8.3 # GPS WATER VAPOR OBSERVATION ERRORS

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1. INTRODUCTION

The primary purpose of this paper is to discuss some of the observation errors associated with retrieving integrated or total atmospheric column precipitable water vapor (IPW) from Global Positioning System (GPS) signal propagation delays caused by the neutral atmosphere. A secondary purpose is to show how occasional discrepancies between operational National Weather Service (NWS) radiosonde soundings and GPS precipitable water estimates impact a numerical weather prediction model assimilating both measurements.

Although GPS water vapor-observing systems provide no direct information about the vertical distribution of water vapor in the atmosphere, they have several advantages over other moisture sensing systems. Some of these advantages include high measurement accuracy; arbitrary temporal resolution; all weather operability (i.e. they provide data under conditions when other observations fail or provide degraded data); no requirement for calibration; high reliability; and low acquisition and maintenance costs. The purpose of this paper is to quantify the observation errors associated with estimating the GPS radio signal propagation delays caused by the neutral atmosphere, and retrieving integrated (total atmospheric column) precipitable water vapor from these delays.

Comparisons of GPS water vapor retrievals with other observing systems, especially radiosondes, have been carried out for 10 years. While uncertainties exist in the absolute water vapor estimation accuracy of any one system, it is firmly established that radiosondes and GPS are capable of providing total column PW estimates with 1-2 millimeter level accuracy under ideal circumstances. In this case, ideal circumstances are defined as radiosondes with known error characteristics launched by skilled technicians under cloud free (non-convective, non-precipitating) conditions in close proximity to one or more continuously operating GPS reference stations equipped with accurate surface meteorological sensors.

Until recently, routine comparisons between GPS water vapor estimates and operational NWS measurements have not been possible except under campaign conditions. As the NOAA ground-based GPS-Met network (Figure 1) expands however, routine comparisons with soundings from relatively close upper-air facilities (Figure 2) become possible. On the basis of a growing number of comparisons, we conclude that GPS sites that are close enough to upper-air sites to be within the same air mass most of the time can be used to quality control radiosonde moisture soundings. Since the most effective way to insure this is to locate the GPS-Met system in close proximity to the radiosonde launch facility, we believe that GPS-Met could be considered as a viable upgrade to the NWS Radiosonde Replacement System.

Fig 1. NOAA FSL GPS-Met network as of November, 2003. Map colors indicate NWS regions.

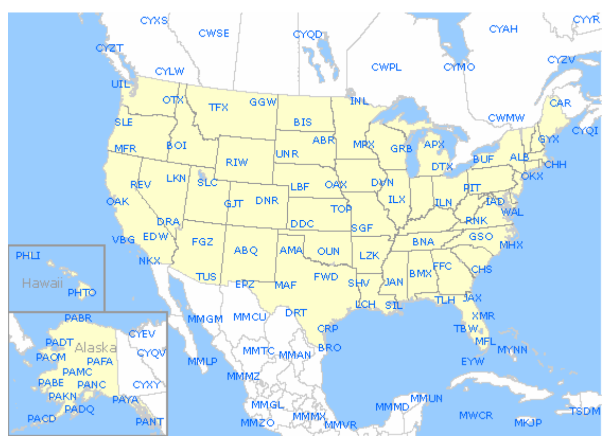

Fig 2. Operational rawinsonde network providing twice daily moisture soundings and other observations at 0 and 12 UTC. Diagram courtesy of the NCAR Research Applications Program (RAP) at http://www.rap.ucar.edu/weather/upper/.

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2. GPS WATER VAPOR RETRIEVAL ERRORS

The accuracy of GPS water vapor retrievals ultimately depends on two factors: the accuracy of the measurements needed to estimate the total refractivity of the neutral atmosphere from the GPS dual frequency carrier phase observables, and the accuracy of the assumptions and/or mathematical models used to perform these functions. The methods used to estimate the neutral (i.e. non-dispersive) atmospheric signal delays from the raw GPS carrier phase observables (described by Marshall et al., 2001, Duan et al., 1996, and others), and retrieve total column water vapor from them (e.g. Bevis et al., 1992, Saastamoinen, 1972) have been evaluated in great detail.

