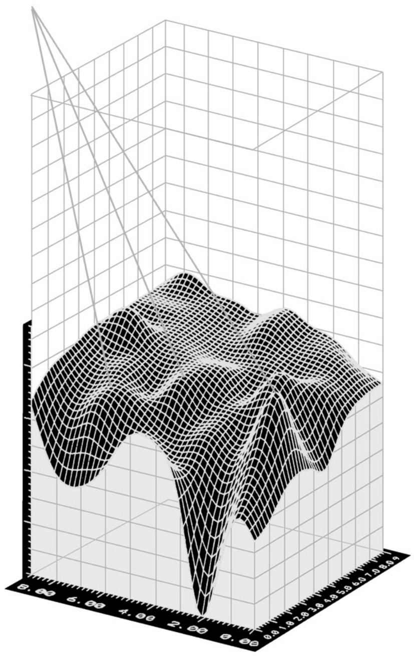

The Effect of Weather Fronts on GPS Measurements

Thierry Gregorius
Geoffrey Blewitt

The University of Newcastle upon Tyne

On the southeast coast of England, not very far from where the Battle of Hastings occurred, lies Herstmonceux Castle — a fifteenth-century manor house that was, for many years, the home of the Royal Greenwich Observatory (RGO). Although the skies above the castle are generally clearer than those above RGO's original home in the London borough of Greenwich, the frequently cloudy and rainy conditions are less than ideal for astronomy. RGO, therefore, built new telescopes on La Palma in the Canary Islands and moved most of its administrative and research facilities to Cambridge in 1990.

The same poor conditions dreaded by astronomers, however, are ideal for studying weather fronts in relation to GPS. The grounds of Herstmonceux Castle (now owned by Canada's Queen's University and operated as an international study center) house an International GPS Service (IGS) station. This site has provided Drs. Thierry Gregorius and Geoffrey Blewitt with a wealth of data for their studies of the effects of weather fronts on GPS measurements, which they recount in this month's column.

Dr. Gregorius studied surveying at the Universities of Karlsruhe (Germany) and New South Wales (Australia), where he graduated with a B.E. in geomatic engineering in 1995. He then went to the United Kingdom to work on geophysical and meteorological applications of GPS at the University of Newcastle upon Tyne. After obtaining his Ph.D. this year, he moved to The Netherlands, where he now works for Shell International.

Dr. Blewitt completed his Ph.D. research in high-energy physics in 1985 at the California Institute of Technology and then spent more than eight years working at the National Aeronautical and Space Administration's Jet Propulsion Laboratory, where he coauthored the GIPSY OASIS software for high-precision GPS applications. In 1994, he returned to the United Kingdom to join the University of Newcastle upon Tyne, where he is now professor of space geodesy in the Department of Geomatics. A governing board member of IGS, he is actively involved in IGS analysis.

"Innovation" is a regular column featuring discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who appreciates receiving your comments as well as topic suggestions for future columns. To contact him, see the "Columnists" section on page 4 of this issue.

Weather fronts are an important meteorological phenomenon that not only bring a change in weather but can also significantly disturb GPS observations. Because they occur in the troposphere, they leave their mark in the tropospheric propagation delay.

In the January 1993 issue of *GPS World*, Fritz K. Brunner and Walter M. Welsch discussed the troposphere's effect on GPS measurements. They correctly mentioned that (in extreme cases) the wet part of the delay can vary by more than 3 centimeters per hour during the passage of a front. In this article, we will explain in more detail why fronts cause such rapid variations in the delay, how that affects GPS precision, and what we can do to reduce or eliminate the problem. First, however, we will provide a quick summary of how atmospheric refraction maps into a GPS positioning error.

ATMOSPHERIC DELAY

As a GPS signal travels from the satellite to a receiver, it passes through the atmosphere, where different layers refract it in various ways. The first layer it encounters is the ionosphere, which is charged with a high number of free electrons that refract the signal. The resulting delay depends on the signal frequency (because the ionosphere is a dispersive medium), which is why we can use data from daul-frequency receivers to easily estimate and almost entirely eliminate the delay's magnitude. The ionosphere actually accelerates the carrier phase (with a net *phase advance*) and slows down the pseudorandom noise codes and the navigation message (with a net modulation or *group delay*).

