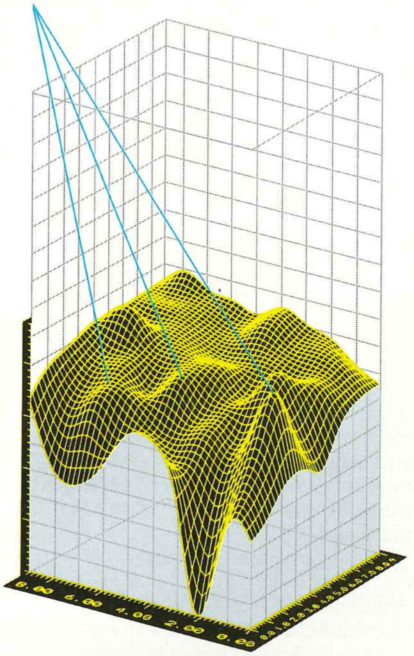

# Carrier Phase Wrap-Up Induced by Rotating GPS Antennas

**Avram K. Tetewsky**
**Frank E. Mullen**

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*GPS receivers are ubiquitous. They are now used for a myriad of applications and can be found in the hands of navy frogmen, mounted on tractors, carried aloft by weather balloons, and orbiting in spacecraft. And the miniaturization of receivers allows them to be embedded in such diverse devices as cellular telephones and artillery shells. GPS receivers work more or less the same way regardless of the kind of platform they are attached to. However, some users have recently concluded that, if the platform is spinning, a rotational effect must be accounted for: carrier phase wrap-up. This effect is the change in the GPS carrier phase caused by rotation of a circularly polarized receiving antenna relative to a circularly polarized GPS signal. If the wrap-up effect is not accounted for, a receiver can make significant position fix errors when fewer than four satellites are in view.*

*In this month's column, we present an intuitive derivation of the effect and summarize the results of an innovative procedure to calculate phase wrap-up. We also present predictions for a common antenna type — the crossed dipole — and compare them with GPS measurements collected from a rooftop spinning-antenna experiment.*

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*"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.*

Guiding rapidly rotating platforms, such as the artillery shell shown in Figure 1, is one advanced GPS application currently under investigation. The militaries of the United States and other governments are interested in further developing guided munitions to enhance their accuracies and reliabilities. GPS is one tool being used to pursue those goals. The figure illustrates the geometry of the problem, showing line-of-sight vectors from each satellite to receiving antennas mounted on the shell, and identifies two typical antenna locations: the base of the shell and the outer circumference.

As an artillery shell spins and moves along its trajectory, and as the satellites move in their orbits, the depression angle, $\theta$, and azimuth angle, $\phi$, for each satellite change with time. The angles ($\theta$ and $\phi$) are both defined with respect to a coordinate frame whose z axis is parallel to the spin axis. For most cases of interest, the shell will be undergoing nontumble flight with uniform rotation. Mathematically, this implies uniform rotation in azimuth so that $\phi(t) = \phi_o + \rho t$, where $\phi_o$ is some initial azimuth at time $t = 0$ and $\rho$ is the rotation rate.

The satellite signals received by the shell's embedded GPS unit will each have a different azimuth offset, $\phi_o$. However, they all will accumulate azimuthal phase at the same rotation rate, typically 1–25 revolutions per second. In addition, the depression angle, $\theta(t)$, is unique for each satellite depending on its particular rise and set times. Because this angle changes slowly as compared with the navigation update rate, it may be considered a constant for the navigation update cycle (typically about 1–10 times per second).

The questions that we had to answer when starting our investigation were the following: Does rotation have any effect on GPS signals? And if yes, how do we quantify the effect as a function of geometry and antenna type? A literature search revealed very few GPS resources addressing antenna rotation. Furthermore, standard radar reference books failed to discuss the phase pattern of the circularly polarized antennas typically used in GPS applications. Finally, current GPS simulators do not contain rotation or circular polarization models. So, we returned to first principles and worked through the full vector field expressions for circularly polarized waves. Our work revealed a nontrivial effect, which we call *carrier phase wrap-up*.

