P1.39 USE OF FEDERAL AND STATE DEPARTMENTS OF TRANSPORTATION CONTINUOUSLY OPERATING GPS REFERENCE STATIONS FOR NOAA WEATHER FORECASTING

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1. INTRODUCTION

The U.S. Department of Defense developed the Global Positioning System (GPS) as a dual-use (military and civilian) satellite-based position, navigation and time transfer system. It provides all-weather, passive, three-dimensional position, velocity, and time information anywhere on Earth. GPS currently provides two levels of service: a restricted precise positioning service (PPS) with a horizontal accuracy of less than 20 meters, and an unrestricted standard positioning service (SPS) with a horizontal accuracy of about 30 meters.

A large number of federal government agencies use GPS as an integral component of their activities. In addition to all branches of the U.S. military, other agencies include the U.S. Department of Transportation, National Oceanic and Atmospheric Administration, U.S. Geological Survey, U.S. Forest Service, and the National Aeronautics and Space Administration. Some of their specific applications are:

- Positive Train Control (PTC), one of the U.S Department of Transportation 10 "Most Wanted" initiatives for national transportation safety.
- National Intelligent Transportation Systems (ITS) applications, such as navigation and route guidance; automatic vehicle location (AVL), public safety services, “mayday” relief, roadway maintenance, public transit, general railroad operations, land surveying, and automated highway systems (AHS).
- Navigation aids for aviation in all phases of flight.
- Maritime safety along the coasts of the continental U.S., the Great Lakes, Puerto Rico, portions of Alaska and Hawaii, and a greater part of the Mississippi River Basin.

In addition to the federal government applications described above, many state and local government agencies across America are now using GPS to improve statewide transportation facilities, and support local and regional planning, surveying and mapping, design, construction, intelligent transportation systems, and emergency (911) response applications. By all accounts, the improvements in engineering accuracy and productivity in the public and private sectors resulting from the use of GPS have made it one of the best investments in the national infrastructure in recent memory.

2. LIMITATIONS ON GPS ACCURACY

In general, these users routinely require levels of GPS position accuracy and signal availability that are beyond the current capabilities of both the SPS and PPS. This is especially true when the activities have a safety of life or property component, as is frequently the case in most federal and a growing number of state services.

The limitations on position accuracy are caused by uncertainties in the parameters used to calculate position using the technique called trilateration. These parameters include the satellite orbits, satellite and receive clocks, receiver noise, and multipath interference. Errors are also caused by the slowing and bending of the GPS radio signals by the upper and lower atmosphere as they travel from the vacuum of space to a receiver at or near the surface of the Earth. In fact, since Selective Availability[1] was

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[1] Selective Availability (SA) is the procedure of denying to most nonmilitary users the full accuracy of the GPS SPS by “dithering” the satellite clock and degrading the broadcast ephemeris.

turned off in 2000, the major source of GPS position error now comes from the ionosphere and troposphere.

3. CONTINUOUSLY OPERATING REFERANCE STATIONS

Techniques have been developed to mitigate most of these problems, improve position and time accuracy, as well as signal availability especially in urban environments. The most effective techniques are called augmentation and error modeling (or stochastic estimation).

Augmentation is defined as the addition of information to the signals received from the GPS satellites to increase integrity, accuracy, and availability. This is usually accomplished through a process called differential GPS (DGPS). In DGPS, errors are calculated at fixed continuously operating reference stations (CORS) in the geographic vicinity of a remote GPS site, and corrections are broadcast (or made available through some other medium such as the internet.) The major components of DGPS are illustrated in Figure 1.

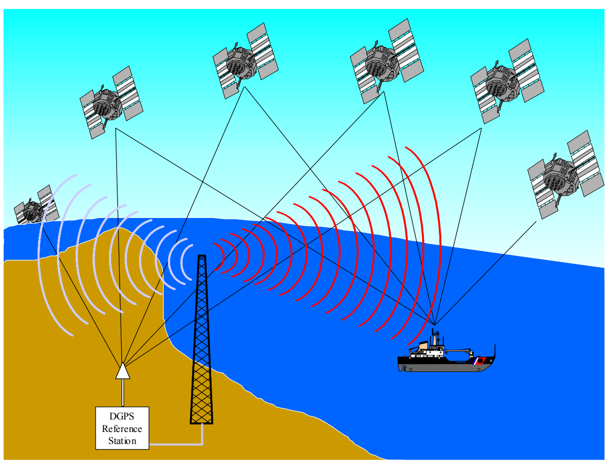

Figure 1. Differential GPS positioning concept (courtesy USCG Navigation Center, 1999.)