The ionosphere's electron content is temporally and spatially highly variable. Under the influence of solar flares and coronal holes and the resulting geomagnetic storms, these variations may become so rapid and unpredictable that the higher-order terms of the delay not eliminated by the ionosphere-free linear combination of the L1 and L2 data could cause a significant bias in the estimated station position — the position of the geodetic marker on which the receiver's antenna rests.

Having passed through the ionosphere, the signal then undergoes a different kind of delay in the neutral atmosphere. Termed nondispersive because it is not frequency-dependent and thus cannot be easily eliminated, this neutral delay is caused by both the stratosphere and troposphere. Because the bulk of the effect occurs in the troposphere, the geodetic community has taken to misnaming the neutral delay as the *tropospheric delay*, a convention that we shall follow here.

We can adequately model the tropospheric delay's dry part (more precisely, the part that is in hydrostatic equilibrium, the bulk of which is accounted for by the dry gases) if we know the surface pressure with high accuracy, which is information a properly calibrated barometer can provide. The tricky aspect is the delay's wet part, caused by water vapor in the tropo-sphere's lower layers. Similar to the ionospheric electron content, the water vapor's spatial and temporal distribution is largely unpredictable and can undergo rapid variations, especially in the presence of a weather front. Surface humidity readings do not usually represent the troposphere's moisture content very well. Therefore, even with surface meteorological data, it is hard, if not impossible, to properly model or predict the wet delay.

THE POSITIONING EFFECT

On top of GPS's inherent geometric weakness because a receiver cannot track satellites below the horizon, tropospheric delay is the main additional ingredient to the heighting error budget. The accuracy of station height determinations is less than that of the latitude or longitude by a factor of two or so.

High-precision GPS software packages account for the tropospheric delay by estimating a zenith delay parameter that is linked to arbitrary elevation angles through a mapping function. Traditionally, tropospheric variations over time have been accounted for by stochastic estimation techniques, ranging in sophistication from Kalman filtering and equivalent approaches to simply estimating a new delay bias at regular intervals, for example every hour. More recently, to account for spatial variations of tropospheric refraction, a number of scientists have attempted additionally to estimate tropospheric gradients in north and east directions to allow for any azimuthal variation in the delay (as opposed to assuming that the delay varies with the vertical elevation angle only), apparently with some success.

For differential positioning (based on double differencing), Brunner and Welsch suggested the following rule of thumb for the propagation of tropospheric error into the GPS estimates of height (for an elevation cut-off angle of 15 degrees): height difference error equals three times the differential tropospheric delay error. In other words, an estimated total tropospheric delay error of 1 centimeter will propagate into a heighting bias of 3 centimeters. Achieving subcentimeter heights, therefore, seems to require modeling and estimating the total delay with an overall accuracy better than 3 millimeters.

One problem with estimating the residual tropospheric delay, though, is the high correlation between the height and tropospheric parameters, which increases even further with higher elevation cut-off angles. Mathematically, it is therefore unclear whether observed, short-term changes in height are attributable to atmospheric variations or to antenna motion. In static mode, one can reasonably assume that the stationary antenna (and the ground in which it is anchored) is stable and, therefore, can attribute any short-term changes to the atmosphere. In kinematic-type surveys, however, this is more difficult to determine.

WHAT IS A WEATHER FRONT?

Although most GPS users know about atmospheric delay and how it contributes to positioning error, they may be unfamiliar with the concept of a weather front. Before we describe how weather fronts affect GPS measurements, we will briefly introduce the physics of fronts.

Out in Front. A weather front is the boundary between two air masses that display differences, especially in temperature, wind direction, and humidity. Depending on the front's direction of motion, it is denoted as either cold or warm. For a stationary observer on the earth's surface, cold air replacing warm air defines a cold front. Conversely, warm air succeeding cold air denotes a warm front. Often, a faster-moving cold front overtakes a warm front from behind, eventually resulting in a more complex, merged front called an *occlusion* (or *occluded front*). Such a front then slowly dissolves as the differences between the bordering air masses gradually disappear.

