Application of IGS Data to GPS Sensing of the Atmosphere for Weather and Climate Research

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Abstract

Water vapor is one of the most important constituents of the atmosphere as it is the principal mechanism by which moisture and latent heat are transported. Consequently, accurate and sufficiently frequent and dense sampling of water vapor is needed for weather and climate research as well as operational weather forecasting. It has been demonstrated that GPS data can be used to measure atmospheric water vapor. The worldwide International GPS Service (IGS) network of GPS tracking stations can be used to sense global atmospheric water vapor if adequate pressure and temperature data are available at these sites. Addition of pressure sensors accurate to 0.3 mbars and temperature sensors accurate to several degrees Kelvin at IGS stations would allow sensing of precipitable water vapor (PWV) over 30 minute intervals with an accuracy better than 2 mm. This paper describes the main ground and space-based applications of GPS to atmospheric sciences and discusses current and future developments and the important role of the IGS. Specifically we will discuss: (a) importance of global water vapor measurements for climate studies; (b) accuracy considerations and suggested design of pressure, temperature and humidity sensors for installation at IGS sites; (c) suggested solutions for meteorological data flow and download issues; (d) conversion of estimated GPS path delay to zenith water vapor; (e) a suggestion for combining delays from all IGS processing centers; and (f) PWV time series - a new IGS product?

Introduction

Tropospheric water vapor plays an important role in the global climate system and is a key variable for short-range numerical weather prediction. Despite significant progress in remote sensing of wind and temperature, cost-effective monitoring of atmospheric water vapor is still lacking. Data from the Global Positioning System (GPS) have recently been suggested to improve this situation (i.e. Bevis *et al.*, 1992). Figure 1 illustrates the problem of current satellite systems for reliably measuring atmospheric water vapor and the promise of ground-based GPS systems.

