The Role of GPS-Meteorology in NOAA's Integrated Upper-Air Observing System

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What is GPS Meteorology?

The NAVSTAR Global Positioning System (GPS) was developed by the U.S. Military (***Figure 1***) to provide accurate positioning, navigation and timing information anywhere on Earth. GPS is a "dual-use" system, which means that its signals are also available for civilian use free of user fees. An artist concept of the next series of GPS satellites is presented in ***Figure 2***.

Radio signals transmitted by the constellation of 24-28 GPS satellites in 20,200 km (10,900 nm) high Earth orbits (***Figure 3***) are refracted (i.e. slowed and bent) as they travel from space to receivers at or near the surface of the Earth (***Figure 4***). Atmospheric refraction is caused by free electrons in the upper atmosphere, and temperature, pressure, and water vapor in the lower atmosphere. The delay or late arrival of the GPS radio signals causes GPS positioning and navigation errors that must be corrected to achieve the highest possible accuracy. The magnitude and variability of the delays depend on regional and local space and tropospheric weather conditions that are constantly in flux.

Fig 1. Launch of GPS Mission IIR-8 emblazoned with the "Lets Roll" nose art that commemorated the 9-11 attack on the World Trade Center and Pentagon.

Fig 2. Artist conception of Boeing GPS Block 2F satellite in orbit.

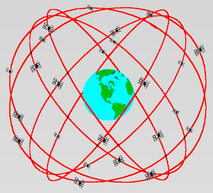


Fig 3. Sketch of the 24-28 NAVSTAR GPS satellite constellation. Satellites are placed in 6 orbital planes inclined 55º to the equator. The satellites make one orbit in 12 hours, hence they rise and set at the same point on the horizon the same time each year.

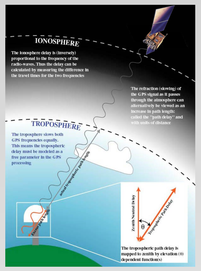


Fig 4. The constituents of the Earth's atmosphere slow and bend the GPS radio signals as they travel from space to receivers at-or-near the surface.

GPS-Met observations are currently made in two ways: from fixed locations at the surface of the Earth (***Figure 5***), and from satellites in low Earth orbit (***Figure 6***).

The first technique allows integrated (total atmospheric column) water vapor (IPW) in the atmosphere directly above a GPS reference station to be retrieved under all weather conditions in real time. In this technique, the line of sight signal delay measurements from four or more satellites are scaled to zenith and averaged to give a very accurate estimate of the average refractivity within the field of view of the GPS antenna.

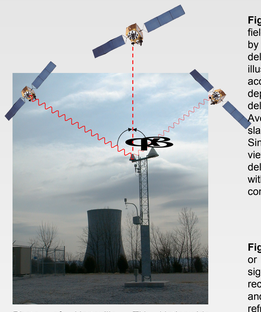


Photo of Hartsville, TN Nationwide Differential GPS Site courtesy of J. Arnold, DoT Federal Highway Administration.

Fig 5. The average signal delay over the field of view of the antenna (left) is computed by scaling the line-of-sight or slant-path delays to the zenith and averaging them as illustrated in Figure 5 to the left. This is accomplished by assuming that signal delay depends only on elevation, and that the slant delay has only a wet and dry component. Averaging minimizes random noise in the slant estimates which can be substantial. Since there are 6 or more GPS satellites in view at all times, the solution of the zenith delay is over-determined and can be made with little error under virtually all weather conditions.

Fig 6. As a satellite in low Earth orbit rises or sets behind the limb of the Earth, the signals traveling from the GPS satellite to a receiver on the LEO spacecraft are slowed and bent in response to gradients in the refractive index of the upper and lower atmosphere. The cumulative effect on the ray path can be expressed in terms of the total refractive bending angle, as shown in Figure 6 below.

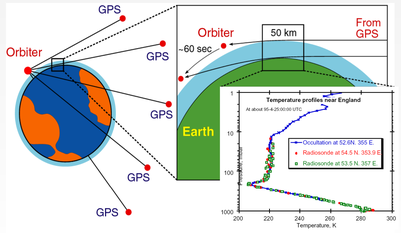


Illustration above courtesy of T. Yunk, NASA JPL.

