SuomiNet: A Real-Time National GPS Network for Atmospheric Research and Education

Project Summary

We propose to develop "SuomiNet", a university-based, real-time, national Global Positioning System (GPS) network for atmospheric research and education. The proposed network, named to honor meteorological satellite pioneer Verner Suomi, will exploit the recently-shown ability of ground-based GPS receivers to make thousands of accurate upper and lower atmospheric measurements per day. SuomiNet's goal is to use the demonstrated power of GPS for academic research and education, by making large amounts of spatially and temporally dense atmospheric data from broad and diverse regions widely available in real-time. 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. SuomiNet builds on the expertise of UCAR's GPS Science & Technology (GST) program in GPS-related atmospheric science, on Unidata's real-time distribution of meteorological data to universities, and on the UNAVCO Facility in developing, deploying and operating GPS networks.

SuomiNet data are relevant to the U.S. Weather Research Program (USWRP), to the international Global Energy and Water Cycle Experiment (GEWEX), and to the National Space Weather Program (NSWP). 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. These topics are central to the USWRP and GEWEX. In addition, TEC and ionospheric scintillation data derived from GPS signal phase and amplitude will help universities address over-arching, fundamental research topics including: (a) the processes that govern the spatial distribution of ionization, (b) the evolution of ionospheric irregularities and scintillation, (c) thermospheric dynamics and its coupling to the ionosphere, and (d) validation, testing and continued development of research models and numerical methods. These topics are high priorities of the NSWP.

SuomiNet is expected to have strong impacts on:

- ***mesoscale data assimilation and modeling,***
- ***ionospheric data assimilation and modeling,***
- ***modeling and prediction of severe terrestrial and space weather,***
- ***regional hydrology and climate studies.***

SuomiNet also has potential applications in:

- *detection and forecasting of low latitude ionospheric scintillation activity and geomagnetic storm effects at ionospheric mid-latitudes,*
- *coastal meteorology,*
- *providing ground truth for satellite radiometry,*
- *correction of synthetic aperture radar data for crustal deformation and topography studies,*
- *detection of scintillation associated with atmospheric turbulence in the lower troposphere,*
- *detection of ionospheric effects induced by a variety of geophysical events.*

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 et al., 1998).

Project Description

Results from Prior NSF Support for Instrumentation

The University Corporation for Atmospheric Research (UCAR) previously received a $2,000,000 grant (EAR-9512212) from the Academic Research Infrastructure (ARI) Program, entitled “Acquisition of GPS Equipment for Consortium Studies of Global Change and Tectonics of the Western Margin of the Americas”. UCAR coordinated the participation of 28 collaborating universities including their combined commitment of $1,343,133 in institutional cost sharing. The NSF award resulted in the purchase of 170 dual frequency GPS receivers. The purchase and distribution of GPS equipment under the award was accomplished by the University Navstar Consortium (UNAVCO) Facility within the UCAR Office of Programs (UOP).

The goals of the proposal were interdisciplinary, including solid Earth and atmospheric sciences research. Specifically, the receivers are being used to measure crustal deformation associated with tectonics and volcanism in the hemisphere of the Americas along the active rim of the eastern Pacific. In addition, the GPS measurements made possible through the ARI award exploit the sensitivity of GPS to processes affecting the signal as it propagates through the atmosphere. Descriptions of scientific results to which the ARI receivers contributed, and corresponding scientific references, are included in the UNAVCO brochure (Stein et al., 1998; www.unavco.ucar.edu/community/brochure).

Research Activities

The atmosphere is flooded with 1.6 and 1.2 GHz (L1 and L2) signals transmitted by 24 GPS satellites. 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 delays that are equivalent to several meters or more of displacement. The key to SuomiNet-enabled research (and education) is to view these delays not as displacement 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, 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 et al., 1998).

Universities and research institutions (hereafter called simply “universities”) participating in SuomiNet have registered to establish 103 SuomiNet sites (Figure 1). 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, monuments, and IDD will be provided by the UNAVCO Facility, Unidata, and GST.