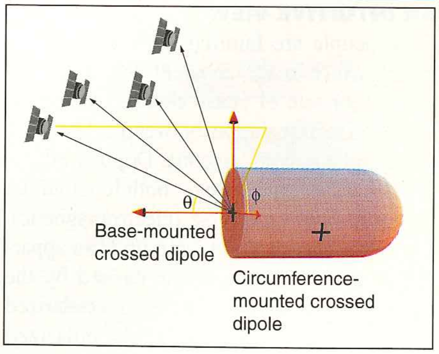


**Figure 1.** A GPS antenna can be mounted on a rotating artillery shell's base or circumference. The base-mounted antenna's boresight is parallel to the shell's spin axis. A GPS satellite's direction, in a coordinate frame whose z-axis is aligned with the spin axis, is given by $\theta$, the depression angle (equal to 90 degrees minus the elevation angle measured from the x–y plane), and $\phi$, the azimuth.

## Electromagnetic Waves and Polarization

An electromagnetic wave is a self-propagating wave with both electric and magnetic field components that are generated by the oscillation of a charged particle. The wave's characteristics, and in fact the possibility for the actual existence of electromagnetic waves, is given by Maxwell's equations — that set of four famous equations relating the electric and magnetic field, which the British physicist James Clerk-Maxwell tied together in the 1860s. The solution of the equations gives rise to a further pair of equations that describe a wave propagating at the speed of light. Maxwell's equations helped to unravel some of the mysteries of light, including its apparent wave nature, as well as foretell of the existence of radio waves.

It can be shown that in free space (a vacuum) or in any homogeneous, isotropic, linear, and stationary medium, the electric and magnetic fields are transverse to the direction of propagation and the fields are mutually perpendicular. If we introduce a coordinate system whose positive z-axis is aligned with the wave's direction of propagation, and assume that wave fronts (surfaces of equal phase at a given time) are locally planar (an excellent approximation far from the transmitter), then the electric and magnetic field vectors lie in the x–y plane. The vector describing the electric field can be decomposed into two orthogonal vectors, one parallel to the positive x-axis and one parallel to the positive y-axis.

If the x- and y-components have the same phase (or are different by an integer multiple of $\pi$), the wave is said to be linearly polarized as the electric field vector is always directed along a fixed line. If the two components differ in phase, their sum describes an ellipse about the z-axis. This is an elliptically polarized wave. If the two components have the same amplitude but are $\pi/2$ (or an odd multiple of $\pi/2$) out of phase, the ellipse becomes a circle and the wave is said to be circularly polarized. Circular polarization has a "handedness." If, at a fixed point in space, the electric field vector rotates clockwise (counterclockwise) for an observer looking from the source toward the direction of the wave propagation, the polarization is right-handed (left-handed).

The signals emitted by GPS satellites are right-hand circularly polarized. Some other satellites, notably spin-stabilized ones, also use circular polarization. Television broadcast signals are typically linearly polarized. In North America, they are transmitted with the E-field oriented horizontally. That is why the few remaining housetop television antennas are horizontally mounted. The radio signals of terrestrial mobile communications systems are typically vertically polarized to permit good signal reception by whip antennas.

Not many people realize that sunlight is polarized. It is initially unpolarized (the electric field changes and oscillates in any direction) but because of scattering by the atoms and molecules making up the earth's atmosphere, sunlight becomes partially polarized. You can easily witness this by rotating a pair of polarizing sunglasses while looking in a direction perpendicular to the direction to the sun (the scattering phenomenon is also responsible for why we see the sky as blue — but that's another story).

— R.B.L.

Carrier phase wrap-up affects GPS receiver operation and GPS navigation fixes in several ways. For the two mounting geometries shown in Figure 1, the rotation causes each satellite to experience a common Doppler shift "error" of $\rho/2\pi$ Hz if $\rho$ is given in radians per second. This shift translates into an equivalent error of $\rho\lambda/2\pi$ in the receiver's clock-drift estimate, where $\lambda$ is the GPS carrier wavelength. For a $\rho$ value of $50\pi$ radians (25 revolutions) per second, this equals about 4.8 meters per second for the L1 frequency. Although relatively small, this error can integrate into large position errors for "clock-hold" solutions used when fewer than four satellites are in view. This condition might be experienced by a GPS receiver in an artillery munition because its antenna would, in general, not be pointing to the zenith and so would "see" only a portion of the sky. Terrain occlusions might also restrict the antenna's view.

