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# GPS Meteorology: Remote Sensing of Atmospheric Water Vapor Using the Global Positioning System

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We present a new approach to remote sensing of water vapor based on the global positioning system (GPS). Geodesists and geophysicists have devised methods for estimating the extent to which signals propagating from GPS satellites to ground-based GPS receivers are delayed by atmospheric water vapor. This delay is parameterized in terms of a time-varying zenith wet delay (ZWD) which is retrieved by stochastic filtering of the GPS data. Given surface temperature and pressure readings at the GPS receiver, the retrieved ZWD can be transformed with very little additional uncertainty into an estimate of the integrated water vapor (IWV) overlying that receiver. Networks of continuously operating GPS receivers are being constructed by geodesists, geophysicists, government and military agencies, and others in order to implement a wide range of positioning capabilities. These emerging GPS networks offer the possibility of observing the horizontal distribution of IWV or, equivalently, precipitable water with unprecedented coverage and a temporal resolution of the order of 10 min. These measurements could be utilized in operational weather forecasting and in fundamental research into atmospheric storm systems, the hydrologic cycle, atmospheric chemistry, and global climate change. Specially designed, dense GPS networks could be used to sense the vertical distribution of water vapor in their immediate vicinity. Data from ground-based GPS networks could be analyzed in concert with observations of GPS satellite occultations by GPS receivers in low Earth orbit to characterize the atmosphere at planetary scale.

## INTRODUCTION

Water vapor plays a crucial role in atmospheric processes that act over a wide range of temporal and spatial scales, from global climate to micrometeorology. Water vapor is the most variable of the major constituents of the atmosphere. It contributes more than any other component of the atmosphere to the greenhouse effect. The distribution of water vapor is intimately coupled to the distribution of clouds and rainfall. Because of the unusually large latent heat associated with water's change of phase, the distribution of water vapor plays a critical role in the vertical stability of the atmosphere and in the structure and evolution of atmospheric storm systems. The advection of water vapor and its latent heat by the general circulation of the atmosphere is an important component of the Earth's meridional energy balance. In addition, water plays a critical role in many chemical reactions that occur in the atmosphere.

Atmospheric scientists have developed a variety of means to measure the vertical and horizontal distribution of water vapor. The radiosonde, a balloon-borne instrument package that sends temperature, humidity, and pressure data to the ground by radio signal, is the cornerstone of the operational analysis and prediction system at the National Meteorological Center in this country and at similar operational weather forecast centers worldwide. Contemporary radiosonde instruments measure temperature and relative humidity with accuracies of ~0.2°C and ~3.5%, respectively, with diminishing performance in cold, dry regions [*Elliot and Gaffen*, 1991]. Although the advantages of in situ measurements that provide good vertical resolution are clear, radiosonde measurements have some serious disadvantages too. Radiosondes are expendable, and the cost of these devices restricts the number of launches to twice daily (0000 and 1200 UTC) at a limited number of stations. Because of these restrictions, radiosonde measurements inadequately resolve the temporal and spatial variability of water vapor, which occurs at scales much finer than the spatial and temporal variability of temperature or winds [*Anthes*, 1983]. In fact, limitations in the analysis of water vapor are the major source of error in short-term (0–24 hours) forecasts of precipitation. Efforts to modernize the National Weather Service and fiscal austerity recently have conspired to degrade the network [*Bosart*, 1990]. Curtailment of National Oceanic and Atmospheric Administration support for the Mexican radiosonde program has resulted in the loss of the 0000 UTC Mexican soundings, which are often crucial in resolving upstream features in the atmosphere that are precursors to severe weather over the southern United States.

Ground-based, upward-looking water vapor radiometers (WVRs) are instruments that measure the background microwave radiation produced by atmospheric water vapor and can estimate the integrated water vapor (IWV) content along a given line of sight. They can simultaneously measure integrated liquid water (ILW) along the same line of sight. WVRs actually measure the sky brightness temperature at two or more frequencies. It is the frequency dependence of the brightness temperature that enables the simultaneous estimation of IWV and ILW [*Resch*, 1984]. The algorithm that is used to retrieve IWV from observation of sky brightness temperature contains parameters which show seasonal and site variations. Thus the retrieval algorithm usually must be "tuned" to local conditions using indepen-

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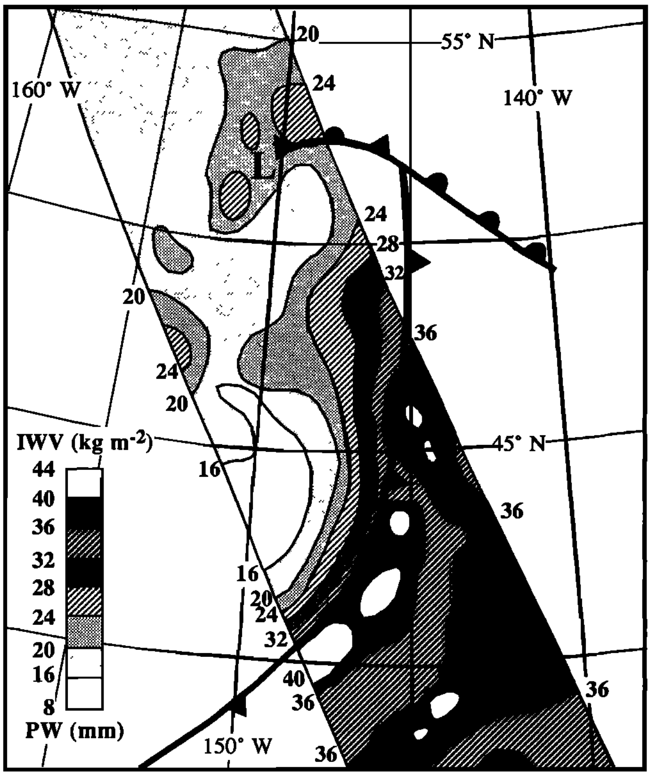


Fig. 1. Nimbus image of vertically integrated water vapor (IWV) within a storm system, redrawn from *McMurdie et al.* [1987]. The units of IWV are in kilograms per square meter. The numbers in the key can be interpreted equivalently as millimeters of precipitable water (PW).

dently obtained meteorological data (usually radiosonde data). Most meteorologists are more familiar with space-based, downward-looking WVRs. While upward-looking WVRs measure water vapor emission lines against the cold background of space, downward-looking WVRs measure the corresponding absorption lines in the radiation from the hot background provided by the Earth. Figure 1 shows an image of IWV for a typical mid-latitude cyclone obtained over the Pacific Ocean by a scanning multichannel microwave radiometer aboard the Nimbus 7 satellite. The recovery of IWV by space-based WVRs is greatly complicated over land by the fact that the temperature of the hot background is quite variable and difficult to determine. A similar problem occurs in the presence of cloud, because the background temperature may change from ~290 K (Earth's surface) to ~220 K (cloud top). These changes are large and important but are not easily specified. It is possible in principle to model these effects, but in most cases it would be a difficult and time-consuming task. For this reason, satellite-based WVRs tend to be more useful over the oceans than over land, and their utility is degraded in the presence of clouds. Ground-based WVRs are not affected by light or moderate cloud cover, though their performance may be degraded in the presence of heavy cloud, and few if any of these instruments provide useful data when it is raining. Ground and space-based WVRs are complementary rather than competing systems. Ground-based units provide good temporal but poor spatial coverage, whereas space-based WVRs have the opposite characteristics.

In this article we present a novel approach to the remote sensing of atmospheric water vapor. The global positioning system (GPS) consists of a constellation of satellites that transmit L band (1.2 and 1.6 GHz) radio signals to large numbers of users equipped with GPS receivers who use the system for navigation, time transfer, and relative positioning. When the constellation is completed in the next few years it will incorporate 21 active satellites and 3 spares orbiting the earth at an altitude of 20,000 km in six orbital planes. During the last few years the practitioners of GPS geodesy, and those of a related geodetic technique known as very long baseline interferometry (VLBI), have devised procedures for estimating the extent to which the atmosphere in general, and water vapor in particular, are slowing the propagation speed of GPS radio (microwave) signals. More specifically, it is possible to determine the "zenith wet delay" caused by the troposphere overlying each GPS (or VLBI) receiver in a network. Since this delay is nearly proportional to the amount of precipitable water above the GPS site [*Hogg et al.*, 1981; *Resch*, 1984], the possibility arises that GPS networks might be used by meteorologists for remote sensing of the atmosphere. (The quantity of atmospheric water vapor overlying a given point on (or above) the Earth's surface usually is stated as the vertically integrated mass of water vapor per unit area (e.g., in kilograms per square meter) or as the height of an equivalent column of liquid water. Since these measures have different dimensions it is convenient to give them separate names. We use the term integrated water vapor when we state the mass of vapor per unit area, and precipitable water (PW) if we refer to the height of an equivalent column of water. Clearly, $PW = IWV/\rho$, where $\rho$ is the density of liquid water. A useful rule of thumb is that the zenith wet delay stated in units of length is roughly 6.4 times the PW.)