For some applications it is convenient to model a front as a two-dimensional boundary surface. In reality, however, it is a relatively thin (40–200 kilometers thick), three-dimensional sheet of air that separates the two contrasting air masses. A front is therefore often referred to as a *frontal zone*. Because of the clash of different wind patterns, temperatures, and humidities, this zone is subject to rather strong turbulence and cloud formation, which then results in precipitation. Near the ground, the evaporation of this rain can increase the air's moisture content up to saturation level (100 percent relative humidity). On a satellite image, we can identify fronts by the long, narrow bands of cloud that accompany them.

Sample Fronts. Figure 1 shows a warm and a cold front moving across the British Isles. Typically, such a system's velocity ranges from 30 to 50 kilometers per hour, with the cold front often moving slightly faster than the warm one. The main difference between warm and cold fronts is their inclination, as can be seen from the schematic diagram in Figure 2. Warm fronts have a very gentle slope, generally not more than 0.5–1 degree, and incline toward their direction of movement because of surface friction and the relatively low density of warm air. Cold fronts, on the other hand, incline backward because their dense, heavy air subsides and slides underneath the lighter warm air. Near the ground, surface friction causes the cold frontal zone to bulge forward. Cold fronts generally have a steeper slope than warm fronts (about 1.5–2 degrees).

Because of its gentle slope, the cross-section of a front can span many hundreds of kilometers. In practice, the cold, warm, and frontal air layers are stacked on top of each other almost horizontally. For a warm front, upper-air clouds associated with the frontal zone can herald the front's arrival at the ground surface 12 hours or more in advance. Note that weather charts always mark the surface fronts, which can lie several hundred kilometers behind (warm front) or ahead (cold front) of the frontal zone at upper levels.

For an observer on the ground, the U.K. Meteorological Office suggests the following telltale signs as the most reliable way of recognizing a front's passage. In advance of a warm front, temperature rises steadily, the wind speed increases, pressure falls, and relative humidity rises because of precipitation. During the passage, temperature rises more intensely, the wind changes direction, pressure stops falling, and the air's moisture content may increase up to saturation level. After the passage, these properties usually do not change much.

This scenario is slightly different for a cold front, and any changes at the passage are often more sudden than for a warm front. In advance of the cold front, the temperature changes little, although humidity and wind speed both increase, and pressure falls slowly. During the passage, temperature falls rapidly, the wind veers, humidity stays high, and pressure may undergo a sudden jump. After the passage, wind and temperature may continue to vary but humidity rapidly falls as the sky clears, with pressure rising slowly. On a weather chart, the surface front is often recognizable as a trough of low pressure, causing a kink in the isobars. Such a trough, however, may also be nonfrontal so that fronts cannot simply be inferred by such anomalies in the pressure field.

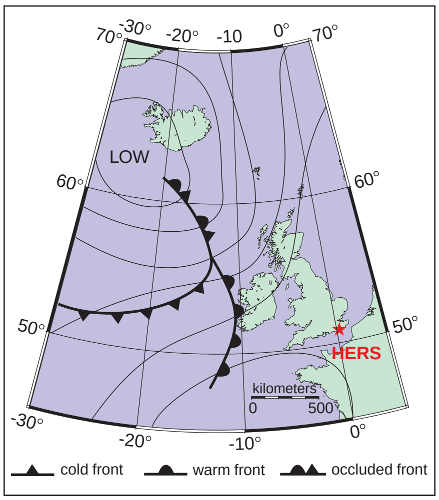

Figure 1. A typical frontal system moving across the British Isles (fictitious example inspired by U.K. Meteorological Office data). The Herstmonceux GPS site is marked with a red star.

The frequency of weather fronts largely depends on a site's latitude or climate. Fronts usually divide polar and tropical air and are therefore mainly found in midlatitudes. In other words, fronts are most frequent in temperate, humid climates. Great Britain, for example, is crossed by weather fronts about once every two to three days. Under stormy conditions, as many as three or four fronts can pass in 24 hours.

THE DELAY EFFECT

The rapid variations weather fronts can cause in the tropospheric delay is well illustrated by Figure 3. The figure shows the passage of fronts over an International GPS Service (IGS) site at Herstmonceux Castle, in southern England, during a 14-day period. Their passage usually stands out as a peak in the delay time series. It therefore is no surprise that such rapid variations can introduce a form of systematic error in the estimated GPS station position (especially in height).

