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Real-time national GPS networks: Opportunities for atmospheric sensing

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Real-time national Global Positioning System (GPS) networks are being established in a number of countries for atmospheric sensing. UCAR, in collaboration with participating universities, is developing one of these networks in the United States. The network, named "SuomiNet" to honor meteorological satellite pioneer Verner Suomi, is funded by the U.S. National Science Foundation. SuomiNet will 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 up to a dozen GPS ray paths in the field of view. These delays can be converted into total electron content (TEC), and integrated water vapor (if surface pressure data or estimates are available), along each GPS ray path. The resulting continuous, accurate, all-weather, real-time upper and lower atmospheric data create a variety of opportunities for atmospheric research. In this letter we describe SuomiNet, its applications, and the opportunity to coordinate national real-time GPS networks to create a global network with larger scientific and operational potential.

1. Introduction

SuomiNet will demonstrate the innovative concept of a university-based national geophysical instrument providing real-time atmospheric data for research and education. It 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). 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. TEC and ionospheric scintillation data derived from GPS signal phase and amplitude will help universities and research institutions 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.

2. Research Applications

Universities have registered to establish 126 SuomiNet sites (Fig. 1). 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. 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 Fig. 2. University investigators, through independent research programs, could 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. 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
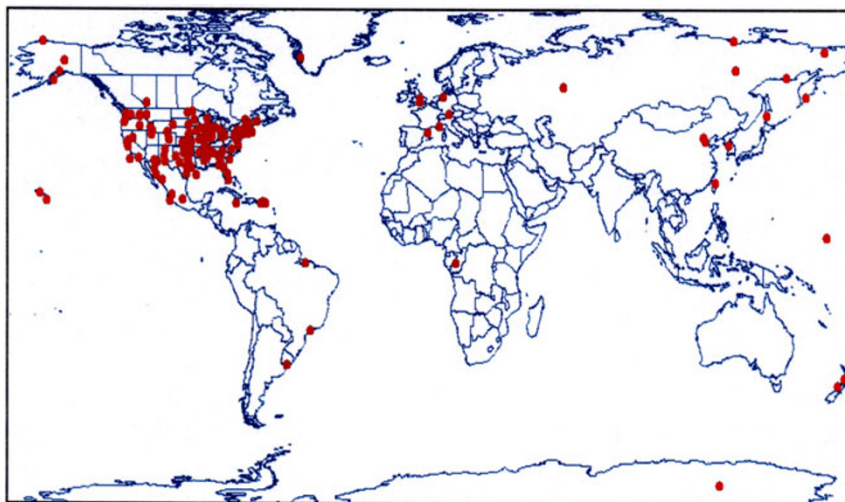
Fig. 1.   Universities have registered the indicated site locations for participation in SuomiNet. For prospective participants, information and on-line registration are available via `www.unidata.ucar.edu/suominet`.
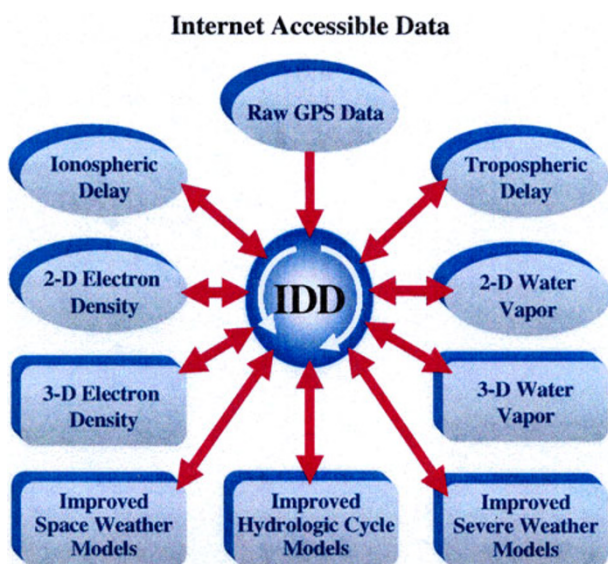

Fig. 2.   SuomiNet data and products to be provided to universities in real-time are represented by the oval symbols. Data products that are expected to be derived from SuomiNet data through independent university research programs are represented by rectangular symbols.

and education objectives, as described below.

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 50-site network in the south-central U.S. (Rocken *et al.*, 1997). Real-time GPS analysis is based on the zero difference method (Alber *et al.*, 2000). An example of real-time atmospheric water vapor from this network is shown in Fig. 3.

2.1   Water vapor in atmospheric processes

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 water vapor 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 water vapor 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 water vapor (Bevis *et al.*, 1992; Rocken *et al.*, 1993; Duan *et al.*, 1996) is complementary to these traditional systems, providing autonomous, frequent, economical, and accurate water vapor data that are unaffected by weather conditions or time-of-day.

Water vapor is a greenhouse gas that plays a critical role in the global climate system. 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. It also presents an opportunity for international collaboration to establish a global real-time GPS network for atmospheric research.

2.2   Sensing atmospheric water vapor with GPS

There are several approaches to GPS sensing of atmospheric water vapor from the ground. The first to be developed uses standard space geodetic techniques (Segall and Davis, 1997) to estimate the 2 to 3 meter 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.*, 1994). The accuracy of GPS sensed PW by this method is better than 2 mm (Rocken *et al.*, 1997).

