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REAL-TIME WATER VAPOR SENSING WITH SUOMINET -- TODAY AND TOMORROW

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1. INTRODUCTION

SuomiNet, a university-based GPS network provides real-time atmospheric sensing capability via the Internet for research and education[1]. SuomiNet is funded by the U.S. National Science Foundation and university cost-share, and is managed by the University Corporation for Atmospheric Research (UCAR). We present examples of real time PW data products currently provided by SuomiNet, and describe real time slant delay analysis and applications that are proposed as an augmentation of SuomiNet.

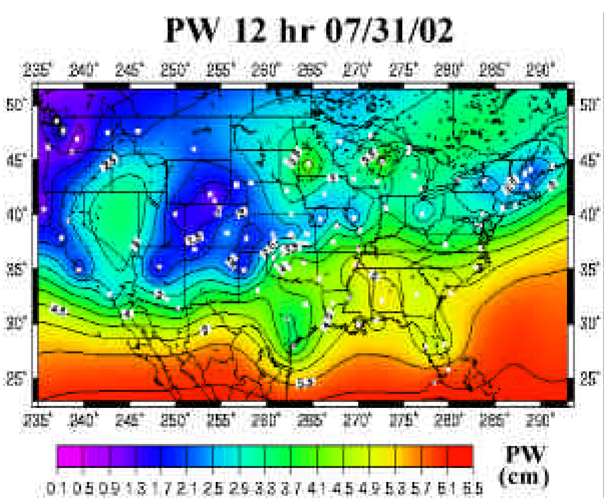

Figure 1. Example hourly precipitable water contour map provided in real-time from SuomiNet and FSL networks. White squares indicate GPS site locations.

2. EXAMPLE DATA PRODUCTS

Universities participating in SuomiNet provide surface meteorological sensors, Internet connections, power, security, and housing for equipment. UCAR provides dual-frequency GPS receivers, antennas, laptop computers, uninterruptible power supplies, standardized software, and real time GPS-sensed PW data. Real-time GPS data are also obtained from the NOAA Forecast Systems Laboratory (FSL) network[2]. An example PW contour map provided from SuomiNet and FSL networks is shown in Figure 1. Clicking on the map (on-line at www.suominet.ucar.edu) zooms to higher resolution, as shown in Figure 2.

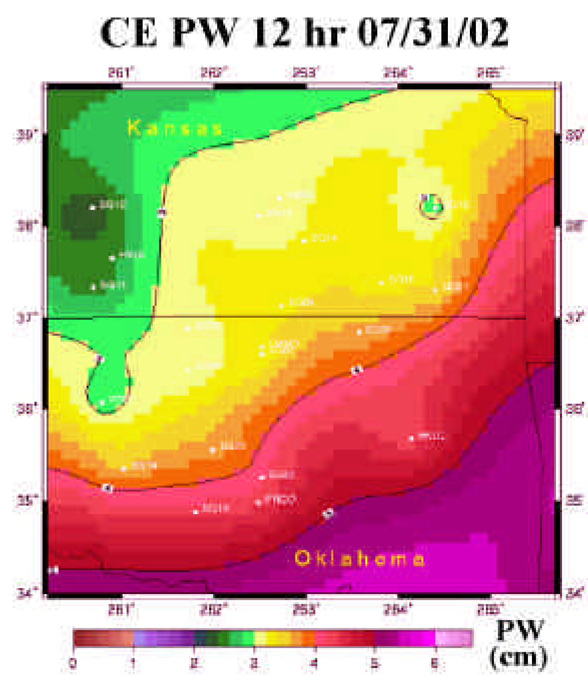

Figure 2. Hourly PW contour map in the Central U.S. The white squares indicate SuomiNet site locations.

In this case, a dry line representing the confluence of dry mountain air and humid gulf air is seen. PW varies from less than 3 cm to greater than 5 cm within a distance of several hundred km. Severe convective storms including tornadoes typically occur in the strong water vapor gradient along the dry line. Example plots of GPS-sensed PW and surface meteorology from the University of Arizona's SuomiNet site are shown in Figure 3. Similar plots for other SuomiNet sites can be obtained by clicking on the white squares (on-line) in the previous figures.

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[1]Ware et al., 2000.

[2]www.gpsmet.noaa.gov/jsp/index.jsp.