Delay Estimation Models. To assess the effect of weather fronts on tropospheric delay, we first estimate the tropospheric zenith delay with GPS (using the random walk model in the least-squares estimation engine, which allows the tropospheric delay parameter to vary over time —— this model characterizes the random component of tropospheric behavior, which is not much different, mathematically, from the steps of a drunken sailor). We then compare these estimates with two models based on surface meteorological observations. We stress that the

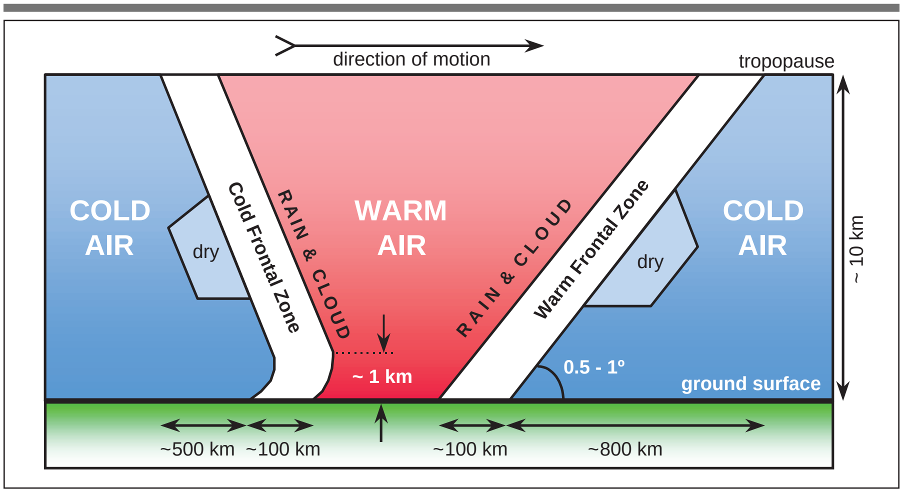

Figure 2. Idealized cross-section of a system containing two fronts. Note that the vertical scale is greatly exaggerated. The dimensions stated (in kilometers) are only rough estimates and can vary considerably from front to front.

humidity recorded on the ground is not usually representative of the water vapor levels found in the troposphere above. Some days, however, do present a high correlation between surface humidity and the wet zenith delay, such that we can test the weather front hypothesis with data acquired under such conditions.

The first model simply uses a standard atmosphere to extrapolate temperature, humidity, and pressure from the ground throughout the troposphere. That is, this model assumes that the troposphere has a certain vertical profile with average physical properties.

The second model, the front model, accounts for fronts and works out separate delays for each air mass using individual

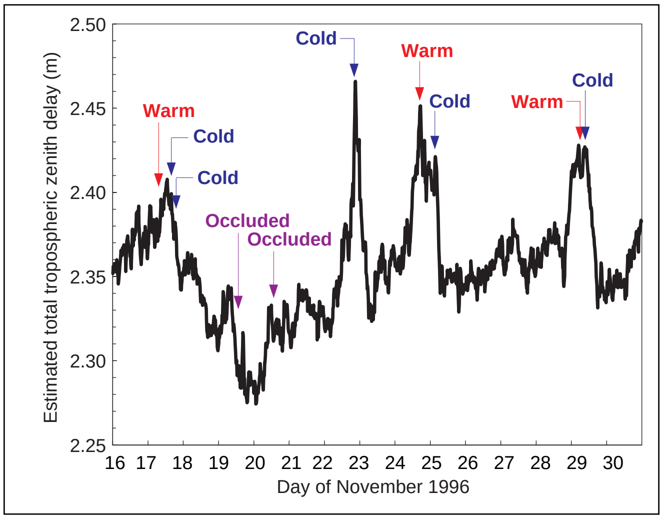

Figure 3. Tropospheric zenith delay at Herstmonceux, southern England, during a fortnight in November 1996. The passages of the surface fronts are marked as warm, cold, or occluded.