U.S. Integrated Earth Observing System

Nowlin, Smith, Harrison, Koblinsky, and Needler proposed the following definition of an integrated observing systems in "*An Integrated, Sustained Ocean Observing System*" at the International Conference on the Ocean Observing System for Climate, in Saint Raphael, France, 18-22 October 1999. According to Nowlin et al., an Integrated Observing System is:

"… an assemblage of observing system elements joined in regular interaction or interdependence… where the separate parts (are) united together to form a more complete, harmonious, or coordinated entity." We (the authors of this poster) extend this definition to include the upper-air regime which we define as the region extending from just above the effective range of surface observations (approximately 10 meters) to the Exosphere where the Earth's atmosphere thins to that of the interplanetary medium."

Fig 7. Vision for Integrated Observations. Monitor global, regional, and storm scale phenomena with the temporal and spatial resolution needed to improve the monitoring and prediction of weather and water events and climate change impacting our nation and the world.

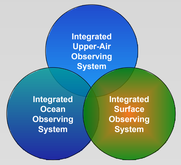


Fig 8. Components of the U.S. Integrated Earth Observing System (IEOS) include:

- Integrated Ocean Observing System (**IOOS**)
- Integrated Surface Observing System (**ISOS**)
- Integrated Upper-Air Observing System (**IUOS**)

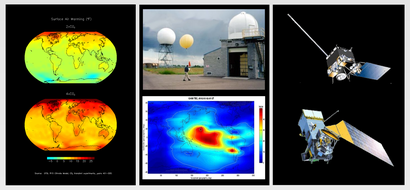
Why We Observe: Observations and the information created from them are critical for monitoring, describing, and predicting the Earth and Space environments. The goals of making these observations are to: enhance human health, safety and welfare; alleviate human suffering; protect the global environment; and achieving sustainable development to the benefit of all nations.

These goals are, to a greater or lesser extent, met by existing remote sensing and in situ observing systems. The big question is, "are these systems and capabilities adequate to meet the current and future needs of the U.S. and the rest of the world community?" The overwhelming opinion of the scientific community is that they are not, and the response of the international community to this is the Global Earth Observing System of Systems, **GEOSS**.

As a rule, existing observing systems were not developed in an integrated manner, but were funded and operated to meet their own purposes. Some of these systems are in danger of disappearing or being severely curtailed, even though the needs that drove their development remain. Other systems such (as GPS Meteorology) have broad applicability, or could be deployed to improve our ability to monitor and predict the atmosphere, but a clear route to testing, maturing, funding, and implementing them operationally within NOAA has not been available until recently.

Studies to date indicate that upper-atmospheric observing systems have a return on investment that is substantial, which can be further increased by more cost-effective integration of data sets and shared use of observational platforms (***Figure 7***). Some of the benefits of the U.S. Integrated Earth Global Observing System (IEOS) (***Figure 8)*** include:

- Improved weather and water information, forecasting, and warning services;
- Reduced loss of life and property from natural and human-induced disasters;
- Improved understanding of environmental factors affecting human health and well being;
- Improved understanding of climate processes, and assessing, predicting, mitigating, and adapting to climate variability and change;



Improved Global Climate Monitoring | RAOBS QC Space Wx Forecasting | Geostationary Satellites Polar Orbiting Satellites

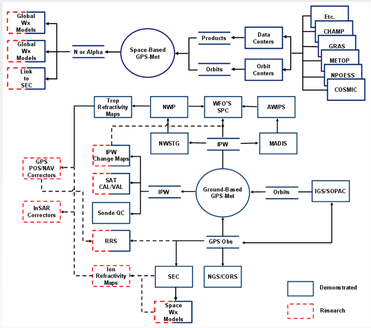


Fig 9. Top: illustration of some of the applications of GPS-Met in IUOS. Bottom: data flow diagram for ground and spaced-based GPS Meteorology under IEOS. Most of the activities associated with **space-based GPS-Met** result from interaction between the National Centers for Environmental Prediction (NCEP) and various LEO satellite data providers and orbit centers. Most of the activities associated with **ground-based GPS-Met** will be carried out operationally when data acquisition, data processing, and data distribution services supporting tropospheric and space weather forecasting, climate monitoring, and other applications transitions from NOAA Research to NWS around 2008.

GPS-Met in IUOS: the NOAA Integrated Upper-Air Observing System

The remainder of our poster concentrates on how ground-based GPS-Meteorology fits into the IUOS. Our discussion focuses on ground vs. space-based GPS-Met because:

- Ground-based GPS-Met is by far the most mature application;
- The observation error covariance is well defined;
- The strengths and weaknesses are well understood;
- Quality control techniques have been developed;
- Observations from about 300 stations over CONUS are already being assimilated into the operational Rapid Update Cycle (RUC13) running at NCEP;
- An operational system architecture and CONOPS is under development;
- NWS forecasters in most NWS regions now rely on GPS-Met data to improve situational awareness during severe weather events, provide a basis to evaluate other observations (e.g. radiosondes and satellites), and verify model predictions.