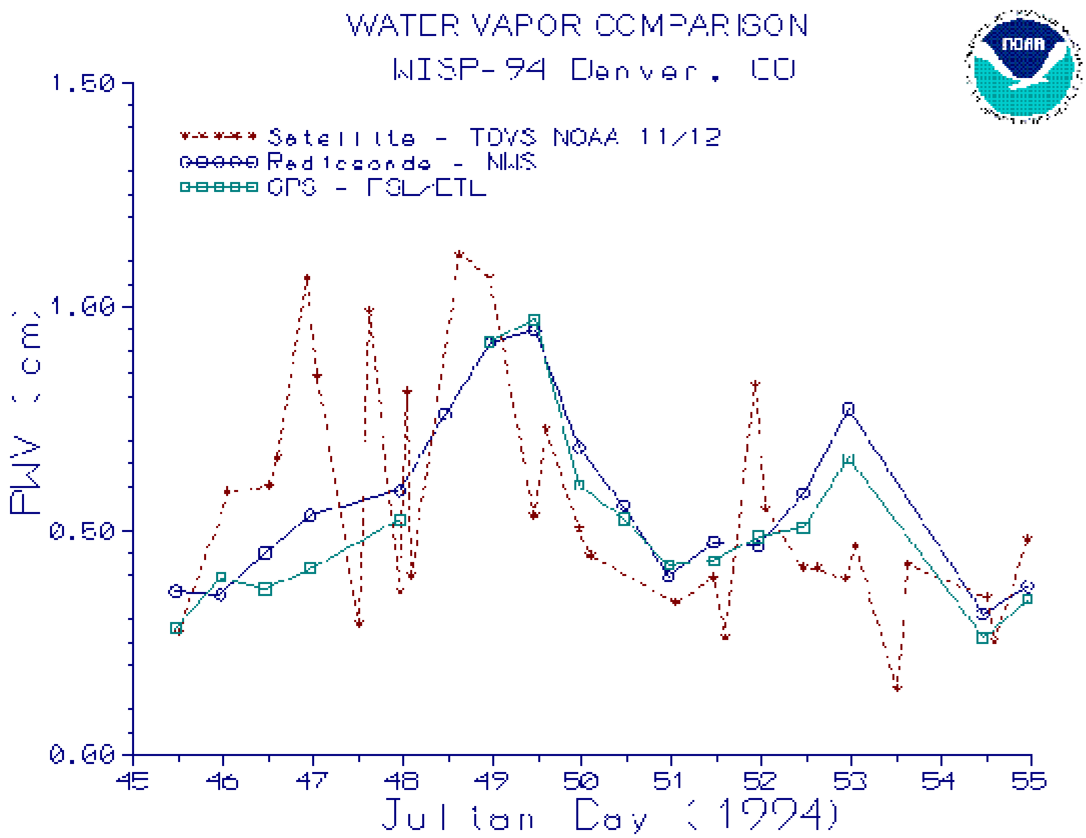

Figure 1. Comparison of satellite, radiosonde and GPS estimates of integrated water vapor during the joint NOAA/UNAVCO WISP-94 experiment. The gure shows that GPS estimates correlate strongly with the radiosonde while the satellite data is less reliable. (Figure courtesy of Russ Chadwick of NOAA/FSL).

The GPS signal is sensitive to the refractive index of the atmosphere, and because this index is a function of pressure, temperature, and moisture, GPS can be used directly for sensing properties of the atmosphere. Small amounts of atmospheric water vapor significantly affect GPS signal propagation velocities. Thus GPS is especially well suited for sensing atmospheric water vapor.

Recent studies have demonstrated (i.e. Rocken *et al.*, 1993, 1995, Duan *et al.*, 1995) that GPS can reliably be used to estimate PWV with 1-2 mm accuracy and 30-minute temporal resolution. The first GPS network, dedicated to PWV estimation, has been established by the National Oceanic and Atmospheric Administration (NOAA) in the United States (Figure 2). Results from operating this network for over 100 days confirm that PWV can be computed reliably from GPS data at the 1-mm rms level.