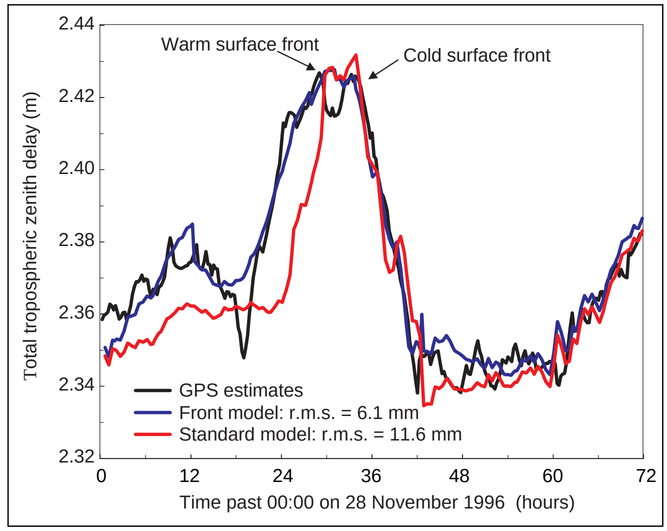

Figure 4. GPS-estimated and model-predicted total zenith path delay at Herstmonceux, 28 to 30 November 1996

temperature and humidity gradients based on typical values published in the literature for warm and cold air masses. To compensate for the lack of upper-air data, which is mostly obtainable only from expensive weather balloons (radiosondes), the front model estimates the front's geometry and velocity to obtain the best possible fit with the GPS estimates. This way, we actually kill two flies with one whack. Not only do we generate a prediction of the tropospheric delay caused by fronts, but we also find out whether GPS could actually have the data strength to explicitly solve for parameters related to weather fronts.

Testing the Models. Figure 4 shows the curve of the total tropospheric zenith delay over three days at Herstmonceux while a warm and a cold front passed by. If we assume that the GPS estimates of tropospheric delay adequately represent the troposphere's true state (which has been suggested by many studies), we can see that the model using a standard atmosphere is relatively inaccurate under frontal influence, especially during the warm front's approach.

The front model, on the other hand, overlaps with the true estimates almost perfectly. What's more, the estimated frontal parameters confirm the typical values for fronts cited in the meteorological literature, and the computed passage times of the surface fronts perfectly agree with those derived from official weather charts. This preliminary example, for which the correlation between surface humidity and wet zenith delay is very high (0.92), indicates that GPS could indeed have the power to resolve the geometry (especially gradient-related parameters, such as the inclination) and passage times of weather fronts with relatively high confidence. Such a capability naturally has potential benefits not just for GPS positioning, but for meteorology and climate research as well.

During the warm front's approach, the total tropospheric zenith delay increased by about 8 centimeters in 11 hours. After the cold front had passed on the ground, the delay dropped back down by about the same amount in 7 hours. When we plot the delays' dry and wet portions separately, it becomes clear that this rise and fall is caused by the wet part of the delay (for example, by water vapor, clouds, and rainfall) during the front's passage (Figure 5). The dry delay actually decreases because it is directly proportional to atmospheric pressure, and the two fronts in this example are linked to a field of low pressure (a *frontal depression*).

FRONTS AND GPS PRECISION

Even though a well-tuned random walk model should in theory be able to cope with rapid variations in delay, removing days affected by fronts from a long time series of GPS heights still improves the repeatability of the vertical station component. Repeatability is a measure of internal precision that is often used to describe the reliability of measurements recorded at permanent GPS sites. It is essentially a standard deviation that also takes day-to-day formal errors into account and is computed as

$$\text{repeatability} = \left(\frac{n}{n-1} \frac{\sum_i r_i^2 / e_i^2}{\sum_i 1 / e_i^2} \right)^{1/2}$$

where n is the number of data points (days), r_i is the daily residual (derived from linear regression of the time series plot) and e_i is the daily formal error (standard deviation).