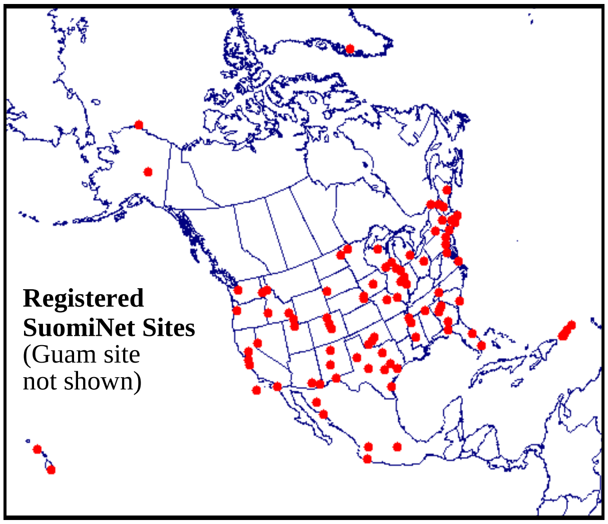

Figure 1. University and research institution sites (103) currently registered for participation in SuomiNet. Additional information and on-line registration are available via www.unidata.ucar.edu/suominet.

GPS, surface meteorological, and other data observed at SuomiNet sites will 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 that will extend 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 additional research and education objectives. For example, SuomiNet sites could be outfitted for atmospheric chemistry applications, as described later.

SuomiNet will provide raw GPS and surface meteorological data, tropospheric and ionospheric delays, 2-D water vapor and TEC data to universities in real-time, as illustrated in Figure 2.

Internet Accessible Data

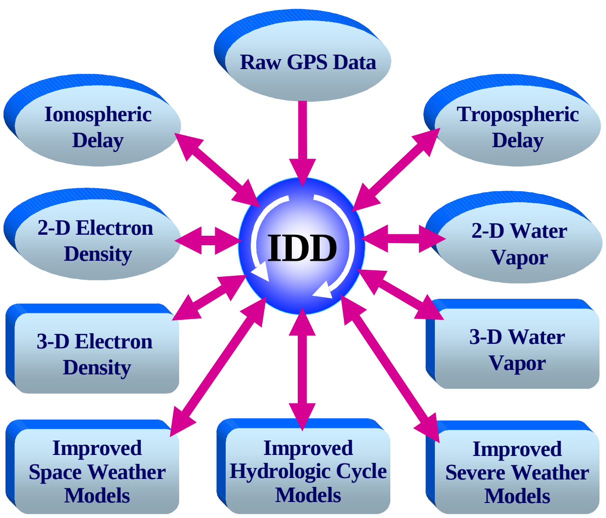

Figure 2. SuomiNet data and products to be provided to universities in real-time are represented by the oval symbols. Data products that are expected to be derived from SuomiNet data through independent university research programs are represented by rectangular symbols.

University investigators, through independent research programs, will assimilate these data into models to provide real-time 3-D water vapor and electron densities, and to enhance space weather and hydrological cycle modeling. SuomiNet data have additional value for a variety of other research and education applications, as described below.

Real-time access to all SuomiNet data and products will be provided to universities via IDD. The feasibility of providing real-time GPS data and products via Internet has 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., 1997a). Examples of real-time atmospheric water vapor and TEC data from this network are shown in Figures 3 and 7.

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. Improved understanding of water vapor and its role in weather and climate is a major objective of national and international research programs including USWRP (uswrp.mmm.ucar.edu/uswrp) and GEWEX, including its Hydrometeorology and Land-Surface, Radiation, and Modeling and Prediction Projects (www.cais.com/gewex/projects.html).

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 et al., 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; Carpenter et al., 1998). 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 U.S. is shown in Figure 3.

Real-Time GPS Sensing of PW
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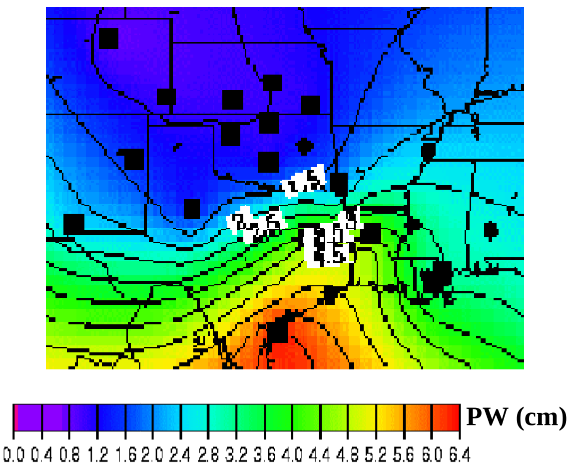


Figure 3. Precipitable water (PW) estimated from GPS measurements in the south-central U.S., as posted on the Web every 30 minutes (Rocken et al., 1997a; www.gst.ucar.edu/gpsrg/realtime.html). Site locations are represented by black squares and dots. The strong water vapor gradient in southeast Texas was accompanied by tornadoes and severe flooding.