In general, theoretical estimates of the accuracy of GPS IPW retrievals (e.g. Baltink et al., 1998) are in good agreement with empirical results derived by comparing GPS water vapor estimates with those made by other moisture sensing systems (Gutman et al., 2003). Based on these comparisons, we can assume that the accuracy of the GPS observations and the assumptions and/or physical models used to make the retrievals are, in general, very good. Under certain circumstances, as described below, the measurements become noisy or the assumptions break down, and the accuracy of the IPW retrieval falls significantly.

NOAA's Forecast Systems Laboratory (FSL) uses the following steps to retrieve IPW from the GPS and ancillary surface meteorological observations at more than 280 stations in near real time:

- Collect GPS range and carrier phase observations;
- Collect surface meteorological observations;
- Acquire GPS satellite orbits and Earth orientation parameters;
- Process GPS data to estimate the zenith-scaled neutral atmospheric (tropospheric) signal delay;
- Separate the signal delay caused by water vapor in the atmosphere from the total tropospheric delay;
- Map the wet signal delay into precipitable water vapor.

2.1 *GPS Observations*

The GPS receiver makes continuous dual frequency (L1 = 1575.42 MHz and L2 = 1227.60 MHz) carrier phase observations that are used to form ionospheric-free double differences as described by Gutman et al., 2003. Sources of initial measurement error include receiver noise, site-dependant multipath, and antenna phase delays.

Receiver noise degrades performance and is generally a function of the GPS receiver/antenna electronics architecture. Multipath (multiple arrivals of the signal from the same satellite) introduces uncertainty in the determination of the range to the satellite, and this introduces noise in the estimation of the zenith-scaled tropospheric signal delay (ZTD). The point at which the range to a satellite is computed is called the antenna phase center. The phase center of an antenna is neither a physical nor stable point in space, but changes with the environment and elevations of the GPS satellites as they traverse the sky.

In practice, we attempt to mitigate these factors to the greatest extent possible by selecting sites carefully and installing GPS antennas in stable and electrically benign environments. Figure 3 illustrates the impact of time dependant variability of measurement noise on the estimation of ZTD at three sites in the NOAA GPS-Met network: Winnfield, LA (blue), Seattle, WA (red), and Boulder, CO (green). The noise is expressed in terms of the Formal Error (or root mean square differences) in 30-minute ZTD estimates. Formal error is estimated every half hour using 60 independent estimates of the ZTD at each site. A 1 cm formal error introduces approximately 1.5 mm uncertainty in the estimation of integrated precipitable water vapor.

In all cases, the high formal errors at 0 UTC are caused by a drop in the amount of data supplied to NOAA by some of the owners of the GPS receivers used in the network. The drop is caused by the data acquisition strategy implemented by some of the GPS data suppliers, and over which NOAA has no direct control. The increase in formal error before and after midnight UTC is an artifact of the sliding window technique used to estimate ZTD in near real time.

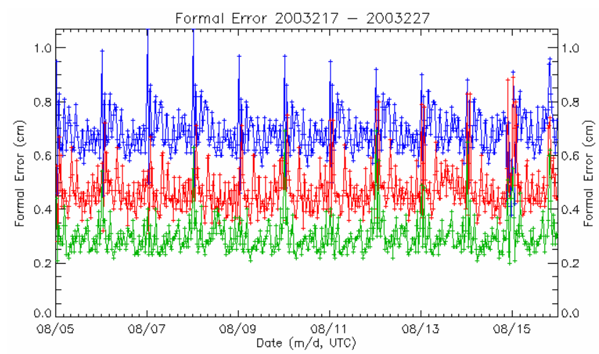

Fig 3. Formal error (RMS difference) in the zenith tropospheric delay estimates at three sites in the NOAA GPS-Met network: Winnfield LA, Seattle WA, and Boulder CO. Differences in the sites are discussed in the text.

