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# Real-time national GPS networks for atmospheric sensing

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**Abstract**

Real-time national global positioning system (GPS) networks are being established in a number of countries for atmospheric sensing. The authors, in collaboration with participating universities, are developing one of these networks in the United States. The proposed network, named "SuomiNet" to honor meteorological satellite pioneer Verner Suomi, is funded by the US National Science Foundation to exploit the recently shown ability of ground-based GPS receivers to make thousands of accurate upper and lower atmospheric measurements per day. Phase delays induced in GPS signals by the ionosphere and neutral atmosphere can be measured with high precision simultaneously along a dozen or so GPS ray paths in the field of view. These delays can be converted into integrated water-vapor (if surface pressure data or estimates are available) and total electron content (TEC), along each GPS ray path. The resulting continuous, accurate, all-weather, real-time GPS moisture data will help advance university research in mesoscale modeling and data assimilation, severe weather, precipitation, cloud dynamics, regional climate and hydrology. Similarly, continuous, accurate, all-weather, real-time TEC data have applications in modeling and prediction of severe terrestrial and space weather, detection and forecasting of low-latitude ionospheric scintillation activity and geomagnetic storm effects at ionospheric mid-latitudes, and detection of ionospheric effects induced by a variety of geophysical events. SuomiNet data also have potential applications in coastal meteorology, providing ground truth for satellite radiometry, correction of synthetic aperture radar data for crustal deformation and topography studies, and detection of scintillation associated with atmospheric turbulence in the lower troposphere. In this paper we describe SuomiNet, its applications, and the larger opportunity to coordinate national real-time GPS networks to maximize their scientific and operational impact. © 2001 Published by Elsevier Science Ltd.

*Keywords:* GPS networks; Atmospheric sensing

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## 1. Introduction

The authors and collaborating universities, with support from the US National Science Foundation (NSF), are establishing a national GPS network designed for real-time atmospheric remote sensing. SuomiNet will augment an existing GPS network located primarily in the central US and including approximately 40 federal and university sites (www.fsl.noaa.gov and www.gst.ucar.edu/gpsrg/realtime.html). SuomiNet will use well-established Internet Data Distribution (IDD) software and protocols to coordinate network sensors and distribute its data in real-time (IDD has evolved over more than a decade to provide real-time atmospheric data to university users). SuomiNet will demonstrate the innovative concept of a university-based *national geophysical instrument* providing critical real-time atmospheric data for research and education.

Continuous, all-weather, real-time GPS moisture data will help advance university research in mesoscale modeling and data assimilation, severe weather, precipitation, cloud dynamics, regional climate and hydrology. In addition, TEC and ionospheric scintillation data derived from GPS signal phase and amplitude will help universities and research institutions (hereafter called simply "universities") address over-arching, fundamental research topics. These topics include: the processes that govern the spatial distribution of ionization; the evolution of ionospheric irregularities and scintillation; thermospheric dynamics and its coupling to the ionosphere; and validation, testing and continued development of research models and numerical methods. Upper and lower atmospheric sensing with ground-based GPS receivers is illustrated in Fig. 1.

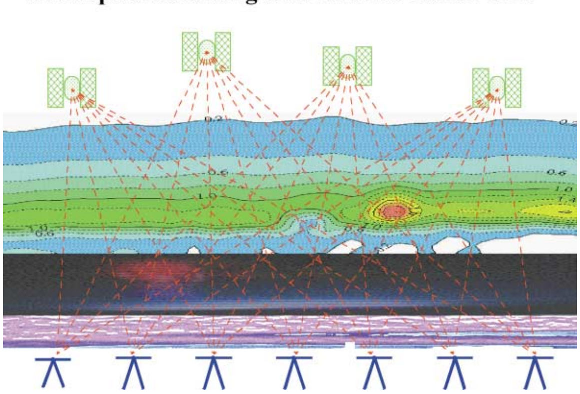


Fig. 1. A variety of useful information regarding upper and lower atmospheric structure and dynamics can be derived from GPS signal phase and amplitude data. In this illustration, the troposphere is depicted by a lidar scan of tropospheric water vapor, the stratosphere and mesosphere by a photo of a red jet and blue sprite (elf.gi.alaska.edu), and the ionosphere by an ionospheric model (janus.nwra.com/nwra/tomr2j.gif).

From an educational perspective, SuomiNet will place state-of-the-art GPS equipment, data, and processing methods in the hands of a large number of university departments, faculty, and students. It is here, in the university setting, where the tremendous potential of GPS in atmospheric research and education can be most effectively realized. The impact of these new data and observation methods on the atmospheric sciences may be dramatic, comparable to the impact GPS data have had in a few short years on the solid-Earth sciences (Stein 1998).

SuomiNet builds on the expertise of University Corporation for Atmospheric Research (UCAR) programs including: the GPS Science & Technology (GST) program (GPS-related atmospheric science), Unidata (real-time distribution of meteorological data to universities), and the University Navstar Consortium (UNAVCO) Facility (developing, deploying and operating GPS networks).

## 2. Research applications

The atmosphere is illuminated with 1.6 and 1.2 GHz (L1 and L2) signals transmitted by the 24 GPS satellites. Phases of signals from a dozen or so of these satellites can be simultaneously observed with mm precision during all weather conditions, using commercial GPS receivers. Observing from sea level, the lower and upper atmosphere induce GPS signal phase path delays of several meters or more. The key to SuomiNet-enabled research (and education) is to view these delays not as signal propagation errors but as atmospheric information. In the upper atmosphere, total electron content (TEC) along each GPS ray path can be measured by combining L1 and L2 phase observations. In the lower atmosphere, dry air, water-vapor and hydrometeors induce delays in GPS signals. However, effects generated by hydrometeors are relatively small (Solheim et al., 1999). As a result, water-vapor — integrated along each GPS signal path — can be inferred if observed or estimated surface pressure is available. Accurate geodetic coordinates also can be derived from these data, as has been amply demonstrated (Stein 1998).

Universities participating in SuomiNet have registered to establish 103 SuomiNet sites (Fig. 2). All sites are registered for atmospheric research applications, and approximately 60% are registered also for geodetic applications. Other research interests emerged during registration, including hydrology (12 sites), and oceanography (7 sites registered by oceanographic research institutions). At each SuomiNet site, participating universities will install and operate a standardized system including a dual-frequency GPS receiver, surface meteorological sensors, and a computer connected to the Internet and configured with IDD software. Participants interested in geodetic applications will install their GPS equipment in appropriate locations on stable geodetic monuments. Technical assistance regarding GPS equipment,

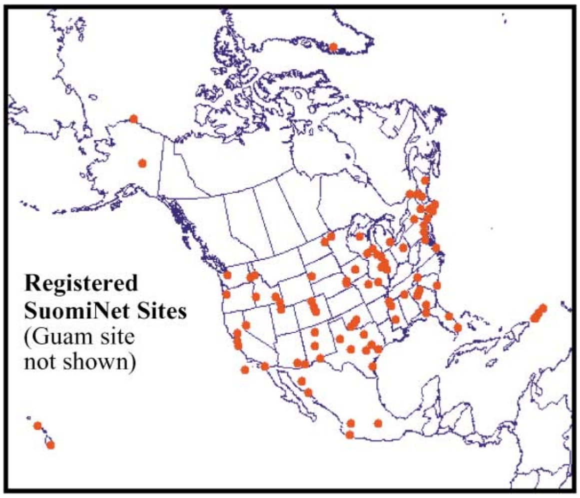


Fig. 2. Universities have registered the indicated site locations for participation in SuomiNet. For prospective participants, information and on-line registration are available via www.unidata.ucar.edu/souminet.