GPS-sensed PW data can be used to improve storm system analysis (Rocken et al., 1995; Businger et al. 1996; Cucurull et al., 1999). 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 meters 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 vapor data on a regional and continental scale that can make a significant contribution to the USWRP and GEWEX. It will also allow the U.S. to join with other countries establishing GPS networks for atmospheric sensing to create a global real-time GPS network for atmospheric research and education.

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 meter zenith 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 is calculated as the product of the zenith delay and a conversion factor (Bevis et al., 1994). The accuracy of GPS sensed PW by this method is better than 2 mm (Rocken et al., 1993, 1997a; 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). The spatial coverage that can be achieved through GPS observations of SW is shown in Figure 4.

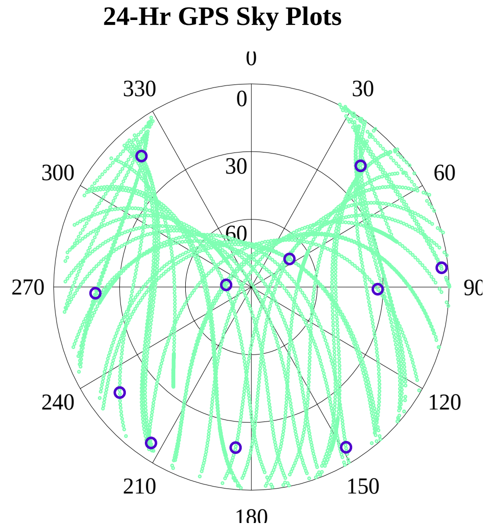


Figure 4. GPS satellite elevation and azimuth tracks (sky plots) observed near Boulder, Colorado during one day (light blue curves) and at one point in time (blue circles). Tracking is blocked by mountains to the west (below 3 degrees), but reaches -0.5 degrees elevation to the east over the plains.

The increased spatial resolution of SW sensing is based on the ability of commercial GPS receivers to track 10 or so GPS satellites at any moment in time. The tracking continues 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 Figure 5. Statistics for similar comparisons of more than 17,000 GPS and pointed radiometer SW data points show an agreement of approximately 1 mm rms (Ware et al., 1997). The high frequency variations seen in the GPS sensed SW data are attributed to small-scale variability in moisture fields.

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 1,000 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., 1998a). 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 (Iwabuchi et al., 1998; Ohtani et al., 1998). 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 Figure 6.

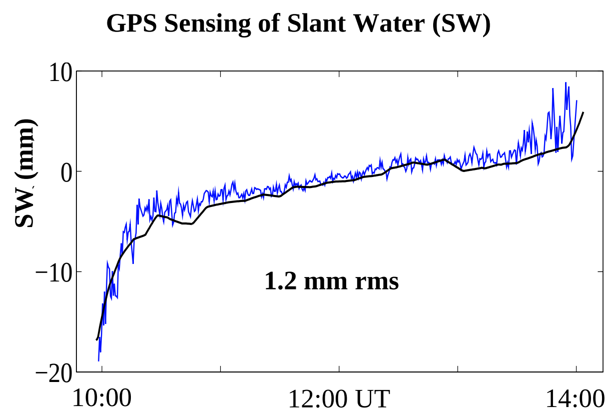


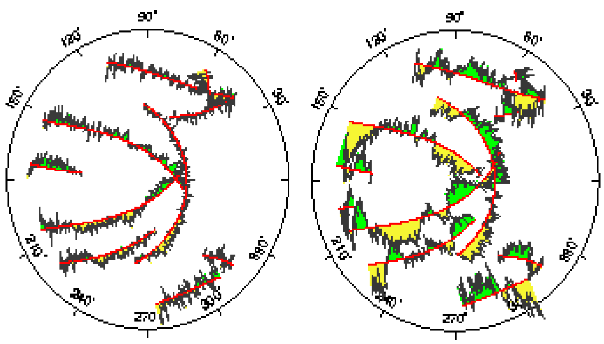
Figure 5. GPS (jagged blue) and pointed radiometer (smooth black) sensed SW and their rms agreement (Ware et al., 1997).

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 of "cloud winds". Estimation of cloud 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 water vapor fields using GPS sensed slant delays was recently demonstrated by Flores 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; Braun et al., 1998; www.gst.ucar.edu/gpsrg/arm.pdf). These studies demonstrate the potential for water vapor tomography using slant 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 prediction models. SuomiNet is expected to improve both factors.