A GPS receiver attempting direct P(Y)-code acquisition experiences another effect; it must account for the additional $\rho/2\pi$–Hz offset when searching for the signal in the two-dimensional pseudorange–by–Doppler offset uncertainty grid. Finally, a circumference-mounted antenna will be subjected to additional spin-modulation terms that increase as the elevation angle decreases. Eventually, these increasing terms can cause a receiver to lose lock on low elevation angle satellites. Users can mitigate this problem by selecting optimum antenna-mounting locations determined by our three-dimensional phase wrap-up theory.

### AN INTUITIVE VIEW

Most people are familiar with the Doppler effect, which is the apparent change in frequency (or rate of phase change) caused by the relative translation between a traveling wave and a moving antenna. Doppler effects occur for any wave type — both longitudinal (acoustic) and transverse (electromagnetic). Similarly, carrier phase wrap-up is an apparent change in carrier phase caused by the changing orientation of a circularly polarized antenna relative to a circularly polarized wave. Thus, carrier phase wrap-up is a property of circularly polarized electromagnetic waves (and elliptically polarized ones too, but that is beyond the scope of this article). Because GPS uses circularly polarized transmissions and antennas, it is sensitive to carrier phase wrap-up (see the "Electromagnetic Waves and Polarization" sidebar for a brief description of polarization).

Consider translational motion of a platform whose spin axis is aligned with the line of sight to a GPS satellite (see Figure 2). As the platform moves toward or away from the source, it encounters transmitted phase fronts at a faster or slower rate. The carrier appears to be either up- or downshifted in frequency. Because the pathlength is physically changing, the entire spectrum occupied by the signal also compresses or expands. This is the well-known Doppler effect that alters both the GPS carrier phase and pseudorange modulation. The effect is the same for both linear and circularly polarized signals.

Now consider antenna rotation. If you rotate a linearly polarized antenna relative to a linearly polarized signal in space (see the left side of Figure 2), the main effect will be a loss of received power whenever the transmit and receive antenna elements are misaligned. GPS satellites transmit right-hand circularly polarized (RHCP) signals (see the right side of Figure 2; actually, the GPS signal specifications permit a small amount of ellipticity) so that inexpensive user equipment, regardless of orientation, can receive signals without losing signal strength.

The electric field (E-field) of a circularly polarized signal is a constant magnitude vector that rotates through 360 degrees every spatial wavelength and every temporal cycle. Although received power is no longer a function of azimuth (for an omnidirectional antenna), a phase effect remains. Specifically, if you rotate in the opposite direction of the circular polarization (toward it), you appear to encounter the phase fronts more often; rotating away from the E-field vector, you appear to encounter them less often.

This effect creates an apparent change with time in the received signal's phase and hence a frequency shift. Because the pathlength is not physically changing, however, the modulation — hence the pseudorange observable — remains unchanged. The entire signal spectrum will just shift up or down in frequency. This rotationally induced frequency shift is unique to circularly polarized transmissions and antennas. It does not occur with linearly polarized antennas receiving linearly polarized transmissions.

In his classic book *Antennas*, John Kraus, professor emeritus at The Ohio State University, describes producing this effect (which he called *rotational Doppler)* in 1957 by mechanically rotating a circularly polarized helical antenna about its boresight. He also discusses using this technique to demonstrate phase modulation and beam steering.

Despite these early developments, the GPS community has not thoroughly discussed phase wrap-up, because its occurrence heretofore has been so limited. Now, however, GPS receivers are small enough to

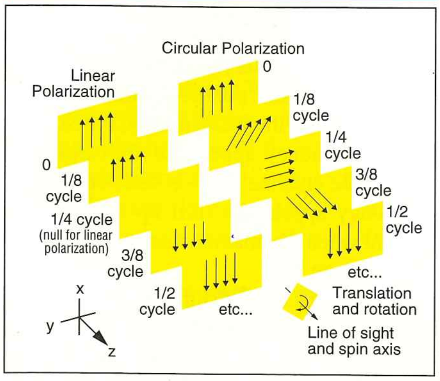


**Figure 2.** A linearly polarized electromagnetic wave is characterized by an electrical (E) field vector that points in the same direction as the wave propagates. If a rotating linearly polarized antenna intercepts the wave, the field's effective amplitude is proportional to cos($\alpha$), where $\alpha$ is the angle between the field polarization and antenna directions. The circularly polarized wave's E-field rotates with a constant amplitude: If a circularly polarized antenna with the same-handed rotation intercepts this wave, the wave induces a constant signal level in the antenna.

insert into smart, spin-stabilized artillery munitions, so engineers will increasingly have to account for phase wrap-up in applications involving spin stabilization. GPS simulator manufacturers may also need to customize their products to service customers who are testing receivers intended for these applications.