Table 1. Links Between GPS-Met and Other Observing/Data Assimilation Systems

APPLICATION	OUTCOME	LEADING TO	RESULTS
GPS-IPW Assimilated into Rapid Refresh Mesoscale NWP Models	Improved 3-h RH forecast accuracy at all levels below 500 hPa	- Improved short range cloud and precipitation forecasts - Improved short range CAPE forecasts - Improved refractivity models	• Improved severe weather forecasts • Improved surface and air transportation weather forecasts • Improved hydrologic forecasts • Atmospheric correctors for high accuracy GPS positioning and navigation • Corrections to interferometric radar (InSAR) data leading to faster and more accurate monitoring of changes in land surface, coastal habitats, and improved soil moisture estimates from space.
GPS-IPW installed at Upper-Air Sites Provides Quality Control for Global RAOB Moisture Soundings	Detection of bad soundings leads to improved moisture observations for NWP, climate statistics, satellite cal/val, and research	- Reduced error in synoptic-mesoscale weather forecast accuracy - Improved climate monitoring - Improved verification of weather and climate models • More accurate verification of satellite observations	- Better weather forecasts - Less time to accumulate critical climate statistics - More accurate and reliable satellite moisture and temperature measurements
Real-time GPS Water Vapor Observations Improve Situational Awareness to Forecasters	Improved short term regional warnings and forecast services	- More lead time during significant weather events - Improved forecast skill - Fewer false alarms	• Improved weather services • Reduced loss of life and property
Observation Verification	Independent checks on the validity of *in situ* and/or remote sensing measurements from satellites, aircraft, and sondes	- Improved data quality - Improved system/sensor reliability	• Better model predictions • Better atmospheric research
Long-term Monitoring and Correction of Biases and Drift in Water Vapor Sensing Systems	More accurate long-term retrievals of physical parameters, especially moisture and temperature.	- Better intercomparisons between different systems and sensors - Correct for changes in calibration, sensitivity or long term instrumental drift - Reconcile measurements from different sensors and platforms over time	- Improved global weather forecast accuracy - Improved climate models and model predictions.

GPS-Met in Short Term Weather Forecasting

Modern numerical weather prediction models such as the 13 Km RUC assimilate measurements from a large number of observing systems. ***Table 2*** shows the observations assimilated into the operational RUC13 running hourly at NCEP's Environmental Prediction Center. ***Figures 10 and 11*** show the impact of adding GPS to an operational NCEP NWP model.

Table 2. Observations assimilated into the 13 km Rapid Update Cycle

NOAA 405 MHz profilers	32	1h
VAD winds (WSR-88D radars)	110-130	1h
Aircraft (ACARS) (V,temp)	1400-4500	1h
Surface/METAR - land (V,psfc,T,Td)	1500-1700	1h
Buoy	100-150	1h
GOES precipitable water	1500-3000	1h
GOES cloud drift winds	1000-2500	1h
GOES top pressure	~10km	1h
SSM/I precipitable water	1000-4000	6h
Ship reports	10's	3h
Reconnaissance dropwinsonde	a few	variable
GPS precipitable water	~275	1h
Boundary-layer (915 MHz) profilers	~20	1h
RASS virtual temperatures	~10	1h
Mesonet observations	~3500	1h

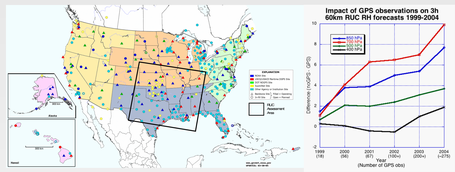


Fig 10. Five years of data denial experiments in the area identified on the map (left) showing the impact of adding GPS observations on RUC 3-h RH forecasts.

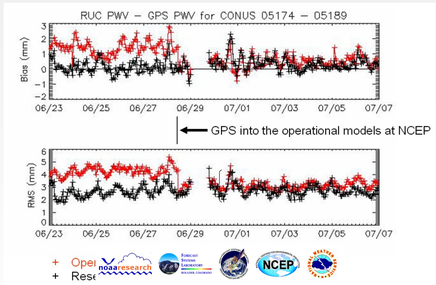


Fig 11. shows the impact of adding GPS IPW observations to the operational RUC. This occurred on 28 June 2005.

