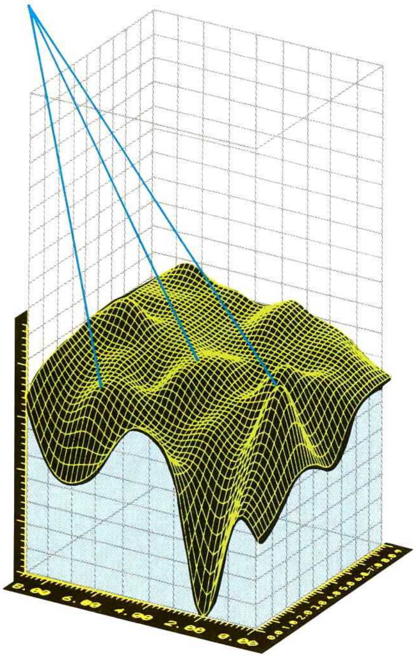

Effect of the Troposphere on GPS Measurements

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As they propagate from a satellite to a receiver on the ground, GPS signals must pass through the earth's atmosphere. In previous columns we have looked at the effect that the ionosphere — the ionized part of the atmosphere — has on GPS signals. This month we examine the effect of the nonionized or neutral part, the bulk of which lies in the troposphere. Our authors are Fritz K. Brunner of the School of Surveying, University of New South Wales, Sydney, Australia, and Walter M. Welsch of the Institute of Geodesy, Universität der Bundeswehr München, in Neubiberg, Germany. Dr. Brunner is a professor of surveying, and his main research interests are geodetic refraction effects and the use of GPS for measuring crustal motion. Dr. Welsch is a professor of surveying engineering and applies GPS to high-precision engineering tasks.

"Innovation" is a regular column in GPS World *featuring discussions on recent advances in GPS technology and its applications as well as on the fundamentals of GPS positioning. The column is coordinated by Richard Langley and Alfred Kleusberg of the Department of Surveying Engineering at the University of New Brunswick. We appreciate receiving your comments as well as suggestions of topics for future columns.*

GPS signals start traveling on their propagation path from a satellite to a receiver through what we call "space" — which is essentially a vacuum — before entering the earth's atmospheric envelope. The ionosphere is the first atmospheric layer encountered relevant to the propagation of the signals. Because the ionosphere is a dispersive medium for radio waves, which means that the propagation velocity depends on the frequency of the waves, one can almost completely eliminate the ionosphere's propagation effects on GPS signals by simultaneously using two different carrier frequencies. For further discussion, see "Ionospheric Effects on GPS" by John A. Klobuchar in the April 1991 issue of *GPS World.* A related article, "GPS — Satellites of Opportunity for Ionospheric Monitoring" by David Coco, appeared in the October 1991 issue.

After passing through the ionosphere, GPS signals travel through the stratosphere and the troposphere (see Figure 1). These layers of the atmosphere are nondispersive at radio frequencies below about 30 GHz because they are electrically neutral. In the troposphere, the lowest part of the earth's atmosphere, temperature decreases with an increase in altitude and almost all of the activity collectively described as "weather" takes place here. The thickness of the troposphere is not the same everywhere. It extends to a height of less than 9 kilometers over the poles and exceeds 16 kilometers over the equator. The stratosphere extends from the upper boundary of the troposphere, called the tropopause, to a height of about 50 kilometers. Because the bulk of the neutral atmosphere lies within the troposphere, the whole neutral atmosphere is often referred to by the misnomer "troposphere." In this article we describe how the neutral part of the atmosphere affects the propagation of GPS signals, the nature of the tropospheric effect, its size and variability, and methods to reduce the effect on GPS position determinations.

The troposphere's nondispersive nature for radio frequencies delays the arrival of the carrier phase and the carrier modulation of both the L1 and L2 signals by the same amount. Because we cannot directly measure tropospheric delay as we can ionospheric delay using the GPS signals themselves, we must resort to modeling.