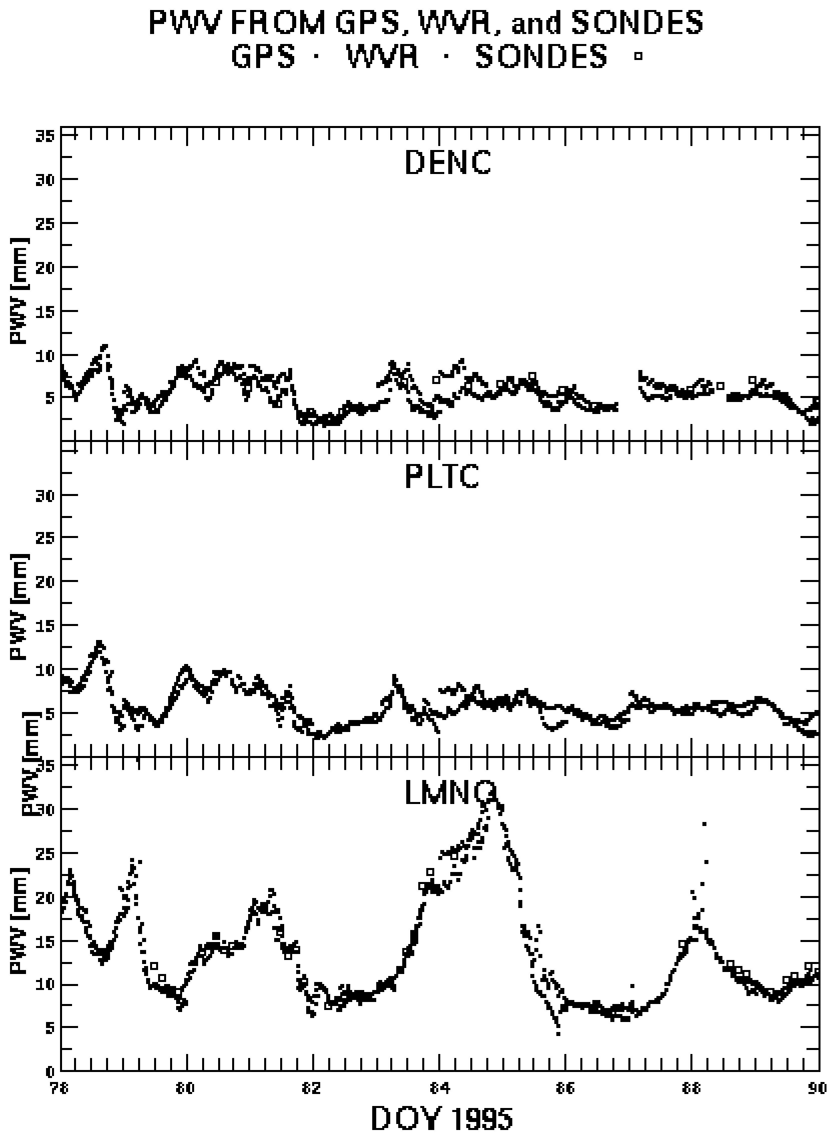

Figure 2: GPS-estimated values of precipitable atmospheric water vapor during March, 1995 for three NOAA/FSL windproler sites in the central United States (Denver, CO, Platteville, CO, and Lamont, OK). GPS estimates are compared to W ater Vapor Radiometers (WVR) and radiosonde data.

Atmospheric scientists have shown that GPS determined integrated water vapor from ground-based observations can significantly improve weather forecasting accuracies (Kuo *et al.*, 1992, 1995). Scientists have reported a worldwide increase in atmospheric water vapor between 1973-1985 (Figure 3, Gaffen *et al.*, 1991). That study was conducted with radiosonde data only, and similar studies in the future could greatly benefit from GPS PWV estimates, because of the inherent homogeneity of the GPS data and their long-term stability.

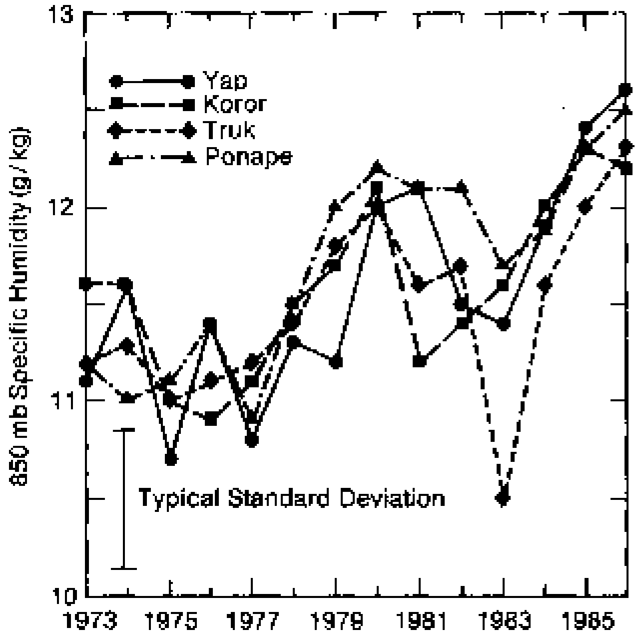

Figure 3 (from Gaf fen *et al.*, 1991). The mean annual specic humidity (g/ kg-1) at four tropical stations from 1973 to 1986 is shown. The error bar represents a typical value of the standard deviation for the monthly means used to calculate the annual values. Similar data for monitoring the global atmosphere could be collected from the IGS network in the future.

While data from ground based GPS stations typically provide integrated PWV, data from a GPS receiver in Low-Earth-Orbit (LEO) can be inverted to measure atmospheric profiles of refractivity, which in turn can provide tropospheric humidity profiles if temperature profiles are known. These space-based atmospheric measurements exploit the fact that a GPS signal that is travelling from a GPS satellite to a LEO is bent and retarded as it passes through the earth's atmosphere.

Yuan *et al.*, 1993. demonstrate that space based GPS measurements could provide a sensitive "thermometer" for global atmospheric change. The first such instrument for global atmospheric soundings was successfully launched on April 1995, by a team of GPS/MET scientists from the University Corporation for Atmospheric Research (UCAR/UNAVCO), the Jet Propulsion Laboratory (JPL), and the University of Arizona (Figure 4).