The prospect of using GPS networks for operational weather forecasting and research is made interesting by the fact that continuously operating GPS networks are now being constructed around the world by geophysicists, geodesists, surveyors and others implementing various classes of positioning capabilities. As new applications, such as real-time differential positioning of aircraft and shipping, are implemented, the number of continuously operating GPS stations is likely to increase very rapidly, particularly in the United States and Europe. By the turn of the century it is likely that at least a few and sometimes many continuously operating GPS stations will be located in every state in the United States. It is probable that every major airport in the United States eventually will incorporate a continuously operating GPS station. These GPS networks might be used to estimate the precipitable water overlying each GPS station every 10 min or so, with an accuracy not yet well determined but probably better than ±5% in nonarid environments. This application involves meteorologists utilizing data from networks established and maintained by nonmeteorologists. At the other end of the potential application spectrum, specially designed, dense meteorological GPS arrays could be used to sense the distribution of water vapor in both space and time, that is, to engage in water vapor tomography.

## Atmospheric Propagation Delays: Geodetic Noise or Meteorological Signals?

GPS was originally designed as a navigational and time transfer system, but since its implementation it has revolutionized the field of geodetic positioning (very precise surveying) and in this context it is now widely employed by geodesists, geophysicists, and surveyors [*Leick*, 1990; *Dixon*, 1991]. In GPS geodesy the distances between GPS satellites and GPS receivers are determined either by measuring the time of flight of the time-tagged radio signals that propagate from satellites to receivers ("pseudoranging") or, over a more extended period of time, by finding the associated path lengths by an interferometric technique ("phase measurement"). Both of these approaches are complicated by the presence of the Earth's atmosphere, which increases the optical path length between satellite and receiver and the corresponding time of flight of the GPS radio signal. One of the key tasks of geodetic GPS processing software is to "correct" the ranges between receivers and satellites so as to remove the effects of the Earth's atmosphere, thereby reducing all optical path lengths to straight-line path lengths. These corrections can be formulated in terms of excess path lengths, signal delays, or phase advances.

Both the ionosphere and the neutral atmosphere introduce propagation delays into the GPS signal. The ionosphere introduces a delay that can be determined and removed by recording both of the frequencies (L1 and L2) transmitted by GPS satellites and exploiting the known dispersion relations for the ionosphere (*Spilker* [1980] and *Brunner and Gu* [1991]; see the appendix for a brief review of ionospheric effects). The delay associated with the neutral atmosphere is effectively nondispersive at GPS frequencies and so cannot be corrected in this way. The neutral atmosphere is a mixture of dry gases and water vapor. Water vapor is unique in this mixture because it is the only constituent which possesses a dipole moment contribution to its refractivity. In fact, for microwaves, its refractivity is dominated by the dipole component. Throughout most of the troposphere the dipole component of the refractivity is about 20 times larger than the nondipole component. For this reason it has become common to treat the dipole component of the water vapor refractivity separately from the nondipole components of the refractivities of the water vapor and other constituents in the atmosphere. These two components are referred to as the "wet" and "hydrostatic" delays. (The hydrostatic delay is often erroneously referred to as the "dry" delay.) Both delays are smallest for paths oriented along the zenith direction and increase approximately inversely with the sine of the elevation angle. That is, either delay will tend to increase by about a factor of 4 from zenith to an elevation of about 15°. Most expressions for the delay along a path of arbitrary elevation consist of the zenith delay multiplied by a mapping function. The mapping function describes the dependence on elevation angle [e.g., *Davis et al.*, 1985].

Geodesists and geophysicists have spent a great deal of effort learning how to model these delays in order to be able to remove them from GPS and VLBI observations [e.g., *Tralli and Lichten*, 1990; *Herring et al.*, 1990]. The hydrostatic delay reaches about 2.3 m in the zenith direction. Given surface pressure measurements, it is usually possible to model and remove the hydrostatic delay with an accuracy of a few millimeters or better. If the atmosphere is in hydrostatic equilibrium and the barometer is well calibrated (error <0.3 mbar), then the hydrostatic zenith delay will be determined to better than 1 mm. The zenith wet delay can be as small as a few centimeters or less in arid regions and as large as 35 cm in humid regions. Although the wet delay is always much smaller than the hydrostatic delay, it is usually far more variable and more difficult to remove. In temperate areas the daily variability of the wet delay usually exceeds that of the hydrostatic delay by an order of magnitude [*Elgered et al.*, 1991]. Because it is not possible to accurately predict the wet delay from surface meteorological measurements [*Resch*, 1984; *Tralli et al.*, 1988], geodesists predict the hydrostatic delay from surface measurements and attempt to measure the wet delay. One approach to measuring the wet delay uses ground-based water vapor radiometer observations [*Resch*, 1984; *Ware et al.*, 1986; *Elgered et al.*, 1991]. However, in an alternative approach, GPS and VLBI geodesists have developed estimation techniques that determine the time-varying zenith wet delay (and any unmodeled or residual zenith hydrostatic delay) from the GPS or VLBI data themselves [*Tralli et al.*, 1988; *Herring et al.*, 1990]. These estimation techniques usually assume azimuthal symmetry of the atmosphere, and they exploit the form of the elevation dependence of the delay (i.e., the mapping function) and the fact that the delay changes little over short periods of time. These analyses typically constrain the variations in the zenith wet delay to between 1 and 20 mm per hour, depending on location and time of year. The zenith wet delay can be recovered from GPS and VLBI data with an accuracy between 5 and 20 mm (as discussed below).

GPS geodesists estimate ionospheric and tropospheric delays only to eliminate them. But ionospheric physicists are beginning to use GPS as a tool to study the ionosphere [*Coco*, 1991]. We believe that in a similar manner meteorologists may be able to exploit GPS as a means of studying the refractivity of the atmosphere and tropospheric water vapor distribution in particular. This may require further innovation in the modeling of the wet and hydrostatic tropospheric delays. Existing models employed by geophysicists and geodesists are somewhat idealized, for example, they normally assume azimuthal symmetry of the atmosphere in the vicinity of a given GPS receiver, whereas azimuthal variations of 20% are quite commonly observed in humid areas [*Rocken et al.*, 1991]. Recent VLBI studies have started to incorporate azimuthal asymmetry models, although these types of solutions are not yet routinely used [e.g., *Herring*, 1992]. Furthermore, the techniques used to estimate hydrostatic and wet delays are focused on correcting the signals recorded at an isolated receiver and not on studying the atmosphere for its own sake, nor on exploiting the power of an array of GPS receivers to study the spatial structure of the propagation delay. Meteorologists and GPS specialists working together should be able to design procedures that can be used to characterize the troposphere in more detail. For example, one can conceive of using arrays of GPS receivers to perform tomographic inversions of the space-time structure of the overlying water vapor distribution (we discuss this below). GPS geodesists are motivated to assist in such an effort because this may lead to better ways of correcting for propagation delays. It is widely appreciated that improved modeling of tropospheric delay is necessary to improve the vertical accuracy of GPS geodesy. Improved vertical accuracy is of great interest to geophysicists and others who study sea, land, and ice level changes in the context of global climate change [*National Research Council*, 1990; *Bilham*, 1991]. It is also attractive to geophysicists performing research on the crustal motion and deformation associated with earthquakes, volcanic activity, and plate tectonics [*Hager et al.*, 1991; *Dixon* 1991].

## Physics of the Atmospheric Propagation Delay

The atmosphere affects microwave transmissions from space in two ways. First, the waves travel slower than they would in a vacuum. Second, they travel in a curved path instead of in a straight line. Both of these effects are due to a variable index of refraction along the ray path. The delay in signal arrival time can be stated in terms of an equivalent increase in travel path length. This excess path length is given by

$$\Delta L = \int_L n(s)\, ds - G \qquad (1)$$

where $n(s)$ is the refractive index as a function of position $s$ along the curved ray path $L$, and $G$ is the straight-line geometrical path length through the atmosphere (the path that would occur if the atmosphere was replaced by a vacuum). Equivalently,

$$\Delta L = \int_L [n(s) - 1]\, ds + [S - G] \qquad (2)$$

where $S$ is the path length along $L$. The first term on the right is due to the slowing effect, and the second term is due to bending. The bending term $[S - G]$ is much the smaller, about 1 cm or less, for paths with elevations greater than about 15°. For rays oriented along the zenith, and in the absence of horizontal gradients in $n$, the ray path is a straight line and the bending term vanishes. Equation (2) is often formulated in terms of atmospheric refractivity $N$, defined by $N = 10^6(n - 1)$, rather than the index of refraction.