Error modeling is defined as the prediction of the impact of the atmosphere (ionosphere and/or troposphere) on the GPS signal. Predictions can either use independent observations (e.g. surface pressure) and a physical model, or estimates of the expected (average) conditions at a place and time that are usually derived from diurnal behavior or climate data. Examples of error models

Stochastic estimation is the process of solving for the tropospheric delay as a free parameter so it can be eliminated to improve the accuracy of the GPS solution[2].

Civilian users of GPS routinely achieve centimeter-level or better accuracy using carrier phase dual frequency receivers (to compensate for the ionosphere), differential surveying techniques, and geodetic processing software that permits stochastic estimation of ionospheric and tropospheric delays. They do this by establishing networks of GPS continuously operating reference stations (CORS) and using the information provided by these networks to reduce inherent ambiguity and uncertainty.

Global CORS networks have been established by organizations such as the International GPS Service (http://igscb.jpl.nasa.gov/) to provide high accuracy GPS orbits, tracking data, and other products for a wide range of international scientific and engineering applications such as geodetic plate motion studies, earthquake deformation, satellite tracking, and GPS meteorology.

CORS networks have also been established nationally as described in Snay (2000). NOAA's National Geodetic Survey (NGS) is working with government, academic, commercial, and private organizations to collectively sponsor and operate the National Continuously Operating Reference Station (National CORS) system. NGS intends to expand the system so that all points in the coterminous United States will be located within 200 km of an operational site at all times. Currently, about 87% of the coterminous United States is located within 200 km of an operational site.

State Departments of Transportation in Alaska, Colorado, Florida, Ohio, Michigan, North Carolina, and Texas (to name only a few) are aggressively deploying local CORS networks to facilitate more specific DGPS applications, including:

- Creating geographic databases for use in Emergency 911 systems.
- Highway inventory, i.e., cantle signs, milepost markers, right-of-way, guardrail, and bridges.

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[2] Stochastic estimation techniques form the basis of ***GPS-Meteorology*** (Duan et al., 1996). Signal delays caused mostly by moisture variability in the troposphere are modeled as a nuisance parameter and eliminated in high accuracy (geodetic) positioning. These delay estimates provide extremely accurate measurements of wet refractivity that are transformed into integrated (total column) water vapor in near real-time under all weather conditions.

- Emergency response services for police, fire and rescue.
- Automatic vehicle location for public transit and other fleets.
- Snowplow guidance for low-visibility situations.
- Inventory of railroad crossings and road centerlines.
- Land-use planning.
- Tracking hazardous materials from origin to destination.
- Mapping pavement-condition data, safety data, accident data, and traffic data.

4. USING FEDERAL AND STATE CORS FOR NOAA WEATHER FORECASTING

Due to the instrumental requirements for high accuracy GPS positioning, it is possible to use the data from federal and state CORS sites to estimate the tropospheric signal delay at each site with extremely high accuracy. The tropospheric signal delay is caused by the refractivity of the non-dispersive or electrically neutral atmosphere, and is associated with temperature, pressure, and water vapor in the lower 9-16 kilometers. The relationship is:

$$N = 77.6\frac{P_d}{T} + 70.4\frac{P_v}{T} + 3.739\frac{P_v}{T^2} \qquad (1)$$

where: N = refractivity = $(n-1)x10^6$
P_d = atmospheric pressure (hPa)
P_w = water vapor pressure (hPa)
T = temperature.