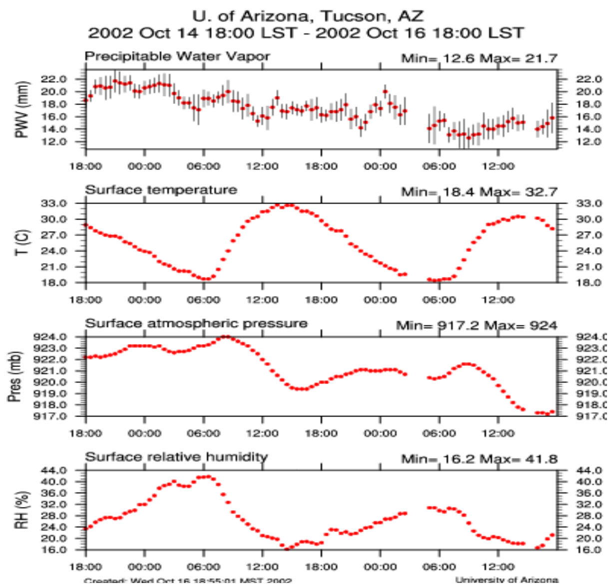

Figure 3. Three day time series of GPS-sensed PW and surface meteorological observations from the University of Arizona SuomiNet site[3].

Water vapor, an important means by which moisture and latent heat are transported, plays a fundamental role in atmospheric processes that act over a wide range of spatial and temporal scales. It is the most important greenhouse gas and it plays a critical role in the global climate system. Improved understanding of water vapor in its three phases, and its role in weather, hydrology, and climate, is a major objective of national and international research programs. Timely and accurate water vapor data are needed to improve mesoscale modeling, short term and severe storm forecasting, climate[4] studies, and hydrology. An example of all weather PW sensing with GPS on a continental scale is shown in Figure 4.

3. GPS SLANT DELAYS

The assumption of azimuthal symmetry limits the accuracy and spatial resolution of GPS sensed PW. However, improved spatial resolution can be obtained by solving for refractive gradients[5]. Even higher spatial resolution can be obtained by solving for GPS slant delays[6]. GPS measurements of slant delays induced by water vapor (slant wet delays) have been validated by comparisons with water vapor radiometer measurements[7]. Radiometers were pointed sequentially along the line-of-sight to each GPS satellite. Linear correlation of 0.99 and rms agreement of 1.3 mm were found for 37 days of comparisons[8].

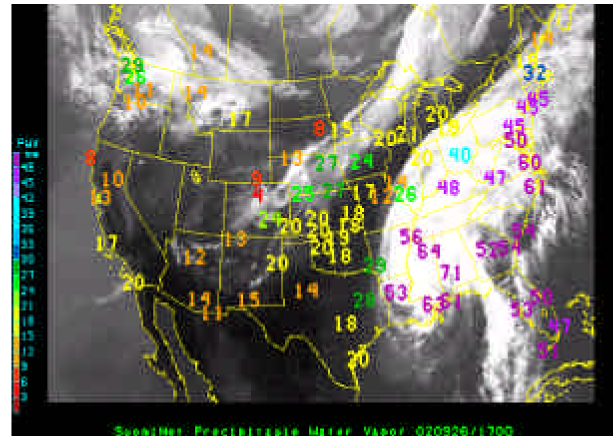

Figure 4. Hurricane Isidore seen in a GOES infrared image with SuomiNet PW (colored numbers in mm). PW values as high as 82 mm were seen during passage of Isidore. Similar real time images are available via www.unidata.ucar.edu.

Example GPS-sensed slant delay observations are shown in Figure 5. Spatial variability of delays induced by water vapor is seen during stormy and stable conditions. Residuals are greater during stormy conditions because of increased variability in water vapor. Similar residual slant delays for selected SuomiNet sites are currently available via the Internet with several day latency[9].

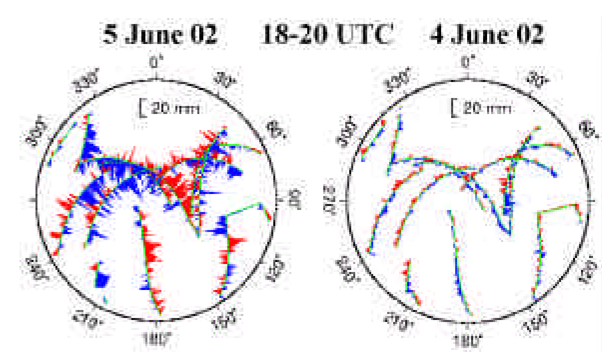

Figure 5. Unmodeled GPS residual slant delays at Lamont Oklahoma during stormy and stable conditions. Zenith is plot center and the horizon is the perimeter. Residuals are plotted about the satellite ground track axis (green). Red represents excess slant delay with respect to modeled slant delay, and blue is less.