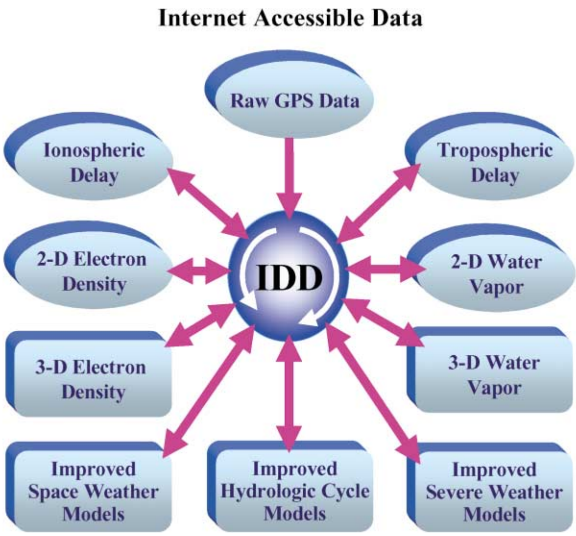


Fig. 3. SuomiNet data and products to be provided to universities in real-time are represented by the oval symbols. Data products that are expected to be derived from SuomiNet data through independent university research programs are represented by rectangular symbols.

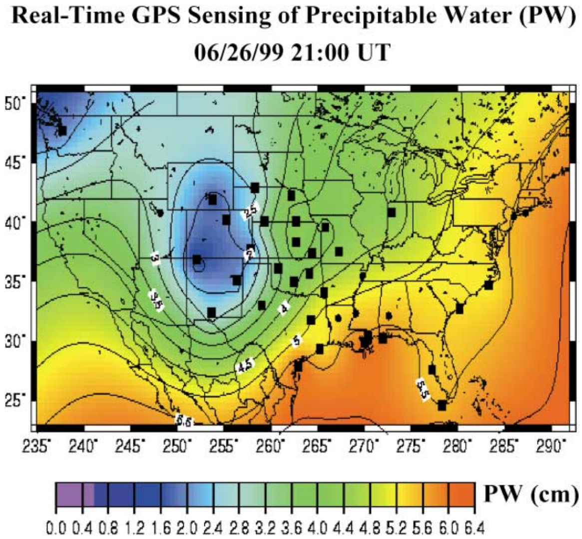


Fig. 4. Precipitable water (PW) estimated from GPS measurements in the south-central US, as posted on the Web every 30 min (Rocken et al., 1997a; www.gst.ucar.edu/gpsrg/realtime.html). Site locations are represented by black squares and dots.

monuments, and IDD will be provided by the UNAVCO Facility, Unidata, and GST.

SuomiNet will provide raw GPS and surface meteorological data, tropospheric and ionospheric delays, 2D water-vapor and TEC data to universities in real-time, as illustrated in Fig. 3. University investigators, through independent research programs, could assimilate these data into models to provide real-time 3D water-vapor and electron densities, and to enhance space weather and hydrological cycle modeling. GPS, surface meteorological, and other data observed at SuomiNet sites will also be distributed in real-time using IDD software and protocols (www.unidata.ucar.edu). IDD is designed to allow universities to request delivery of specific data sets directly to their computers, as soon as they are available (Domenico et al., 1994).

An IDD characteristic relevant to SuomiNet is that the data streams are accessible at no cost (either for data or software) to any college or university, large or small. The system design also allows any participant to inject additional observations or derived products into the IDD for delivery to other interested members of the network. Coordinated real-time control of GPS and other SuomiNet equipment, such as sampling frequency, data type and format, data latency, and other sensor parameters will be provided via IDD. Thus, SuomiNet will demonstrate the concept of a *national geophysical instrument* coordinated via Internet. Once demonstrated, this concept has the potential to address many additional research and education objectives, as described later.

The feasibility of providing real-time GPS data and products via Internet has already been demonstrated during the past several years using GPS and surface meteorological data from a 30-site network in the south-central U.S. (Rocken et al., 1997b). Examples of real-time atmospheric water-vapor and TEC data from this network are shown in Figs. 4 and 10.

### 2.1. Water vapor in atmospheric processes

Water in its three phases has a profound influence on weather and climate. Water-vapor, the 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 widely recognized that moisture fields are inadequately defined in global, regional and local weather analysis and forecasting. This inadequacy stems from the sparsity of water-vapor observations, combined with the high spatial and temporal variability of moisture fields (Trenberth and Guillemot, 1996). Traditional water-vapor observing systems include radiosondes, surface-based humidity sensors, surface and satellite-based radiometers, and research aircraft. Ground-based GPS sensing of atmospheric moisture, demonstrated by university researchers (Bevis et al., 1992; Rocken et al., 1993), is complementary to these traditional systems, providing autonomous, frequent, economical, and accurate moisture data that are unaffected by weather conditions or time of day.

Timely and accurate moisture data are needed to advance mesoscale modeling research (e.g., McPherson et al., 1997), and to improve the quality of short-term cloud and precipitation forecasts (Emanuel et al., 1995). Universities at the leading-edge of this research are running real-time mesoscale models for numerical weather prediction (Mass and Kuo, 1998). Included are Pennsylvania State University (Warner and Seaman, 1990), Colorado State University (Cotton et al., 1994), the University of Utah (Horel and Gibson, 1994), the University of Washington, North Carolina State University, the University of Wisconsin, the University of Michigan, the University of Arizona, the University of Oklahoma and other universities. For example, the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma produces real-time mesoscale (10–100 km) and storm scale (1–10 km) forecasts (Xue et al., 1996). This group is using real-time weather radar (NEXRAD) data to improve prediction of severe storms (Droegemeier et al., 1998). They expect that assimilation of high-resolution moisture field data derived from GPS will allow modeling of convection before it is detected by radar reflection from hydrometeors (Droegemeier, 1998). An example of real-time column water-vapor or "precipitable water" (PW) estimated from GPS network data in the south-central US is shown in Fig. 4.