If the surface pressure is known at the elevation of the GPS antenna with reasonable accuracy (approximately 0.5 hPa), then the total wet and dry refractivity directly above the site can be objectively separated with little error. Mapping the resulting wet signal delay into integrated or total column precipitable water vapor (IPW) is accomplished in a straightforward manner if the mean vapor weighted temperature of the atmosphere (T_m) is known. The latter is usually estimated using the surface temperature and a simple linear regression to worldwide radiosonde observations as described in Bevis et al., 1992. However, it has recently been shown that a somewhat better estimate of T_m can be derived from a numerical weather model over the conterminous United States.

The most accurate IPW retrievals are always made when the GPS antenna and surface meteorological sensors, especially the pressure sensor, are in close proximity[3]. In the following example, the GPS antenna and surface meteorological instruments are separated by about 10 meters horizontally and 1.7 meters vertically.

Figure 2 is a comparison of GPS and radiosonde-measured water vapor during the International H2O (IHOP-2002) experiment in Spring, 2002. Radiosondes were launched at the Department of Energy Atmospheric Radiation Measurement (ARM) facility located approximately 9 kilometers south of the GPS-Met instrument at the Lamont Oklahoma NOAA Profile Network site, LMNO2.

During the IHOP experiment, 222 independent GPS and radiosonde water vapor comparisons were made under all weather conditions. The mean difference between the two observing systems was 0.2 mm of IPW, the standard deviation is 1.7 mm, and the correlation coefficient is better than 0.98. These results are typical of GPS-IPW accurcy at CORS sites where GPS and accurate surface meteorological sensors are collocated.

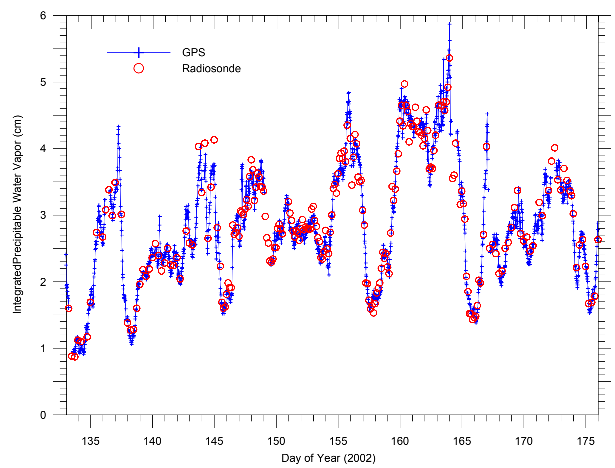

Figure 2. Time series plot of GPS and radiosonde water vapor measurements made during the IHOP 2002 experiment, May 13 and June 25, 2002.

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[3] Surface meteorological sensors are being installed by NOAA FSL at all DOT Nationwide Differential GPS sites. This is a collaborative effort to evaluate the impact of NDGPS observations on weather forecast accuracy, especially as it impacts multi-modal transportation safety. NOAA surface sensors have approximately the same accuracy as instruments installed at typical Road Weather Information System (RWIS) or Mesonet sites established by most state departments of transportation to monitor and transmit weather surface conditions in near real-time.

While it is always desirable to have surface meteorological sensors installed at CORS sites, it is not always practical to do so from an engineering or economic standpoint. The question then is, “how far apart can these observations be made and still yield useful results for weather forecasting?” The answer, from an objective forecasting perspective, is close enough so that the IPW retrieval error is smaller than the numerical weather prediction analysis error without the GPS. Gutman and Benjamin (2001) determined the latter to be 3-5 mm IPW, depending on location.

We performed a series of experiments (described in Gutman et al., 2003) to determine the dependence of atmospheric pressure prediction accuracy on vertical and horizontal distance, geographic region, and time of year. To do this, we compared pressure data from operational National Weather Service Automated Surface Observing System (ASOS) barometers with data derived from high quality digital barometers installed at CORS sites. The comparisons were made at 17 sites during the winter and 13 sites during the spring of 2001. The sites were separated by 3 km to 53 km horizontally, and 2 meters to 200 meters vertically.

We verified that the vertical pressure gradient dominates the equation since it exceeds the horizontal gradient by approximately 5 orders of magnitude. Even under non-hydrostatic conditions, when the horizontal pressure gradient is significant and local wind flow is high, the impact (while important) tends to be spatially localized and relatively short-lived.