On the shortest path through the troposphere — the one in the zenith direction — the tropospheric time delay results in an increase in measured apparent range of about 2.4 meters. The delay grows with increasing zenith angle and reaches about 9.3 meters for a zenith angle of 75°. With simple models, the zenith delay can be predicted very easily to an accuracy better than 20 centimeters. Therefore, tropospheric propagation effects are not a concern in GPS navigation and low-accuracy positioning. For geodetic positioning using carrier-phase observations, however, the tropospheric effect may be a severe accuracy limitation, especially for the vertical position component. An error of 1 centimeter in modeling the tropospheric zenith delay can result in a vertical position error of about 3 centimeters.

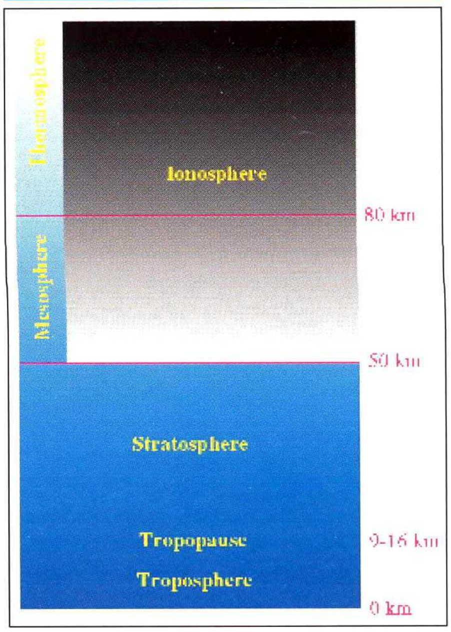


Figure 1. The layers of the atmosphere.

NATURE OF THE DELAY

The neutral atmosphere changes the speed and direction of the propagation of radio waves. Both effects can be related to the variation of the refractive index, n, of the medium. The refractive index is defined as the ratio of the speed of light in a vacuum (identical for radio waves) to the speed of propagation in the medium. The propagation direction is described by the famous law of geometrical optics: Snell's law of refraction. Because the refractive index of air is only slightly larger than 1, it is frequently convenient to use, instead of n, the refractivity N, which is simply $10^6 \times (n-1)$.

The refractivity of a particular parcel of air is dependent on the density of the parcel, which is the sum of the density of the dry air constituents and the density of water vapor in the parcel. We can therefore express the refractivity of a particular parcel of air as the sum of two terms

$$N = N_A + N_W$$

where N_A is proportional to the total density of air, and N_W is mainly determined by the density of the water vapor contained in the air parcel. The densities, in turn, are a function of the pressures of the dry gases and water vapor and their temperature. Figure 2 shows a typical height profile of N_A and N_W as derived from radiosonde (instrumented weather balloon) data. The shaded area indicates the overall variability of the wet component.

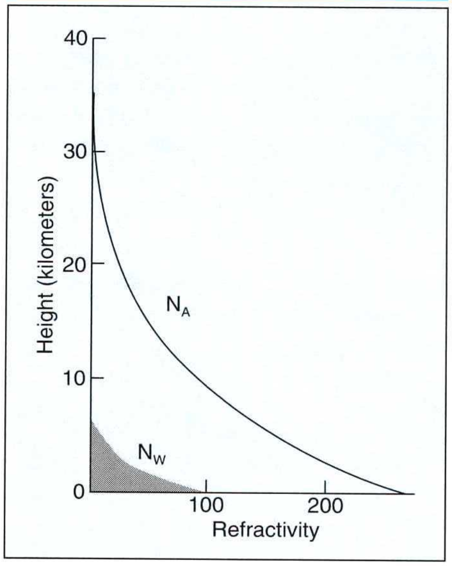
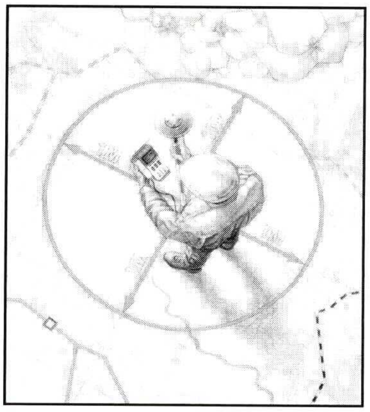
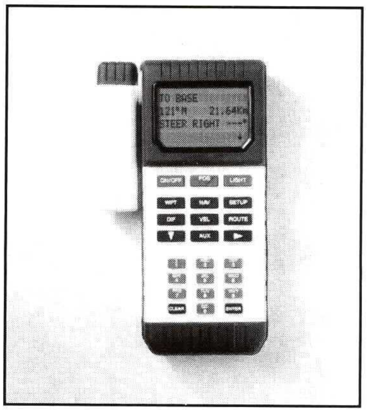