The GPS-Met site near Winnfield, LA (plotted in blue) is located in a heavily wooded area of north-central Louisiana. Unrestricted views of the GPS satellite constellation are limited to elevations above about 30 degrees by thick stands of conifers trees that surround the site. When the view of the sky is restricted, the number of satellites being continuously tracked goes down, and the scatter in the ZTD estimate increases, in this case to about 0.7 mm (~ 1.1 mm IPW) rms. It is a good practice to locate GPS sites in areas that maximize sky visibility.

The GPS site near Seattle, WA (plotted in red) is located atop the NWS Forecast Office at Sand Point. The antenna is mounted on a 3 meter high tower that is firmly anchored to the foundation of the building. The view of the sky at this location is unrestricted in all directions, but multipath and the effect of the tower itself on the antenna phase center contribute to an uncertainty of about 0.7 mm to the IPW estimates at this location.

The site in Boulder, CO is atop the David Skaggs Research Center. The antenna is mounted on a 1.8 meter rigid mast guyed to the building. The view of the sky is unrestricted except directly to the West where the sky view below 40 degrees is cut off by the Flatirons, a rock formation that is part of the Front Range of the Rocky Mountains. The site on the roof of the building was selected to minimize multipath. Zenith tropospheric delay error is about 0.3 cm which translates into an IPW uncertainty of less then 0.5 mm IPW.

The point here is that several factors impact the accuracy of the ZTD estimate in complex and sometimes unpredictable ways. While it is always good practice to use the best GPS receivers and antennas possible, minimize the impact of multipath through careful site selection, and use the best antenna monument. None of the sites discussed here are delivering poor IPW estimates since the observation errors in each case are well below the analysis errors of the numerical weather prediction models assimilating these data (Gutman and Benjamin, 2001).

2.2 *Surface Meteorological Observations*

Two types of surface observations are required to parse the tropospheric signal delay into its wet and dry components (Bevis et al., 1992). Surface pressure measurements are used to estimate the zenith hydrostatic delay (Saastamoinen, 1972) and can do so with an error of about 0.5% under normal conditions (Resch, 1984). Surface temperature measurements can be used to estimate the mean temperature of the atmosphere with an error of about 2%.

In general, surface pressure measurements with accuracy of about 0.5 hPa, and surface temperature measurements with accuracy of about 2 degrees are sufficient to keep the IPW retrieval error budget below 0.5 mm IPW (Gutman et al, 2003).

2.3 *Satellite Orbit Accuracy*

Because of the requirement for real-time improved GPS satellite orbits to support operational weather forecasting activities for meteorological agencies worldwide, the relationship between GPS satellite orbit accuracy and IPW retrieval accuracy has been extensively studied. Ge et al. (2000) and others have shown that if the GPS satellite orbits are known with high accuracy (errors less than 25 cm rms) then orbit uncertainties will have negligible impact on the accuracy of IPW retrievals.

The strategy employed by FSL to acquire real-time orbits with sufficient accuracy to generate operational GPS-Met products uses hourly updates to the SOPAC-generated International GPS Service (IGS) ultra-rapid orbit (Fang et al., 1999) and a sliding window technique. In practice, a 2-h orbit prediction based on the hourly orbit has about the same level of accuracy as the ultra-rapid orbit with 12-h latency.

On rare occasions, real-time orbit prediction accuracy degrades rapidly causing large errors in IPW retrieval accuracy. Several causes for these failures have been identified, including: data processing hardware and software problems at SOPAC; IGS/JPL (NASA Jet Propulsion Laboratory) and U.S. Naval Observatory (USNO) parameter delivery (or receipt) problems; observations from the IGS tracking network are slowed or stop; and unannounced orbital maneuvers of the NAVSTAR GPS satellites by USAF.