GPS-sensed PW data can be used to improve storm system analysis (Rocken et al., 1995; Businger et al. 1996). In addition, improved vertical structure of water-vapor and short-term precipitation forecasts can be obtained by assimilating surface humidity and PW data into mesoscale models (Kuo et al., 1996). Park and Droegemeier (1996) showed that simulations of thunderstorms can be quite sensitive to the distribution of water-vapor in their near environment. Crook (1996) studied the sensitivity of thunderstorm initiation in northeastern Colorado to the distribution of temperature and moisture in the atmospheric boundary layer. Utilizing the fact that water-vapor 2 m above the ground is relatively well specified by existing sensor networks, the study examined variations from these values as a function of height within the boundary layer. The finding was that thunderstorm initiation is most sensitive to the temperature profile while thunderstorm strength is most sensitive to water-vapor content. Hence, better measures of water-vapor content across the entire depth of the boundary layer, as measured by SuomiNet, are likely to yield better thunderstorm forecasts.

Water-vapor is a greenhouse gas that plays a critical role in the global climate system (Starr and Melfi, 1991). This role is not restricted to absorbing and radiating energy from the Sun (Stokes and Schwartz, 1994), but includes the role of water-vapor on the formation of clouds and aerosols, and on the chemistry of the lower atmosphere. SuomiNet will provide accurate real-time water-vapordata on a regional and continental scale. It will also allow the US to join with other countries establishing GPS networks for atmospheric sensing (see Section 4) to create a global real-time GPS network for atmospheric research and education.

### 2.2. Sensing atmospheric moisture with GPS

There are several approaches to GPS sensing of atmospheric water vapor from the ground. The first to be developed (Bevis et al., 1992) uses standard space geodetic techniques (Dixon, 1991; Hager et al., 1991; Segall and Davis, 1997) to estimate the 2 to 3 m zenith phase delay induced in GPS signals by the neutral atmosphere. Residual signal delays to each satellite are mapped as the cosecant of the satellite elevation angle (Niell, 1996), based on the assumption that the atmosphere is azimuthally homogeneous. This gives an average zenith delay, from which the hydrostatic or "dry" component, estimated from surface pressure, is subtracted. PW (precipitable water) is calculated as the product of the zenith delay and a conversion factor (Bevis et al., 1992). The accuracy of GPS sensed PW by this method is better than 2 mm (Rocken et al., 1993, 1997b; Duan et al., 1996).

The assumption of azimuthal symmetry (Davis et al., 1993; Elosegui et al., 1998) limits the accuracy and spatial resolution of GPS sensed PW. Higher spatial resolution can be obtained by solving for the integrated water-vapor or "slant water" (SW) along each GPS ray path. SW is obtained by solving for the total slant delay along each ray path, and then subtracting the dry component of the slant delay. The dry slant delay can be estimated from surface pressure measurements or from three-dimensional numerical weather models (Chen and Herring, 1996). A schematic illustration of GPS ray paths for SW sensing is shown in Fig. 5.

The spatial coverage that can be achieved through GPS observations of SW is shown in Fig. 6.

The increased spatial resolution of SW sensing is based on the ability of commercial GPS receivers to track up to a dozen GPS satellites at any moment in time. The tracking

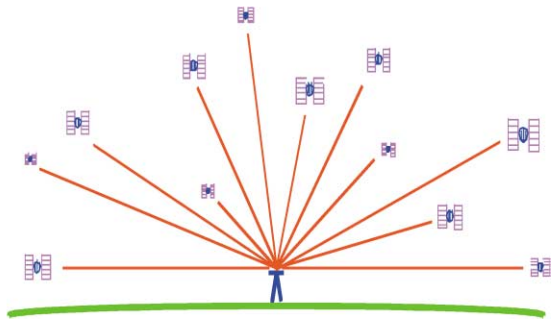

Fig. 5. Signals from up to 12 GPS satellites can be tracked by a ground-based GPS receiver. SW can be simultaneously sensed along all of the GPS ray paths.

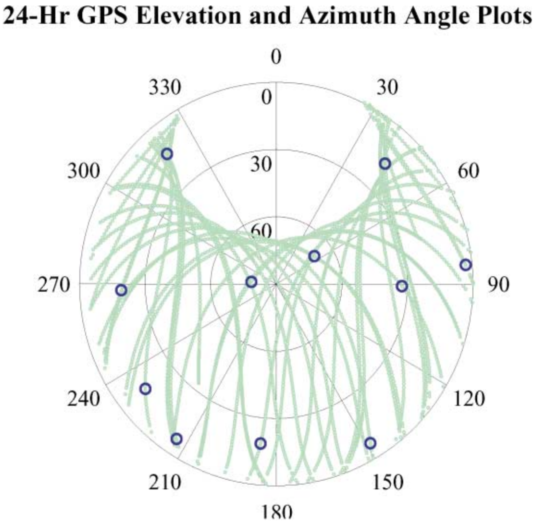


Fig. 6. GPS satellite elevation and azimuth tracks ("sky plots") observed near Boulder, CO during one day (light blue curves) and at one point in time (blue circles). A GPS receiver is located at the center of the plot. Tracking is blocked by mountains to the west (below 3°), but reaches −0.5° elevation to the east over the plains. SW ("slant water" — integrated water-vapor along a slant path) can be estimated simultaneously along the ray paths to each satellite in view.

can be continued down to about a half a degree below the horizon as a result of refractive bending. At zero-degree elevation, a GPS ray reaches an altitude of 2 km at a distance of about 200 km from a ground-based GPS antenna.

A comparison of SW sensed by GPS and by water-vapor radiometers pointed sequentially along the line-of-sight to each GPS satellite is shown in Fig. 7. The high-frequency variations in the GPS sensed SW data are attributed to small-scale structures in the moisture field. These small scale structures are not observed in the radiometer data, which are averaged over a 5° field of view at 8 min intervals. Comparison of GPS and pointed radiometer data determined GPS sensed SW noise levels at 0.8 mm rms near 10° elevation

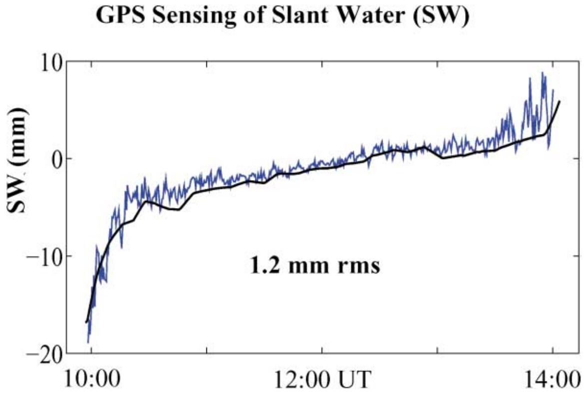


Fig. 7. GPS (jagged blue) and pointed radiometer (smooth black) sensed SW ("slant water" — integrated water-vapor along a GPS ray path) and their rms agreement (Ware et al., 1997).

angle, decreasing to 0.3 mm rms near the zenith (Braun et al., 2000).