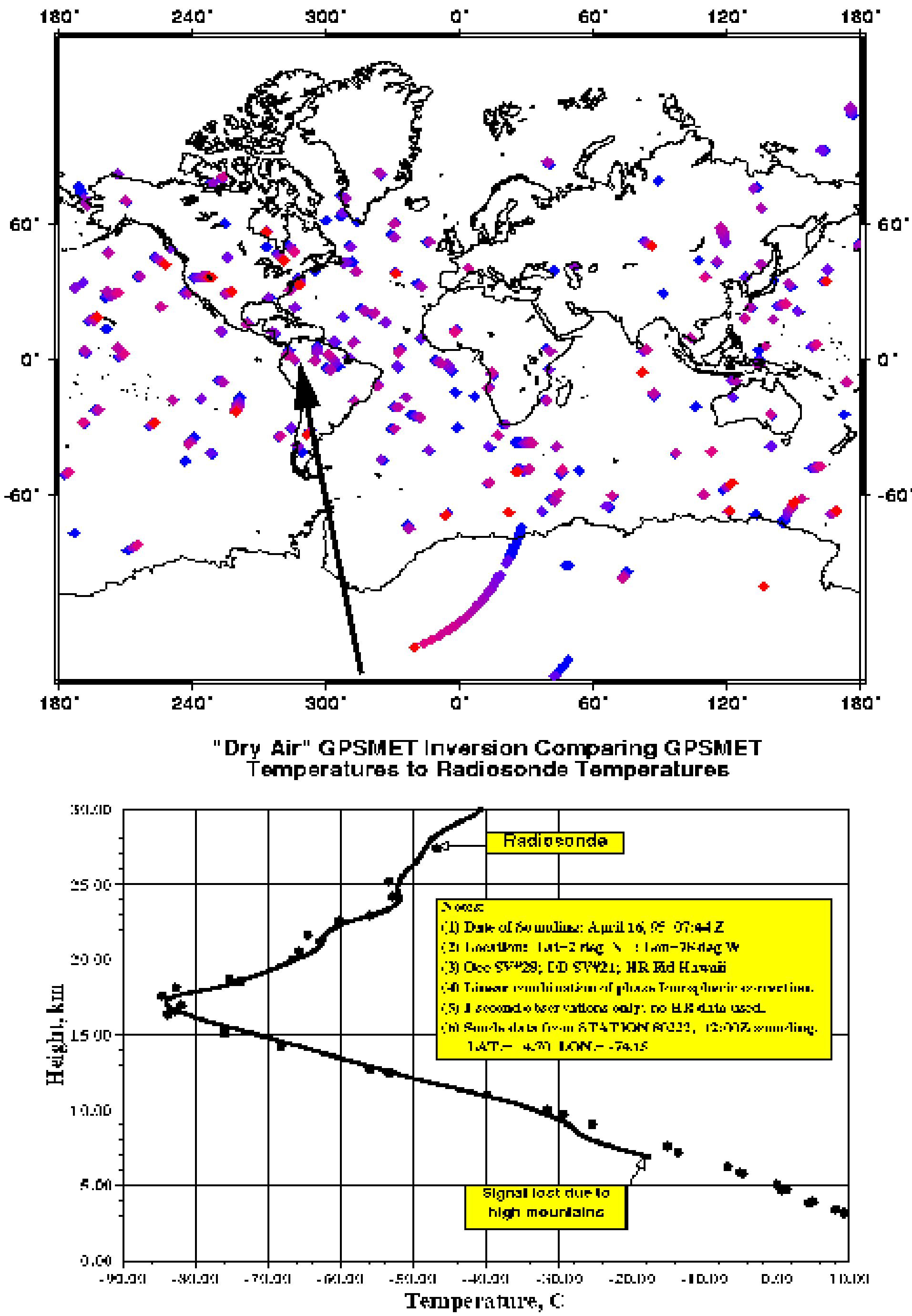

Figure 4 shows in the top panel the locations of radio occultation soundings during a 12-hour time period on April 16, 1995. The bottom panel compares the results of an initial inversion for a location above the Andes, as indicated by the arrow .