While these arguments explain carrier phase wrap-up in the simple case, where the depression angle $\theta$ is 0, GPS engineers and simulator vendors will want three-dimensional models that can predict phase wrap-up for any geometry and mounting location. In the next section we will present the full three-dimensional results but skip the formal mathematical derivation, which can be found in the references listed in the "Further Reading" sidebar. To simplify the explanations, our discussions will neglect ionospheric dispersion, tropospheric propagation delay, and relativistic effects.

## GENERAL MODEL

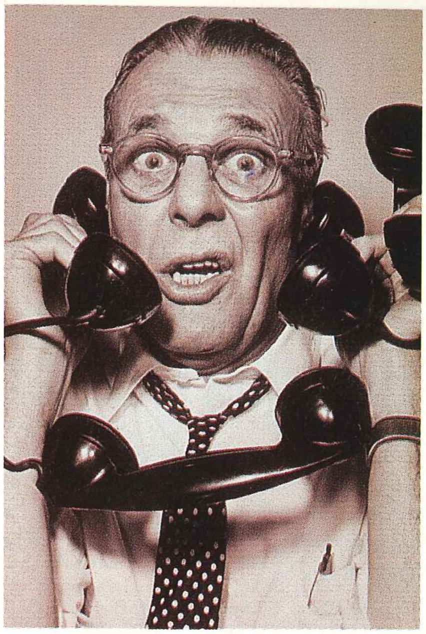
The entire electromagnetic signal propagation model used for GPS usually reduces to a simple band-pass transfer function. The propagation of an electromagnetic signal, including the receiving antenna's response, can be modeled as a filter, where the input to the filter is the electromagnetic signal transmitted by the spacecraft antenna, and the output is the signal passed by the receiving antenna to the GPS receiver. The ratio of the filter output to its input, as a function of frequency, is called the *transfer function.*

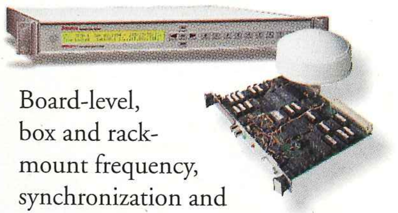
For a P(Y)-code GPS receiver, this transfer function has a frequency response centered at either the L1 or L2 frequencies, spans a bandwidth capable of passing the 10-megabit-per-second P(Y)-code, and has gain and phase that vary with the line-of-sight geometry as well as with frequency. The gain determines the received signal level; the slope of the phase-versus-frequency plot (known as the *group delay*) determines the delay of the modulation (and hence the pseudorange); and each sinusoidal frequency component of the signal is phase shifted according to the phase-versus-frequency component of the transfer function. Because most line-of-sight geometry variations are slow compared with the navigation update cycle, the GPS propagation transfer function is usually considered to be time invariant during a few seconds.

Unfortunately, most published propagation transfer functions are based on antenna pattern models that do not account for circular polarization effects. Figure 3 summarizes the standard models used in GPS textbooks and simulators, as well as the terms we use to incorporate phase wrap-up considerations.

**Calculations and Analysis.** We base our new wrap-up term calculations on the following assumptions:

- The GPS satellites are far enough away that the GPS signal in space is assumed to be a plane wave; its direction of propagation and polarization remain unaffected by small changes in the receiving antenna's position.
- The receiving antenna can be approximated by a pair of crossed dipoles driven in quadrature. (Circular polarization can always be expressed as the sum of two linear polarizations combined in quadrature. The issue is whether the far-field pattern for each polarization of a typical GPS antenna, such as a 3-centimeter-square microstrip patch, is similar to the far-field pattern of a single dipole. If the patch dimensions are small compared with the GPS wavelength, then this should be a reasonable approximation.)
- The dipoles used in the receiving antenna models are infinitesimally small, Hertzian dipoles. Therefore, the current induced by the incoming plane waves can be calculated from the projection of the E-field onto the dipole (mathematically, a dot product). This approach simplifies the analysis without altering the validity of the phase wrap-up effect.