Though much remains to be learned, the applicability of GPS sensing to the measurement of atmospheric moisture has already been demonstrated, over areas that are largely distinct from the planned SuomiNet coverage. For example, Naito et al. (1998) describe the Japanese five-year, ten-agency, GPS Meteorology Program. The program uses data from the 1000 site Japanese GPS network, originally established for earthquake research and hazard mitigation. Data from this network are now being used also for numerical weather prediction and climate research (Tsuda et al., 1998). Goals include use of GPS sensed SW data to improve mesoscale modeling and forecasting, and use of the resulting analysis to improve GPS survey accuracy. An example of increased variability in GPS slant delays observed by the Japanese network during a typhoon, presumably from increased water-vapor variability, are shown in Fig. 8.

GPS observations can also be used to measure the velocity of strong refractive features moving above a network. For example, Herring and Shimada (1998) used slant delay time series from the Japanese network to estimate the velocity and height of "water-vapor winds". Estimation of water-vapor winds by this method is complementary to established techniques that extract atmospheric motion vectors from satellite cloud and moisture images (Holmlund, 1998). Large improvements are expected when high-resolution wind and moisture field data are assimilated into mesoscale models (Kuo, 1998).

Four-dimensional characterization of atmospheric refractivity using GPS-sensed slant delays was recently demonstrated by Elosegui et al. (1999). Another approach uses data from an array of low-cost, single-frequency (L1) GPS receivers spaced by 1 to 2 km to characterize four-dimensional water-vapor fields (Meertens et al., 1998; www.gst.ucar.edu/gpsrg/arm.pdf). These studies demonstrate the potential for water-vapor tomography using slant

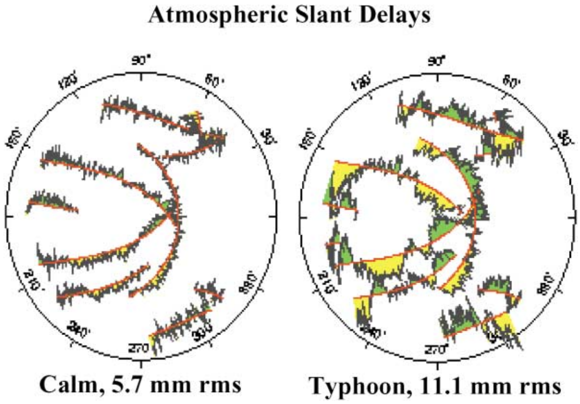


Fig. 8. Four hours of atmospheric slant delays plotted vs. the observed GPS satellite azimuth and elevation angles (Herring and Shimada, 1998) as viewed by a GPS receiver located at the center of the "sky plot". Green (positive) and yellow (negative) perturbations are plotted perpendicular to the satellite trajectories (red). The larger slant delay variations seen during typhoon conditions are attributed primarily to changes in water-vapor.

Fig. 9. An L1 receiver system deployed for volcano studies at Long Valley, CA. The system, including solar power and a radio modem communication link, was developed by the UNAVCO Facility (www.unavco.ucar.edu/science_tech/volcano/l1). Hardware cost for this system is less than $4000.

path data from closely spaced GPS arrays. The practicality of using single-frequency receivers is enhanced by proximate dual-frequency receivers and by good TEC (total electron content) prediction models. SuomiNet is expected to improve both factors. An L1 receiver system is shown in Fig. 9.

Amplitude data from ground-based GPS receivers may be useful in studies of atmospheric turbulence. Minami et al. (2000) report observations of enhanced scintillation in GPS signals when both the atmospheric turbulence intensity and watervapor mixing ratio are large. In this study, the detailed structure of meteorological disturbances was determined using boundary layer radar, radiosonde, laser ceilometer and GPS data. The relationship between GPS amplitude scintillation and atmospheric turbulence can be further studied using SuomiNet.

Assimilation of SW data in models can simultaneously constrain the integrated water-vapor along a dozen or so GPS ray paths. A simulation experiment demonstrated that a network of GPS stations with 40 km spacing can be used to determine atmospheric water-vapor structure with high-resolution (MacDonald, 1999; MacDonald et al., 2000). Additional research is needed to fully utilize GPS moisture data in mesoscale modeling and prediction (e.g., Guo et al., 2000; Fang et al., 1998). However, assimilation operators for GPS sensed SW and "water vapor wind" data must first be developed and tested. The most appropriate place for this to occur is in university settings, at the forefront of real-time mesoscale modeling and data assimilation research. The availability to university researchers of thousands of GPS slant delay observations per hour on a national scale is expected to stimulate significant advancements in mesoscale analysis and prediction.

### *2.3. Sensing the ionosphere with GPS*

SuomiNet data promise to have an even greater impact on the ionospheric research than on meteorology, since the ionosphere is a very data sparse region compared to the neutral atmosphere. One of the primary goals of the NSWP is the development of global ionospheric models that can assimilate all types of ground and space-based observations. GPS provides a timely and cost-effective method of obtaining ionospheric data. Based on the frequency dependence of ionospheric delays, integrated TEC along the ray path from each GPS satellite in view can be estimated from dual-frequency GPS data. Large numbers of real-time TEC observations are the data sets needed for the three-dimensional ionospheric data assimilation and modeling. This capability is currently under development at several universities. The US military is assisting by funding the development of a global ionospheric model. The joint military research laboratory — university project began in April 1999 and will continue for 5 years.

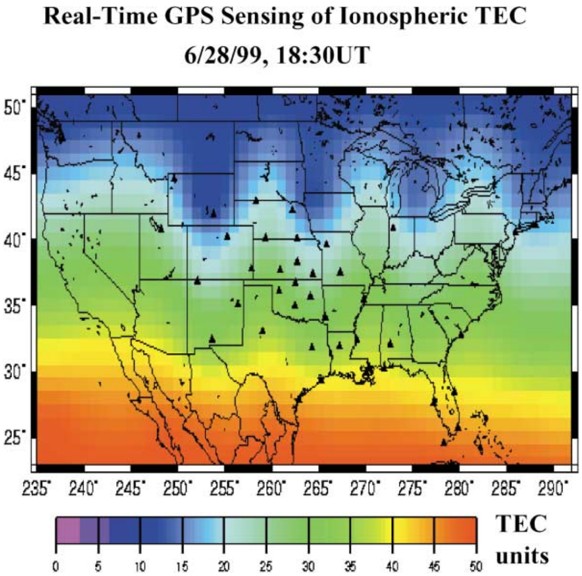


Fig. 10. Example real-time contour map of GPS-sensed ionospheric TEC in the south-central US Maps are posted every 30 min at www.gst.ucar.edu/gpsrg/realtime.html. GPS sites are shown as black triangles.