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[3]www.atmo.arizona.edu/products.
[4]Dai et al., 2002; Gradinarsky et al., 2002.
[5]Bar-Sever et al., 1998.
[6]Ware et al., 1997; Alber et al., 2000; Braun et al., 2001.
[7]Braun et al., 2001.
[8]Braun et al., 2002.
[9]www.gst.ucar.edu/gpsrg/realtime/ slant_plots.html.

Slant delays can be used to estimate the velocity of refractive features moving above a GPS network. For example, slant delay time series from the Japanese GPS network were used to estimate the velocity of refractive signatures[10], analogous to "cloud winds" estimated from geostationary satellite imagery[11]. Large improvements are expected from assimilation of high resolution wind and moisture fields into mesoscale models[12].

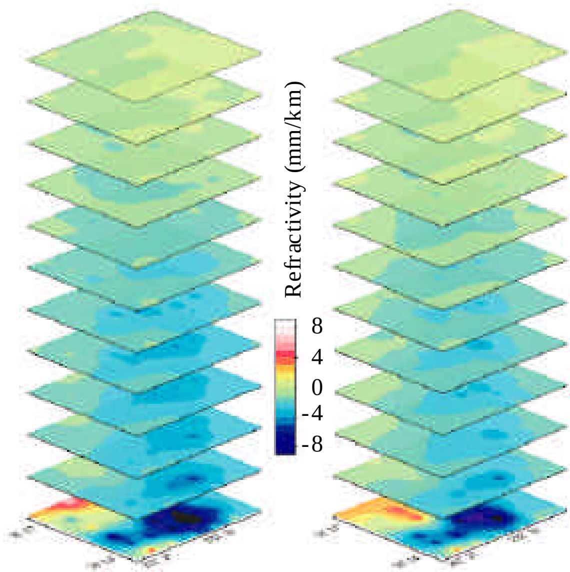

Figure 6. Water vapor tomography based on slant GPS observations from a 24 site network[13]. Scale is approximately 5 x 5 km horizontal and 5 km vertical. The two tomographic solutions are 10 min apart.

Slant GPS measurements, particularly at low elevation angles, can be used to improve water vapor analysis. At zero degrees elevation, a GPS ray extends more than one hundred km in the boundary layer. The accuracy of slant delay observations below 2 degrees elevation is better than 1%[14]. A ray path at low angles intersects many cells in a high resolution model, providing strong constraints on water vapor distribution[15].

Four dimensional characterization of water vapor fields[16] and vertical profiling of atmospheric refractivity[17] have been demonstrated using slant GPS. Four dimensional refractivity based on slant delays from an array of GPS receivers spaced by 1 to 2 km is shown in Figure 6. These studies demonstrate the potential for slant GPS in high resolution water vapor analysis.

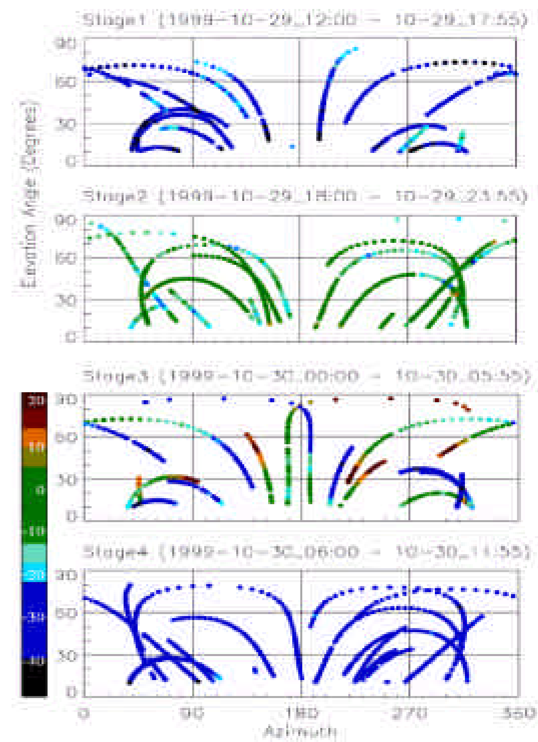

Figure 7. Observed minus modeled slant wet delays (mm) from a simulated 64-site GPS network in the Central U.S.[18]. High variability in water vapor associated with squall line passage through the network is indicated by the many changes in color of the "worm plot" during the third 6-hr time series (Stage 3).