Amplitude data from ground-based GPS receivers may be useful in studies of atmospheric turbulence. Minami et al. (1999) report observations of enhanced scintillation in GPS signals when both the atmospheric turbulence intensity and water vapor 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.

Atmospheric Slant Delays



Calm, 5.7 mm rms **Typhoon, 11.1 mm rms**

Figure 6. Four hours of slant delays plotted vs. GPS satellite azimuth and elevation angles (Herring and Shimada, 1998). Green (positive) and yellow (negative) perturbations are plotted perpendicular to the satellite sky track (red). A satellite directly above the site would appear in the center of each plot, and a satellite on the eastern horizon would appear on the right.

Additional research is needed to fully utilize GPS moisture data in mesoscale modeling and prediction (e.g., Gou et al., 1998; Fang et al., 1998). Assimilation of SW data in models could simultaneously constrain the integrated water vapor along a dozen or so GPS ray paths. However, assimilation operators for GPS sensed SW and “cloud 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.

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 (www.ofcm.gov/nswp-ip/text/cover.htm) 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 (Manucci et al., 1993). Large numbers of real-time TEC observations are the precisely the data sets needed for the three dimensional ionospheric data assimilation and modeling. This capability is currently under development at several universities. The U.S. military is assisting by funding the development of a global ionospheric model. The joint military research laboratory - university project will begin in April 1999 and will continue for 5 years.

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 U.S. An example of a real-time TEC map derived from ground-based GPS data is shown in Figure 7.

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; Schreiner et al., 1998) were used with ground-based IGS data to model the temporal evolution of three-dimensional electron density on a global scale during ionospheric storms (Hernandez-Pajares et al., 1998). The tomographic model was solved with one hour, 10 x 10 degree, 8-layer resolution. For each storm, 1 million delays and 400 occultations were assimilated to solve for 3,000 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.

Real-Time GPS Sensing of Ionospheric TEC
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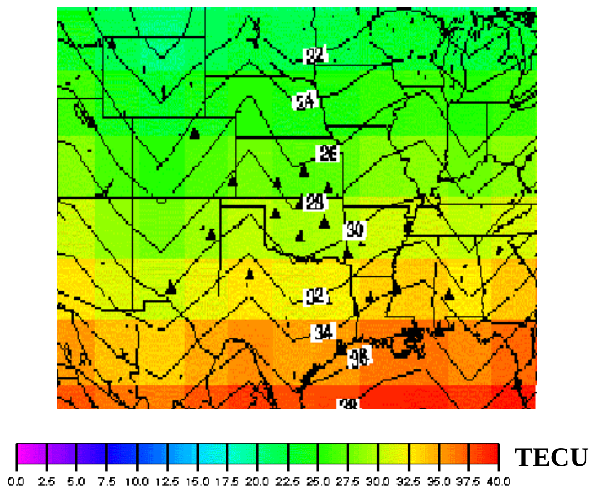

Figure 7. Example real-time contour map of GPS sensed ionospheric TEC in the south-central U.S. Maps are posted every 30 minutes at www.gst.ucar.edu/gpsrg/realtime.html. GPS sites are shown as black triangles.

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 one second or less. For example, a SuomiNet site at Guam is well positioned to study the onset of equatorial scintillation activity. A strong, enhanced upward ExB drift is required to create the ambient ionospheric conditions responsible for this activity. The enhanced ExB 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 (ExB 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/sec) of electron density structures with 0.15 degree 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., 1998b).

The effects of ExB 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 will 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 mostly in place. SuomiNet will make a significant contribution to this infrastructure, providing thousands of TEC measurements hourly. University researchers can assimilate these data into high-resolution 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 et al., 1998; Taiwan: Liou et al., 1999), combined with thousands of GPS occultation observations (e.g., www.cosmic.ucar.edu) will stimulate the rapid development of global-scale ionospheric models.

Additional SuomiNet 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 networks 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 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). The potential for SuomiNet in interdisciplinary research is suggested by Figure 8, and is further described below.

Coastal Meteorology. Development of methods for estimation of PW 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 (Spiess 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 U.S. 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 will be installed and operated on moored buoy systems located offshore from California and Hawaii. The buoys will 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.