Hemispheric and global mapping of vertically averaged TEC has been demonstrated using GPS data from the International GPS Service (IGS) network (igscb/jpl.nasa.gov) including approximately 200 GPS stations distributed worldwide (Zumberge et al., 1997). These two-dimensional horizontal maps are made using a Kalman filter and a mapping function to convert slant to vertical measurements (e.g., Wilson et al., 1995; Ho et al., 1996). More complex modeling of the ionosphere has been demonstrated using IGS data and a stochastic tomographic approach with a two-layer model (Juan et al., 1997). The model characterized low-resolution time-varying three-dimensional TEC structure on a global scale. A similar approach provides real-time maps of global TEC, plus one and two day predictions via Internet (www.cx.unibe.ch/aiub/ionosphere.html). SuomiNet will contribute high-resolution TEC data to improve the fidelity of ionospheric mapping, modeling and prediction over the US. An example of a real-time TEC map derived from ground-based GPS data is shown in Fig. 10.

The potential for ionospheric modeling is much greater if space-based GPS occultation data are also available. For example, GPS observations from low Earth orbit (e.g., Ware et al., 1996; Rocken et al., 1997b) were used with ground-based IGS data to model the temporal evolution of three-dimensional electron density on a global scale during ionospheric storms (Hernandes-Pajares et al., 1998). The tomographic model was solved with 1 h, $10 \times 10$ degree, 8-layer resolution. For each storm, 1 million delays and 400 occultations were assimilated to solve for 3000 unknowns. Results were verified using the International Reference Ionosphere and ionosonde data. Howe et al. (1998) simulated the use of ground and space-based GPS data in four-dimensional ionospheric modeling, with resulting large improvements in model resolution and accuracy.

Ionospheric scintillation occurs in equatorial, mid-latitude, and auroral zones, induced by geomagnetic storms, solar conditions, Rayleigh–Taylor instabilities, and other known and unknown mechanisms (e.g., Fremouw et al., 1978; Basu and Basu, 1981; Yeh and Liu, 1982; Aarons, 1997). SuomiNet sites located in each of these zones will be able to measure variations in GPS phase and amplitude induced by ionospheric scintillation at sampling intervals of 1 s or less. For example, a SuomiNet site at Guam is well positioned to study the onset of equatorial scintillation activity. A strong, enhanced upward $E \times B$ drift is required to create the ambient ionospheric conditions responsible for this activity. The enhanced $E \times B$ drift causes TEC to decrease dramatically. The GPS receiver at Guam (or any other GPS receiver situated near the magnetic equator) can measure this decrease (e.g., Kelley et al., 1996; Musman et al., 1997). An hour and a half later small-scale plasma density irregularities are expected to form. These irregularities can be detected by the same GPS receiver.

During geomagnetic storms, SuomiNet TEC observations could be used to determine whether the mid-latitude ionospheric response to the penetration of high-latitude electric fields ($E \times B$ drift), or to the propagation of traveling ionospheric disturbances (TIDS) initiated by traveling atmospheric disturbances (TADS) (e.g., Beach et al., 1997; Taylor et al., 1998). For example, two-dimensional maps of TEC perturbations derived from data observed at 900 GPS sites in Japan showed the spatial structure, time evolution, and velocity (tens to 100 m/s) of electron density structures with 0.15° latitude and longitude resolution (Saito et al., 1998). Similar analyses could be used to relate the occurrence of gravity waves in the lower atmosphere associated with storms, topography, and jet streams (Fritts and Nastrom, 1992; Nastrom and Fritts, 1992), as observed in rocketsonde (Tsuda et al., 1994), radar (Murayama et al., 1994), lidar (Whiteway and Carswell, 1995), and GPS occultation data (Tsuda et al., 2000).

The effects of $E \times B$ drift are felt simultaneously at all latitudes while the TIDs propagate from high to low latitudes with a characteristic velocity. This velocity can be uniquely determined, using data from the mid-latitude chain of SuomiNet receivers. Another question related to geomagnetic storms is the longitudinal extent of the ”positive phase” of ionospheric storms, defined as the enhancement in electron density at local sunset on the first day of the storm. The open question is whether this enhancement exists over a wide longitudinal sector, as the Earth rotates through the sunset terminator. The large east–west chain of SuomiNet receivers should be able to answer this question, unequivocally.

Because of the phenomenal growth of GPS, the large and growing numbers of regional and global GPS networks, and the development of global GPS occultation capability, the infrastructure for fully three-dimensional ionospheric tomography is becoming established. SuomiNet will make a significant contribution to this infrastructure, providing thousands of TEC measurements hourly over the US University researchers can assimilate these data into high-resolution regional ionospheric models. SuomiNet data, and data from similar networks in Japan (mekira.gsi-mc.go.jp), Europe (www.cx.unibe.ch/aiub/ionosphere/html; www.ieec.fcr.es/gps/intro.html) and elsewhere (e.g., IGS: igscb.jpl.nasa.gov; China: Li and Mao, 1998; Taiwan: Liou et al., 2000), combined with thousands of GPS occultation observations (e.g., www.cosmic.ucar.edu) should stimulate the rapid development of global-scale ionospheric models.

### 2.4. Additional applications

A key to understanding the Earth system is learning how and why various geophysical quantities vary in space and time. As a result, considerable attention has been directed toward building net-works of instruments to make these observations. Such networks include weather stations, seismometers, strainmeters, tide gauges, and a variety of other instruments. Historically, advances in instruments have provided the data that drove dramatic advances in understanding the phenomena in question. Recent advances in computer and Internet technology permit even further advances, as it is now possible for the individual sensors in the network to return data in real time, and for sensor observation modes (such as sampling frequency) to be easily coordinated. SuomiNet moves beyond the use of the Internet merely for data transmission, it will also use the Internet to coordinate sensors. Hence, the opportunity is presented to develop a national geophysical instrument yielding synchronous data of previously unobtainable timeliness, and quality. The resulting data, instrumentation, sensor coordination and data distribution methods present a unique opportunity for university research and education in the coming decade (Fulker and Ware, 1997). SuomiNet has considerable potential to stimulate interdisciplinary research, an important and difficult goal for contemporary science (Metzger and Zare, 1999). Examples of potential interdisciplinary science applications for SuomiNet data are described below.

*Coastal meteorology*: Development of methods for estimation of PW (precipitable water) from buoy-based GPS data is planned by SuomiNet participants at the Scripps Institution of Oceanography. By doing so, they aim to improve the accuracy of GPS buoy positioning which, combined with underwater acoustic ranging, is used to measure seafloor crustal motion (Speiss et al., 1998). GPS sensing of moisture from buoys holds promise for other applications. For example, buoys moored offshore from the west coast of the US could provide data that are valuable for coastal meteorology, and drifting buoys with satellite links could provide moisture data for mesoscale (and global) modeling research. Buoy-based GPS sensing could also provide TEC data for global ionospheric modeling research, as well as ocean current and water temperature data for El Niño, tropical cyclone, and climate related research. As part of SuomiNet, two GPS systems may be installed and operated on moored buoy systems located offshore from California and Hawaii. The buoys would be connected via radio modem to the Internet, demonstrating the use of GPS observations from buoys for coastal meteorological research applications. Recognizing the potential of SuomiNet for coastal meteorology and oceanography, participating universities are planning to establish 20 SuomiNet sites in coastal regions.

