies from these orbits, reducing the data latency to 30–60 min. As prerequisites to accomplish these goals, we must establish a technique to assimilate GPS–IPW data into analyzed moisture fields, perform collocation studies and sensitivity tests, and evaluate the results. Most of these activities are under way at the NOAA's FSL/Forecast Research Division (FRD) in Boulder, Colorado, using the Mesoscale Analysis and Prediction System (MAPS; Benjamin et al. 1994, 1996, 1998a, available online at http://maps.fsl.noaa.gov/). MAPS is the research version of the Rapid Update Cycle (RUC) that runs operationally at the National Centers for Environmental Prediction. MAPS/RUC is a high-frequency, state-of-the-art atmospheric data assimilation and numerical forecast system that provides frequent updates of tropospheric conditions over the contiguous United States and adjacent regions. Plans are being developed to carry out these activities at smaller scales using the Local Area Prediction System (Albers et al. 1996, available online at http://laps.fsl.noaa. gov/).

1) Data assimilation

Two different methods to assimilate GPS IPW data into MAPS/RUC are being evaluated: optimal interpolation (OI) using the general procedure proposed by Gandin (1963), and three-dimensional, variational analysis (3D-var) using the method described by Eyre (1994). While all comparisons and analyses have thus far been accomplished using OI, the intent is to perform future sensitivity tests and evaluations in both MAPS/RUC and LAPS using 3D-var.

In OI, GPS–IPW data are read into a previously calculated background field. Either the background or the IPW observations are adjusted for equal surface pressure, and the two are subtracted to calculate IPW residuals. A univariate OI analysis of the IPW residuals is performed using GPS observational errors estimated from statistical comparisons of GPS–IPW with other observing systems, such as radiosondes, forecast errors, and horizontal covariance estimated from those forecast errors for single-level moisture variables. This results in an IPW increment field from which a percentage change can be calculated at each model grid point. The IPW increment is then distributed to the background forecast profile of water vapor such that the absolute moisture at each level will be adjusted (up or down) by an equal percentage. Note that the shape of the moisture profile remains unchanged. The results are checked to ensure that supersaturation does not occur at any level. If it does, the vertical moisture distribution in the column is adjusted so that the correct change in IPW is still achieved, but without supersaturation. The analysis is then continued using the adjusted single-level moisture observations.

2) Collocation studies and sensitivity tests

Collocation studies involve the comparison of GPS–IPW with model precipitable water vapor output using upper-air moisture data from radiosondes, Geostationary Operational Environmental Satellites (GOES), and (to a lesser extent) the Polar Orbiting Environmental Satellites.

Prior to the first model comparisons, a set of GOES data was collected for comparison with GPS. GOES data have the potential to provide a significant impact to model forecasts due to the high temporal resolution but are limited to clear-sky conditions. They are also more accurate over water than land due to the larger variability of the surface brightness temperatures over land. GPS measurements also have high temporal resolution but are not limited by clouds. Figure 9 shows comparisons of GOES satellite, GPS, and radiosonde IPW data. For these comparisons only the infrared satellite sensors were used. Statistical results (Table 5) show high correlation and a 2–3-mm offset between the GPS and satellite IPW. We believe this offset is due to the variability of the surface brightness temperature measured by the satellites and the accuracies of surface temperatures used to initialize the satellite retrieval. Periods in Fig. 9 with no satellite data are cloudy periods as confirmed from radiosonde flights where the relative humidity