Atmospheric Sensing with Ground-Based GPS

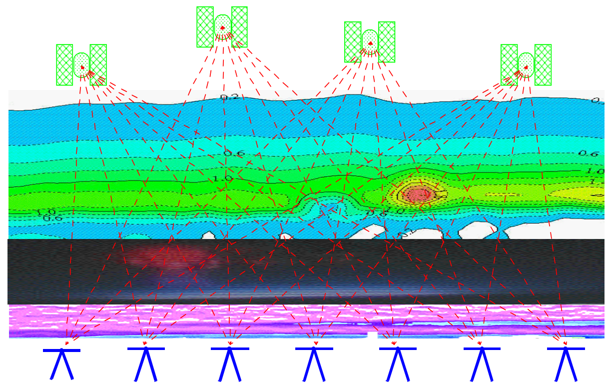

Figure 8. A variety of useful information regarding upper and lower atmospheric structure and dynamics can be derived from GPS signal phase and amplitude data. In this illustration, the troposphere is depicted by a lidar scan of tropospheric water vapor, the stratosphere and mesosphere by a photo of a red jet and blue sprite (elf.gi.alaska.edu), and the ionosphere by an ionospheric model (janus.nwra.com/nwra/tomr2j.gif).

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 horizontal 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 aircraft 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 U.S. 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 (1998). 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 U.S. 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 U.S. 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, 1990; 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 U.S. (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 will 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.

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 (Gabriel et al., 1989; 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, 1998). Potentially, a combination of SAR and GPS technology could provide accurate high resolution (~10 meter) 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); 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; ExB; 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 data are 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; Rao 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/gamma-ray.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.

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 U.S. 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 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 U.S. 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.*

- *in **Japan**, the world's largest array of 1,000 GPS stations was established for earthquake hazard research and mitigation (Figure 9; 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).*

One of 1,000 Japanese GPS Network Sites

Figure 9. GPS network sites in Japan are housed in 5 meter tall stainless steel towers, as shown above. The sites are maintained by private companies under government contract; communications are provided via telephone.

There are many opportunities for complementary applications of SuomiNet and other GPS networks. For example, real-time PW and TEC contour maps shown in Figures 3 and 7 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.

University Participation

Universities, research institutions, and investigators registered for participation in SuomiNet are listed in Table 1. All 103 sites are registered for atmospheric applications, and a subset of 61 sites are registered for combined atmospheric and geodetic applications. A majority of the registered sites are located in the interior of the continental U.S. 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.

Table 1. Universities and sites registered for participation in SuomiNet. A total of 103 sites are registered for atmospheric (A, 42 sites) and atmospheric plus geodetic (AG, 61 sites) applications. Oceanographic institutions are highlighted in red; registrants expressing hydrological interests are highlighted in blue.

University / Institution	Investigator	Use
U Hawaii	S Businger	AG
U Metropolitana - Puerto Rico	F Díaz	A
Indiana State U	S Silva	AG
Valparaiso U	B Wolf	AG
U Alabama - Huntsville	K Knupp	A
U Nebraska - Lincoln	C Rowe	AG
U Wisconsin -Milwaukee	P Roebber	AG
Agricultural Research Service	R Malone	A
U Puerto Rico - Mayaguez	G Mattioli	AG
Scripps Institute Oceanography	J Orcutt	AG
U Arizona	B Herman	A
U Colorado - CIRES	D Anderson	A
New Mexico Tech	K Minschwaner	A
McGill U - Canada	R Rogers	A
U Metropolitana - Puerto Rico	J Arratía	AG
Woods Hole Ocean Inst	B Walden	A
Scripps Inst Oceanography	D Chadwell	AG
U Idaho	J Oldow	AG
U Wisconsin - Madison	C DeMets	AG
U Texas - Austin	S Nerem	A
Old Dominion U	J Klinck	AG
Plymouth State College	J Zabransky	AG
U Virgin Islands	D Storm	AG
U Texas - Austin	S Nerem	A
Agricultural Research Service	Stark/Dillard	A
U Texas - El Paso	S Harder	AG
Agricultural Research Service	J Garbrecht	A
U Idaho	J Oldow	AG
Scripps Institute Oceanography	D Chadwell	AG
U Washington	C Mass	A
Cornell U	M Wysocki	A
Arecibo Observatory	S Gonzalez	A
Colorado State U	S Cox	AG
U Georgia	G Hoogenboom	A
U North America - Mexico	E Cabral-Caño	AG
So Dakota Sch Mines & Tech	P Zimmerman	A