We concluded that the appropriate way to extrapolate pressure is to continue a nearby observation vertically from a quasi-equapotential surface (for example altimeter setting) to the actual elevation of the GPS antenna, rather than estimate it from a digital terrain model. The primary reason for this is that digital elevation models (DEM’s) have finite resolution and only reflect the average terrain in a grid cell. Under conditions of high vertical relief, DEM’s can carry substantial errors that will introduce significant errors into the estimation of the zenith hydrostatic delay (Saastamoinen, 1972).

Figure 3 is a comparison of GPS and radiosonde-measured water vapor at the Gaylord MI CORS site belonging to the Michigan Department of Transportation (NOR2). The distance between the GPS antenna and the ASOS (KGLR) located at the Gaylord, Otsego County Airport is 11.8 m vertically and 3050.8 m horizontally.

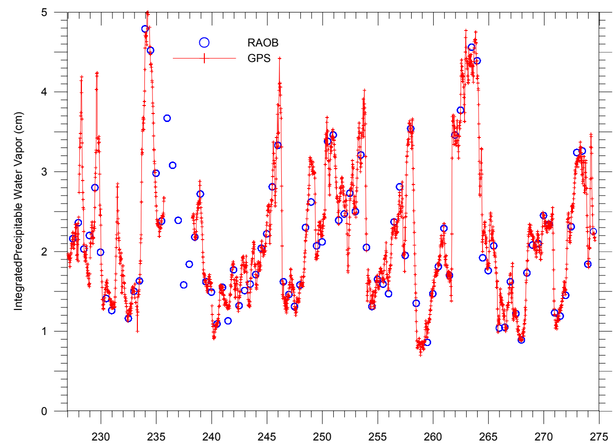

Figure 3. Time series plot of GPS and radiosonde water vapor measurements at Gaylord, MI between August 15 and October 1, 2002. The pressure sensor and GPS antenna are separated by about 3 km horizontally and 12 m vertically. The mean difference, standard deviation, and correlation coefficient are 0.2 mm, 1.59 mm, and 0.984 respectively.

5. GPS IMPACT ON WEATHER FORECASTS

One of the most significant results of the ongoing assessment of GPS impact on weather forecast accuracy is that the magnitude of the impact increases as the GPS network expands (Smith et al., 2002). The significant growth achieved in 2002 is the result of two factors: the near real-time availability of CORS data provided by state departments of transportation, and the ability to use existing surface meteorological sensors to parse the GPS-derived signal delays into their wet and dry components without having to deploy a dedicated sensor package at each site.

Figure 4 shows the configuration of the GPS-Met network in October 2002. The network consists of two types of GPS-Met sites: “backbone sites” with collocated surface meteorological sensors that are operated and maintained by U.S. Department of Transportation, and NOAA. The other type are “infill sites” that are operated and maintained by other organizations including state and local government agencies, universities, and the private sector. Infill sites may or may-not have collocated surface met sensors, but the major distinction is that the infill sites carry no obligation concerning maintenance or data availability.

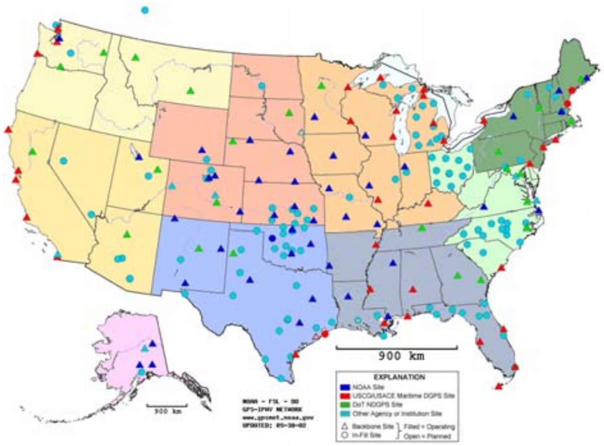

Figure 4. Configuration of the NOAA GPS-Met Demonstration Network in October 2002. Backbone sites are represented by triangles, and circles denote infill sites.