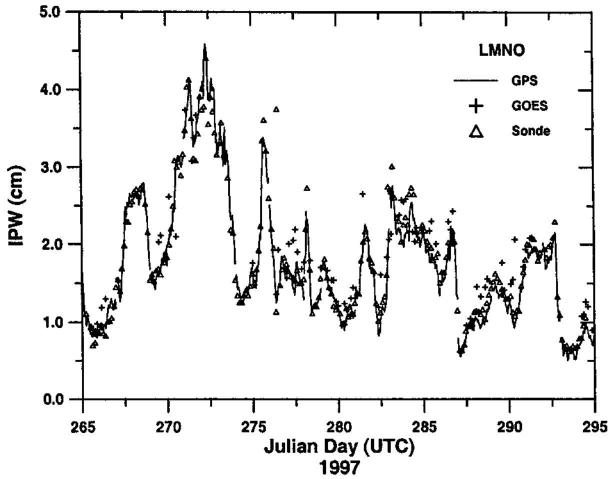

FIG. 9. GPS–IPW, GOES–IPW, and ARM radiosonde IPW time series comparison: LMNO 1997.

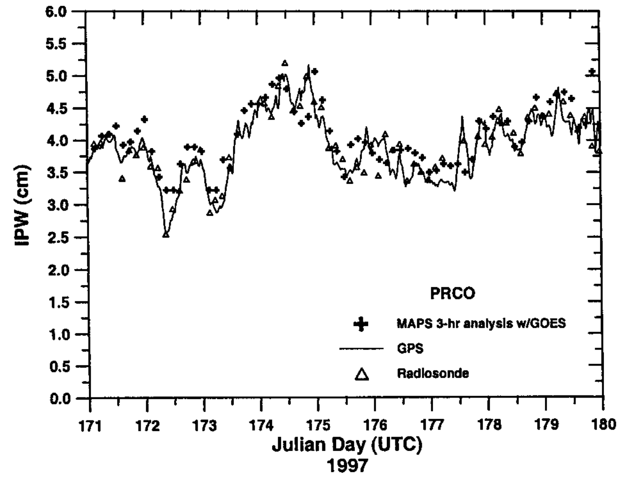

FIG. 10. MAPS 3-h analysis IPW, GPS–IPW, and ARM radiosonde IPW time series comparison: PRCO 1997.

(RH) was more than 95% at several consecutive levels within the profile. Note how the GPS–IPW and radiosonde data still track for these periods.

Figure 10 is a plot comparing MAPS analysis (not forecast) output IPW values every 3 h with those derived from GPS–IPW observations. The MAPS IPW output data are interpolated to the location of the NPN site near Purcell, Oklahoma, between 20–29 June 1997 (days 171–180). Moisture data assimilated into MAPS/RUC included all available NWS radiosonde and surface observations along with cloud-free GOES, precipitable water estimates. TIROS Operational Vertical Sounder and GPS–IPW data were not included. These model results are compared with GPS–IPW at the profiler site, and radiosonde-derived IPW data acquired at the U.S. Department of Energy ARM CART facility located approximately 1 km north of the profiler site.

The results portrayed in Fig. 10 are typical of those found for other GPS–IPW sites. In general, we see good agreement between the analyzed data and the observations with occasional differences that sometimes exceed 30%. Table 6 quantifies the differences between MAPS analyses and GPS, MAPS analyses and radiosondes, and radiosondes and GPS. With high confidence, the mean differences between the GPS and radiosonde observations are smaller than the differences between the MAPS analyses and the (GPS or radiosonde) observations. One explanation of this is that even in one of the most data-rich regions on earth, the central United States, there is room for improvement of both the assimilation techniques and physics in the mesoscale model descriptions of the moisture field. A coastal site, NDBC, comparison shows an offset and variability between RUC and GPS of twice that found inland. Coastal regions, where IPW variability and absolute magnitude are usually greatest, are known to have the largest model errors (Benjamin et al. 1998b). Since we believe that the accuracy of MAP/RUC is typical of state of-the-art NWP models, we conclude that this is further confirmation of the findings of the U.S. Weather Research Program First Prospectus Development Team regarding the need for additional moisture observations to improve numerical forecasting, especially quantitative precipitation forecasting (USWRP P1 1995).