U Maine	A Leick	AG
U Washington	H Edmon	AG
Lehigh U	P Zeitler	AG
Purdue U	G Petty	AG
Instituto Tecnología Sonora	J Garatuza	A
U Colorado - Colo Springs	M Mack	A
U Texas - Austin	S Nerem	AG
U Houston	J Lawrence	A
Saint Louis U	C Graves	AG
Texas A&M U	D Wiltschko	AG
Woods Hole Ocean. Inst	B Walden	A
U California - Davis	L Kellogg	AG
San Jose State U	M Voss	A
U Georgia	T Mote	A
U Idaho	J Oldow	AG
Millersville U - Pennsylvania	R Clark	AG
U Illinois	M Ramamurthy	A
U Colorado	D Anderson	A
Lyndon State College	N Atkins	A
U No America - Mexico	E Cabral-Caño	AG
U Washington	A Qamar	AG
Rensselaer Polytechnic Inst	R McCaffrey	AG
Goddard Space Flight Center	D Chesters	AG
U Connecticut	L Liu	AG
U Wisconsin - Madison	C DeMets	AG
Oregon State U	C Goldfinger	AG
U Nebraska - Lincoln	C Rowe	AG
LW Experimental Watershed	Garbrecht/Starks	A
Calif State U - Monterey Bay	S Rafkin	AG
U Charleston	L Mills	AG
Columbia U -LDGO	Bell/Koczynski	AG
U Connecticut	N Worobey	A
Woods Hole Ocean Inst	B Walden	A
Northwestern U	S Stein	AG
U Puerto Rico - Mayaguez	M Velez-Reyes	AG
U Minnesota	P Morin	AG
U Missouri - Columbia	St Qi Hu	AG
U Utah	G Mace	AG
U Memphis	P Bodin	AG
U Colorado - Boulder	D Anderson	A
Florida State U	P Ruscher	AG
National Sedimentation Lab	C Alonso	A
Florida Institute of Technology	G Maul	AG
Woods Hole Ocean Inst	B Walden	A
U North Dakota	S Kroeber	A
Utah State U	J Sojka	A
U Idaho	J Oldow	AG
U Texas	S Nerem	A
Jackson State U	P Croft	AG
U Alaska - Geophysical Inst	J Freymueller	AG
U Miami	B Albrecht	A

U Albany	D Knight	AG
U Alaska - Geophysical Inst	J Freymueller	AG
SW Watershed Res Center	D Goodrich	AG
Iowa State U	D Yarger	A
U Nevada - Desert Res Inst	A Huggins	AG
Guadalajara U - Mexico	Meulenert Peña	AG
Calif State U - Monterey Bay	R Kvitek	AG
U Texas - Austin	S Nerem	AG
Agricultural Research Service	D Bosch	A
U Nebraska	K Hubbard	A
U North Carolina - Asheville	A Huang	AG
Institute Environment - Sonora	C Watts	A
NW Watershed Res Center	C Slaughter	AG
U Michigan	P Samson	A
U Oklahoma	F Carr	A
Los Alamos National Lab	S Nerem	AG

Description of Research Instrumentation

The principal functions of SuomiNet are observation, communication and analysis of GPS data, sensor coordination, data product distribution, and data management. Each of these functions, and SuomiNet site equipment, are described below.

Data observation. Participating universities and research institutions will establish GPS receivers and ancillary equipment at 103 sites distributed nationally. Assistance in GPS equipment specification, procurement, testing, installation, maintenance and data communication will be provided by the UNAVCO Facility. Web-based materials already in place will be augmented to assist in these activities. The UNAVCO Facility is sponsored by NSF and NASA to develop and support the use of GPS for geoscience applications. 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 Figures 10-12.

Data communication, data product distribution and station coordination. These activities will be accomplished using IDD, 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.

Antenna Mount for Atmospheric Applications

Figure 10. 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.

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

Data analysis at UCAR will be accomplished 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, 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 Figures 3 and 7. 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 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.

SuomiNet Site Equipment includes 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., Figure 10). 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 (Figure 12). 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.

Atmospheric and Geodetic Installation

Figure 11. 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.

NSF cost share will be applied to procurement, testing, and shipping of the dual-frequency GPS receiver, antenna, antenna mount and protective dome, and the LDM/IDD computer, and for technical support in equipment installation and maintenance. This approach provides standardized hardware, software and support. NSF will also support data gathering, data reduction into PW and TEC products, and data management activities by GST, Unidata and UNAVCO, principally in the first year of the project (see Project and Management Plans section for details). Independent funding for most of the ongoing SuomiNet support activities will be sought for the second year of the project and beyond.

University cost share will purchase surface meteorological sensing equipment, lightning protection, radio modems and antennas, backup power equipment, and enclosures. Also included in university cost share is funding for SuomiNet equipment installation and maintenance. Universities are encouraged to submit proposals as appropriate to fund research and education applications for SuomiNet and SuomiNet data.