The impact of a recent orbital problem is illustrated in Figure 4. Stations spaced thousands of kilometers apart experienced simultaneous highly correlated changes in ZTD that mapped directly into IPW errors. The impact on ZTD formal errors is also shown.

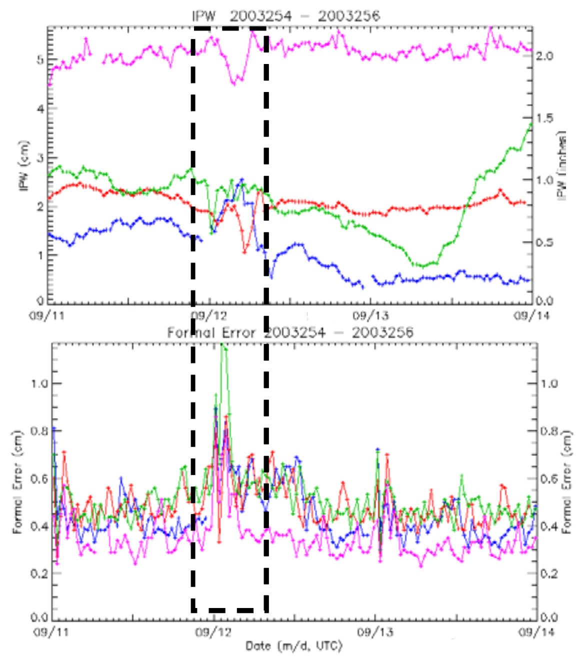

Fig 4. Example of the impact of an orbit prediction problem on IPW retrieval accuracy. IPW time series shown in the upper plot, and formal errors are shown below. College, AK in blue, La Jolla, CA in red; Bartlett, NH in green, and Key West, FL in fuchsia.

Steps to mitigate the impact of orbit prediction problems are currently under evaluation. Options include: SOPAC hardware redundancy and automatic fail-over; backup communication paths from SOPAC to IGS/JPL, USNO, the IGS global tracking stations, and from SOPAC to Boulder; and possible agreements with U.S. Air Force concerning notification to operational users like NOAA at the start and end of all NAVSTAR orbital maneuvers.

2.4 *GPS Data Processing*

One major assumption in GPS-Met data processing permits us to objectively estimate ZTD and map it into IPW in an unambiguous manner. This assumption is that tropospherically induced signal delays depend primarily on the elevation of the satellite above the horizon, and not the direction from which the radio signals come. The geodetic community that developed the GPS data processing techniques commonly refers to this as the assumption of azimuthal symmetry. It is clear that this assumption is false at face value since significant weather events are commonly associated with high temperature, pressure, and moisture gradients that map directly into radio-refractivity gradients. The question then is, in reality, how good an assumption is azimuthal symmetry?

It turns out that the signal delay caused by the path length through the atmosphere dominates the refractivity structure under the majority of conditions (Resch, 1984). While local variations in refractivity associated with clouds, fronts, and other boundaries cause second order variations that can deviate from this by as much as 3-5%, these cases are quite rare.

Until such time as all-weather GPS techniques can be developed that can unambiguously separate these anomalies from the background, it remains the province of other techniques such as water vapor radiometry or long baseline interferometry to detect these anomalies.

2.5 *Parsing the Delays and Mapping the Wet Component into IPW*

The errors associated with parsing ZTD into its wet and dry components, and mapping the wet component into IPW have also been discussed in great detail (Bevis et al., 1992, Bevis et al., 1994).

The advantages to using a numerical weather model to estimate the mean vapor weighted temperature of the atmosphere as opposed to using a surface temperature measurement and a climate model were discussed by Gutman et al. (2003). In general, we believe that the small improvements gained when there are departures from the normal temperature lapse rate, are overwhelmed by the problems associated with modeling errors.