*Hydrology*: A major report: "Opportunities in the Hydrologic Sciences" (National Research Council, 1991), noted that hydrology is a data-poor science. In particular, atmospheric analyses interpolate and extrapolate radiosonde measurements from coarsely and irregularly spaced land locations, with inadequate spatial and temporal resolution, to represent small-scale hydrological processes (Roads et al., 1994). The availability of distributed, accurate, timely, GPS sensed atmospheric moisture data on a continental scale is expected to stimulate rapid advancement in hydrology. These data can be assimilated into mesoscale models along with other data for use in estimating four-dimensional water-vapor fields, allowing estimation of water-vapor flux into watershed regions, and on continental scales. In addition, great potential exists for improving air-craft and satellite-based radiometric data by correcting for atmospheric moisture effects using SuomiNet data. The resultant improvements in remotely sensed surface temperatures should yield significantly improved estimates of sensible heat flux and evapotranspiration.

Recognizing the value of improved atmospheric moisture data for hydrology, participating hydrologists have registered 8 SuomiNet sites in experimental watersheds maintained and operated by the Agricultural Research Service (ARS) of the US Department of Agriculture. These watersheds have been heavily instrumented with rain gauges, soil moisture, stream flow (flumes) and other hydrological and atmospheric sensors (e.g., Post et al., 1998). The ARS, working closely with universities and research institutions, operates long-term experimental watersheds across the country and has on-site staff to maintain instruments and collect data. Research goals include improved understanding of the coupling of atmospheric and surface parameters in the hydrological cycle, improved modeling and prediction of stream flow variability and flooding in individual watersheds and on regional and continental scales. Information on the ARS experimental watersheds is available via hydrolab.arsusda.gov/wdc/arswater.html .

*Regional climatology*: The sensitivity of ground-based (and space-based) GPS data to regional and global climate change was demonstrated in global climate model simulations by Yuan et al. (1993) and by Stevens (1999).

Major advantages of these data for climatology are their all-weather availability and long-term stability without calibration. SuomiNet will provide continuous PW estimates from 100 sites distributed across the US with better than 2 mm accuracy. In addition, once the appropriate variational methods have been developed, slant GPS delays can be directly assimilated into mesoscale models. Chen and Herring (1996) compare slant delays in microwave (VLBI) signals at low-elevation angles with results from ray tracing through mesoscale models. The results show strong coherence, but distinct differences are also evident, implying that VLBI (and GPS) slant delays can be used to improve three-dimensional moisture (and pressure) fields modeled using radiosonde data alone. Similar results for GPS sensed PW were reported by Kuo et al., (1996) and Businger et al. (1996).

Regional climate research is likely to benefit from improved moisture field definition. For example, Min and Schubert (1997) studied the climate signal in regional moisture fluxes derived from global analyses, finding PW anomalies associated with extreme climate conditions (major drought and flood) in the Great Plains of the central US. However, they found that the moisture flux estimates from three major global analyses disagreed by as much as 25%, and concluded that inadequate definition of moisture fields in the models is responsible for a major part of this disagreement. GPS sensed moisture data is expected to be useful for the GEWEX Continental Scale International Project (GCIP) designed to improve understanding of large scale hydrological cycles (Schaake and Coughlan, 1991; www.ogp.noaa.gov/gcip). In particular, SuomiNet moisture data should help improve understanding of the nocturnal Great Plains Low Level Jet, which accounts for approximately one-third of all moisture transport into the continental US (Helfand and Schubert, 1995).

*Ground truth for satellite radiometry*: Microwave and infrared satellite radiometers are widely used as nadir sensors of atmospheric water-vapor (for example, GOES and TOVS water-vapor sensors described by Menzel et al., 1998; and Stankov, 1998). These satellite systems provide valuable water-vapor measurements over oceans, where atmospheric data are otherwise scarce. However, satellite radiometers are less accurate for sensing tropospheric water-vapor over land, particularly during cloudy conditions. High resolution four-dimensional water-vapor fields based on SuomiNet data could provide ground truth for comparison with satellite sensed water-vapor over North America. Potentially, improved understanding of algorithms and methods for satellite radiometer observations over land could result, leading to improved satellite sensing of water-vapor over poorly instrumented land areas.

*Topographic SAR corrections*: Signal delays induced by atmospheric moisture can significantly degrade interferometric synthetic aperture radar (SAR) sensitivity to crustal deformation or topography. The method combines time-sequenced observations from aircraft or satellites to produce high-resolution images that are sensitive to Earth topography and its deformation in time (Massonnet et al., 1993), and to refractivity changes in the troposphere. However, the method cannot differentiate between a signal delay caused, for example, by water-vapor heterogeneities in the atmosphere and Earth surface deformations. The high-temporal sampling characteristics of GPS observations can be used to complement the high-spatial resolution of the interferometric SAR images. The GPS observations can be used to determine the long-wavelength atmospheric signal in the interferometric SAR images, and consequently correct these images in deformation studies (Zebker et al., 1997). If there is no surface deformation during the time interval of data acquisitions, SAR imagery can be used to fill spatial gaps in water-vapor observations by GPS receivers (Hanssen, et al., 1999). Potentially, a combination of SAR and GPS technology could provide accurate high-resolution ($\sim$ 10 m) moisture data for microscale research including studies of severe weather, convection and downbursts. In summary, SuomiNet could significantly increase the impact of SAR interferometric imaging in solid-Earth and atmospheric research.

*Ionospheric signatures of geophysical events*: SuomiNet data may contain detectable ionospheric gravity wave signals generated by a variety of geophysical and artificial sources. Included are earthquakes (Calais and Minster, 1995); volcanoes (Kanamori, 1998); tsunamis (Najita et al., 1974); tornadoes and severe storms (Bedard, 1998); Transient Luminous Events (TLEs) including sprites, jets and elves (Marshall et al., 1998; Pasko et al., 1997; Lyons et al., 1998; Uppenbrink, 1999); meteors, meteorites and space debris (Bedard and Bloemker, 1997); and rocket launches (Calais and Minster, 1996). Sampling parameters of SuomiNet GPS receivers can be coordinated using IDD, allowing the network to be "tuned" on a local, regional or national scale for optimum sensitivity to specific ionospheric events. For example, by "turning up" the sampling frequency in specific regions at specific times, SuomiNet could observe ionospheric signals related to geomagnetic storms; $E \times B$; gravity-acoustic waves generated by jet streams, severe storms and their interactions with topography; and other geophysical events.