The IGS and Atmospheric Science

Ground-based and space based meteorological GPS applications already benefit from the services provided by the IGS. Ground based analysis often uses IGS orbits, and data from the IGS network are of critical importance for the analysis of GPS/MET LEO data.

In addition to these current services to the atmospheric community, the IGS can also directly provide time series of mm-level precipitable water vapor if the following were done:

a. IGS data sites would collect surface pressure, temperature, and humidity data.
b. These surface meteorological measurements were made available to the data and processing centers together with the GPS data.
c. The IGS processing centers would compute tropospheric zenith delay corrections at agreed upon time intervals.
d. The delay corrections from all processing centers should be converted to precipitable water vapor and combined into weekly time series of precipitable water vapor to be published by the IGS.

The IGS water vapor time series would become available several days to weeks after real-time and would be most useful for climate studies rather than weather prediction.

The IGS could contribute to weather forecasting if high-quality GPS satellite orbits were made available in real-time. These rapid orbits could be used for PWV estimation by regional GPS networks dedicated to weather prediction.

PWV Accuracy Considerations

High accuracy GPS software estimates the total tropospheric delay in the zenith direction at regular time intervals. This delay is approximately 250 cm at sea level and has two components. Wet delay is caused by atmospheric water vapor, and dry or hydrostatic delay by all other atmospheric constituents. The hydrostatic delay of a zenith GPS signal travelling to an atmospheric depth of 1000 mb is approximately 230 cm. Assuming hydrostatic equilibrium, this delay can be predicted to better than 1 mm with surface pressure measurement accuracies of 0.5 mb. The error introduced by the assumption of hydrostatic equilibrium depends on winds and topology but is typically of the order of 0.01%. This corresponds to 0.2 mm in zenith delay. Extreme conditions may cause an error of several mm (Elgered, 1993).

Wet GPS signal delay ranges from 0 to 40 cm in the zenith direction. Zenith wet delay (ZWD) is highly variable and cannot be accurately predicted from surface observations. PWV is the depth of water that would result if all atmospheric water vapor in a vertical column of air were condensed to liquid. One centimeter of PWV causes approximately 6.5 cm of GPS wet signal delay. This 6.5-fold "amplification" effect is important for accurate PWV measurement with GPS.

Tests during which we biased pressure measurements by known amounts showed that an error in pressure measurement can be related to the resulting error in estimated PWV as:

(1) $\delta PWV \sim 0.4 \times \delta Pressure$

where dPWV is the error in PWV in units of mm and dPressure is the pressure error in mb. Thus to keep the contribution of the pressure error below 0.1 mm PWV a barometer should be calibrated to better than 0.25 mb.

Because GPS software estimates the delay due to the wet troposphere (ZD), this delay has to be converted to PWV. This conversion can be accomplished without incurring any significant additional errors using the equation (Bevis *et al.*, 1992):

(2) $PWV = \Pi \times ZD_{GPS}$

The factor P is approximately 0.15. This value varies with location, elevation and season by as much as 20%, but can be determined to ~ 2% if P is computed as a function of surface temperature. Thus the requirement for the measurement of surface temperature at the GPS site. Temperature accuracy requirement is not very strict and ~2 degrees K is sufficient.

Using the NCAR/Penn State mesoscale model, Kuo *et al.*, 1995, have shown that the combination of PWV and surface humidity data benefit numerical models significantly. 20% improvement in numerical weather forecasting accuracy was achieved when PWV time series were introduced. Almost as much additional improvement was achieved when the surface humidity was available. We therefore recommend that the IGS sites should collect 3 meteorological data types: pressure (P), temperature (T), and humidity (H). Accuracy requirement for relative humidity is ~2%. Estimates of the effect of the major error sources on PWV estimation are summarized in Table 1.