Although sensitivity tests of short-range MAPS precipitation and moisture forecasts to GPS IPW observations at FSL are just beginning (Benjamin et al. 1998b), several conclusions have already been reached.

- Sensitivity experiments must include all available datasets (e.g., GOES IPW) to avoid unrealistically large impact of GPS–IPW on the models.
- GOES IR water vapor data have limitations. Most significant is probably that they are only available in cloud-free areas. From a forecasting perspective, the need for IPW information is usually highest in the cloudy regions. Other limitations include a slightly moist bias with respect to other observing systems

TABLE 5. GPS and satellite comparisons.

Combination	No. of points	Mean differences (cm)	Std differences (cm)	Correlation (r)
Sonde–GPS	752	0.06	0.20	0.97
GOES–Sonde	384	0.15	0.27	0.91
GOES–GPS	560	0.23	0.23	0.93

TABLE 6. Differences between integrated precipitable water vapor from 3-h MAPS/RUC analyses, GPS, and radiosondes at Purcel, Oklahoma, 20–29 Jun 1997.

Combinations	No. of points	Mean differences (cm)	STD differences (cm)	Min/Max (cm)
MAPS–GPS	71	0.18	0.25	0.55/−0.69
MAPS–Sonde	64	0.135	0.32	1.26/−0.63
Sonde–GPS	64	0.049	0.20	0.55/−0.40

(Wolfe et al. 1996), and that these data cannot (presently) be used when surface pressure is less than 950 mb due to the current unavailability of surface pressure for GOES–IPW retrievals (S. G. Benjamin 1998, personal communication).
- Typical forecast errors over the central United States are small (≈2 mm). This means that very accurate IPW data from GPS are needed to make a positive impact on forecast accuracy.
- More GPS–IPW observations are required to facilitate the forecast impact assessments. The best locations for these measurements will be along the coasts where current forecast errors are greatest.

To date, only one forecast experiment has been analyzed. It involved a parallel MAPS/RUC run, with and without GPS–IPW, to test 12-h forecast sensitivity. The experiment (Benjamin et al. 1998b) resulted in some fairly strong, local variations in convective precipitation on the order of 6–8 mm seen as both increases and decreases. Another interesting feature seen in the precipitation field was widespread propagation of the effects of GPS–IPW coupled with gravity wave propagation throughout the model domain. This was observed in the southeast quadrant (southeastern United States) of the model domain where the atmosphere is conditionally unstable and the initiation of convection has been changed.

d. Automated GPS processing

Figure 11 is a diagram of the GPS–IPW data flow and processing. As discussed before, we are taking advantage of the NPN infrastructure shown by the smooth rectangle where a GPS receiver and antenna were deployed at NPN sites in combination with the existing PSOS and NPN communications link. New site configurations have been incorporated into the GPS–IPW network since the initial integration at NPN sites. These include using a GPS surface observing system (GSOS) (Gutman et al. 1996) designed in coordination with the National Data Buoy Center for installation at NPN sites without a PSOS and at USCG DGPS sites depicted by the ovals. This surface meteorological package (Fig. 12) consists of pressure, temperature, and relative humidity sensors with a memory capacity similar to the GPS receivers (7–10 days). Pictures of field mounted GSOS units can be seen in Figs. 2c and 2d. The rectangles represent the GPS Hub as it now exists. The GPS data acquisition computer, GPS Hub, is located in Boulder, Colorado, and performs the following activities:

- remotely monitors the status of all GPS receivers;
- automatically initiates the downloading of GPS data every 30 min;
- takes corrective action to restart a receiver in the event of a malfunction;