Figure 2. Typical height profiles of refractivities N_A and N_W.

Close inspection of Figure 2 reveals a few interesting points. First, the variability of N_A is very small within the troposphere because of the nearly constant ratio of the constituents of air, with the exception of water vapor and condensed water. Second, N_A is negligible at heights of about 40 kilometers and above. Therefore, only the troposphere and the stratosphere are important as electrically neutral propagation regions for satellite signals. The density of atoms and molecules in the higher regions — the mesosphere, which extends from about 50 to 80 kilometers, and the thermosphere, which ranges from about 80 to 500 kilometers or so — is too small to have a measurable effect. Third, the wet refractivity is only significant at heights below the troposphere. The mixing of dry air and water vapor is a rather complicated process depending mainly on weather conditions. Thus the N_W profiles show strong variations with height, time, and location and are very difficult to predict. This variability of the wet refractivity is highest in the atmospheric boundary layer, which extends from the ground up to a height of about 1.5 kilometers, and in the cloud layers that do not usually extend much beyond a height of 4 kilometers.

The lower the elevation angle of the incoming GPS signal, the more it is adversely affected because it must travel a longer path





through the troposphere. Therefore, in GPS work, we usually avoid using satellite observations below an elevation angle of 15°. For the rest of our discussion of the tropospheric effect, we assume a cut-off angle of 15°. Furthermore, below this angle, multipath effects may bias the results of using dual-frequency data to remove ionospheric propagation effects. (Multipath contamination arises when a GPS receiver acquires signals both directly from the satellite and via reflections off nearby structures or the ground.)

In general, a radio signal propagates through the troposphere with variable velocity along a curved path. The curvature correction is zero in the zenith direction and less than 1 centimeter for a 15° elevation angle. The correction is easily incorporated into the formulae modeling the delay, and we need not consider it further.

The tropospheric delay a GPS signal experiences is the integration of the refractivity all along the propagation path. Figure 3 shows a typical example of the variation of the tropospheric delays as a function of elevation angle to a GPS satellite. The top curve is the total density delay, and the shaded area indicates the range of water vapor delays. The extreme variability of the water vapor delay is the crucial problem of tropospheric delay effects, which are the sum of the top and bottom curves.

Figure 3 indicates that it should be possible to express the tropospheric delay at a certain elevation angle as the product of the tropospheric zenith delay and a function that maps the increase in delay with an increasing zenith angle. Just as N is the sum of N_A and N_W, the zenith delay can consequently be expressed as the sum of the zenith total density delay of air (t_A) and the zenith water vapor delay (t_W). For any elevation angle down to 15°, we can use the same mapping function for the total density and wet delays, so that:

$$\text{tropospheric delay} = \text{mapping function} \times (t_A + t_W).$$

Typical values for t_A are between 2.3 and 2.4 meters whereas the t_W values range between a few millimeters for the polar regions and a few centimeters for desert conditions to 40 centimeters or more for tropical areas. The great advantage of modeling the tropospheric delays as zenith delays multiplied by a mapping function is that one can measure the zenith delay value from meteorological observations; alternatively, one can model or estimate a zenith delay for each site as an unknown parameter in the least-squares