Table 1: ERROR SUMMARY
FOR 30-MINUTE GPS/PWV ESTIMATION

ERROR-SOURCE	SIZE OF ERROR [MM] δPWV	δZD	COMMENT
ORBIT	0.2	1.3	10 CM ORBIT RMS, 1000-KM BASELINE
PHASE MULTIPATH	0.3	2.0	SITE AND ANTENNA DEPENDENT
COORDINATE ERRORS	0.5	3.0	1-CM VERTICAL ERROR ASSUMED
BAROMETRIC PRESSURE	0.1	0.6	0.25 MB MEASUREMENT ACCURACY
HYDROSTATIC ASSUMPTION	0.0	0.2	CAUSED BY WIND + TOPOLOGY
SURFACE TEMPERATURE ERROR	0.0	0.0	NO SIGNIFICANT EFFECT ON DRY DELAY
DELAY TO PWV CONVERSION	<0.1	-	2% ERROR IF SURFACE TEMP. KNOWN
REFERENCE WVR ERROR	0.9	6.0	INSTRUMENT + RETRIEVAL ERROR

The orbit error effect in Table 1 was estimated based on the assumption that GPS orbit errors of 10 cm cause baseline length errors of about 4 mm over distances of 1000 km. We assumed further that the vertical baseline coordinate error caused by orbit errors for the long baseline is also 4 mm. This vertical coordinate error corresponds to a zenith delay error of about 1.3 mm and thus to an error in PWV of 0.2 mm (Rothacher, 1992). These errors increase with increasing orbit error. The contribution of a 50-cm orbit error for a 1000 km baseline would be 1 mm PWV. For long baselines highest orbit accuracies are therefore required.

The effect of phase multipath was evaluated by computing the differential PWV between two sites separated by only a few meters. For such short baselines zenith delay and PWV are identical at both ends of the baseline and any differences in estimates of this delay are due to multipath (if identical GPS antennas are used).

Coordinate and barometric pressure errors were discussed above, and errors due to the hydrostatic assumption, temperature error and delay to water vapor conversion error are small.

One important error listed in Table 1 is the 6 mm delay (or 0.9 mm PWV) error due to a water vapor radiometer (Gary *et al.*, 1985, Westwater *et al.*, 1989). For small GPS networks of significantly less than 500 km aperture a water vapor radiometer (WVR) at one reference site in the network is required for levering. Levering is the process to correct for errors in the zenith delay that are common at all stations in the network. For larger networks, with baselines of ~ 1000 km levering is generally not required.

The Climate and Meteorological "Clam" Sensor Package

We have built a prototype "Climate and Meteorological Sensor Package" (CLAM) for suggested installation at IGS sites. The most important features of the CLAM are:

1. 0.2 mb accuracy, less than 0.02 mb/year drift (> 5-year calibration cycle)
2. 0.5 K temperature accuracy
3. 2% humidity accuracy - biannual simple inexpensive sensor chip change-out
4. 2 watts at 40-250 VAC, or 12 to 30 VDC
5. Writes surface meteorology data directly to the GPS receiver - uses the GPS receiver as data logger
6. Since data are in the GPS data file, data retrieval protocol from field sites to the data centers requires minimal or no changes
7. Price of each CLAM is about US$2.5 k in parts (US$1.8K for pressure sensor)

The most expensive component of the CLAM is the pressure sensor. However, we selected a very accurate sensor with low drift rate to avoid the requirement for re-calibration of the instrument.

The CLAM is controlled by a microprocessor, which is programmed to go through the following steps every 10 minutes (this time interval can be changed). First the time will be read from the GPS receiver, and then P,T, and H will be read from the sensors. With this information CLAM generates a 39-character string of Year:Month:Day:Hour:Minute:Second P [mb] T [K] H [%], such as the suggested example string: "#@& 95 04 26 18:30:00 1013.11 21.1 36".