Averaging and the assumption of azimuthal symmetry limits the accuracy and spatial resolution of GPS sensed PW.
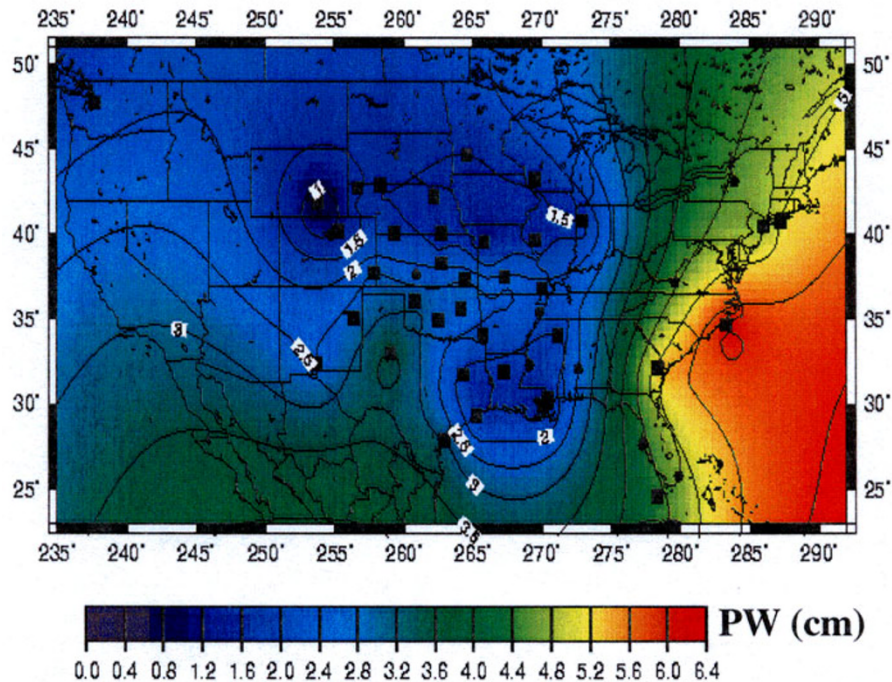
Real-Time GPS Sensing of Precipitable Water (PW)
9/15/99 18:00 UT

Fig. 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.*, 1997; `www.gst.ucar.edu/gpsrg/realtime.html`). Site locations are represented by black squares and dots. Hurricane Floyd made landfall in South Carolina at this time.

Higher spatial resolution can be obtained by solving for the integrated water vapor or "slant water" (SW) along each GPS ray path (Ware *et al.*, 1997). 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 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 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. Comparison of GPS and pointed radiometer data determined GPS sensed SW noise levels at 1.4 mm rms near 10 degrees elevation angle, decreasing to 0.3 mm rms near the zenith (Braun *et al.*, 2000). Various experiments demonstrate that GPS sensed SW data can be used to determine atmospheric water vapor structure with high resolution (Hirahara, 2000; Flores *et al.*, 2000; MacDonald and Xie, 2000; MacDonald *et al.*, 2000; Seko *et al.*, 2000).

2.3 Sensing the ionosphere with GPS

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 (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. Combined with data from real-time networks in other countries and from GPS receivers in orbit (Ware *et al.*, 1996), three dimensional ionospheric modeling on a global scale can be achieved (Howe *et al.*, 1998).

2.4 Additional applications

Real-time GPS network data can be used for a variety of additional applications, including:

Coastal Meteorology. Estimation of PW (precipitable water) from buoy-based GPS data has been demonstrated (Dodson *et al.*, 1999; Brooks *et al.*, 2000). GPS sensing of water vapor 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 water vapor 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.

Hydrology. 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 water vapor 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.

Climatology. Ground and space based GPS data are sensitive to regional and global climate change (Yuan *et al.*, 1993; Stevens, 1999). Major advantages of GPS data for climatology are all-weather availability, long term stability without calibration, and continuous sampling. Regional climate research will benefit from improved water vapor field definition by GPS sensed PW and SW data. Global climate research will benefit from long term calibration of radiosonde and satellite radiometric water vapor observations with GPS PW data.

Ground Truth for Satellite Radiometry. Microwave and infrared satellite radiometers are widely used as nadir sensors of atmospheric water vapor. 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 GPS network data could provide ground truth for comparison with satellite sensed water vapor. 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 water vapor can significantly degrade interferometric synthetic aperture radar (SAR) sensitivity to crustal deformation or topography. The high temporal sampling characteristics of GPS network data 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). In summary, GPS sensed water vapor data could significantly increase the impact of SAR interferometric imaging in solid-Earth and atmospheric sciences.

Ionospheric Signatures of Geophysical Events. GPS network data may contain detectable ionospheric gravity wave signals generated by a variety of geophysical and artificial sources. Included are earthquakes; volcanoes; tsunamis; tornadoes and severe storms; sprites, jets and elves; meteors, meteorites and space debris; and rocket launches (Ware

et al., 2000). GPS networks can sample at 1 Hz, 10 Hz or higher, allowing detection of ionospheric signals generated by a variety of geophysical events.

Atmospheric Chemistry. Improved estimates of water vapor flux are expected when GPS sensed water vapor 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. In addition, regional and global GPS networks could be augmented with additional sensors. For example, hydroxyl, ozone, fluorocarbon, carbon monoxide, sulfate, or nitrate sensors could be added. 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.

3. 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, climatology, 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, and that their data are freely exchanged. This will ensure that the scientific and operational potential of real-time GPS networks is fully realized.

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