The refractivity of the atmosphere is a function of its temperature, pressure, and water vapor pressure. *Smith and Weintraub* [1953] suggested the relationship

$$N = 77.6(P/T) + 3.73 \times 10^5(P_v/T^2) \qquad (3)$$

where $P$ is the total atmospheric pressure (in millibars), $T$ is the atmospheric temperature (in degrees Kelvin), and $P_v$ is the partial pressure of water vapor (in millibars). This expression is considered accurate to about 0.5% under normal atmospheric conditions [*Resch*, 1984]. In most contexts the first term in (3) is considerably larger than the second. A more accurate formula for refractivity is provided by *Thayer* [1974]:

$$N = k_1(P_d/T)Z_d^{-1} + k_2(P_v/T)Z_v^{-1} + k_3(P_v/T^2)Z_v^{-1} \qquad (4)$$

where $k_1 = (77.604 \pm 0.014)$ K mbar$^{-1}$, $k_2 = (64.79 \pm 0.08)$ mbar$^{-1}$, $k_3 = (3.776 \pm 0.004) \times 10^5$ K$^2$ mbar$^{-1}$, $P_d$ is the partial pressure of dry air (in millibars), and $Z_d^{-1}$ and $Z_v^{-1}$ are the inverse compressibility factors for dry air and water vapor, respectively. Both of these factors, which are corrections for nonideal gas behavior, have nearly constant values that differ from unity by a few parts per thousand [*Owens*, 1967]. The uncertainties in the constants of (4) limit the accuracy with which the refractivity can be computed to about 0.02% [*Davis et al.*, 1985].

*Saastamoinen* [1972] showed that the total atmospheric delay can be partitioned into a large quantity which depends only on surface pressure, called the "hydrostatic delay," and a smaller quantity which is a function of water vapor distribution and is called the "wet delay" (see *Davis et al.* [1985], for details). Many authors refer to the hydrostatic delay as the "dry delay," but we avoid this usage. The largest contribution to the hydrostatic delay is that of the dry air. Nevertheless, the hydrostatic delay usually includes a significant contribution from water vapor (due to the nondipole component of water vapor refractivity), and so the term dry delay is misleading. Wet delay is a more appropriate term in that it is produced solely by atmospheric water vapor (due to the dipole component of its refractivity), though it should be kept in mind that it is not the only delay produced by water vapor.

*Elgered et al.* [1991] adopted a model in which the zenith hydrostatic delay (ZHD), in millimeters, is given by

$$\Delta L_h^0 = \text{ZHD} = (2.2779 \pm 0.0024)P_s/f(\lambda, H) \qquad (5)$$

where $P_s$ is the total pressure (in millibars) at the Earth's surface, and

$$f(\lambda, H) = (1 - 0.00266 \cos 2\lambda - 0.00028H) \qquad (6)$$

accounts for the variation in gravitational acceleration with latitude $\lambda$ and the height $H$ of the surface above the ellipsoid (in kilometers). The troposphere accounts for about 75% of the total hydrostatic delay.

The second component of total delay is known as the wet delay $\Delta L_w$. The zenith wet delay (ZWD) is given by

$$\Delta L_w^0 = \text{ZWD} = 10^{-6}\left[k_2' \int (P_v/T)\, dz + k_3 \int (P_v/T^2)\, dz\right] \qquad (7)$$

where $k_2' = (17 \pm 10)$ K mbar$^{-1}$, the integral is along the zenith path, and the delay is given in the units of $z$ [*Davis et al.*, 1985]. It is usually adequate to approximate this expression by

$$\Delta L_w^0 = (0.382 \pm 0.004)K^2 \text{ mbar}^{-1} \int (P_v/T^2)\, dz \qquad (8)$$

These expressions can be evaluated from profiles of $P_v$ and $T$ provided by radiosondes, if such data are available. Almost all of the wet delay occurs in the troposphere, and most of it occurs in the lower troposphere.

Although some effort has been made to develop models that can be used to predict the zenith wet delay from surface measurements, their predictive value is very poor compared to the surface model given above for the zenith hydrostatic delay [*Resch*, 1984; *Tralli et al.*, 1988, *Baby et al.*, 1988]. In practice, the wet delay must be measured using radiosonde launches or WVRs or derived by stochastic or other forms of parametric modeling of the GPS or VLBI data themselves.

We must use one or more mapping functions to relate zenith path delays to delays along paths with arbitrary elevation angles. The total delay for a path with an elevation angle $\theta$ can be computed from the hydrostatic and wet zenith delays via

$$\Delta L = \Delta L_h^0 M_h(\theta) + \Delta L_w^0 M_w(\theta) \qquad (9)$$

where $M_h(\theta)$ is the hydrostatic mapping function and $M_w(\theta)$ is the wet mapping function. Various forms have been proposed for the wet and hydrostatic (or "dry") mapping functions [e.g., *Chao*, 1972; *Black and Eisner*, 1984; *Lanyi*, 1984; *Davis et al.*, 1985]. These functions differ in the number of meteorological parameters that are incorporated. For example, *Chao*'s [1972] mapping functions, one each for $M_h$ and $M_w$, make no reference to meteorological conditions, whereas the hydrostatic mapping function derived by *Davis et al.* [1985] incorporates surface temperature, pressure and relative humidity, the height of the tropopause, and the tropospheric temperature lapse rate. Because the mapping functions $M_h$ and $M_w$ are similar above elevation angles of 10°–15°, and GPS observations at lower elevations are rarely used, it is possible to lump the two delays together and estimate them jointly [*Tralli and Lichten*, 1990]. Nearly all of the mapping functions that have been suggested in the literature assume no azimuthal variation in path delay. Recent VLBI studies indicate that azimuthal asymmetry effects at 15° elevation typically produce a root-mean-square (rms) variation of 7 mm, but at times this effect can be as much as 5 times larger. The assumption of azimuthal symmetry may cause significant errors when the local troposphere has large lateral temperature, pressure, or humidity gradients [*Gardner*, 1976; *Davidson and Trask*, 1985], as usually accompany strong frontal weather systems (Figure 1).

## Estimating Integrated Water Vapor From an Observed Wet Delay

It is possible to derive an approximate relationship between the vertically integrated water vapor (IWV) and an observed zenith wet delay [*Askne and Nordius*, 1987]. Following *Davis et al.* [1985], we introduce the weighted "mean temperature" of the atmosphere, $T_m$, defined by

$$T_m = \frac{\int (P_v/T)\,dz}{\int (P_v/T^2)\,dz} \tag{10}$$

Combining (7), (10), and the equation of state for water vapor we obtain

$$\mathrm{IWV} = \int \rho_v\,dz \approx \kappa \Delta L_w^0 \tag{11}$$

where $\Delta L_w^0$ is the zenith wet delay, and the "constant" $\kappa$ is given by

$$1/\kappa = 10^{-6}(k_3/T_m + k_2')R_v \tag{12}$$

where $R_v$ is the specific gas constant for water vapor. The water vapor content of the atmosphere is sometimes stated as the height of an equivalent column of liquid water, which we refer to as the precipitable water (PW). Numerically, the IWV is just the product of $\rho$ and PW, where $\rho$ is the density of water. Since PW and ZWD both have units of length, their ratio

$$\mathrm{PW/ZWD} = \mathrm{PW}/\Delta L_w^0 = \kappa/\rho \tag{13}$$

is a dimensionless quantity.

In order to achieve the best possible retrieval of IWV or PW from an observed zenith wet delay, via equation (11) or (13), the constant $\kappa$ should be estimated using a value for $T_m$ that is "tuned" to the specific area and season. This can be done, for example, by statistical analysis of a large number of radiosonde profiles. If we choose a single value of $T_m$ for all areas and seasons, say $T_m = 260 \pm 20$ K, then (11) is accurate only to about 15%. A more powerful approach would be to use operational meteorological models to predict the actual value of $T_m$. In the event that operational model output is not available, an alternative approach is to estimate $T_m$ solely on the basis of the observed surface temperature.

If the Earth's atmosphere were isothermal, then $T_m$ would be constant and equal to surface temperature. However, since the atmosphere usually has a negative temperature gradient up to the tropopause, $T_m$ will be the average temperature of atmosphere weighted by the pressure of water vapor, as indicated by (10). Therefore we should expect that $T_m$ will depend on surface temperature, and tropospheric temperature profile, and on the vertical distribution of water vapor. The surface temperature dependence is born out by a comparison of $T_m$ computed from (10) using radiosonde profiles of $P_v$ and $T$ and the values of surface temperature $T_s$ reported at the time of launch. In Figure 2 the ratio ZWD/PW and $T_s$ are shown as a function of time, based on 748 radiosonde profiles from Albany, New York. Inverting these results for the dependence of $T_m$ on $T_s$ yields $T_m \approx 55.8 + 0.77\,T_s$, with an rms scatter about this regression of 4.4 K. The rms scatter about this simple regression indicates that $\kappa$ can be recovered at this site with an rms error of less than 2% from just knowledge of the surface temperature. An analysis of 8718 radiosonde profiles spanning approximately a two-year interval from sites in the United States with a latitude range of 27° to 65° and a height range of 0 to 1.6 km yields a linear regression $T_m \approx 70.2 + 0.72\,T_s$, with an rms deviation from this regression of 4.74 K (Figure 3), which is a relative error of less than 2%. Less than 3% of the data points deviate from the regression by more than 10 K, and we suspect that many of these points reflect unusual levels of error in the corresponding radiosonde data. We conclude that $\kappa$ can be determined from surface temperature observations with a relative rms error of about 2% and that even in the worst cases the error in $T_m$ would induce errors in the recovery of IWV from $\Delta L_w^0$ of less than 4%.