3. POSSIBLE USE OF GPS WATER VAPOR RETRIEVALS FOR RADIOSONDE AND SATELLITE QUALITY CONTROL.

As seen in Figure 5, long term comparisons of GPS-IPW retrievals with PW derived from radiosondes at the Department of Energy Southern Great Plains (SGP) Atmospheric Radiation Measurement (ARM) Facility between 1996 and 1999 reveal no long term bias and a standard deviation of about 2 mm PW. Other comparisons are consistent with this result and suggest that radiosondes PW estimates are, in a statistical sense, slightly dry (on the order of 0.5 mm) compared with GPS-Met retrievals.

Figure 6 is a map of the GPS-Met network with the radiosonde sites within the 60 km version of the Rapid Update Cycle (RUC 60) verification area discussed by Smith et al., 2004. Within this region, the 9 upper-air sites (identified in Table 1) are within 50 km of a GPS receiver.

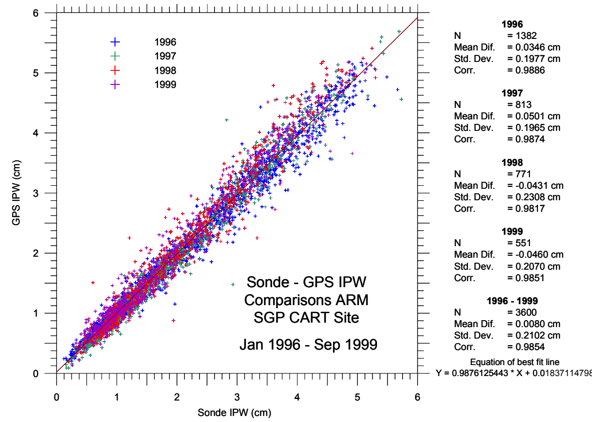

Fig 5. Comparison of 3600 GPS-IPW retrievals and radiosonde PW over 3 years at the Department of Energy Atmospheric Radiation Measurement Site near Lamont, OK.

TABLE 1. GPS and radiosonde sites identified in Fig 6.

GPS Site		Upper-Air Site
Hartsville (htv1)	–	Nashville (bna)
Kansas City (kan1)	–	Topeka (top)
Little Rock (lroc)	–	Little Rock (lzk)
Stennis (ndbc)	–	Slidell (sil)
Purcell (prco)	–	Norman (oun)
Amarillo (txam)	–	Amarillo (ama)
Arlington (txar)	–	Fort Worth (fwd)
Corpus Christi (txcc)	–	Corpus Christi (crp)
Odessa (txdo)	–	Midland (maf)

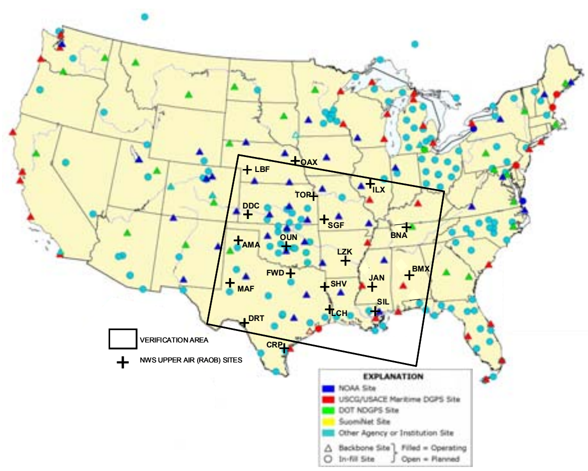

Fig 6. RUC 60 verification area (Smith et al., 2004) showing the location of the 9 NWS upper-air and GPS-Met sites used in the 90 day comparison of PW described below.

Figure 7 is a scatter plot of radiosonde–derived PW and GPS-IPW retrievals at the nine sites identified in Table 1. Table 3 presents the statistics of all comparisons, while Table 4 presents the statistics with statistical outliers removed. An outlier is defined as a difference greater than 2 rms or 1.9 std dev.