GPS-Met in IUOS: the NOAA Integrated Upper-Air Observing System

Quality Control for Global Radiosonde Observations

After more than 60 years, radiosondes are still the single most important upper-air observing system because they provide the standard data set for numerical weather prediction, regional weather forecasting, hydrology and air quality, climatology, and research. RAOBS also provide "ground-truth" for satellite-derived estimates of temperature, moisture and other parameters.

Radiosonde moisture soundings are difficult to verify because (1) they are launched infrequently from widely spaced locations and (2) other independent observations are rarely available for comparison. Numerical models assimilating radiosondes usually weight them heavily, so using a model to verify a RAOB sounding is always interesting. In similar fashion, verification of satellite retrievals of temperature, moisture and other parameters can also be difficult because of the lack of redundant observations. This is especially true in remote locations.

As a consequence, the accuracy of regional weather/water warnings & forecasts and global climate predictions ultimately depend on the accuracy of a few critical upper-air observations. It's hard to imagine that significant improvements in weather & climate models, and the forecasts derived from

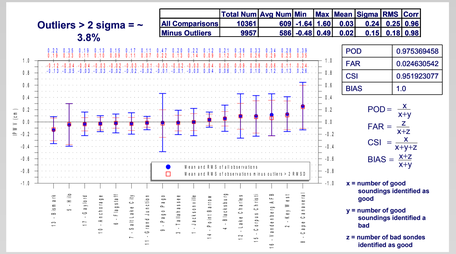


Fig 12. Differences between GPS and NWS RAOBS at 17 sites for one year. Differences exceed 2-sigma in about 4% of the launches. This is quite significant in the U.S. since this corresponds to ~ 3 erroneous soundings every 12 hours. These large differences are usually associated with non-systematic the over-reporting of RH and appear to be caused by sensor malfunctions that manifest themselves by a tendency for RH not to decrease above the tropopause. Left undetected, these problematic soundings can significantly impact regional weather forecast accuracy and contaminate global climate records.

Real-Time GPS-Met Improves Forecaster Situational Awareness

In 2004, we conducted a survey to determine which WFO's were using GPS-Met and how they were using it. Forecasters at Blacksburg, Flagstaff and other WFOs observed that when the environment is rapidly changing, having higher temporal resolution (30 minute) GPS moisture observations can be very helpful (***Figure 13***). They told us that high temporal frequency GPS moisture observations improve overall situational awareness, and this almost always makes a positive impact on forecast services during active weather. They also believe that GPS moisture observations will help them improve warning lead times during emergency situations like flash flood events.

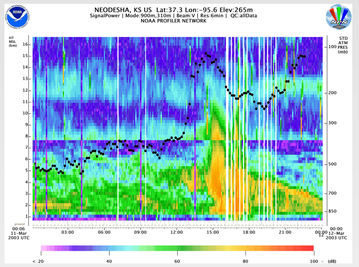


Fig 13. Convective storm revealed from signal power in the vertical beam of the NOAA Profiler Network site near Neodesha, KS on 11 March 2003. The PW time series from the GPS-Met system at the site reveals the build-up of moisture associated with the thunderstorm.

Defining water vapor thresholds from climatology, and noting how PW changes with time, may help forecasters infer where the moist boundary layer is deepening with time and where the first storms are likely to form (***Figure 14***). Finally, forecasters at the SPC have found that GPS IPW data can be used to track the return flow of moisture off the Gulf over a stable layer. Obviously, this cannot not be detected from surface observations alone. Knowing this, SPC feels that they can improve their forecasts of where severe elevated convection will form.

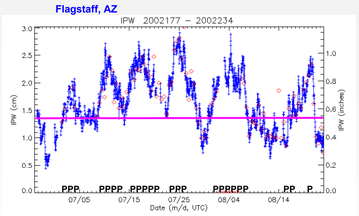


Fig 14. Precipitation in Flagstaff, AZ during the 2002 Monsoon season. Blue crosses are GPS-IPW observations, red diamonds are radiosonde observations, **P** denotes a precipitation event, and the fuchsia line denotes a threshold based on climatology. Image courtesy of Mike Staudenmaier, Science and Operations Officer, WFO Flagstaff.

GPS-Met in IUOS: the NOAA Integrated Upper-Air Observing System

Observation Verification

The more we rely on satellite or aircraft remote sensing observations or *in situ* observations in remote locations, the greater is our need for observation verification and validation. There are several ways to accomplish this, some more efficacious than others. As technology advances, and new ways of making measurements are developed or made more economical, it becomes feasible to make comparative measurements of the same parameters using totally independent techniques. One such technique is Ground-Based GPS Meteorology.