## Estimating Atmospheric Delay From GPS and VLBI Data

Virtually all high-accuracy GPS data processing software packages in use today include among their functions the estimation of tropospheric delay parameters. In most cases these parameters are estimated at the same time as the station and satellite coordinates are being estimated. While most software packages eliminate clock errors through double differencing, a technique in which one combines observables in such a way that clock errors are canceled out [*Leick*, 1990], other software packages process the undifferenced data by introducing an explicit model for clock drift. Several packages are capable of modeling tropospheric delays in more than one way. For example, one may choose to predict the zenith hydrostatic delay (ZHD) from surface meteorological measurements and model only the zenith wet delay (ZWD). In this case the ZWD model will tend to absorb

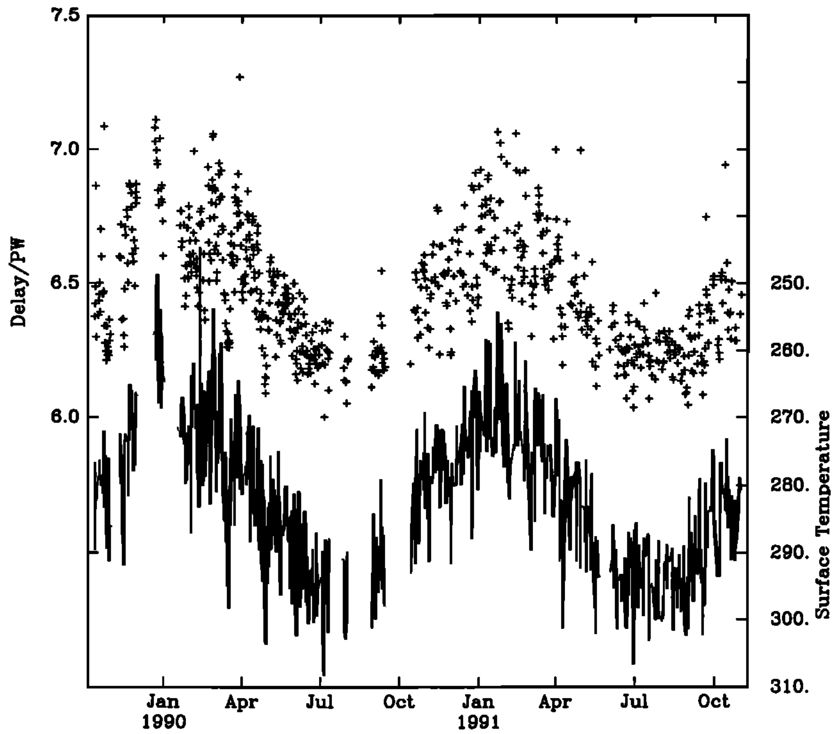


Fig. 2. Values of (1) the dimensionless ratio of zenith wet delay (ZWD) to precipitable water (PW) and (2) surface temperature ($T_S$) from an analysis of 2 years of radiosonde data from Albany, New York. Note that the ZWD is given in units of equivalent excess path length and that PW is the vertically integrated quantity of water vapor stated as the height of an equivalent column of liquid water. (IWV = PW multiplied by the density of water).

errors in the modeling of the ZHD. Another approach is to measure the wet delay, using a WVR, and to model only the residual wet delay due to the instrumental and calibration errors of the WVR. In some situations it is reasonable to model the total zenith delay as a single entity. The following discussion assumes that the ZWD is being modeled, but keep in mind that further generalization is possible.

The simplest estimation approach is to assume that the ZWD is constant for a given time interval and to estimate its value as part of the overall least squares inversion. Typically, practitioners of this approach assume that the ZWD is constant for an interval ranging from 1 hour to 1 day. Depending on the length of the survey, this may mean that only one tropospheric parameter is estimated at each station or perhaps as many as 24 per GPS day. This standard least squares approach (the "deterministic" approach) usually involves placing some constraints on the value of the ZWD, and perhaps on its rate of change, to keep it within reasonable bounds.

A more sophisticated approach utilizes the fact that temporal variation of the ZWD has exploitable statistical properties. The ZWD is not likely to change by a large amount over a short period of time (such as 10 min). In fact, the ZWD can be viewed as a stochastic process, and the process parameters can be estimated using a Kalman filter or a related class of optimal filters based on the state-space, time domain formulation [*Gelb*, 1974]. Some VLBI and GPS processing packages model clock errors as a stochastic process whose parameters are estimated along with the tropospheric process parameters [*Herring et al.*, 1990; *Lichten and Border*, 1987]. In order to estimate the ZWD or an alternative tropospheric quantity via a stochastic filter it is necessary to choose a specific class of stochastic process to represent fluctuations in this tropospheric parameter. Ideally, this choice would be based on insight into the underlying physical processes. In practice, the class of stochastic process is usually selected on the basis of the observed power spectrum of the system being modeled. Most practitioners assume that the ZWD can be modeled as a random walk process or as a first-order Gauss-Markov process [*Treuhaft and Lanyi*, 1987; *Lichten and Border*, 1987; *Tralli et al.*, 1988; *Herring et al.*, 1990]. The stochastic process noise typically is chosen so as to constrain the variation of the ZWD to between 1 and 20 mm per hour depending on location and time of year.

Retrieval of the ZWD by stochastic filtering has been tested more extensively in the context of VLBI rather than GPS geodesy because of the very long continuous observation periods that are available to VLBI geodesists and because VLBI geodesists have routinely monitored atmospheric water vapor using WVRs at many of their sites, which provides some basis for comparison. The VLBI technique is similar to GPS in that it involves recording and correlating radio signals from extraterrestrial radio sources (quasars), and it observes at two frequencies in order to determine the ionospheric delay. It has some significant differences too. The VLBI measurement is similar to that used to implement time-of-flight determinations in GPS geodesy ("pseudoranging"), but it does not utilize the phase of the carrier wave as does GPS geodesy ("phase measurement"). VLBI and GPS have relative strengths and weaknesses in inverting for the atmospheric delay. For example, VLBI enjoys a stronger geometry of sources in the sky, and its directional antennas track down to lower elevation an-

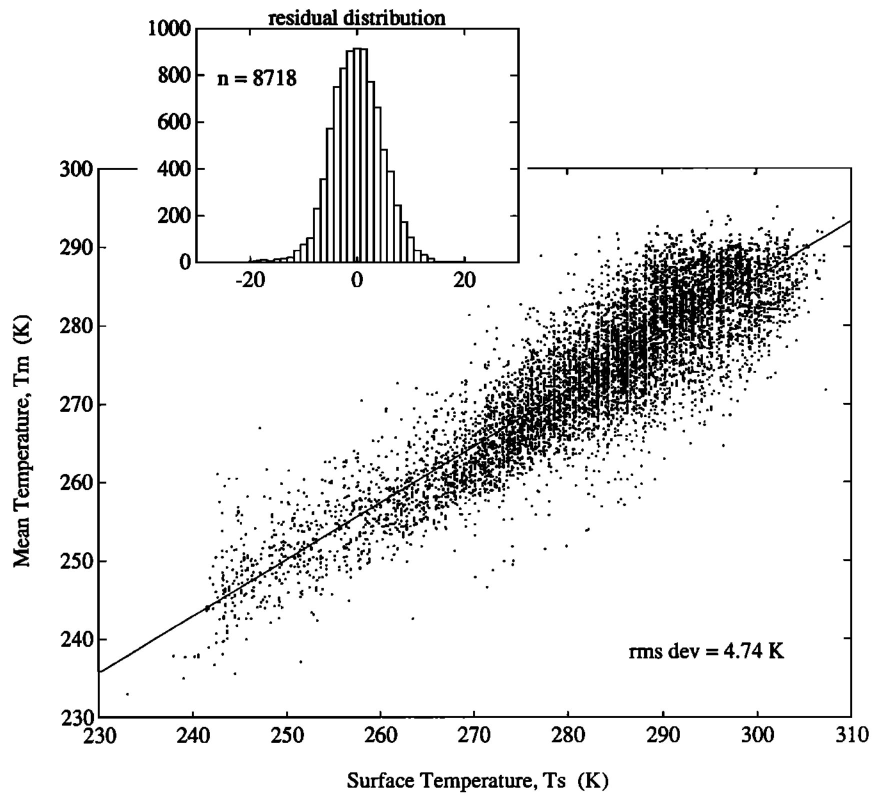


Fig. 3. Relationship between $T_m$ and $T_S$ determined from the analysis of 8718 radiosonde profiles acquired between fall 1989 and fall 1991. The solid line shows the linear regression through all of the data. The profiles used are from 13 stations in the United States, whose latitude ranges from that of Fairbanks, Alaska, to that of West Palm Beach, Florida. The stations used have WBAN numbers 70200, 70261, 72203, 72270, 72291, 72366, 72381, 72387, 72391, 72393, 72618, 72606, and 74494. The histogram depicts the distribution of residuals (observed minus predicted) about the linear fit.

gles, but GPS is capable of totally eliminating clock errors (which can trade off with tropospheric parameter estimates) via the double-differencing technique. The recovery of the zenith wet delay from VLBI data by Kalman filtering has been discussed by *Herring et al.* [1990]. *Elgered et al.* [1991] have discussed the results of an extensive intercomparison of the ZWD, as estimated by stochastic filtering of VLBI data, and the ZWD, as estimated from WVR observations. The two plots in Figure 4 show typical intercomparisons for sites at the Haystack Observatory, Massachusetts, and Mojave, California. Note that the two sets of estimates track each other very well, but in the case of the Haystack data there is an offset or bias of about 17 mm. The source of these long-term biases is not well understood. If long-term biases are removed, then the rms discrepancy between WVR and Kalman estimates of the ZWD are usually ~10 mm or less. The typical level of bias is ~10 mm. Because the offset between the stochastic and WVR estimates almost certainly derives from errors in both techniques, it is likely that the bias between the stochastic estimate of the ZWD and the true ZWD is typically less than 10 mm.