*Atmospheric chemistry*: Improved estimates of water-vapor flux are expected when GPS sensed moisture data are properly assimilated into meteorological models. Water-vapor flux is useful for modeling of dispersion and chemical processes associated with trace gases, pollutants, water-vapor, and aerosols. After SuomiNet has been established, university researchers may consider adding other sensors at all (or a subset of) SuomiNet sites. For example, hydroxyl, ozone, fluorocarbon, carbon monoxide, sulfate, or nitrate sensors (e.g., Comes et al., 1997; Davis et al., 1997) could be included at SuomiNet sites, as appropriate. These sensors, coordinated via IDD, could be used for local, regional and continental atmospheric chemistry studies.

*Astronomy*: On August 27, 1998, an extremely intense gamma ray flare passed through the solar system, rapidly ionizing the exposed part of the Earth's nightside upper atmosphere, producing ionization levels usually found only during daytime (hail.stanford.edu/gammaray.html). This gamma ray flare originated at a faint X-ray star, located in the distant reaches of our galaxy, some 23,000 light years away. Similar events could be easily detected in GPS observations of TEC. This example illustrates the potential for SuomiNet in unforeseen interdisciplinary research opportunities.

### 2.5. Other GPS networks

SuomiNet will be one of many GPS networks worldwide, and it will not be the only one used to measure characteristics of the atmosphere. However, SuomiNet will provide unique and timely atmospheric sensing capability over the US SuomiNet is optimized to stimulate university participation in atmospheric remote-sensing activities made possible by GPS.

We wish to stress this optimization characteristic. Sensor networks often are designed to test a particular set of hypotheses, in which case theoretical analyses and simulations can be employed to rationalize a particular sensor configuration. In contrast, SuomiNet will support an extraordinarily broad and interdisciplinary set of studies on poorly observed, characterized or understood atmospheric features. Therefore, we have not attempted to optimize sensor locations to support specific studies, but have chosen a strategy that optimizes student and faculty participation in an emerging domain of atmospheric measurement, one that promises new knowledge, leading to new operational regimes. We think it is critical for the education and research community, broadly defined, to be involved immediately in such advances. In order to maximize the scope of scientific studies that can be undertaken by SuomiNet participants and other investigators, we will seek bi-directional, real-time data exchange agreements with the operators of other high-quality GPS networks that exist or are being planned, including:

- In North America, various agencies have sponsored the establishment and operation of GPS networks for scientific research, navigation, and engineering. Examples include the ARI receivers described in the Prior Results section; the Southern California Integrated GPS Network (SCIGN; milhouse.jpl.nasa.gov); the Coordinated Reference System (CORS; www.ngs.noaa.gov/CORS/cors-data.html); and a central US network established by NOAA with assistance from UNAVCO and universities to demonstrate the value of GPS-sensed PW data for weather modeling and forecasting (www-dd.fsl.noaa.gov/gps.html). Other North American GPS networks are described by Showstack, 1998a.

**One of 1,000 Japanese GPS Network Sites**

Fig. 11. GPS network sites in Japan are housed in 5 m tall stainless-steel towers, as shown. The sites are maintained by private companies under contract; communications are provided by telephone.

- In Japan, the world's largest array of 1000 GPS stations was established for earthquake hazard research and mitigation (Fig. 11; mekira.gsi-mc.go.jp). Applications for this network have been expanded to include meteorological, climate, and ionospheric research.
- In Europe, scores of continuous GPS stations have been established for weather, climate, and ionospheric research (Emardson et al., 1998; metix.nottingham.ac.uk/wavefron/index.html).
- Globally, the International GPS Service (IGS) has coordinated the establishment and operation of a global-GPS network including several hundred stations. The original focus of the IGS was geodesy, but its focus has expanded to include ionospheric, tropospheric, sea level, and global-change applications (igscb.jpl.nasa.gov/projects/projindex.html).

There are many opportunities for complementary applications of SuomiNet and other GPS networks. For example, real-time PW and TEC contour maps shown in Figs. 4 and 10 use data from a combination of agency and university sites. SuomiNet, although focused primarily on university sites and users, will also coordinate with other networks and users where appropriate.

## 3. University participation

Universities have signed up to establish more than 100 SuomiNet sites for atmospheric applications, and a subset of 61 sites for combined atmospheric and geodetic appli-

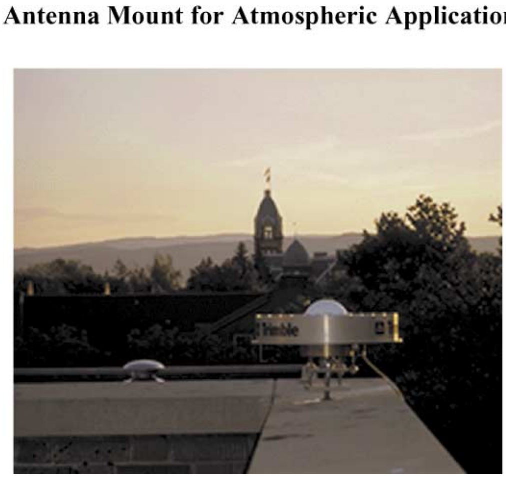


Fig. 12. Standardized GPS-choke ring antenna mounted on the roof of Lind Hall at Central Washington University. Similar installations are expected for universities interested only in atmospheric applications.

cations (via www.unidata.ucar.edu/suominet). A majority of these sites are located in the interior of the continental US. However, a variety of other site environments are registered including 2 arctic coastal, 8 tropical coastal, 7 island, 2 buoy, and 1 tropical buoy. In addition, 12 SuomiNet sites are registered by hydrologists for collaborative watershed research, and 7 by oceanographic research institutions. Overall, the variety of site environments and interests registered for SuomiNet demonstrates its broad interdisciplinary research and educational potential as perceived by universities and research institutions.

## 4. Description of research instrumentation

The standard equipment at a SuomiNet site will include a dual-frequency GPS receiver and antenna, surface meteorology (pressure, temperature, and humidity) sensors, a PC configured to run local data manager (LDM) and IDD software and protocols, radio modems for Internet connection (optional), cabling, equipment housing, and an antenna mount. For the 42 sites registered by universities for atmospheric applications only, the GPS antenna, its protective dome, and leveling mount will be mounted (in most cases) on the roof of an academic building (e.g., Fig. 12). The GPS receiver, computer, and ancillary equipment will be located within the building. For the 61 sites registered by universities for atmospheric and geodetic applications, a geologically stable site location away from buildings and multipath is needed (Fig. 14). In this case, radio modems, an enclosure for security and protection from the weather, and an Invar monument set in concrete are included. Site selection and monument construction are the responsibility of participants having geodetic research and education interests. The UNAVCO Facility will provide technical advice and assistance regarding site construction and monumentation to all SuomiNet participants. The cost of equipment for a SuomiNet site is approximately $15,000 for an atmospheric only site and $30,000 for an atmospheric plus geodetic site. This cost reflects special pricing offered by GPS equipment manufacturers through the UNAVCO Facility for use in university research. Cost sharing between the NSF and participating universities has been proposed.