As part of FSL's contribution to the International H2O experiment (IHOP-2002) that was carried out in the U.S. Southern Great Plains between May 25-Jun 15, 2002, we used GPS observations to verify hourly GOES TPW products derived from GOES 12 Sounder radiances.

We first compared GPS IPW retrievals with PW derived from radiosondes launched every 3 hours at 5 sites in the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) Southern Great Plains Testbed (***Figure 14)***.

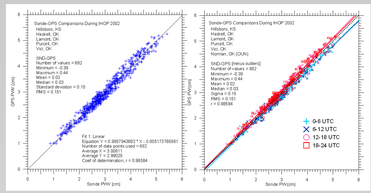


Fig 14. Scatter plots showing all comparisons between GPS and Raobs (left), and comparisons binned by time-of day (right) during IHOP-2002. A day-night bias (sondes wetter than GPS at night and dryer than GPS during the day) was discovered that appears to be common to all Viasala RS-80A radiosondes used by ARM and NWS at that time during warm weather.

We then compared GPS IPW at the 5 sites with PW from the GOES 12 sounder. Comparisons were made every hour, and the criteria used for selecting a matched pair of observations was distance < 10 km, acquisition time < 24 min. A scatterplot of GOES vs GPS IPW for the experiment is presented on the left side of ***Figure 15***, and the statistics of the differences are shown on the right side. The correlation between GPS and GOES decreases as IPW increases. The root mean square differences and standard deviations are relatively constant throughout the day, while the bias changes in a complex manner that minimizes around 00 UTC and maximizes around 18 UTC. The differences around 00 UTC are comparable to the errors normally assigned to GOES PW products.

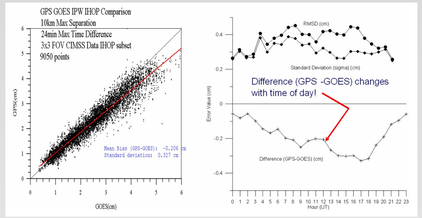
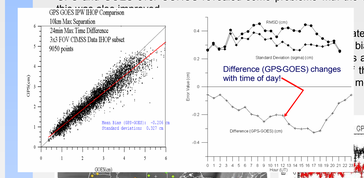


Fig 15. Differences between GOES 12 and GPS IPW during the IHOP-2002 experiment. The scatterplot on the left indicates that PW correlations decrease with increasing IPW. The statistics on the right show bias (GPS-GOES) plotted below the 0.0 baseline, and standard deviation and root mean square differences plotted above the 0.0 baseline.

Because of the importance of satellite remote sensing to the future of GEOSS and IUOS, we collaborated with NESDIS Office of Research and Applications (ORA), and the Joint Center for Satellite Data Assimilation (JCSDA) to identify the probable causes and solutions to this behavior. FSL created a web page (http://gpsmet.noaa.gov/cgi-bin/sat/goes.cgi) where GPS and GOES retrievals could be automatically computed and displayed (***Figure 16***) and statistics could be computed for later analysis.

Initially, ORA discovered that some of the quality control flags in the GOES physical retrieval algorithm were not set properly, and this was promptly corrected. Next, comparisons between GPS and GOES over CONUS revealed some problems with the cloud-clearing algorithm, and



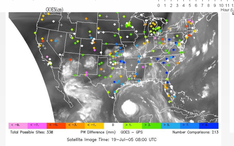


Fig 16. Web-based application developed by FSL to facilitate the investigation of differences between GOES (10 and 12), radiosonde, and GPS IPW measurements.

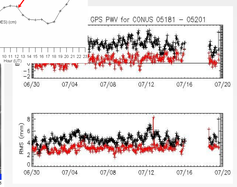


Fig 17. Comparisons between GOES 10 and GOES 12 PW estimates over CONUS. Average number of comparisons every hour is 50 for GOES 10 and 150 for GOES 12.

Conclusions

The key to improved atmospheric observations that serve the broad public good lies in the integration of observing systems and data sets to maximize their utility for as many users and purposes as possible. GPS-Met observations provide cost effective measurements of upper-atmospheric moisture under all weather conditions that improve NWP model forecast accuracy. Comparison of GPS with radiosondes and satellites is leading to improved utilization of these global observing systems. The return on investment is substantial, which can be further increased by continued integration of data sets and shared use of observational platforms.