Given the massively overdetermined nature of GPS inversions, and the similar approaches that GPS and VLBI geodesists have taken to tropospheric modeling, we would expect that stochastic estimation routines in GPS processing software would perform at similar levels to those employed in VLBI processing software. Although many GPS processing packages include tropospheric parameter estimation, few of the research groups using them have made systematic comparisons of the ZWD estimated from the GPS data and the ZWD determined using WVRs or radiosonde data. One notable exception is the research group at Jet Propulsion Laboratory (JPL) that has developed and applied a GPS processing package called GIPSY [*Lichten and Border*, 1987] and has made several interesting intercomparisons of geodetic and tropospheric parameter estimation for cases where the ZWD was recovered from GPS data alone via stochastic filtering and where the recovery of the ZWD was achieved or calibrated using WVRs [*Tralli et al.*, 1988; *Dixon and Kornreich Wolf*, 1990]. Figure 5 shows an intercomparison of stochastic and WVR-based estimates for the ZWD based on observations from Central America in January 1988. It is worth noting that the GPS satellite constellation early in 1988 was considerably weaker (geometrically) than that available today. There has also been some comparison of GPS- and VLBI-estimated wet delays, discussed by *Tralli et al.* [1992]. The rms agreement in this study was below 10 mm in all but one case. The recovery of the ZWD by stochastic modeling of GPS data is comparable to that achieved by VLBI geodesists.

The JPL group was the first to adopt a stochastic estimation module for atmospheric modeling within a GPS processing package. Most of the other major GPS processing packages took the deterministic rather than stochastic approach to estimating atmospheric delays. At the time of this writing, however, most groups producing high-accuracy

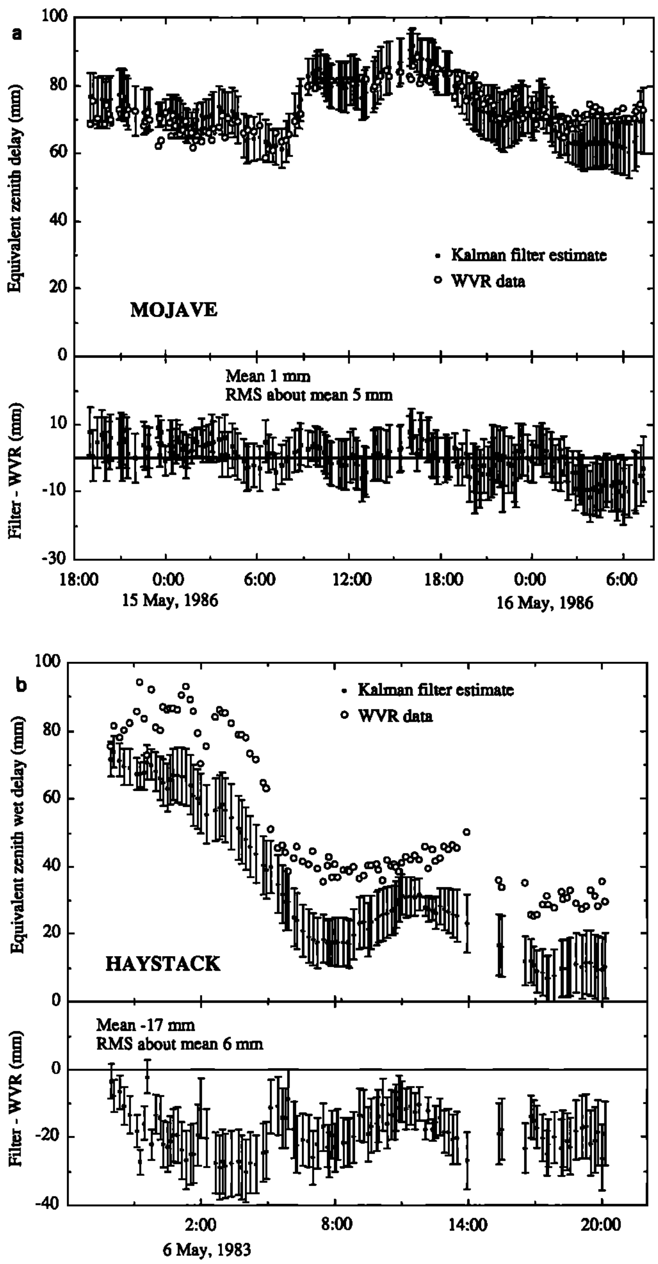


Fig. 4. Estimates of the zenith wet delay obtained by stochastic filtering of VLBI data and from collocated water vapor radiometer (WVR) measurements [after *Elgered et al.*, 1991]. The intercomparisons shown are for VLBI sites at (*a*) Mojave, California, where a new R-series WVR was used, and (*b*) the Haystack Observatory, Massachusetts, where an old R-series WVR was used. The stochastic estimates at each site differ from those reported by *Elgered et al.* [1991] because new atmospheric mapping functions have been employed.

GPS processing software have incorporated or are incorporating both stochastic and deterministic algorithms in the latest versions of their codes.

There is good reason to suppose that we can significantly improve the performance of ZWD retrieval from GPS data. First, GPS meteorology would focus on networks that operated continuously, or at least for periods of several months. This would enable massive averaging of the daily solutions for the network geometry, so that the corresponding geometrical parameters could be removed from the statistical analysis during a second pass through the data, thereby focusing more resolving power on the inversion for the ZWD history. Second, the number of GPS satellites is still increasing, so the number of observations per unit time that can be used in the inversion for the ZWD is going to increase until the GPS satellite constellation is complete. Third, the number and quality of global tracking stations in networks such as the Cooperative International GPS Network and the Deep Space Network is steadily increasing, and as a result, the GPS satellite orbits are becoming better controlled. Since the orbital parameters are among the unknowns estimated during GPS data analysis, and there exist trade-offs between orbital and tropospheric parameters, strengthening the control on the orbits will strengthen the inversion for the ZWD. Finally, we may be able to improve the algorithms used to invert for tropospheric delays. Even if we exclude this last factor, we expect to be able to retrieve the ZWD on a more or less routine basis with less than 10 mm of long-term bias and less than 10 mm of random noise.

## TOTAL ERROR BUDGET ON INTEGRATED WATER VAPOR RETRIEVAL

The error budget for the recovery of IWV from geodetic measurements comprises several distinct error sources, some of which are independent of the total IWV and others which are proportional to the IWV. The results presented here suggest that in nonarid environments the inversion from path delay to IWV will introduce errors of less than 5% under nearly all conditions. The remaining error sources are related to the accuracy with which the path delay can be recovered from the geodetic measurements (GPS in the cases considered here). Noise in the GPS carrier phase measurements, as propagated through the Kalman filtering techniques, typically introduces rms errors of less than 10 mm in the path delay. In the limited comparisons between zenith path delays estimated from VLBI and GPS data, the rms difference between estimates varied between 3 and 29 mm, with a typical value of 10 mm [*Tralli et al.*, 1992]. The case with 29 mm rms difference is considered anomalous and may have been affected by some of the additional error sources discussed below. Errors in the ZWD arising from the standard dual-frequency range correction are of the order of 3 mm under normal ionospheric conditions (see the appendix). The effects of atmospheric dynamics on the hydrostatic delay are likely to introduce errors of considerably less than 1% (23 mm) of the hydrostatic delay and typically would be only a few millimeters. If station barometers are calibrated to better than 0.3 mbar, then the effects of this noise source on the hydrostatic delay will be less than 1 mm. The effects of multipath signals (i.e., reflected rather than direct signals received at the antenna) on the GPS phase measurements is difficult to quantify since it depends on the type of antenna and the environment in which the antenna is positioned. Multipath signals grow with decreasing elevation angle and therefore can alias into zenith delay estimates. Previous experience with GPS multipath signals suggests that this error source is likely to be less than 100 mm on the carrier phase measurements made at 15° elevation angle, and therefore it perturbs the zenith delay measurements by less than 20 mm. Multipath signals typically have periods of less than 20 min and therefore should average out rapidly. Fortunately, recent developments in antenna design and process-