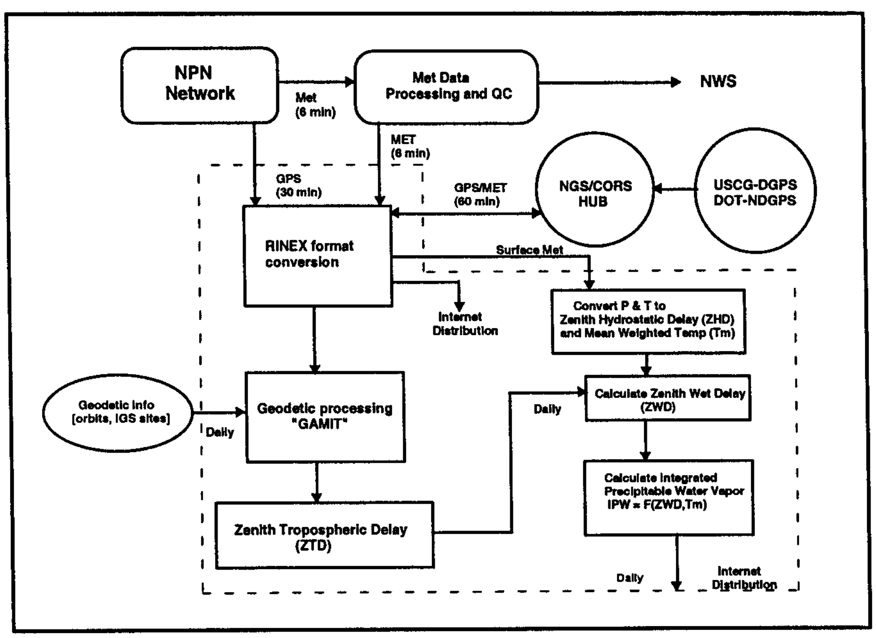

FIG. 11. GPS–IPW data flow–processing diagram. Region within the dotted line is controlled by the GPS Hub.

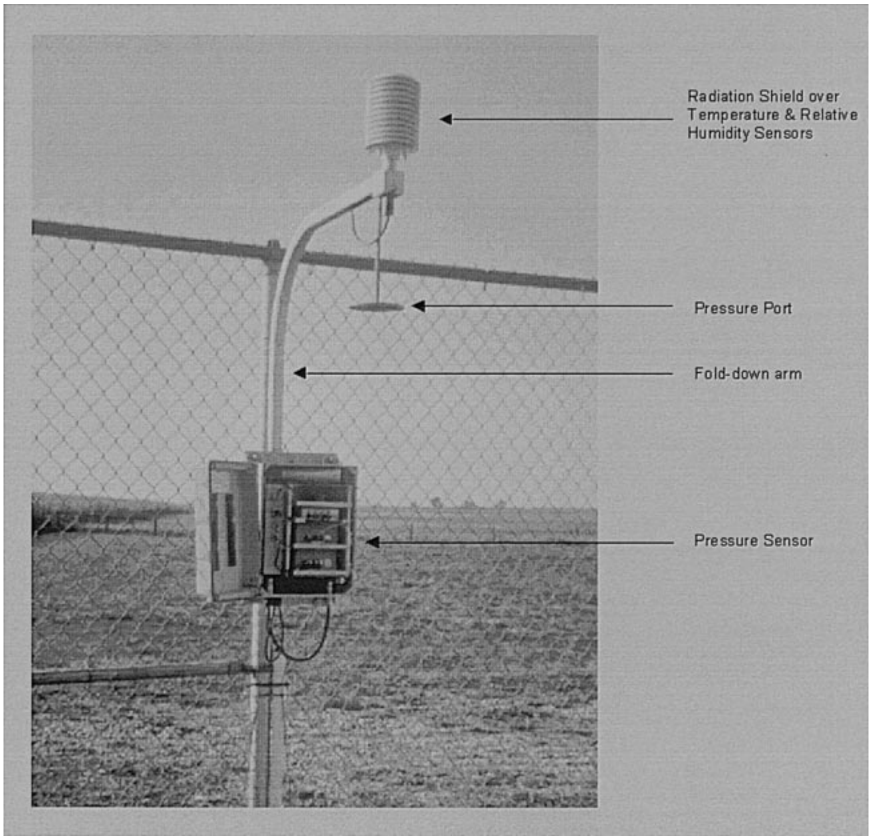

FIG. 12. GPS Surface Observing System: temperature, relative humidity, and pressure.