UCAR support for the ongoing operation and maintenance of SuomiNet will be provided through a combination of existing UCAR program activities and new efforts funded via proposals to the USWRP, the NSWP, and other relevant initiatives. Data handling, analysis and management will benefit from existing GST, Unidata, and UCAR programs including the expertise and infrastructure held by Unidata for real-time atmospheric data distribution; by GST in real-time collection and conversion of raw GPS data into PW and TEC data products; and by UNAVCO in real-time GPS station operations, data management and archiving. In addition, UCAR's COSMIC program (www.cosmic.ucar.edu), a follow on to the GPS/MET experiment (Ware et al., 1996; Rocken et al., 1997a), has agreed to make significant computing resources available for SuomiNet data analysis. These computing resources, on loan from industry, are available to SuomiNet until they are needed for COSMIC data analysis in late 2002.

Impact on Education

From the theoretical to the practical, GPS applications are becoming ubiquitous across a wide range of science and engineering disciplines. SuomiNet will place state-of-the-art satellite remote sensing (GPS) equipment and data products in the hands of hundreds of university faculty and students, with enormous implications and potential for education. Students can gain valuable insights into: 1) fundamental elements of GPS, 2) system capabilities and limitations, 3) experimental methods and design, 4) methods of reduction, analysis, assimilation, visualization, and interpretation of GPS data, and 5) mathematical modeling and statistical decision-making. SuomiNet creates a powerful, cost-effective, national instrument for university research and education, by merging GPS technology and the Internet.

SuomiNet does more than provide timely, freely available data from a national network of GPS receivers and ancillary sensors. It also provides a valuable framework for Internet sensor coordination, data distribution and development of applications and data products that will benefit education. Common application software developed by an interdisciplinary community of users could be used in the classroom for modeling, real-time analysis, visualization, and interpretation of the four dimensional upper and lower atmosphere, including its response to a variety of geophysical events.

Monument and Antenna Mount for Atmospheric and Geodetic Applications

Figure 12. GPS antenna and monument established by the University of Utah for combined atmospheric and geodetic measurements, with assistance from the UNAVCO Facility.

SuomiNet provides a valuable opportunity for interdisciplinary research and education where few currently exist. A network of GPS receivers and ancillary sensors capable of supporting a broad range of applications is, in itself, strong incentive for crossing disciplinary boundaries to solve common problems. For example, knowledge of satellite orbit dynamics and the use of GPS data for weather, space weather and geodetic research go hand-in-hand; GPS sensed atmospheric moisture data can be used to improve mesoscale models, the models can in turn be used to estimate moisture flux for hydrological research and to improve GPS positioning accuracy; GPS sensed TEC data can be assimilated into ionospheric models, the TEC data may also contain signatures of gravity waves generated by geophysical events including earthquakes, severe storms, meteorite and space debris impacts, tsunamis, rocket launches, and TLEs including sprites, jets, and elves.

An emerging area requiring interdisciplinary research and education to which SuomiNet can contribute is natural hazards and emergency management (Showstack, 1998b). A national real-time network of GPS receivers could contribute new data types relevant to severe weather and space weather hazards. Interested universities will have the opportunity to develop educational programs in natural hazards and emergency management (NHEM) that incorporate GPS technology and data. These academic programs, whether traditional or Internet-based, could be as inherently interdisciplinary as the corresponding natural hazard and emergency management activities. As an example, an interdisciplinary NHEM degree and certification program currently in development at Millersville University takes advantage of existing programs in geology, geography, meteorology, oceanography, and social studies (human impacts). The community-based interdisciplinary underpinnings of SuomiNet can provide significant benefits to such programs in the form of technology, data and educational materials.

Fundamental to education today is the integration into the learning environment of technology for analysis, visualization and interpretation. Students must acquire proficiency in information technology to be competitive. Job announcements in scientific disciplines require evidence of experience with operating systems, general and discipline-specific software applications, and a variety of other computing experiences. SuomiNet combines a suite of national GPS receivers and ancillary sensors with an established system for Internet data distribution and sensor coordination, and online tutorials (e.g., www.unavco.ucar.edu). Interested students can gain multi-faceted experience in instrumentation, signal conditioning, data processing, assimilation, analysis and visualization techniques, modeling, and computer science.