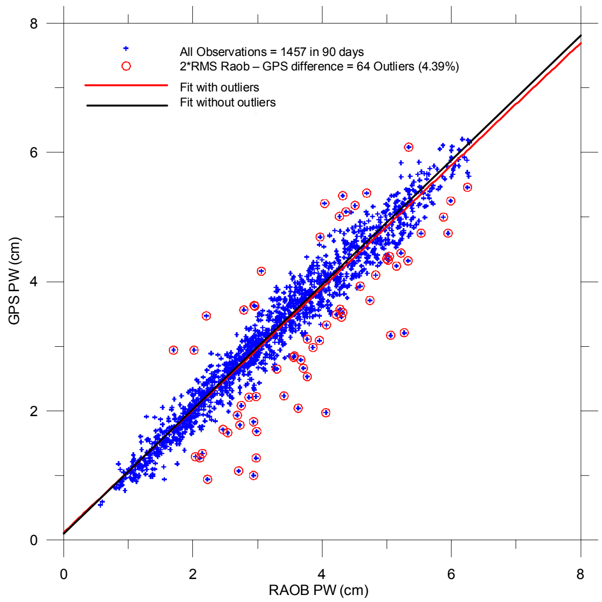

Fig 7. Scatter plot of radiosonde–derived PW and GPS-IPW retrievals over a 90-day period at the nine sites identified in Table 1.

TABLE 2. Statistics for Fig 7 with Outliers.

Number = 1457
Average X = 3.28552
Average Y = 3.22708
Minimum = -12.6
Maximum = 20.9
Mean = 0.5844
Std Dev = 3.1442
RMS = 3.1969
Corr Coef = 0.968657
Linear Fit: Y = 0.9472139431 * X + 0.1149875458

TABLE 3. Statistics for Fig 7 without Outliers.

Number = 1393
Average X = 3.26014
Average Y = 3.22456
Minimum = -6.3
Maximum = 6.4
Mean = 0.3558
Std Dev = 2.3844
RMS = 2.410
Corr Coef = 0.9821
Linear Fit: Y = 0.9570183077 * X + 0.1045482899

Having established a tentative benchmark for the expected accuracy of a GPS-Met retrieval with respect to an operational radiosonde PW estimate, it is now possible to apply this to a real-word case. Figure 8 is a plot of the differences between the analysis and one-hour forecast of IPW using the RUC 20 km model. The main features on this map are an exceptionally large bulls eye located in the vicinity of Blacksburg, VA and a smaller one in the vicinity of Detroit/White Lake, MI.

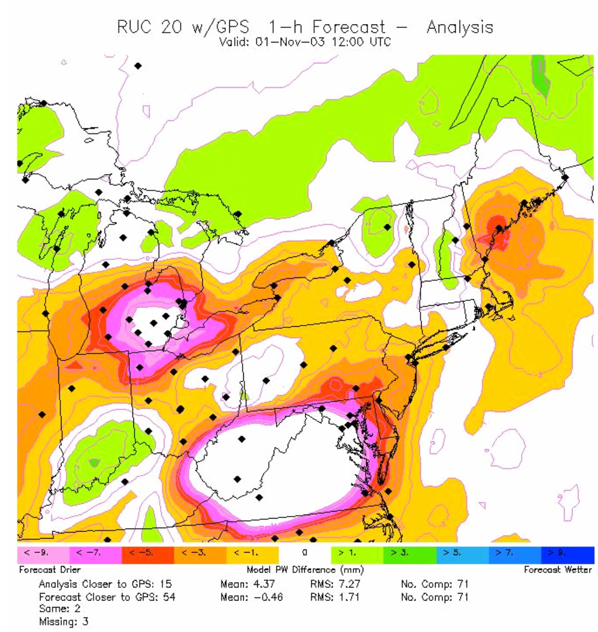

Fig 8. Plot of PW differences between the RUC one-hour forecast valid at 12 UTC on 01 November 2003, and the PW analysis at 12 UTC.