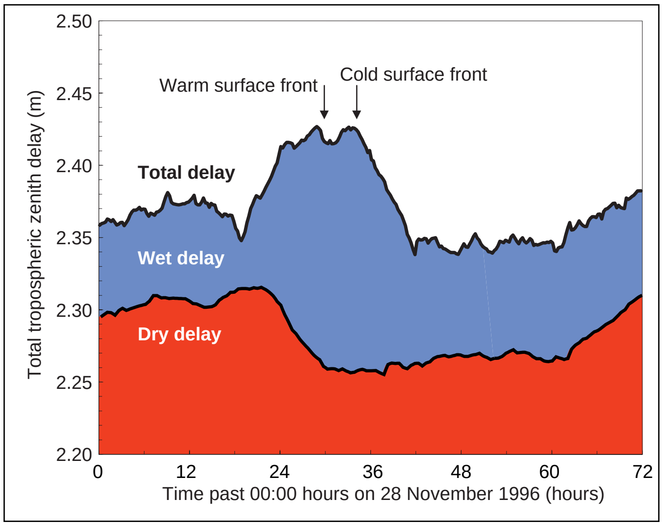

Figure 5. Total, dry, and wet delays as fronts pass

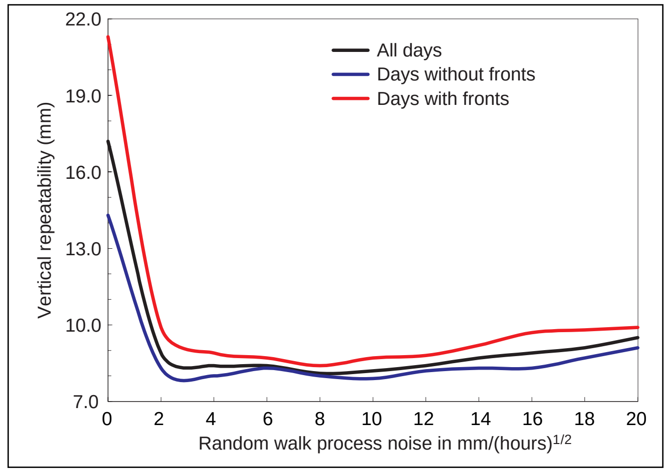

Figure 7. Repeatability as a function of random walk process noise and the passage of weather fronts at Herstmonceux. Days affected by weather fronts are more sensitive to the choice of process noise level. The number of days processed for each time series is 155 for 'all days', 57 for 'days with fronts' and 98 for 'days without fronts.' The values shown for zero process noise have not actually been derived with a random walk model. In this case, the tropospheric delay was estimated as a constant parameter over successive 24-hour periods (see text).

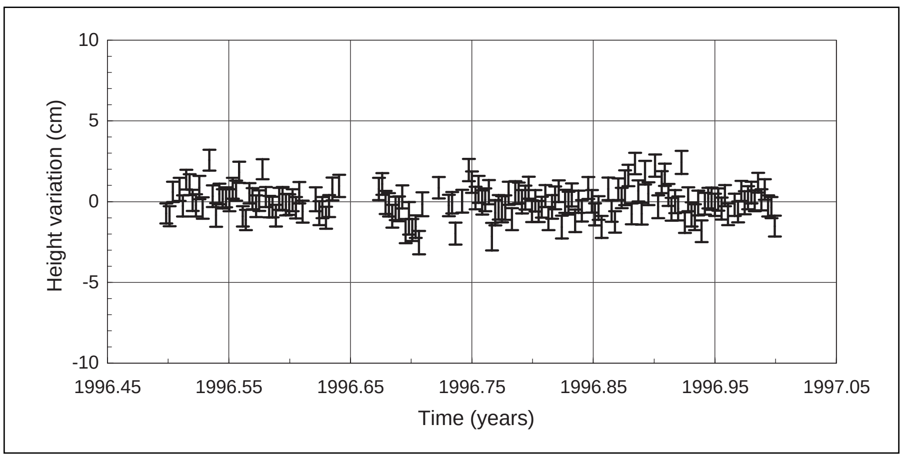

Figure 6. Height variability time series of Herstmonceux, southern England. The repeatability is 8 millimeters (derived with the best processing strategy).

Improving Repeatability. For example, the repeatability of a six-month series of daily height estimates at Herstmonceux (Figure 6), where fronts are frequent and the GPS receiver tracks data 24 hours a day, improves by as much as a millimeter (from about 8 to 7 millimeters), depending on the level of process noise applied in the random walk model. When we compare the time series of frontal and nonfrontal days separately, the repeatability of the series containing only the days affected by fronts is considerably worse. Depending on the level of process noise, the discrepancy reaches almost 2 millimeters.