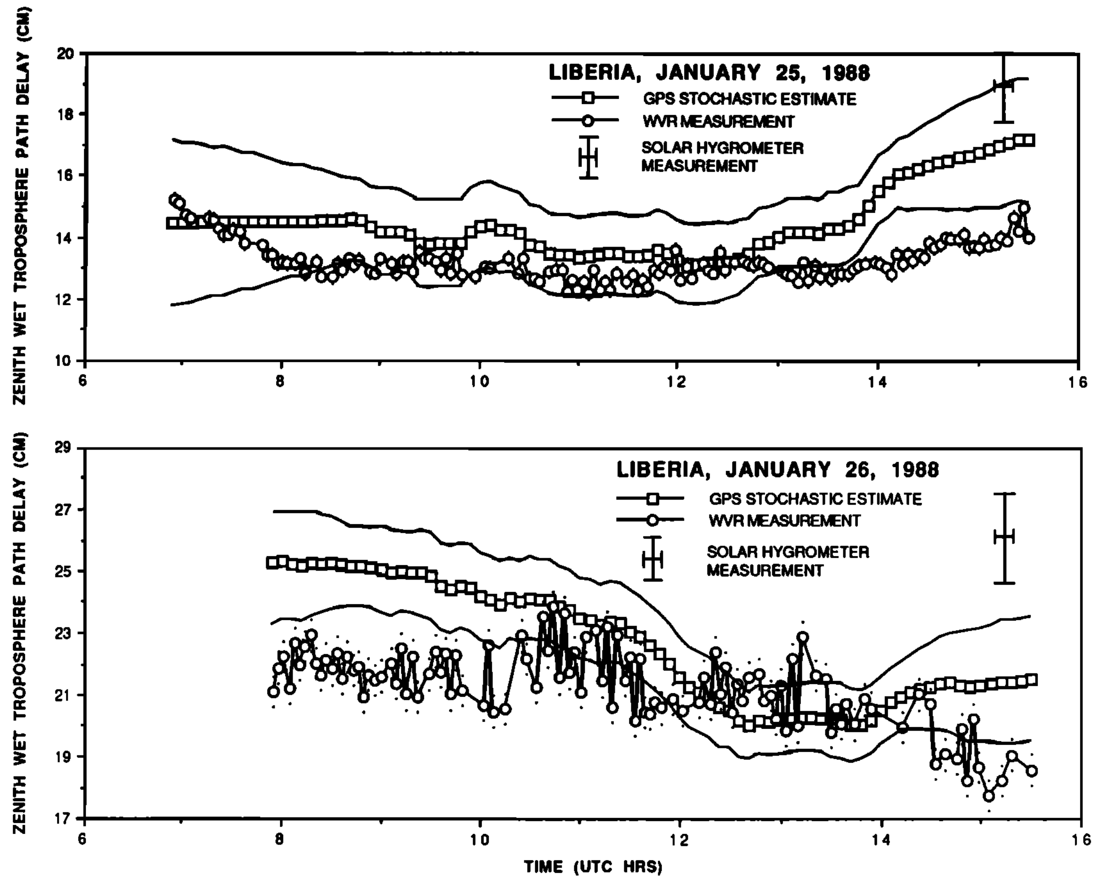


Fig. 5. Estimates of the zenith wet delay obtained from WVR measurements, and from stochastic filtering of GPS data, for a site in Central America in January, 1988 [from *Dixon and Kornreich Wolf*, 1990]. The solid curves indicate approximately the $\pm 1\text{-}\sigma$ formal error range for the GPS-derived estimates. Crosses at 1515 UTC show solar hygrometer measurements made near local sunrise. The dots in the lower plot indicate the formal errors in the WVR measurements.

ing are reducing the multipath problem. The effects of incorrect modeling of the elevation angle dependence of the hydrostatic delay have been under intensive study by the VLBI community in recent years because of their use of very low elevation angle data (as low as 5°) [e.g., *Herring*, 1992]. These studies indicate that at elevation angles of 20° or more the rms errors from this source are typically less than 1 mm.

Ultimately, our estimates on the accuracy of IWV recovery are based on the comparisons on VLBI, GPS, and WVR results. The comparison of these data types has typically shown rms differences of the path delay estimates of less than 10 mm about mean differences of typically less than 10 mm. We therefore conclude that the precipitable water typically should be recoverable with an rms error of less than 2 mm + 2% of the PW and biases of less than 2 mm.

## SOME POTENTIAL CLASSES OF GPS METEOROLOGY

A great number of meteorological applications can be envisioned for the GPS-derived water vapor data, involving topics as diverse as storm and frontal systems, global climate change, and atmospheric chemistry. We visualize three separate classes of "GPS meteorology," which we discuss below, beginning with the least complex application.

### *Mapping of Integrated Water Vapor Using Existing Geodetic GPS Networks*

GPS is one of most important innovations of the last century in the fields of surveying and navigation, and the number of GPS receivers in use has been increasing exponentially with a double time of less than one year, and the space-based portion of the system is not yet fully operational! There is no doubt that continuously operating GPS systems will be deployed worldwide in very large numbers in the coming decade. GPS networks are likely to be particularly dense in North America and Europe. We have noted above that stochastic filters and other statistical techniques can be used to recover the zenith wet delay from GPS data and that it is possible to estimate the IWV from an observed zenith wet delay (via equation (11)). The IWV recovered in this way from data recorded by a given GPS receiver would apply to the immediate vicinity of that GPS station. Given a sufficiently dense network of receivers, it would be possible to map the distribution of IWV in some detail. A key point is that the data sets required for the regional monitoring of IWV would be available at little cost to the meteorological community.

One can get some idea of the rapid spatial and temporal changes in the ZWD that are associated with weather systems from Figure 1. This figure shows an image of IWV for a typical mid-latitude cyclone obtained over the Pacific Ocean by a scanning multichannel microwave radiometer (SMMR) aboard the Nimbus 7 satellite. Data from the SMMR and the special sensor microwave imager have been used to diagnose the distribution of IWV associated with cyclones in both hemispheres [*Katsaros et al.*, 1989]. The units for IWV in Figure 1 are kilograms per square meter. Here, 1 kg $m^{-2}$ of IWV is roughly equivalent to 6.4 mm of path delay. One can see that the IWV "signal" can vary by more than a factor of 3 from just behind the front to just ahead of it. The corresponding change in the value of the zenith wet delay is from ~8 to ~28 cm. As the front passes over a stationary observer, this change could occur in as little as 1 hour or as long as 12 or more hours, depending on the speed of the front. Since it is possible to recover the ZWD from GPS data with an accuracy of 1 or 2 cm, changes of this magnitude should be easily resolved.

### *Tropospheric Water Vapor Tomography Using Meteorological GPS Networks*

One can conceive of GPS networks designed specifically to optimize their value for remote sensing of the atmosphere. This class of network would be constructed and maintained by and for meteorologists. When the GPS satellite constellation is completed in 1993 it will consist of 21 satellites with orbital periods of 12 hours. At least four satellites will be visible at any time anywhere on Earth, and five or six satellites will be visible much of the time. A satellite that passes directly above a receiver will take about 6 hours to cross the sky. Most satellites do not pass directly overhead a given ground station but traverse the sky at low to moderate elevation angles, sometimes rising and setting twice within a given 24-hour period. If one imagines the set of vectors passing from a single receiver to each visible satellite, realized every 10 min throughout the day, these vectors clearly pass through the atmosphere with a wide range of elevations and azimuths. Now conceive of a 5 × 5 grid of such receivers, spaced say 1 km apart. The total set of vectors criss-crossing the troposphere above the network constitutes a sampling geometry somewhat reminiscent of that employed in CAT scan tomography.

Actually, the situation is fundamentally different from CAT scan tomography in that a CAT scan target is not changing during the period in which the observations are collected, and therefore the fact that observations along different vectors through the target were collected at different times is irrelevant. In contrast, the atmosphere does change over periods long enough for receiver satellite vectors to sweep across the sky, and so we must take into account that most of the vectors realized in a given day do not cross instantaneously. We may exploit the fact that the atmosphere changes only slowly and modify existing methods of tomographic analysis accordingly. For example, we might divide the atmosphere above the network into a suite of boxes (a three-dimensional grid) and estimate the water vapor content in each box, subject to the condition that this quantity is a stochastic process whose process variance is constrained according to height, site, and season. Alternatively, we might parameterize the water vapor distribution in terms of a triple series of orthogonal polynomials defined over the spatial coordinates and require that each unknown coefficient in this series evolves in time as a stochastic process. We coin the term "stochastic tomography" to refer to this generalization of conventional tomographic analysis. (A more "deterministic" approach to the problem would be to assume that the water vapor distribution could be represented as a quadruple series of orthogonal polynomials defined over the space-time aperture of the network.)