Our analysis technique consists of modeling the transmitted circular polarization as a complex vector that is a function of depression and azimuth angle, $\boldsymbol{E}_{cp}$; modeling the combined effects of the receiving antenna's mounting geometry and complex quadrature summing network as a complex vector $\boldsymbol{m}$; and modeling the antenna's response using the third assumption listed earlier. The antenna's complex response to the circular polarization portion of the transmitted E-field becomes the additional transfer function that will correctly account for circular polarization effects. This additional wrap-up transfer function is:

$$H_{wp}(\theta(t), \phi(t), f) = \mathbf{E}_{cp} \cdot \mathbf{m}$$

where the gain and phase shift of $H_{wp}$ can be calculated as

$$A_{wp} = |H_{wp}(\theta(t), \phi(t), f)|$$

$$\Phi_{wp} = \arg\left(H_{wp}(\theta(t), \phi(t), f)\right)$$

**Base Mounted.** When one carries out the three-dimensional dot product for the shell-base-mounted antenna, identifying the wrap-up gain and phase terms is quite simple. The additional phase portion of the wrap-up transfer function is $-\phi$, and the magnitude portion of the wrap-up transfer function is the $(1+\cos(\theta))$ amplitude gain pattern of a circularly polarized antenna. The amplitude term shows a 6-decibel loss in power as the line of sight makes a 90-degree depression angle with respect to the spin axis (which for the base-mounted case is also aligned with the antenna boresight).

The phase wrap-up factor, $-\phi$, is new. It shows that the base-mounted circularly polarized crossed dipole's phase depends directly on the antenna's orientation with respect to the carrier source. The GPS geodetic surveying community has long known this and models antenna orientation accordingly (including the phase wrap-up effect, which it terms *phase wind-up*) in its high-precision data analysis software.

The effect of rotating a crossed-dipole antenna is calculated by letting $\phi$ vary with time. For the simple case of rotation at a constant angular velocity about the boresight, let $\phi(t) = \phi_o + \rho t$, where $\rho$ is the antenna's rotation rate. When the antenna rotates in such a way that the angle $\phi$ increases with time at $\rho$ radians per second (looking down on the antenna from the positive z-axis, it turns clockwise with the incident RHCP field), the carrier frequency appears to shift down by exactly the antenna rotation rate. The carrier frequency appears to shift up by the same amount when the antenna rotates in the opposite direction.

Because the carrier shift is independent of the depression angle, $\theta$, it is the same for all channels. If all measurements are weighted equally, only the GPS clock real-time rate solution is directly affected. However, if the GPS receiver has fewer than four satellites in view and attempts to propagate the clock-rate solution during the outage period without correcting for this common frequency shift, the resulting position fix will grow in error by

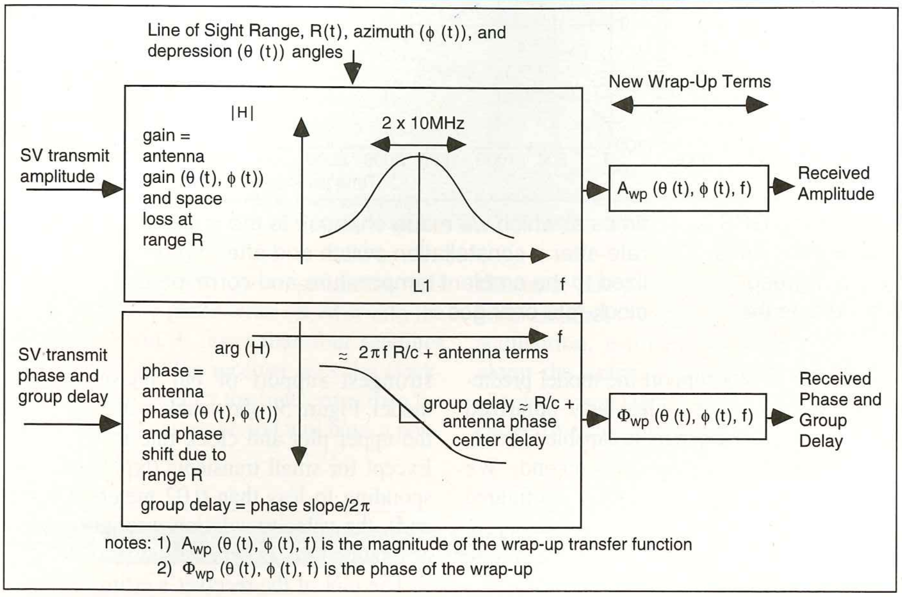
$$\mathrm{DOP} \times \mathrm{FF} \times (\rho\lambda/2\pi) \times \Delta T \text{ meters}$$

where DOP is a dilution of precision factor, FF is a filter "memory" factor, and $\Delta T$ is the outage period until four satellites become visible again. As an example, let's assume

DOP is 5, *FF* is 0.1, $\rho$ is $10\pi$ radians per second, and $\Delta T$ is 60 seconds. For L1 measurements, the error at the end of the outage period would be almost 30 meters.