- in the event of a communications failure, automatically recovers GPS data stored on receivers once communications are reestablished;
- notifies an operator in the event of an unrecoverable error;
- automatically receives or initiates the transfer of surface meteorological data;
- converts the raw GPS and surface meteorological data into the Receiver Independent exchange Format (RINEX);
- places the RINEX data into an anonymous ftp (file transfer protocol) directory for access by outsides agencies, including NGS as part of the Continuously Operating Reference Stations;
- automatically FTP rapid orbit files and all other files from SIO necessary for GAMIT processing; and
- automatically processes GPS and meteorological RINEX data from all sites into water vapor data using geodetic and water vapor processing software.

The GPS Hub also tracks system performance, reliability, and maintainability. This system operates for long periods without intervention or calibration, collects data continuously as per GPS receiver preprograming, and stores data for approximately 7 days on the GPS receiver in the event of a communications failure. An example of the final output containing geodetic and meteorological information is shown in the appendix of this paper. Processing time is dependent on the total number of stations.

Processing of IPW using GAMIT at ERL in Boulder, Colorado, began in March 1996. From March until December 1996, SIO and ERL made parallel runs. Over this period the GPS Hub was refined for automatic unattended operation. Comparisons with other sources of IPW (NWS, ARM/CART) continued. Figures 13–15 show some recent comparisons of GPS–IPW to other measurement techniques. This type of comparison is necessary to build a baseline relative to existing water vapor monitoring systems and determine if in fact we have a stable operational system. These data are also the first long-term high temporal resolution GPS–IPW dataset and provide seasonal information as well as form the basis for an all-weather climatological dataset. Figure 13 is a time series of the IPW from GPS, radiosonde, and WVR data. The WVR data are 30-min-average periods of WVR data with what appear to be spikes were shown intentionally. The large spikes most likely represent moisture on the reflecting mirror. It should be noted that many of the smaller variations in the WVR time series correlate with the GPS time series and therefore depict true small-scale moisture features. Radiosonde data are shown for both an ARM (PRCO) and

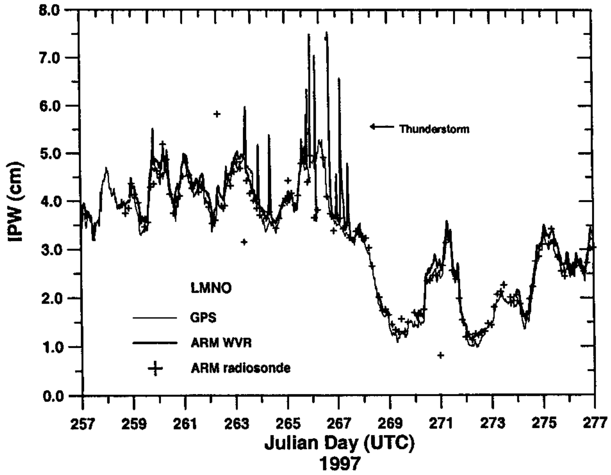

FIG. 13. GPS–IPW, ARM radiosonde IPW, and WVR IPW time series: LMNO 1998.