Some commercial software packages assume that the tropospheric delay remains constant and estimate it as such in the least-squares process. This is obviously less than ideal, particularly under variable conditions in the troposphere. In the Herstmonceux example, the vertical repeatability is 17 millimeters when using this strategy. In this case, the effect of weather fronts is much more detrimental compared with when employing the more flexible and powerful random walk model. By eliminating the days affected by fronts, the repeatability improves by 3 millimeters, and the difference between frontal and nonfrontal days is statistically significant by a large margin (14 versus 21 millimeters).

This proves that GPS observations acquired during periods of frontal influence can be systematically biased, as shown in Figure 7. One should not use such data, therefore, for high-accuracy GPS applications if the processing software is of the "black box" type and less sophisticated than the high-precision packages available from various research institutions.

Vertical Velocity. The effect of weather fronts on GPS is confirmed by the vertical site motion derived from the height time series. Whereas the repeatability is only a measure of internal precision, this vertical "velocity" actually gives an indication as to the global accuracy of the estimated station height. In our example, the vertical velocity magnitude does indeed become smaller (from –3.1 to –0.6 millimeters per year) and agrees with what is expected from geophysical considerations when removing days affected by fronts from the time series. (Southern England is thought to subside by less than 1 millimeter per year because of postglacial rebound in Scotland.) This indicates that the front-free solution represents the true situation more correctly, although the six-month timespan of this example is too short to provide conclusive results in this matter.

If we knew the exact beginning and end times of the periods during which weather fronts had a noticeable effect on the estimated tropospheric delay, then their effect on the station height repeatability could be worked out more accurately and would, without a doubt, be higher still than the figures we present here. Classifying a whole day as frontal even if only a few hours were under the influence of a front certainly weakens the results. Without extensive upper-air data, however, no objective measure for determining those periods of influence exists, and if we tried to guess their times by inspecting the plots of estimated tropospheric delay, we would introduce a human, subjective bias. Thus, one has to remember that weather fronts can have a detrimental effect on GPS that is at least as bad as we suggest in this article.

The Horizontal Factor. The effect on the horizontal station component is similar to what we found for height, only much smaller in magnitude. Our experiments with the Herstmonceux site have shown that the degradation of the horizontal repeatability is as much as 80 percent smaller than that of the vertical and therefore largely negligible.

REMEDIES AND POSSIBILITIES

We have estimated that, depending on the weather front's intensity and the estimation strategy used, a front can degrade the heights in a regional network by as much as several millimeters. This effect is worst if the GPS data-reduction software is unable to solve for the tropospheric delay in a time-varying manner, which is the case for many commercial packages.

Several ways to overcome the problem exist. The most obvious is to simply not perform a survey when a front is crossing the area. Also, a front may not affect solutions from a small GPS network, because most errors will cancel out in differential mode. However, weather fronts are likely to degrade the station heights, if the baselines are longer than 10 kilometers or so. Therefore, before conducting a GPS campaign, one should check the weather forecast for any fronts. If height precision is important, wait, perhaps, until the fronts have passed.

Ideally, the troposphere should be monitored by launching radiosondes or deploying water vapor radiometers during the survey. One would then feed the results into GPS processing software capable of making optimal use of such information. Both these methods, however, are very expensive, and radiometers lose their reliability during periods of rainfall (which, unfortunately, usually accompanies the passage of weather fronts). Alternatively, estimating frontal parameters in addition to the tropospheric delay could possibly improve the station height.

Supplementing with Satellites. In the future, cheaper satellite-based systems could replace or complement radiosondes. A constellation of low-orbiting microsatellites with onboard GPS receivers presents one potential solution. To investigate such a possibility, the University Corporation for Atmospheric Research and others have been analyzing data from the MicroLab-1 prototype satellite for several years. This so-called GPS/Met system aims to combine space-based GPS measurements with currently available meteorological data and thus provide global coverage of detailed temperature and humidity profiles throughout the atmosphere. The observed gradients could then be fed back into a user's GPS processing software, possibly resulting in higher positioning accuracy.