Figure 9 is a time series plot of radiosonde PW observations at the NWS upper-air site at Blacksburg, VA (RNK) and GPS IPW observations at the same location. The large spike in the 12 UTC analysis and 3-h forecast is probably the result of a faulty RH sensor. Unfortunately, the two versions of the RUC model (with and without GPS) did not flag this as a bad observation. The error propagated for 12 hours in the forecasts for the version of the RUC without GPS, when another launch with a problematic sensor exacerbated and extended the problem for another 12 hours. In contrast, the version of the RUC model assimilating GPS was quickly able to contain and correct this, at least in the case of the moisture totals.

In this and numerous other cases, comparison of GPS and radiosonde moisture appears to provide a very reliable method to identify problematic sondes and limit the negative impact on the NWP model assimilating them.

4. CONCLUSION

GPS-Met provides retrievals of integrated (total column) precipitable water vapor with comparable

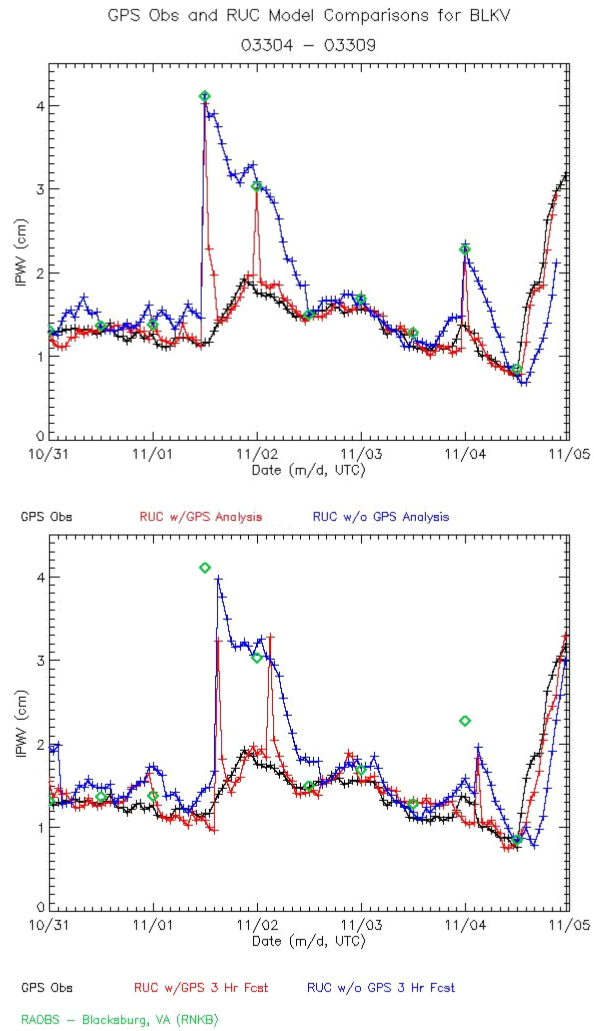

Fig 9. Time series plots of PW at the Blacksburg, VA upper-air site (rnk). The analysis with and without GPS are on the upper panel, and the 3-h forecast with and without GPS are seen in the lower panel.

accuracy to a radiosonde. The ability to estimate IPW in near real-time means that it should be possible to determine if a moisture sounding has been successful by the time the sonde has reached 500 hPa.

What is required is for the GPS and radiosonde launch point to be close enough to ensure that the observations are of the same air mass. The best way to insure this is to collocate GPS-Met systems at upper-air sites.

The Radiosonde Replacement System provides NOAA with a simple and cost effective way to accomplish this. As a consequence, we suggest that a future upgrade to RRS include dual frequency GPS receivers and stable monuments at upper-air sites to provide the most accurate and reliable data for forecasters, modelers, and satellite validation.

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