As the number of sites in the network increases, primarily through the addition of CORS sites belonging to state departments of transportation, we expect to see the trend toward larger positive impacts on precipitation forecasts continue (Figure 5). 2003 will test this hypothesis since it will be the first winter season with substantial coverage in the Great Lakes region.

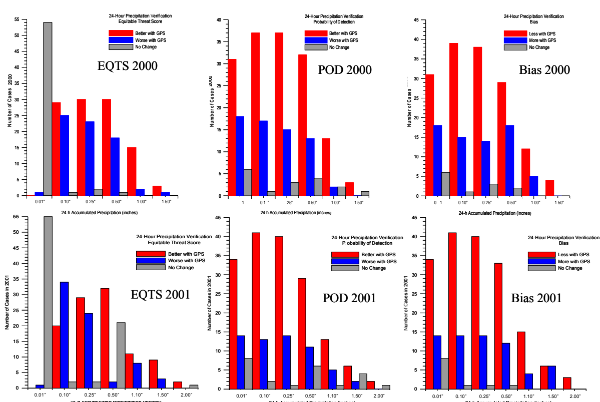

Figure 5. 24-hour precipitation forecast verification statistics for 2000 and 2001. In each bar chart, red represents the improvement in forecast skill, blue is worse skill, and gray is no change. The metrics are equitable threat score (EQT), probability of detection (POD) and bias. In general, improvement is observed at all levels of precipitation above 0.01” in 2000, and above 0.1” in 2001.

6. ACKNOWLEGEMENTS

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7. REFERENCES

Benjamin, S., T. Smith, B. Schwartz, S. Gutman, and D. Kim, 1998: Precipitation forecast sensitivity to GPS precipitable water observations combined with GOES using RUC-2. 2nd Symp. on Int. Obs. Sys., AMS, Phoenix.

Bevis M., S. Businger, T.A. Herring, C. Rocken, R.A. Anthes and R.H. Ware, 1992. GPS Meteorology: Remote Sensing of Atmospheric Water Vapor using the Global Positioning System, *J. Geophys. Res.,* 97, 15787-15801.

Duan, J.M., M. Bevis, P. Fang, Y. Bock, S.R. Chiswell, S. Businger, C. Rocken, F. Soldheim, R.H. Ware, T.A. Hering, and R.W. King, 1996. Remote Sensing Atmospheric Water Vapor using the Global Positioning System, *J. Appl. Meteor*, 35. 830-838.

Gutman, S.I., S.G. Benjamin, 2001. The Role of Ground-Based GPS Meteorological Observations in Numerical Weather Prediction, GPS Solutions, Volume 4, No. 4, pp. 16-24.

Gutman, S.I., S. Sahm, J. Stewart, S. Benjamin, and T. Smith, 2003. A New Composite Observing System Strategy for GPS Meteorology. 12th Symposium on Meteorological Observations and Instrumentation, AMS, Long Beach.

Saastamoinen, J., 1972. Introduction to Practical Computation of Astronomical Refraction, Bull. Geod., 106, 383-397.

Smith, T.L., S.G. Benjamin, B.E. Schwartz, B.E., and S.I. Gutman, 2002. Impact of GPS water vapor data on RUC severe weather forecasts. 21st Conference on Severe Local Storms, paper J5.3 (joint session with the NWP/WAF conference) San Antonio, TX Aug. 12-16.

Smith, T.L., S.G. Benjamin, B.E. Schwartz, B.E., and S.I. Gutman, 2000. Using GPS-IPW in a 4-D data assimilation system. Earth, Planets and Space, 52, 921-926.

Smith, T.L., S.G Benjamin, B.E. Schwartz, and S.I. Gutman, 1999. Using GPS-IPW in a 4D Data Assimilation System, The International Symposium on GPS Application to Earth Sciences (GPS'99 in Tsukuba), October 18-22, Tsukuba, Ibaraki, Japan.

Snay, R.A. (2000). The National and Cooperative CORS systems in 2000 and beyond, Proc. ION GPS-2000, Salt Lake City, UT, September 19-22, 55-58.