GPS-sensed PW data can be used to improve storm system analysis[19]. In addition, improved vertical structure of water vapor and short term precipitation forecasts can be obtained by assimilating slant delays into mesoscale models[20].

An example of slant delay sensitivity to the passage of a squall line is shown in Figure 7. High variability is clearly evident in slant delays during passage of the squall line which could not be captured by a state-of-the-art mesoscale model. For this case, slant delay comparison between model and observation was limited to elevation angles above five degrees where ray bending can be ignored. Below five degrees, corrections for ray bending become more important. In a separate

[10]Herring and Shimada, 1998.
[11]Holmlund, 1998.
[12]Kuo et al., 1996.
[13]Braun et al., 1999.
[14]Pany, 2002.
[15]MacDonald et al, 2002.
[16]Flores et al., 2000; Seko et al., 2000; Yoshihara et al., 2001.
[17]Lowry et al., 2002.
[18]Ha et al., 2002b.
[19]Cucurull et al., 2000, 2002; Gutman and Benjamin, 2001; Ha et al., 2002a,b.
[20]Ha et al., 2002a.

study, significant improvements in precipitation threat scores were obtained with assimilation of slant delays in an observing system simulation experiment (Figure 8).

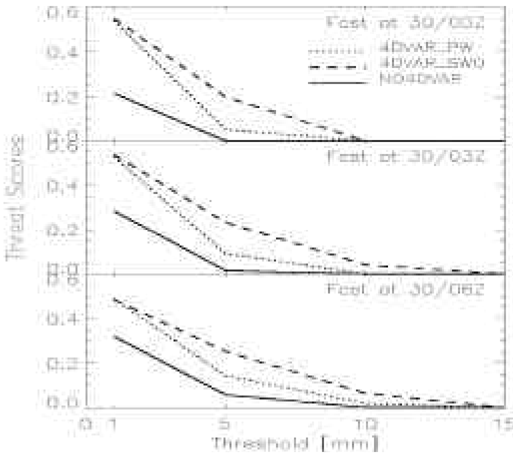

Figure 8. Threat scores of 3-hr accumulated rainfall using 4DVAR assimilation of slant wet delay and PW, compared to forecasts without 4DVAR. Perfect runs are compared at 00, 03, and 06 UTC on 30 October, 1999. Higher threat scores were obtained with slant wet delay assimilation for all precipitation threshold amounts[21].

An Observing System Simulation was conducted to determine whether three-dimensional water vapor fields could be recovered from a high-resolution network (40-km spacing) of GPS receivers, in combination with surface moisture observations and a limited number of water vapor soundings[22]. The assumed (ground-truth) water vapor density is shown in Figure 9. Results from three dimensional variational analysis of simulated slant delay network observations, and of radiosondes only are shown in Figure 10. A dry line representing the confluence of dry mountain air from the west and moist gulf air from the east dominates the water vapor field. The location and magnitude of major convective storms is resolved in the slant delay analysis, but not in the radiosonde analysis. It was concluded that high-resolution slant GPS measurements may allow diagnosis of three dimensional water vapor, with applications for mesoscale weather prediction.

High resolution three dimensional wind fields can also be obtained from slant delay analysis, if continuous thermodynamic[23] and wind soundings are available[24]. For mesoscale features, the winds tend to adjust to the mass field and it is apparent that thermodynamic data with mesoscale resolution are just as critical for the creation of a mesoscale initial condition as wind data[25].

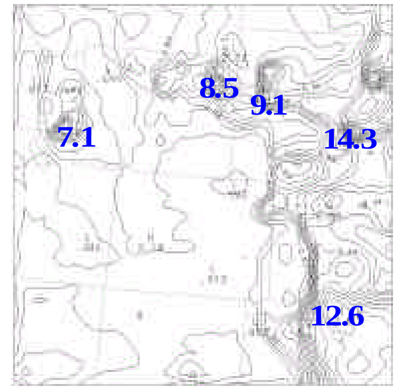

Figure 9. Ground-truth water vapor density (g/m^3) at 750 m height showing water vapor structures associated with major convective storms.

Figure 10. Water vapor density (g/m^3) analysis at 750 m height (above) based on 3DVAR assimilation of simulated slant delays and continuous thermodynamic profiles, at the same time as the previous figure. Water vapor analysis based on radiosondes at sites marked by black dots is shown below. The slant delay analysis shows the location and magnitude of major convective storms not seen in the radiosonde analysis.

[21] Ha et al., 2002a.
[22] MacDonald et al., 2002.
[23] Ware et al., 2002.
[24] MacDonald et al., 2001.
[25] Fritsch et al., 1992.