If such a network was operated for many months, its geometry could be found with great accuracy by averaging a large number of daily geodetic solutions. By 1993, satellite ephemerides (orbital paths) will be known to great accuracy in nearly real time by virtue of automatic processing of data from a global tracking network (indeed, such a system is already under construction at Scripps Institute of Oceanography). The point is that the geometry of the situation, both on the ground and in space, will be exactly known, and so estimating this geometry need not complicate the recovery of the signal delay observed along a given receiver satellite vector. (Additionally, it may be advantageous in some contexts to minimize receiver clock noise by employing external atomic clocks.) It should be possible in such a context to determine a good estimate of the signal delay along each receiver satellite vector. Because these vectors densely sample the troposphere above the network, it should be possible to determine the spatial structure of this delay as a function of time. Given a means either to estimate or measure the vertical temperature profile above the network, the space-time distribution of the propagation delay can be transformed into the space-time distribution of water vapor. (We assume that the hydrostatic delay can be recovered adequately using surface measurements.) In areas such as the United States and Europe, which enjoy well-developed meteorological observation networks, operational models of the atmosphere may well provide sufficient control of the temperature profile so that local sensing of the temperature distribution may not be necessary to support GPS tomography of water vapor distribution.

Of course, the geometry of the network would be designed according to the particular needs of its users. Presumably, it would always contain a subnet whose spacing was smaller than or comparable to the vertical extent of the lower troposphere. But it need not be set up as a square grid. Other geometries, such as a logarithmic spiral, have been used to study the ionosphere [*Gourevitch et al.*, 1989]. Although a meteorological network designed for water vapor tomography would be much smaller and denser than the regional GPS networks described in the previous section, it would probably be necessary to incorporate some data from outlying sites. Most GPS-processing software uses a double-differencing scheme to eliminate the influence of satellite and receiver clock errors on parameter estimation. Because of this differencing the GPS data may be more sensitive to relative than to absolute tropospheric changes. The tropospheric delay at one station is called the absolute delay, while the relative delay is the differential tropospheric delay between two stations. Absolute tropospheric delays can be estimated for stations that are widely separated (>100 km) because the elevation angles of the various satellites are significantly different. Closely spaced stations are better suited to the recovery of relative delays, and the tropospheric parameters recovered at these stations will usually be highly correlated. It should be possible to resolve this problem by augmenting the observations obtained from a dense meteorological array with observations collected at a

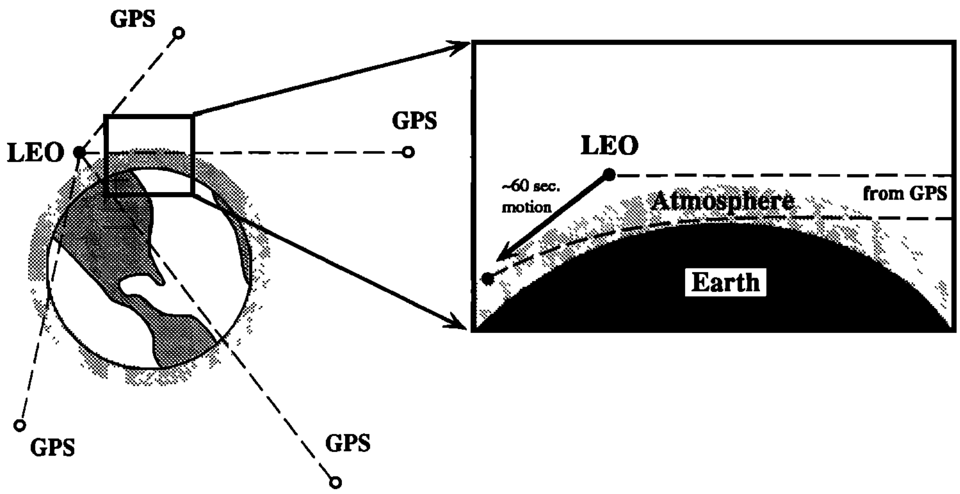


Fig. 6. A schematic diagram of the GPS occultation concept [after *Hardy et al.*, 1992]. A low Earth orbit (LEO) satellite receives signals from GPS satellites orbiting at heights of about 20,000 km. The expanded view illustrates that in the 60 s or so prior to the occultation of a GPS satellite by the Earth the signals propagating from the GPS satellite to the LEO satellite are refracted by the Earth's atmosphere.

small number of distant GPS stations. Indeed, should the meteorological community embrace the concept of GPS meteorology, it might prove advantageous to run a small number of "fiducial" sites across the nation at locations where frequent sounding of the atmosphere occurs on a regular basis, allowing prior constraints to be introduced into the analysis of any network which incorporates GPS data from these sites.

Although the data gathering and processing requirements of this technique are of necessity demanding, the potential benefits are exciting indeed. The structure and evolution of storms ranging from thunderstorms to mid-latitude cyclones and hurricanes are strongly affected by the release of latent heat and therefore are extremely sensitive to the distribution of water vapor. The prospect of determining the full three-dimensional distribution of water vapor, for example, in a developing mid-latitude frontal system, through GPS tomography may provide an important data source to document the evolution of precipitation structures within these storm systems.

### *GPS Occultations Observed From Space*

The radio occultation technique was developed and refined in order to study the atmospheres of Mars, Venus, and several outer planets and their moons [*Fjeldbo and Eshelman*, 1968; *Eshleman et al.*, 1977; *Lindal et al.*, 1981]. This well-established technique could now be applied much closer to home. Phase measurements of GPS signals as they are occluded by Earth's atmosphere (Figure 6) could provide atmospheric refractivity soundings and so yield information on global atmospheric temperature, humidity, and ionospheric structures [*Yunck et al.*, 1988; *Gurvich and Krasil'nikova*, 1990; *Chiu et al.*, 1991; *Hardy et al.*, 1992].

A GPS receiver in low Earth orbit (LEO) can observe roughly 600 GPS occultations per day. A typical GPS occultation measurement effectively samples over a horizontal path of roughly 200 km with a vertical resolution of 1 km (Figure 6). Results from the Voyager missions suggest that temperature soundings of Earth's stratosphere, from 8 to 45 km altitude, could achieve accuracies of 1 K or better. Where significant tropospheric moisture is present, temperature can be measured by GPS occultation if humidity is modeled, or vice-versa. In cold and dry conditions such as those found during polar night, temperature soundings may be obtained down to altitudes of 1 km or so. In the tropics, operational models predict temperature distribution more reliably than humidity, and so the emphasis would be on humidity soundings.

Early opportunities may exist to test the GPS occultation concept. Several hundred new private communication satellites have been announced for launch in the next several years (see Table 1). Many of these satellites will carry GPS receivers for tracking and attitude measurements. In addition, satellites such as TOPEX/POSEIDON, Gravity Probe

TABLE 1. Communication Satellites Proposed for Launch in the Next Several Years Which May Carry GPS Receivers [*Ware et al.*, 1992]

| Company | Satellite Name | Number of Satellites |
|---|---|---|
| Constellation Communication Corporation | Aries | 48 |
| Ellipsat Incorporated | Ellipso | 24 |
| Inmarsat | System 21 | 21 |
| Leosat Incorporated | Leosat | 18 |
| Motorola | Iridium | 77 |
| Orbital Sciences Corporation | Orbcomm | 24 |
| Qualcomm/Loral | Globalstar | 48 |
| Smolsat | Smolsat | 36 |
| Starsys | Starnet | 24 |
| TRW/Defense Systems Incorporated | Odyssey | 12 |
| | Total | 332 |

Ellipso plans call for a Molniya orbit and the others for low Earth orbit. The number of possible occultation observations and their vertical resolution decreases as the altitude of the orbit increases. For example, GPS receivers in geostationary orbit can observe roughly 50 occultations per day with a vertical resolution of 10 km. In low Earth orbit roughly 600 occultations can be observed per day with a vertical resolution of 1 km. Plans for Iridium do not include GPS receivers at this time.

B, ARISTOTELES, and EOS B will carry GPS receivers, and other U.S. and foreign government satellites may be similarly equipped.

In order to explore the potential of the GPS occultation technique, simulations should be conducted with two-dimensional models that include climatology, ionospheric conditions, and distributions of temperature, humidity, cloud liquid water, and rain. In addition, appropriate GPS receiver hardware, software, and antennas must be specified, developed, and tested in orbit. Overall, GPS occultation measurements promise to provide valuable data for weather, climatology, and global change research.

If the early excitement about the GPS occultation technique survives an expanded analysis, then it would be of interest to consider how the ground-based GPS approach advocated here could be coupled with its more exotic cousin. Consider, for example, the lateral extent of the atmosphere sampled during occultation (Figure 6). Clearly, if several ground-based GPS receivers were embedded in this region and could provide estimates of lateral gradients in the IWV, it would be possible to devise increasingly sophisticated retrieval algorithms with which to process the occultation data. Given that both ground-based and space-based GPS techniques for atmospheric sounding are in their infancy, it would be premature to spend much time speculating on their possible synergy. We provided this section just to indicate the enormous potential of GPS meteorology.