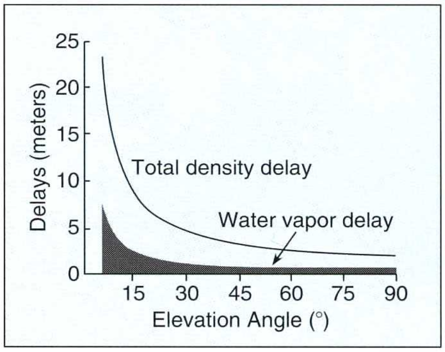


Figure 3. Propagation delays (in meters) as a function of elevation angle. The values for 90° elevation are t_A and t_W, respectively.

adjustment of GPS observations instead of delay values at all elevation angles.

The formulation of an accurate mapping function is fairly simple for elevation angles larger than 15°. A commonly used mapping function is the one associated with the Saastamoinen tropospheric delay model, which is expressed as a function of the elevation angle of the chord between the receiver and a GPS satellite. For a cut-off angle of 15°, the accuracy of Saastamoinen's mapping function is better than 5 millimeters. This mapping function is hard to beat for simplicity and accuracy, which explains its wide use in GPS data processing.

MEASUREMENTS

The barometric pressure at the GPS antenna is the key measurement for calculating t_A, which is why we chose to use N_A, the refractivity related to the total density of air. There are essentially two methods for measuring the basic data needed to calculate the water vapor delay: water vapor radiometry and radiosonde data. As emphasized earlier, water vapor delays show high spatial and temporal variations. For the atmospheric correction of very long baseline interferometry (VLBI) observations, researchers developed water vapor radiometers (WVRs), very sensitive radio receivers that can be used to infer the water vapor delay in any direction with high accuracy.

A WVR measures the brightness temperature (radiation energy) of all water vapor molecules along the line in which the passive antenna points. These instruments usually operate with two frequencies: 22 GHz to measure the water vapor content, and 31 GHz to measure the liquid water of clouds. The WVR measurements can be used to calculate water vapor delays with an accuracy of slightly better than 1 centimeter. However, the equipment is fairly expensive and the use of water vapor radiometers for GPS surveys will not become a standard technique in the near future, if ever. But for fundamental VLBI or GPS reference stations, WVR measurements offer an accurate and efficient way to measure the water vapor delay as a function of elevation angle and azimuth.

Radiosondes measure the pressure, temperature, and humidity of the surrounding air at various heights during a nominally vertical ascent. The humidity of an air parcel is directly proportional to the water vapor pressure and inversely proportional to the ambient temperature. The radiosonde data can therefore be used to calculate the refractivities. The radiosondes drift, however, with the varying wind field and generally produce no observations in the zenith above the GPS site. Furthermore, the operation of radiosondes requires considerable infrastructure, which is expensive. As a result, special radiosonde launches are rarely used in research projects and certainly not in routine GPS survey work.

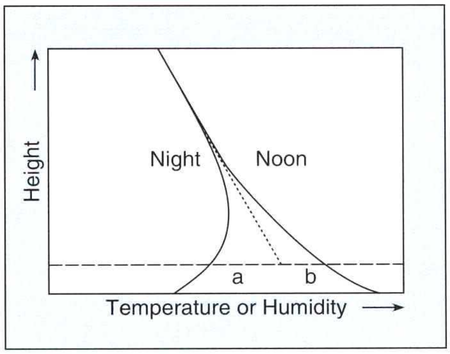


Figure 4. Schematic height variation of temperature or humidity at night and at noon. The ground proximity effects (a and b) are shown at the measurement height (dashed line).