Many of the anticipated developments stemming from geophysical research using GPS will find direct application in the classroom. For example, over 250 investigators use the Penn State/UCAR mesoscale model, version 5 (MM5) in research, operational forecasting, and education. Enhanced PW monitoring has the potential to significantly improve the definition of moisture fields. Using MM5 as a component in numerical weather prediction, students can learn first-hand the benefits of high resolution data for model initialization and investigate the causes of disparities between simulation and observation. The same could be said for ionospheric modeling studies using TEC. These studies can form the basis for masters theses and doctoral dissertations in several fields.

GPS equipment, methods and data will be widely distributed under SuomiNet. Students who are dispersed geographically, with diverse ethnicity, and studying a variety of disciplines, stand to gain from SuomiNet.

Specifically, 15 universities that are minority-serving or do not grant doctoral degrees are participating in SuomiNet directly or through participation in Unidata, including: Arecibo University, California State University at Monterey Bay, Clark Atlanta, Florida International University, Guadalahara University, Jackson State University, Lyndon State College, Universidad Metropolitana, New Mexico State University, University of New Mexico, University of Puerto Rico, New Mexico Technical University, University of North America, Instituto Tecnología Sonora, and San Jose State University. SuomiNet represents a unique opportunity to join geographically and ethnically diverse universities to develop an innovative, cost-effective, national GPS network for research and education.

Project and Management Plans

Three basic management functions are needed for development of SuomiNet: (1) GPS equipment and computer specification, procurement, configuration, testing and shipping, (2) installation of equipment, computer and IDD software at each site, and (3) data gathering, conversion into data products, and data management. These functions will be carried out in a coordinated fashion by GST/UNAVCO and Unidata. The UNAVCO Facility has extensive experience in development and installation of permanent GPS stations, Unidata in dissemination of real-time atmospheric data to universities using IDD, and GST in conversion of GPS data into real-time PW and TEC data products posted on the Web.

After the GPS receiver and computer have been purchased, the IDD software installed, and the system has been tested, the equipment will be shipped to participating universities. Guidelines to assist participants in site selection, equipment installation and maintenance, computer configuration, and Internet connection will be provided on the Web by UNAVCO and Unidata. Technical assistance will be provided via email. Building on the current real-time network, data streams from newly established SuomiNet sites will be included in real-time SuomiNet data flow as they come on line. Raw SuomiNet data will be converted to PW and TEC by GST and posted on the Web. Unidata will assist with real-time data distribution via IDD. SuomiNet data and data products will be managed and archived by UNAVCO using its well established data management system, making use of additional on-line and long term atmospheric data archives at UCAR and NCAR where appropriate.

Overall coordination and guidance of the SuomiNet project will be the responsibility of **PI Randolph Ware**, GST Director. Guidance and coordination of the UNAVCO Facility in its SuomiNet roles is the responsibility of **Co-PI Seth Stein**, UNAVCO Scientific Director and Professor of Solid Earth Sciences at Northwestern University. Responsibility for Unidata in its specified roles is the responsibility of **Co-PI Dave Fulker**, Unidata Director, with guidance from Unidata's Policy, and User Committees. SuomiNet guidance will also be provided by **Co-PI's: Dave Anderson,** ionospheric scientist at the University of Colorado; **Susan Avery,** Professor of Electrical Engineering and Director of CIRES at the University of Colorado; **Richard Clark,** Professor of Earth Sciences at Millersville University; **Kelvin Droegemeier,** Director of the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma; **Joachim Kuettner,** Distinguished Chair for Atmospheric Sciences and International Research at UCAR; **Bernard Minster,** Professor of Geophysics at the University of California at San Diego; and **Soroosh Sorooshian,** Chair of the Hydrology Department at the University of Arizona.

Timeline and Long Term Expectations

For the short term, university and NSF funds will be used to develop and operate SuomiNet as a national geophysical instrument for research and education. We expect that 60% of the SuomiNet sites will be installed and operating during the first year, 30% during the second year, and the remaining 10% during the third year. Short term goals include development of methods for assimilating GPS moisture and electron density data into weather and space weather models. This work will be carried out by universities with funding obtained via independent research grants. As the state of the art advances, government agencies may establish operational systems for collecting and processing GPS data and derived products. We will encourage the integration of SuomiNet functions (such as IDD systems for distributing raw data and derived products) into these systems as appropriate. However, research opportunities that are unanticipated or of long duration are likely to emerge from SuomiNet, and the relevant UCAR entities--Unidata, GST, and UNAVCO--will provide the infrastructure needed to support these activities, seeking supplemental funds if they are needed from appropriate sources. Thus, SuomiNet has the potential to continue well beyond the five year period covered by this proposal. It is anticipated that universities and funding agencies will remain involved as long as SuomiNet serves their research and education interests.

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