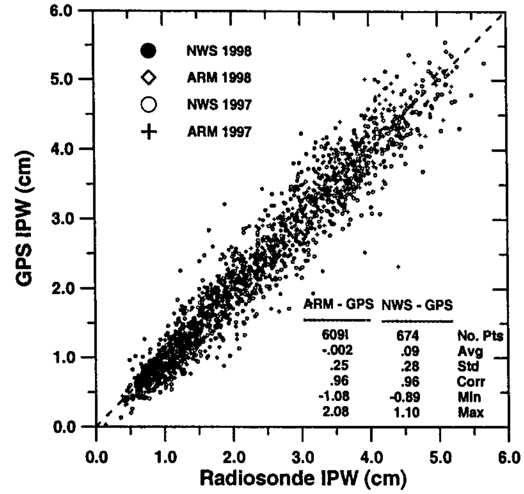

FIG. 14. ARM (PRCO) and NWS (Norman, OK) radiosonde IPW vs GPS–IPW (PRCO) scatterplot 1997–98. Statistics for 1997 only.

NWS site (Norman, Oklahoma) in Fig. 14. Despite the spatial separation of some 40 km to the NNE, the NWS data are still highly correlated with a mean difference of less than 1.0 cm. A comparison of GPS–IPW to a WRV for 1997 (Fig. 15) depicts even better agreement and less scatter than with the radiosondes (Fig. 14). This is not unexpected since the radiosonde drifts with the wind and might be measuring a different portion of the atmosphere than either the GPS or WVR. By comparing these recent results to the initial results from 1995, found in Tables 3 and 4, we can see slight improvement in the differences and correlations. These improvements are primarily a result of improvements to the GPS processing. As in the initial 1995 comparisons, radiosonde and WVR data have been minimally quality controlled. Westwater et al. (1998) presents results from the fall 1997 Water Vapor IOP at Lamont, Oklahoma. Extensive effort was made to calibrate the WVRs and to quality control all comparison data sets. IPW comparisons for this period show differences of less than 0.05 cm IPW. This accuracy, as stated in Westwater et al. (1998), can be further improved in the algorithms and by establishing the ultimate accuracy of each instrument.

5. Conclusions

GPS is a cost-effective and reliable means of obtaining continuous IPW measurements over land. GPS–IPW systems are capable of measuring IPW in the atmosphere with an accuracy better than a few millimeters (with respect to a radiosonde or WVR) over distances of about 1000 km. These GPS systems operate continuously and function reliably under moist (>4.0 cm) and dry (<0.25 cm) IPW conditions.

Our results indicate that the differences between IPW calculated with precise orbits and rapid orbits are negligible, usually within 0.5 mm. Neither accuracy nor precision are lost by using rapid orbits. In the past year, predicted orbit accuracies have improved to the point where calculating IPW in real time, with approximately the same level of accuracy now achieved using rapid orbits, appears imminent. Work on improving predicted orbits continues at institutions worldwide, along with the techniques to continuously monitor predicted orbit accuracy and to perform on-the-fly quality control. These are necessary before real-time GPS IPW can be implemented operationally by NOAA or other meteorological services.

Preliminary results from comparisons with satellite data suggest that GPS–IPW and satellites are complementary systems. GPS–IPW can provide information in cloudy regions and also serve as a surface-based reference value that should improve the accuracy of satellites over land. A collaborative research effort with NOAA's National Environmental Satellite Data and In-

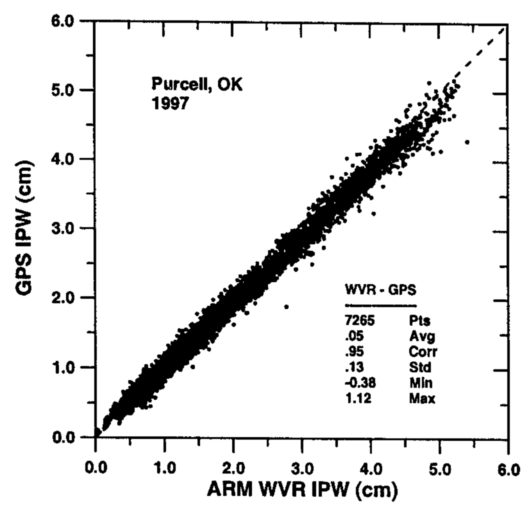

FIG. 15. ARM WVR IPW vs GPS–IPW scatterplot: PRCO 1997.