METEOROLOGICAL GROUND DATA

Many meteorological models have been developed to calculate the zenith delays from meteorological observations made near the ground at the time of the GPS measurements. This approach is especially useful for determining the zenith delay t_A, which is related to the total air mass contained in the vertical column above a GPS station and thus directly proportional to the barometric pressure at the antenna height. Consequently, the accuracy of the pressure measurement controls the attainable accuracy of t_A (for example, a pressure error of 50 pascals, which is equivalent to 0.5 millibars or about 0.015 inches of mercury, gives rise to a 1.2-millimeter error in t_A).

However, the wet zenith delay is only weakly related to the meteorological surface conditions, which generally are poor indicators of the humidity distribution above the receiver. All known models suffer from serious inaccuracies caused by this fact. Most models relate the humidity profile to a power law of the pressure profile, which leads to t_W being expressed simply as a function of surface humidity and temperature. Using an extensive radiosonde data set, we have calculated the accuracy of these types of models to be no better than 30 millimeters.

In general, the tropospheric delay models using meteorological ground observations have produced rather poor, and in most cases worse, results compared with the results from the default model values that replaced the actual observed meteorological values. We would like to comment on this surprising finding. Taking accurate meteorological observations is a somewhat difficult task, and frequently large observation errors can occur. In addition, the closeness of the ground and very local micrometeorological conditions severely affect meteorological observations. The dynamic processes in the atmosphere start to smooth out these ground proximity effects at heights of about 50–100 meters above the ground. The observation errors as well as the ground proximity effects on the humidity and temperature measurements affect the whole wet refractivity profile (and therefore the calculated zenith delay) significantly. For example, an error of 5 percent for the relative humidity or a temperature error of 2 °C each cause a zenith delay error of 12 millimeters. Ground proximity effects are usually two to three times as large as these values with a dominant diurnal variation.

Figure 4 schematically shows the diurnal variation of temperature or humidity with height. The two extreme profiles refer to inversion and convection conditions. Inversion conditions typically occur during nighttime when the air layers close to the ground are cooler than the higher air layers caused by the ground's radiation loss. Convection conditions occur during periods (around noon) when the sun heats the air layers near the ground, which then typically rise as thermals. Naturally, the full 24-hour variation of the atmospheric profiles will be within these two extreme cases. The ground proximity effect is revealed as the temperature or humidity difference between the measured values at a certain height above the surface and those projected to that height using the constant atmospheric gradient in the troposphere (see the dotted line in Figure 4). In most cases, the diurnal variation of the water vapor is similar to the diurnal variation of the temperature. Of course, the errors in humidity or temperature distribution models are in addition to the observation and ground proximity errors.

As we have mentioned, the meteorological observations at GPS sites frequently are not representative of the propagation paths and applying them has been detrimental to GPS results. As a remedy, meteorological data of a standard atmosphere are used. Usually such a standard atmosphere is created by defining reference pressure, temperature, and humidity at sea level and then using the height of the GPS site as the sole variable to calculate the meteorological values for a site. Obviously these values are now independent of time and actual weather conditions. Excellent results have been obtained using such standard atmospheric data as input for the Saastamoinen model in processing GPS data.

ESTIMATING ZENITH DELAYS

Naturally, the standard atmospheric model will fail to describe the actual meteorological conditions at a GPS site during a particular observation session. Let us call the difference between the actual zenith delay and that calculated from a standard model the *residual zenith delay*. Note, we have now lumped t_A and t_W together. A highly successful analysis method is to include the estimation of this unknown residual zenith delay for each GPS station in the least-squares adjustment of the carrier-phase observations. Most postprocessing software programs provide an option for this procedure.