The principal SuomiNet functions including observation, communication and analysis of GPS data, sensor coordination, data-product distribution, and data management are described below.

*Data observation*: Participating universities and research institutions will establish GPS receivers and ancillary equipment at nationally distributed sites. Assistance in GPS equipment specification, procurement, testing, installation, maintenance and data communication will be provided by the UNAVCO Facility (sponsored by the NSF and NASA to develop and support GPS applications in geosciences). Web-based materials already in place will be augmented to assist in these activities. It has extensive experience in GPS equipment testing and procurement, in the development, installation and operation of continuous GPS stations, and in GPS data management (www.unavco.ucar.edu). Typical real-time GPS stations are shown in Figs. 12 and 13.

*Data communication, data product distribution and station coordination*: These activities will be accomplished using (IDD) internet data distribution, the system that has evolved as the primary means of real-time data distribution by Unidata and its approximately 150 university users. It uses local data management (LDM) software and protocols (www.unidata.ucar.edu/packages/ldm) and the Internet. The real-time data usage heritage that eventually led to IDD is described by Suomi et al. (1983). The current IDD is a distributed system comprised of campus based LDMs, each of which implements a "push" protocol for rapidly relaying data from neighbor to neighbor, even in the presence of network congestion. Methods based on more than a decade of continuous experience in real-time data distribution are embodied in IDD, including the capability for station coordination.

Each SuomiNet site will include a computer configured to receive executable code via IDD. This will allow for coordination of sensor parameters at all, or any subset of, SuomiNet sites. In this manner, SuomiNet sites can be coordinated for specific observations on local, regional, and continental scales. For example, the sampling frequency of SuomiNet GPS receivers could be adjusted to 1 Hz or higher to optimize sensitivity to scintillations generated by boundary layer turbulence in the neutral atmosphere, or to look for ionospheric effects associated with meteor showers, geomagnetic storms, and upper stratospheric/mesospheric disturbances including sprites, jets, and elves. A condition for

**Atmospheric and Geodetic Installation**

Fig. 13. A solar-powered GPS site with radio modem telemetry established by the University of Utah for atmospheric and geodetic applications, with assistance from UNAVCO. The site is located in a geologically stable location with a radio telemetry link to campus. The enclosure beneath the solar panel contains GPS receiver equipment and batteries. Similar installations are expected for universities interested in combined atmospheric and geodetic applications.

**Monument and Antenna Mount for Atmospheric and Geodetic Applications**

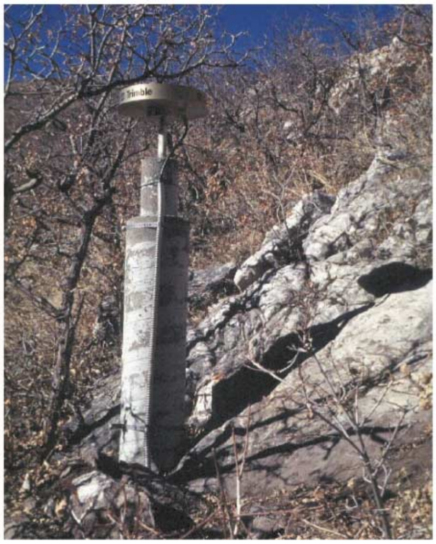

Fig. 14. GPS antenna and monument established by the University of Utah for combined atmospheric and geodetic measurements, with assistance from the UNAVCO Facility.

participation in SuomiNet is that all SuomiNet data must be made freely available via IDD in real-time.

*Data analysis*: This activity will be carried out at UCAR using well-established automated procedures. Initially, raw GPS data from all SuomiNet sites will be collected and processed into water-vapor and TEC data products by GST (UCAR's GPS Science & Technology program), using well established automated procedures. GST has been providing real-time GPS-sensed PW, TEC, and related data products in real-time via the Web for the past three years. Examples of real-time PW and TEC data products are shown in Figs. 4 and 10. Any university will be able to access SuomiNet data at any level ranging from raw data to derived data products, and to make their own data products available (e.g., PW, SW, TEC, mesoscale or ionospheric model outputs, moisture flux, geodetic coordinates, etc.), using the IDD system.

Universities will be able to set-up their own data collection and analysis activities and to provide additional data products. For instance, "sky plots" of atmospheric slant delay are currently provided by MIT on a daily basis from networks in California and Asia (bowie.mit.edu/ ~tah). University groups could provide real-time maps showing ionospheric and tropospheric features causing scintillations, moisture flux into specific watersheds, strong moisture gradients associated with tornado hazards, etc. Thus, interested universities will have opportunities to develop their own programs to use SuomiNet data or derived products for a variety of atmospheric and related research and education activities.

*Data management*: This activity will be carried out by the UNAVCO Facility using its existing on-line data management and archiving system including its data search, geographic mapping and display system. To ensure ready availability of data and data products to the atmospheric community, Unidata will provide real-time access via IDD. Short- and long-term atmospheric data management and archiving will be provided by existing UCAR systems such as the CODIAC atmospheric data management system (www.joss.ucar.edu/codiac) and the NCAR mass data storage system (www.scd.ucar.edu/dss), as appropriate. In addition, UNAVCO's seamless data archive concept (www.unavco.ucar.edu/data/#gsac) could be expanded to include atmospheric data archived at other university and agency sites.

## 5. SuomiNet status

The NSF has decided to fund SuomiNet. On-line registration for participation remains open (see the Web page at www.unidata.ucar.edu/suominet). If demand exceeds resources, SuomiNet sites will be selected to achieve broad geographic coverage and gain a large, diverse set of participating institutions, each with applications that are scientifically and educationally compelling.

## 6. Conclusions

Real time national GPS networks for atmospheric sensing are being established or planned in a number of countries around the world. The resulting continuous, accurate, all-weather, real-time GPS networks will provide a major stimulus to mesoscale modeling and data assimilation, severe weather, precipitation, cloud dynamics, regional climate, hydrology, modeling and prediction of severe terrestrial and space weather, detection and forecasting of low-latitude ionospheric scintillation activity and geomagnetic storm effects at ionospheric mid-latitudes, and detection of ionospheric effects induced by a variety of geophysical events. Real-time GPS data also have potential applications in coastal meteorology, satellite radiometry, correction of synthetic aperture radar data for crustal deformation and topography studies, and boundary layer turbulence. It is important that national real-time GPS networks are coordinated to use common data formats and exchange protocols. This will ensure that the exciting scientific and operational potential of real-time GPS networks is fully realized.

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