# Recent Improvements in the Retrieval of Precipitable Water Vapor


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## BIOGRAPHY

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## ABSTRACT

Atmospheric parameters derived from Global Navigation Satellite System (GNSS) are increasingly being used in numerical weather prediction and long-term climate monitoring. We characterize the impact of three analysis strategies on the retrieval of precipitable water vapor (PW). Two of these strategies integrate GNSS analysis techniques with numerical weather prediction (NWP) analysis fields. The first uses direct mapping functions computed from NWP fields to model and estimate the atmospheric state within the GNSS software. The second uses vertical profile information from NWP fields to compute the mean temperature of the atmosphere used to scale zenith wet delay into PW. The third modification assesses the impact of horizontal gradient estimates in the retrieval of PW. The impact of these changes is quantified using extended time series of observations for ground stations within North America, and compared against observations collected with microwave radiometers. The impact on seasonal and diurnal signals is investigated.


## INTRODUCTION

Global Navigation Satellite Systems (GNSS) can be used to remotely sense atmospheric water vapor in all weather conditions [*Bevis, et al.*, 1992; *Rocken, et al.*, 1991; *Rocken, et al.*, 1995]. The vertically integrated amount of water vapor above a location, when scaled to its equivalent liquid amount, is called precipitable water vapor (PW). Numerous networks of stations are now routinely retrieving PW for atmospheric studies [*Hagemann, et al.*, 2003; *Ohtani and Naito*, 2000; *Rocken, et al.*, 1997; *Wolfe and Gutman*, 2000]. Results collected with these networks have been used to investigate the accuracy of moisture fields in numerical weather models [*Haase, et al.*, 2003; *Yang, et al.*, 1999]. GPS PW, or the related quantities of zenith wet delay (ZWD) and zenith total delay (ZTD), have been directly assimilated into numerical weather models to improve their predictive capability [*Cucurull, et al.*, 2004; *De Pondeca and Zou*, 2001; *Kuo, et al.*, 1993; *Kuo, et al.*, 1996]. Additionally, continuous time series of GPS PW are now being used to detect and quantify spatial and temporal variations in water vapor on seasonal and diurnal time scales [*Dai, et al.*, 2002; *Hagemann, et al.*, 2003]. Each of these applications benefit from GNSS PW retrievals that are free from biases, scale errors or periodic variations that might be misinterpreted as an atmospheric signal. For example radiation balance studies, which are fundamentally at the core of climate change science, require the most accurate estimates of PW available. A 2% error in total column water vapor corresponds to a 1 W/m$^2$ error in downwelling radiation [*Revercombe, et al.*, 2003].

## DATA ANALYSIS STRATEGY

A network of 83 stations was used in this study (Figure 1), with solutions being computed for just over 200 days in 2004 and 2005. The majority of stations are located in the continental United States, with a number of additional sites in Canada. Four stations were part of the International GPS Service (IGS) and were used to align the network to the IGSb_00 global reference frame through the minimization of a Helmert transformation onto the published coordinates [*Altimimi*, 2001]. The Bernese Version 5.0 software was used [*Hugentobler, et al.*, 2004] with all solutions being computed using ionosphere free double difference observables. Satellite orbits from the IGS were used in all processing steps and ocean loading parameters were applied to the station positions during the estimation routines. A minimum elevation mask of 5° was used in the analysis software, however most stations were configured to stop tracking satellites at 7°. The IGS_01 elevation dependent phase center corrections were applied to all antenna patterns with the relative phase center patterns being extended below their lowest published elevation angle by assuming that the phase centers do not vary significantly from the 10° corrections.

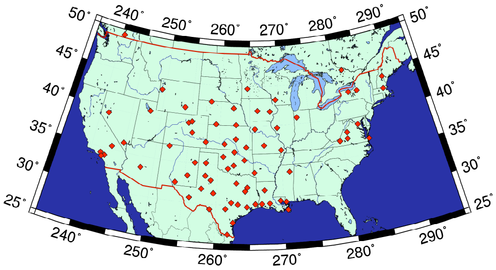


**Figure 1: Map of GPS stations used.**

This study quantifies the impact of three changes in the analysis procedure. These differences are summarized in Table 1. The first difference is in the mapping of the dry delay. The standard mapping function used in the Bernese software is described by Niell [2000] and relates the atmospheric delay to its equivalent zenith amount with an analytical expression relating a standard atmosphere and a 1/sin(θ) expansion. Direct mapping functions computed from NWP model fields were first proposed by Rocken et al. [2001] and should allow for an improved mapping of the dry delay. The NWP model that was used in this study was the Global Forecast System (GFS) model published at 6-hour intervals with 1.25° grid spacing and 11 vertical levels (using a model top of 100 hPa). Ray-tracing routines were used to compute the mapping functions at each GPS station and then linearly interpolated in time.