Usually one unknown residual zenith delay is estimated per site and session. Such a model tends to average any variations of the residual zenith delay. Passages of weather fronts across a GPS site can cause changes in the wet delay of greater than 3 centimeters per hour. It is therefore advantageous to model the residual zenith delay by a *stochastic model,* which treats the unknown residual zenith delay as a time-varying parameter. A highly effective stochastic model is the *random walk process,* the name of which is derived from the statistical analysis of the path followed by a person taking fixed-length steps in arbitrary directions. In the case of the tropospheric path delay, the zenith delay is modeled at every epoch as the sum of the previous zenith delay value plus the noise of a purely random process called the *process noise*. This process noise is characterized by its variance, which is chosen empirically. It constrains the delay changes. The mathematical adjustment is carried out using a sequential Kalman filter. Stochastic modeling of the tropospheric delay has shown excellent results in comparison with direct WVR measurements. In several VLBI experiments the accuracy attained was better than 1 centimeter in the zenith delay, even during rapid changes of the water vapor delay.

EFFECTS ON GEODETIC NETWORKS

Double-differences of GPS phase observations greatly reduce the effect of errors in satellite and receiver clocks: differencing between pairs of receivers removes the satellite clock error; differencing between pairs of satellites removes the receiver clock error. Processing a set of double-differences provides the relative coordinate differences between the two GPS receivers — a geodetic baseline. Considering the tropospheric effect, we can show that only the difference of the tropospheric delays at both stations affects the baseline result. As a result, we can expect a significantly reduced tropospheric effect for very short baselines, where the GPS signals travel along nearly the same paths through the atmosphere. Larger differences in station heights and larger station separations reduce this positive correlation of the tropospheric effects.

We note that even without any tropospheric propagation errors, an inherent geometrical weakness exists in the GPS baseline results that usually makes the determination of height differences worse by a factor of about 3 compared with the horizontal baseline components. The factor 3 is related to a cut-off angle of 15°.

Now we need to consider how the tropospheric errors propagate into the GPS results. The tropospheric errors predominantly affect the height differences. For the usual cut-off angle of 15°, a rule of thumb says

height difference error =
3 × the differential tropospheric effect.

A residual tropospheric delay error of 1 centimeter (between the baseline stations) causes a 3-centimeter error in the height difference. Modeling the tropospheric delay by a standard atmosphere (taking into account only the height dependence of the meteorological parameters) and, of course, taking advantage of the reduction of the actual tropospheric delays by forming differences, has shown that the GPS height difference errors are generally on the order of 2–5 centimeters. The use of actual meteorological observations at the GPS sites together with conventional height profiles has often produced disappointing results.

The tropospheric zenith delays can be estimated as time-varying (stochastic) or constant unknown parameters. On one hand, the advantage of this procedure is that the network solutions are essentially free of tropospheric biases. On the other hand, the precision of the height determination is worse by a factor of about 3 for the parametric and about 6 for the stochastic estimation compared with the horizontal component determination using a cut-off angle of 15°. Theoretically, the use of a lower cut-off angle could reduce this high correlation between tropospheric parameters and heights and consequently allow for a more accurate height determination. However, multipathing effects are prohibitive when signals below a 15° elevation are used.

CONCLUSION

Most commercial GPS processing software packages use the Saastamoinen model and either standard atmosphere or observed meteorological data to calculate the zenith delay. In addition, most of these packages provide for the estimation of the residual tropospheric zenith delay values.

Tropospheric delay errors mainly affect the accuracy of height differences. Today this must be considered the main limitation of the attainable accuracy using GPS, which seems to be around 2.5 centimeters for height differences of baselines longer than about 50 kilometers. The most effective and efficient method for dealing with the tropospheric effects is estimating tropospheric zenith delay values at each site. One average value for each session can be estimated, or alternatively an individual value can be estimated for every observation epoch constrained by a stochastic model. The price we pay for estimating the tropospheric effects is the high correlation between tropospheric zenith delays and heights. We could expect an improvement if we used GPS observations at low elevations. However, multipathing effects make it an impractical option below 15°. Therefore, more accurate modeling of the water vapor delays of GPS signals remains a challenge if height differences need to be determined with an accuracy better than about 2.5 centimeters.

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