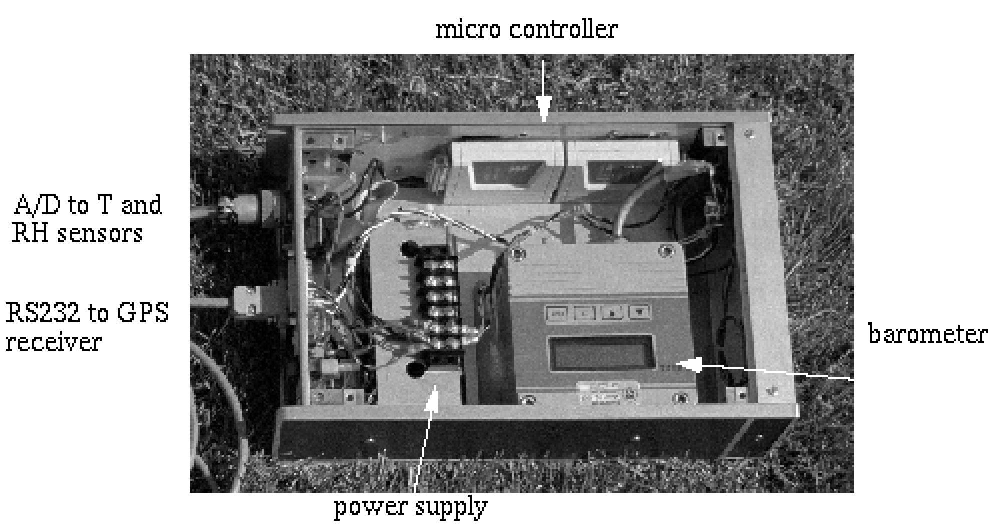

Photo of the prototype Climate and Meteorological Sensor package (CLAM) suggested for installation at IGS sites. T emperature and relative humidity sensors and pressure port inlet are at the end of a 10-meter cable for outdoor installation.

This string is written to the GPS receiver. When data from the receiver is downloaded this information appears currently in the RINEX observation files as comment lines. The special characters "#@&" at the beginning of the string are identifiers to allow simple extraction of these strings from the RINEX data files.

Thus the meteorological data will be downloaded and sent to the IGS data centers without any changes in current IGS procedures. Users interested in these meteorological data can strip this information from the GPS data file and write it to RINEX meteorological files.

The IGS community should decide at which point to separate meteorological and GPS observation data. This could be done during downloading, during translation of the observation data to RINEX or at a later stage.

The CLAM has so far been tested with the AOA TurboRogue receiver only. Microprocessor programs to operate the CLAM with other receivers can be written. The current setup should be considered a prototype. Ultimately the meteorological data, will be stored and time-tagged by the GPS receiver, and it should be written directly into RINEX meteorological data files during downloading.

Zenith Delay and PWV Computation at the IGS Processing Centers

We propose that the IGS analysis centers agree on specific times for which to compute GPS zenith correction values. The GPS community should seek input from atmospheric scientists to select a reasonable time interval.

Each analysis center could provide the total zenith delay used in its analysis every N*Dt hours starting at 00:00 UTC."*N*" could be a different integer number for different processing centers, Dt is the shortest reasonable time interval between different zenith delay estimates.

It is important that all analysis centers provide estimates of total delay, and not incremental corrections computed by their software relative to an *a priori* delay based, for example, on default atmospheric parameters. Total tropospheric delay values determined at the processing centers and formal errors, should be included in SINEX solution files, currently under development.

The processing centers could use the surface meteorological data available from the IGS sites to separate dry and wet delay and to compute PWV.

Alternatively, a new type of associate data processing center could take on the task of correctly combining the delays computed at the various processing centers, applying the meteorological data and computing combined IGS time series of precipitable water vapor. These time series could be made available to the meteorological and atmospheric research communities at the same time as other IGS products become available.

Summary and Conclusion

Ground based and space based GPS applications to atmospheric monitoring are already strongly supported by the activities of the IGS. In addition time series of accurate PWV from the global IGS network could be produced by the IGS community with a small amount of additional effort. These PWV time series would be of great value for scientists involved in climate, weather, aviation, and hydrology research.

IGS analysis centers compute zenith delay corrections for GPS data analysis. If surface meteorological data were available from IGS sites these delay estimates could be converted to estimates of integrated atmospheric precipitable water vapor. An associate IGS processing center could be selected to combine the time series of delay, estimated by the various centers, to provide the combined IGS PWV time series.

We have developed a prototype meteorological sensor package CLAM with three major design priorities: (a) Ease of installation and integration with current IGS operations, (2) High accuracy and low pressure sensor drift, (3) Low cost. We propose to operate CLAM at a trial IGS site while preparing for the installation at a larger number of sites world-wide.

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