The second change is in the computation of the mean atmospheric temperature $\mathbf{T_m}$ that relates zenith wet delay to PW. Standard analysis techniques rely on a statistical relationship between surface temperature ($\mathbf{T_s}$) and $\mathbf{T_m}$ computed from an analysis of atmospheric profiles from radiosondes [*Bevis, et al.*, 1994]. We use a slightly modified version of this linear relationship based on a personal communication from Dr. Mike Bevis, ($\mathbf{T_m}$ = 85.63 x 0.668 $\mathbf{T_s}$) and will be called Bevis_95. The modification to this standard scaling computed $\mathbf{T_m}$ directly from the GFS analysis fields that were used in the direct mapping step. As in the direct mapping, it is expected that the NWP analysis will provide a better representation of the true atmospheric conditions at any instant in time.

The third change is in the estimation of horizontal gradients. These parameters were set up at 720-minute intervals and should allow for an improved modeling of the atmosphere in the presence of pressure gradient fields associated with the general poleward decrease in tropopause height and synoptic scale pressure fields.

**Table 1: Differences in Analysis Strategies.**

| Solution | Dry Mapping | Zenith Interval | Gradient Interval | Tm |
|---|---|---|---|---|
| NM | Niell | 30 min | None | Bev95/GFS |
| NG | Niell | 30 min | 720 min | Bev95/GFS |
| DM | Direct (GFS) | 30 min | None | Bev95/GFS |
| DG | Direct (GFS) | 30 min | 720 min | Bev95/GFS |

## ANCILLARY DATA

The Atmospheric Radiation Measurement (ARM) program operates five microwave water vapor radiometers (MWR) in the Southern Great Plains region of the United States [*Revercombe, et al.*, 2003]. These instruments use the 22 GHz water vapor absorption line to infer PW from atmospheric brightness temperatures. They are generally considered to be highly accurate, but have some difficulties in the presence of heavy clouds and precipitation. These five instruments are collocated with GPS receivers and provide a useful observation to compare GNSS retrieval techniques. We use the MWR data after applying a slight modification to the retrievals that account for a error in the half-width model of the 22 GHz absorption line [*Liljegren, et al.*, 2005].

## RESULTS AND DISCUSSION

Direct mapping of the hydrostatic delay appears to slightly moisten most PW estimates. The average ratio of PW derived from direct mapping to those derived using standard Niell mapping is shown in Figure 2. A clear spatial pattern can be seen from these results, with the majority of the stations being wetter by up to 2% using the direct mapping strategy. The one exception appears to be stations with relatively high altitudes (those in the Rocky Mountains, and one at Macdonald Observatory in TX) where there is almost no impact of direct mapping.

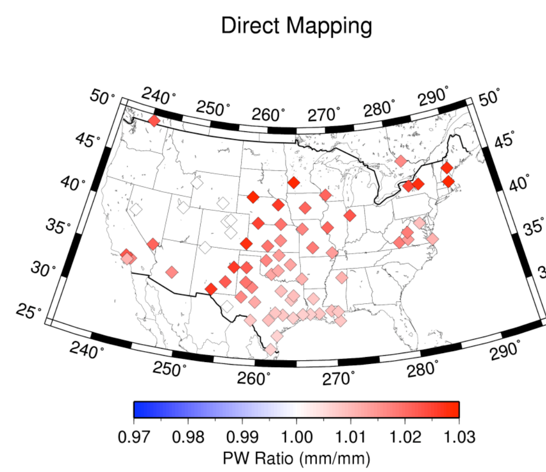


**Figure 2: Ratio of PW estimates with and without direct mapping of the dry delay.**

On a daily average, the use of $\mathbf{T_m}$ calculations from the GFS model has almost no affect on the retrieval of PW (Figure 3). Ratios of retrieved PW with and without direct $\mathbf{T_m}$ calculations are less than 1% for all but one station. As a daily average, the impact of direct $\mathbf{T_m}$ calculations on PW retrievals was small. Diurnally, a significant signal can be seen Figure 4. This figure plots the average of PW using the Bevis_95 $\mathbf{T_m}$ computation from surface temperature and the $\mathbf{T_m}$ computed from the GFS model as a function of the UTC hour of the day. A diurnal trend can be seen with amplitude of just over 1%. This diurnal signal is probably caused by the under sampling of the atmospheric profile from twice daily radiosonde launches.