## DISCUSSION

Water vapor plays an essential role in the dynamics and thermodynamics of many atmospheric storm systems and the hydrologic cycle on local, regional, and global scales. Because water vapor shows great spatial and temporal variability, its distribution is difficult to resolve by conventional means. Errors in the initial conditions of water vapor in operational numerical models contribute greatly to the errors in the short-term (0–24 hours) precipitation forecasts. Emerging networks of continuously operating GPS receivers offer the possibility of observing the horizontal distribution of integrated water vapor or, equivalently, precipitable water with unprecedented coverage. These measurements could prove extremely useful in operational weather forecasting and in fundamental research into atmospheric storm systems, atmospheric chemistry, and the hydrologic cycle. Long-term, global measurement of IWV could provide vital information on regional and global climate change [*Randall and Tjemkes*, 1991]. Most theorists believe that global warming will cause systematic changes in the total water vapor content of the atmosphere. These changes in atmospheric water vapor may be easier to detect than the associated changes in atmospheric temperature.

A significant practical motivation for mesoscale field programs such as the Genesis of Atlantic Lows Experiment (GALE) [*Dirks et al.*, 1988] and STORM-FEST [*STORM Project Office*, 1991] has been the limited success of operational models to predict precipitation patterns and severe weather, despite significant gains in the skill of predicting synoptic-scale circulations. The disparity in the prognostic skill for precipitation and synoptic-scale patterns is a consequence of the formation of precipitation on scales essentially smaller than those resolved by present-day global models and the lack of mesoscale data (currently limited in resolution by the spacing of the radiosonde network) with which to initialize regional fine-mesh models. During the past decade there has been considerable effort to develop regional fine-mesh primitive-equation models of the atmosphere and apply them to operational, short-range weather forecasting and mesoscale research problems in the mid-latitudes. An essential ingredient for the initialization and testing of the new regional models are sets of observational data that span both the synoptic scales and mesoscales. Recent modeling studies [*Kuo et al.*, 1992] indicate that assimilating precipitable water observations into mesoscale numerical weather models would significantly improve precipitation forecasts. Continuously operating networks of GPS receivers could be used to help document the presence of mesoscale moisture gradients in the atmosphere such as dry lines [*Schaefer*, 1974; *McCarthy and Koch*, 1982; *Parsons et al.*, 1991]. Dry lines are commonly observed over Texas and Oklahoma from May through July, as warm, dry air descending from the Mexican plateau and/or the Rocky Mountains meets extremely humid air from the Gulf of Mexico. In the absence of strong flow across the mountains, the pressure signal associated with dry lines is overwhelmed by the moisture signal, making GPS data especially appropriate. Similarly, GPS data may also have special application to sensing cold fronts aloft (CFA). This term was recently used by *Hobbs et al.* [1990] to denote cold frontal zones whose bases are above the surface in the lower or middle troposphere. The CFA is marked by a zone of moisture as well as temperature contrast [*Businger et al.*, 1991; *Locattelli et al.*, 1989] and has been associated with enhanced precipitation and the triggering of squall lines.

In discussing the possibilities of GPS meteorology, one of the first questions that arises is its advantages and disadvantages relative to the now well-established technique of water vapor radiometry. Under good operating conditions, ground-based WVRs may constitute a better means of sensing IWV than does recovering the wet delay from GPS observations. Furthermore, WVRs can measure ILW as well as IWV, and ILW contributes very little to the wet delay (nor is it measured by radiosondes). However, WVRs have some shortcomings too. Unlike GPS receivers, WVRs are not "all-weather" instruments. Nearly all WVRs produced to date do not generate useful data when it is raining heavily, and their performance may be degraded in the presence of heavy cloud or light rain. GPS receivers have advantages over WVRs in that they are more rugged instruments, are being produced in large numbers, and are far less costly (their price has been dropping 25–50% every year). Perhaps the most important potential advantage of GPS over ground-based WVRs is that GPS receivers are going to exist in huge numbers over wide areas in just a few years, and the use of this resource for meteorological purposes could occur at little incremental cost. It is possible that many of the applications discussed herein could be implemented using GLONASS (a system similar to the GPS constructed by the former Soviet Union) and future space-based radio navigation systems.

Another concern that often arises in the context of GPS technology is the effect of "selective availability" (SA). The Department of Defense implemented SA in March 1990 in order to deny most civilian users of the system the maximum achievable accuracy in single-point positioning (navigation) applications. Although this policy has angered many civilian users of GPS, it has not had a significant impact on geodetic (relative positioning) applications [e.g., *Rocken and Meertens*, 1991]. Provided that all receivers sample the GPS signal close to simultaneously, the effects of SA can be eliminated after the fact. Consequently, SA is not a significant problem for ground-based GPS meteorology.

Meteorological studies of water vapor using geodetic methods should bring benefits to the geodetic community as well as to atmospheric science. These studies should provide better stochastic models of the wet delay, particularly with respect to its spatial variability. GPS specialists have not yet exploited the fact that the ZWD is coherent in space as well as in time. Meteorologists can help geodesists to make better use of operational weather models and to tune assigned parameters (such as stochastic process noise) according to a priori information on the meteorological context of a given station. At the very least it should be possible to develop indicators of conditions in which the existing classes of stochastic models will not represent the water vapor variability well, thereby enabling analysts to flag geodetic solutions that should be considered suspect due to unfavorable atmospheric conditions.

## APPENDIX: IONOSPHERIC EFFECTS ON GPS SIGNALS

We did not discuss above the nature of the ionospheric contribution to the overall error budget for the ZWD, but the magnitude of this contribution is implicit in our discussion of total system performance. Empirical comparisons between results obtained using VLBI, WVR, and GPS observations establish a total error budget (including ionospheric and other effects) for the estimated ZWD of ~10-mm rms random error and ~10-mm long-term bias using present techniques. Implicitly, the ionospheric contribution is typically at or below this level. We include this section to provide additional information on the phenomenology of ionosphere-induced errors.

The free electrons of the ionosphere, which extends from about 50 to about 1000 km above the Earth's surface, affect the propagation of radio waves. At frequencies above about 30 MHz, radio waves pass through the ionosphere but suffer dispersion. The phase velocities of carrier waves are increased, but the group velocities of modulations superposed on the carrier waves are reduced. The magnitude of phase advance and group delay are similar, the effects differ only in sign. The magnitude of the group delay is, to a good approximation, proportional to the total electron content (TEC) along the path between satellite and receiver and inversely proportional to the square of the carrier frequency. By making measurements at two sufficiently widely spaced frequencies the ionospheric effect can be modeled and largely removed from the observations. It is for this reason that GPS satellites transmit signals on two carrier frequencies: L1 at 1.57542 GHz and L2 at 1.22760 GHz (with wavelengths of about 190 and 244 mm, respectively).

The TEC varies substantially both in time and space, with extreme values of about $10^{16}$ and $10^{19}$ el $m^{-2}$. The TEC is mainly a function of incident solar radiation flux. For example, during the day the ionizing effects of incident solar energy increase the TEC, and at night free electrons tend to recombine with ions, and TEC is reduced. The TEC is affected by a wide range of phenomena including the sunspot cycle, the rotation of the sun, traveling ionospheric disturbances (TIDs), and more rapid ionospheric scintillations, the Earth's magnetic field, season, location, and direction. A typical daily average zenith delay due to the ionosphere is 10 m. The delay can change by an order of magnitude between day and night. TIDs, which are thought to be related to weather patterns, have spatial wavelengths between several hundred and several thousand kilometers and temporal periods between 10 min and several hours. They typically cause ~10% fluctuations in the total ionospheric delay.

A dual-frequency GPS receiver records the differential group delay between the L1 and L2 frequencies, and the total delay at either frequency can be estimated from this observation using a model for ionospheric dispersion. The standard dual-frequency correction described by *Spilker* [1980] ignores third- and higher-order terms in the refractive index of the ionosphere. Nevertheless, it achieves (for elevation angles $\geq 15°$) a residual range error (RRE) of less than 30 mm in all but unusual circumstances [*Brunner and Gu*, 1991]. The RREs generated by the standard model tend to decrease with increasing elevation angles; at zenith the RRE is almost always less than 10 mm. Because the ZWD normally is estimated at each epoch using observations from four or more satellites, the residual range errors may partially cancel during the computation of the ZWD. More importantly the mapping function used in the computation of the ZWD tends to reduce the influence of large RREs obtained at low elevations. Thus one would expect the ionosphere RREs under normal conditions to induce ZWD errors of less than 10 mm and usually of the order of a few millimeters. Recent improvements in the dual-frequency range correction algorithm, which involve approximate expressions for the higher-order effects, can reduce the residual range error to less than 2 mm at any elevation angle [*Brunner and Gu*, 1991]. The suggestion is that when these new algorithms are introduced into GPS processing software, ionospheric error sources contaminating GPS-derived estimates of the ZWD should be reduced by an order of magnitude to ~1 mm or less, except under extraordinary circumstances such as a major magnetic storm.

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