A phase plot of the base-mounted antenna is simply the negative of the azimuth angle; the azimuth term directly phase modulates the GPS carrier. In most cases, the azimuth angle varies at a uniform rate so the only effect is an apparent frequency shift. Because the phase plots are independent of depression angle, this frequency shift is common to all channels. We will denote the term $-\phi$ as the *ideal* phase wrap-up term.

**Circumference Mounted.** Although the base-mounted phase wrap-up functions are extremely simple, and almost intuitively obvious once you see them, the full three-



notes: 1) $A_{wp}$ (θ (t), ϕ (t), f) is the magnitude of the wrap-up transfer function
2) $\Phi_{wp}$ (θ (t), ϕ (t), f) is the phase of the wrap-up

**Figure 3.** The effect of the transmission media and a receiving antenna's properties on an electromagnetic signal's received amplitude and phase can be modeled by a transfer function. This model includes the new phase wrap-up terms.

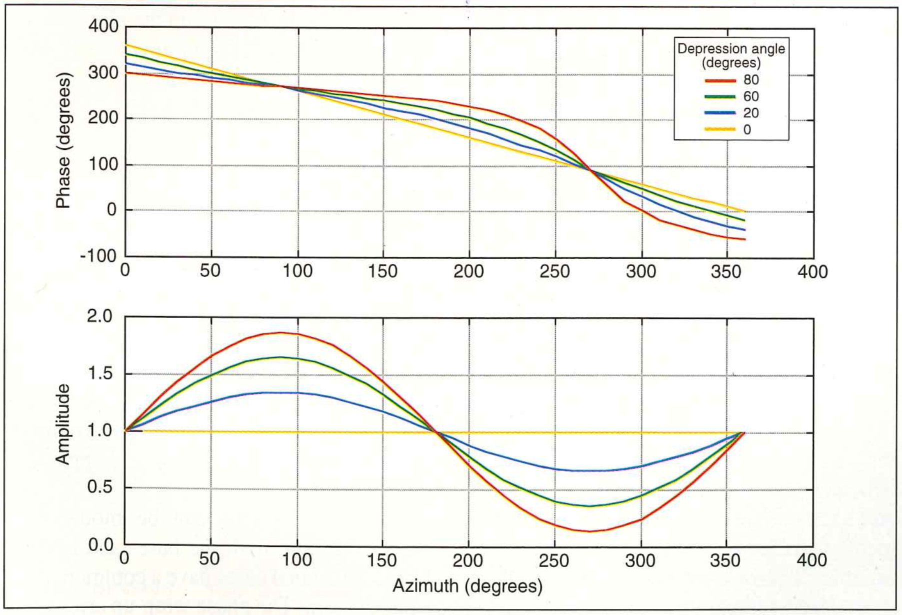


**Figure 4.** The phase and amplitude of the new transfer-function model's phase wrap-up component for a circumference-mounted antenna is shown to equal the ideal (base-mounted antenna) phase wrap-up term plus a residual component that is a function of depression angle and azimuth.