formation Service continues to compare surface- and satellite-based IPW measurements and determine if techniques can be developed to use surface-based GPS measurements to improve satellite water vapor retrievals. It is hoped that GPS–IPW sites along the coasts can be used to seamlessly merge offshore and onshore satellite-derived moisture fields along with filling data voids in cloudy regions. Combined, these efforts should provide accurate high temporal and spatial IPW data to numerical models for improved cloud and precipitation forecasts. The models are capable of distributing the total integrated GPS measurement both vertically (profile) and horizontally throughout the model domain. Initial comparisons with model runs show significant differences during periods of rapid change and large variability which suggests GPS–IPW input should improve model results.

The NOAA GPS-IPW network has been in operation since 1994. This network has grown from 3 initial sites to 35 operational sites and by January 2000 to 55 sites with the complete instrumentation of the NPN. Geodetic processing software has been automated to produce 48–30-min IPW values on a daily basis available to the scientific community.

Future plans for this technology are numerous. A growing number of federal agencies are deploying GPS receivers for reasons other than weather forecasting and climate monitoring. Many of these sites will become GPS–IPW sites through the addition of the GSOS. In a similar fashion, existing surface meteorological sites, such as the NWS Automated Surface Observing System, are being considered as possible GPS–IPW sites with the addition of GPS receivers and antennas. These combined efforts will leverage the extensive investment in GPS and surface meteorological equipment already made to aid the meteorological community in monitoring atmospheric moisture.

Acknowledgments. We would like to thank members of other organizations, including Dr. Yehuda Bock and Peng Fang of Scripps Institute of Oceanography for their unending efforts in helping to automate the GAMIT processing on GPS Hub. Dr. Mike Bevis and Dr. Steve Businger of the University of Hawaii for their guidance and foresight in the development of the GPS technique. Dr. Chris Rocken and Teresa van Hove of UNAVCO for their help in the early stages of this project. Bill Strange and Neil Weston of NGS for their assistance in accessing data from the CORS network. Finally, we would like to thank Anthony Simon who was the person directly responsible for getting the GAMIT code running on our system and writing software to download the GPS and meteorological data necessary to calculate IPW.

APPENDIX

GPS–IPW Output File

Site	Year	JJJ.dd	hhmmss UTC	IPW cm	Press mb	*T* C	RH %	TD m	WD m	HD m	T_m K	PI	FE	Flags
LMNO	1997	085.8333	20:00:00	0.457	985.60	19.10	29.0	2.275517	0.0285	2.2470	280.512	6.247	0.6	
LMNO	1997	085.8542	20:30:00	0.508	985.00	19.20	27.0	2.277325	0.0317	2.2456	280.584	6.245	0.5	Mb
LMNO	1997	085.8750	21:00:00	0.514	984.50	19.30	28.0	2.276596	0.0321	2.2445	280.656	6.243	0.5	
LMNO	1997	085.8958	21:30:00	0.489	983.80	19.30	28.0	2.273418	0.0305	2.2429	280.656	6.243	0.6	
LMNO	1997	085.9167	22:00:00	0.491	983.40	19.50	28.0	2.272616	0.0306	2.2420	280.800	6.240	0.6	
LMNO	1997	085.9375	22:30:00	0.487	983.10	19.30	29.0	2.271700	0.0304	2.2413	280.656	6.243	0.6	
LMNO	1997	085.9583	23:00:00	0.493	982.90	19.20	33.0	2.271600	0.0308	2.2408	280.584	6.245	0.6	
LMNO	1997	085.9792	23:30:00	0.535	982.60	18.30	36.0	2.273653	0.0335	2.2401	279.936	6.259	0.7	

TD = ZTD, WD = ZWD, HD = ZHD, PI = π (variable wet delay mapping function), FE = formal error, and Flags = GPS Hub data processing flags.

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