The GPS/Met system's only limitation is that atmospheric profiles are still difficult to determine for the troposphere's bottom layer because of problems related to signal propagation, including multipath and topographic obstructions. Unfortunately, most water vapor is found in that particular region. One could alleviate this problem by incorporating data from permanent ground networks, such as IGS stations, into the GPS/Met analysis.

Fixing the Time Series. For permanently operating GPS stations, the most straightforward remedy is to remove the periods affected by fronts from the time series. If users don't want to rely on daily weather information, they could use an algorithm that detects fronts or other major tropospheric disturbances from the GPS data alone. We have developed and tested algorithms to provide indicators or *indices* of such tropospheric disturbances. We found they successfully improved the long-term repeatability of most mid-latitude and tropical station coordinates.

These indices work on a very simple principle: We first quantify the troposphere's variability for each day using an objective measure and then eliminate those days that suffer from tropospheric variability higher than a certain, empirical threshold. This cutoff must be carefully tuned to avoid rejecting too much data from the time series. To quantify the troposphere's behavior, we first plot the estimates of total tropospheric zenith delay for each day (one data point every 15 minutes, as done for Figures 3 through 5). Along this curve, we can then simply count the number of gradients greater than, for example, 1 centimeter per hour. If any day has more than a certain number of steep gradients, we eliminate it from the time series.

When fine-tuning the threshold to reject exactly the same number of days as those affected by weather fronts, we found that the overlap was 70 percent. With this index, we can thus detect fronts from GPS data alone with 70 percent accuracy (over southern England). By rejecting all days suffering from tropospheric variability above that threshold, the vertical repeatability improves similarly as when excluding known frontal days from the series.

Other Options. One can use alternative indices instead of counting the number of steep gradients — for example, the fractal dimension of the plotted curve, which is a tool developed in chaos theory. Because the plot of tropospheric delay versus time is in two dimensions, the curve will have a dimension between one and two (hence the term *fractal*). The more the curve jumps about, the closer its dimension will be to two. Excluding days from the time series yielding a fractal dimension higher than a certain threshold will again improve the station repeatability.

Inspired by the concept of fractal dimension, we developed another index obtained by simply working out the length of the curve over the reference interval of 24 hours: the longer the curve, the higher the tropospheric variability on that day. Again, by using an appropriate threshold, we can improve the vertical coordinate repeatability of most permanent GPS stations.

We found that the gradients method achieves the highest front detection rate, whereas the curve length index usually produces the greatest improvements in repeatability. The index using fractal dimension tends to pick out the most variable days while maximizing the amount of data being retained in the time series. However, the fact that none of the methods achieve a 100 percent front detection rate indicates that other forces are also at work that occasionally produce tropospheric disturbances similar to those caused by fronts.

CONCLUSION

Overall, users need only worry about weather fronts in midlatitudes and if the GPS network employed is reasonably large (spanning, say, more than 10 kilometers). The problem is most severe for permanent GPS sites because fronts introduce a systematic bias in station coordinate time series. In small, local networks, all stations will probably be affected in more or less the same way, such that any errors would largely cancel out when forming double differences. Mainly the station height is affected; the bias in the horizontal component seems to be largely negligible.

To recap, the best remedy to prevent unnecessary height errors is to avoid surveying during the passage of weather fronts. If this is impossible and the highest level of accuracy is required, the tropospheric delay parameter should be estimated in a stochastic way, allowing it to vary over time within realistic bounds. Ideally, one would launch radiosondes at regular intervals during the GPS survey and implement an explicit weather front model in the tropospheric delay estimation. Because this scenario is highly unlikely, all that can be done right now is to discard data affected by fronts. Alternatively, modifying the GPS processing software to estimate frontal parameters could possibly lead to improvements in height.

In the future, satellite-based atmospheric sounding systems could also provide crucial, high-resolution, water vapor data. Feeding such humidity profiles back into one's own network processing (using software capable of handling such information) could significantly improve the vertical station position and could possibly eliminate the weather front problem altogether.

ACKNOWLEDGMENTS

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Further Reading

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MANUFACTURERS

The International GPS Service site at Herstmonceux Castel uses an **Allen Osborne Associates, Inc.** (Westlake Village, California) SNR-8C GPS receiver.