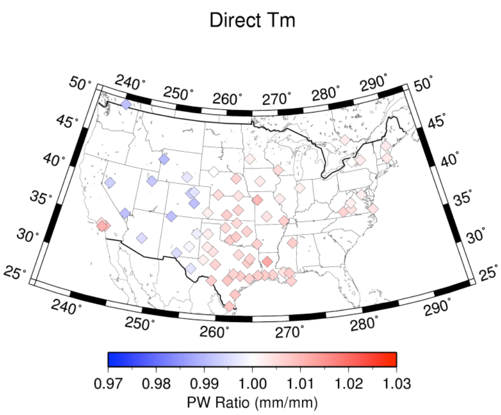


**Figure 3: Ratio of PW estimates with and with direct Tm calculations.**

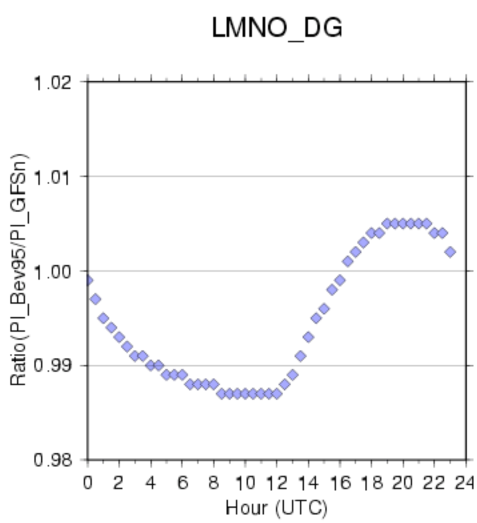


**Figure 4:Diurnal variation of PW ratio computed with and without direct Tm computation for station LMNO.**

Twice daily gradient estimates also created a slightly wetter PW retrieval (Figure 5). There is a clear spatial pattern in the gradient estimation analysis, with stations at higher latitudes and New England being slightly drier than the rest of the stations.

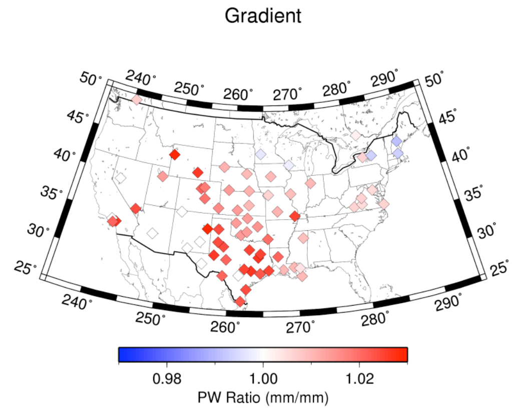


**Figure 5: Ratio of PW estimates with and without additional gradient parameters estimated.**

A comparison of the GPS stations collocated with the MWR showed linear correlation coefficients of greater than 0.99 for all stations. An example is shown for station HBRK in Figure 6. The GPS PW retrievals were 3-6% dry with respect to the MWR, even after the direct mapping, direct $\mathbf{T_m}$ and gradient estimation strategies were applied.

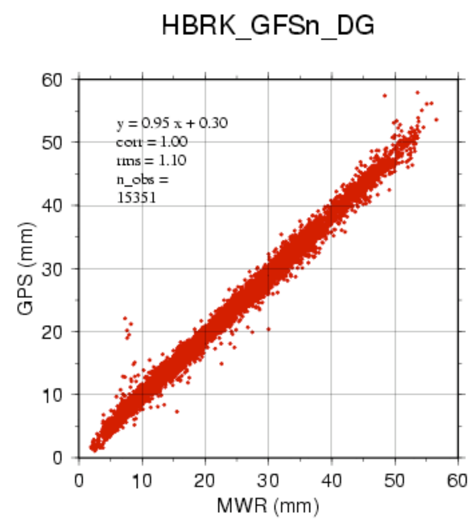


**Figure 6: Scatterplot of GPS PW at station HBRK to collocated MWR.**

There was a slight improvement in the root mean square (rms) agreement between the GPS PW and the MWR PW when Direct Mapping, Direct $\mathbf{T_m}$ and gradient estimation strategies were applied. The improvement was between 1 and 7% for all GPS stations with collocated radiometers. This slight improvement is probably an indication that the combined analysis methods allow for a more realistic modeling of the observations within the analysis software.

**SUMMARY**

Three modifications to standard analysis techniques were tested from a network of 83 stations in North America. The time period extended for more than 200 days in 2004 and 2005. Generally each modification induced a slight moistening in the PW retrievals, with spatial variations in the Rocky Mountains, Gulf Coast, and New England. A diurnal variation was observed only in the computation of $\mathbf{T_m}$, and no seasonal signal was noticed in any of the processing changes. When compared to a collocated MWR instruments, the GNSS retrievals were dry by up to 6%.

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