4. GPS NETWORKS FOR ATMOSPHERIC SENSING

There are currently two GPS networks in the U.S. designed for real-time sensing of atmospheric water vapor: the NSF-UCAR SuomiNet[26], and the NOAA-FSL Ground-Based GPS Meteorology Demonstration Network[27]. SuomiNet is designed for university-based research and education, and the FSL network is designed for operational forecasting. UCAR and FSL are collaborating on development and validation of analysis and assimilation methods, and by sharing real-time GPS network data.

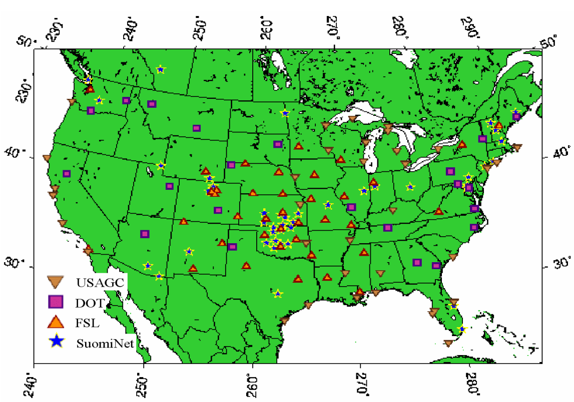

Figure 11. National GPS networks providing real-time atmospheric sensing[28].

Other GPS networks designed for navigation and surveying are providing real-time measurements to UCAR and FSL. Included are the U.S. Coast Guard, the U.S. Army Corps of Engineers, the Department of Transportation, the National Geodetic Survey, and various state governments. National networks providing real-time GPS sensing of the atmosphere are shown in Figure 11. Global networks providing GPS sensing of the atmosphere are shown in Figure 12.

Based on the promise of slant GPS to provide significant improvements in short-term forecasting, NOAA is considering a National MesoNet including 5,000 GPS sites. The network will also include more than one hundred wind and thermodynamic profiler sites to provide vertical anchoring for variational analysis. The National MesoNet would provide high resolution three dimensional wind and water vapor fields for short-term precipitation and severe storm forecasting, hydrology, aviation weather, and high resolution dispersion analysis.

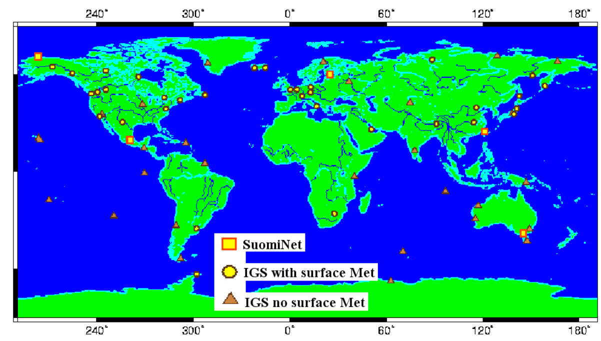

Figure 12. Global GPS networks providing atmospheric sensing[29]. Only IGS[30] sites are shown in the continental U.S. and Canada.

We expect additional growth for national and international GPS networks capable of atmospheric sensing. We will analyze real-time data from these networks as they become available. For example, UCAR is working with UNAVCO Inc.[31] toward obtaining real-time data from more than 100 GPS stations planned for the NSF-funded Plate Boundary Observatory (Figure 13).

Figure 13. Real-time GPS sites planned as part of the Plate Boundary Observatory[32] (PBO).

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[26] www.suominet.ucar.edu.
[27] Gutman et al., 2003; gpsmet.fsl.noaa.gov.
[28] www.gst.ucar.edu/gpsrg/realtime/ map_images/us.gif.
[29] www.gst.ucar.edu/gpsrg/realtime/indexGlobal.html.
[30] International GPS Service; igscb.jpl.nasa.gov.
[31] www.unavco.org.
[32] www.earthscope.org/pbo.html.

5. SUMMARY

Universities participating in SuomiNet provide real time GPS observations from more than 70 sites concentrated in the U.S, with additional sparse global distribution. UCAR analyzes these observations to provide accurate real time precipitable water data in all weather conditions and at all times of day, for research and education. UCAR is proposing to expand SuomiNet capability to provide real time GPS slant delays from SuomiNet and other U.S. networks capable of real time observations. Availability of slant GPS data will allow universities to advance mesoscale modeling and forecasting research, and climate monitoring. In particular, improvements in short term and severe storm forecasting are expected, with applications also in hydrology, dispersion forecasting, and climate research.

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