GPS IN DEPTH

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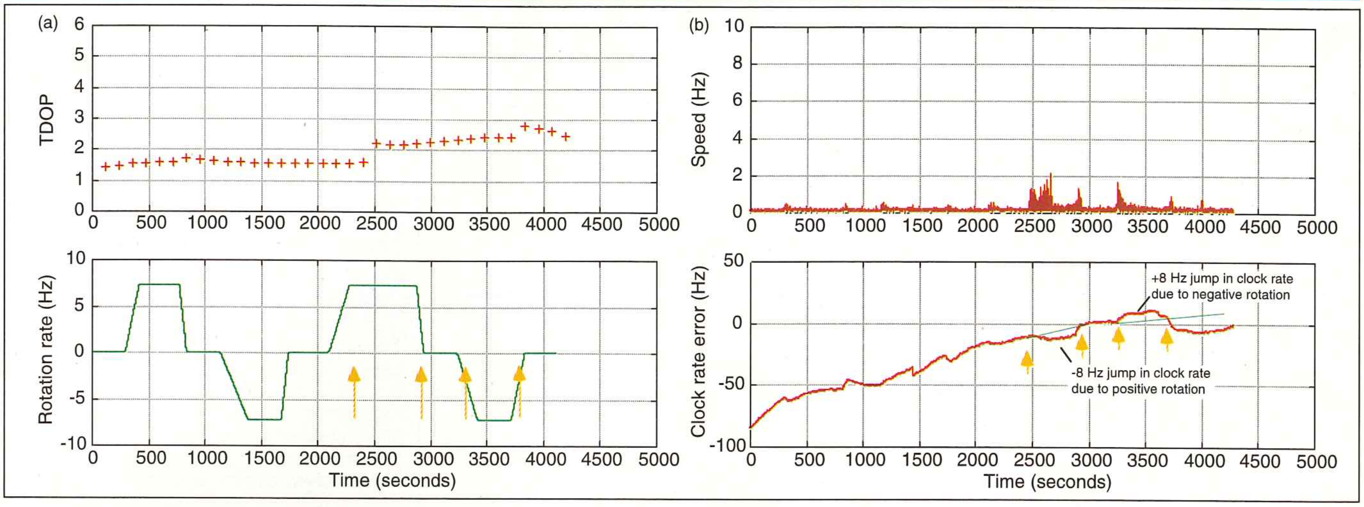

**Figure 5.** A rooftop experiment demonstrated that for a GPS antenna rotated about its boresight at specified rotation rates (a) the measured velocity and clock-rate errors (b) agreed with those predicted by our model. The arrows indicate the times at which we made changes to the antenna's rotation rate after a constellation switch and after the receiver stabilized to the ambient temperature and corresponding times of clock-rate changes.

dimensional analysis reveals some unexpected surprises when you examine the circumference-mounted case. Consider the results for a circumference-mounted antenna, shown in Figure 4. Unlike the base-mounted case, the phase terms are now functions of the depression angle. Thus, each satellite has a different phase wrap-up error. However, the phase term appears to be the sum of the ideal $-\phi$ phase wrap-up term plus some small perturbation that increases as the depression angle deviates from the spin axis. In fact, we can consider it to be the sum of two terms: the ideal phase wrap-up term $-\phi$ and a small depression angle–dependent residual term.

The ideal phase wrap-up term causes a common frequency offset on all channels and occurs for both the base- and circumference-mounted cases. All effects caused by this term, as cited for the base-mounted case, carry over to the circumference-mounted case. However, the residual spin-modulation terms cause additional errors for circumference-mounted locations. The additional phase dynamics will cause each channel's tracking loops to yield different errors, thus the root-mean-square noise on a fix will be larger than that of a nonrotating receiver's fix. In some cases, if the spin modulation terms are large or fast enough compared with the tracking-loop bandwidths or the linear range of the tracking loop's discriminator functions, the loops could break lock.

## EXPERIMENTAL DATA

To test our model for phase wrap-up, we performed a rooftop experiment at Draper Laboratory using a rotating base-mounted antenna. The results support the model predictions. We mounted a circularly polarized patch antenna on a spin table capable of rotating at ±10 revolutions per second. We employed a keyed P(Y) receiver configured to reduce low elevation angle satellite use, to minimize satellite constellation shifts, and to eliminate selective-availability errors.

We varied antenna rotation rate between plus and minus eight revolutions per second in the sequence 0, +8, 0, −8, 0, +8, 0, −8, 0. The length of time for each rotation rate was approximately five minutes, but the spin-table inertia made it impossible to control the duration precisely. We read the spin rate from a tachometer, recorded it by hand, and logged and processed all receiver data electronically.

We expected that, in the absence of satellite switching, discrete changes in rotation rate would produce discrete changes in clock-rate error, and that the changes in clock-rate error would be equal and opposite in response to equal and opposite antenna rotation rates; we expected the velocity estimate to be unaffected.

Figure 5a shows time dilution of precision (TDOP) and spin-table rotation rate during the data collection. The low value of TDOP indicates that the receiver was making precise solutions for time throughout the experiment, so velocity and clock-rate data were reliable. The discontinuities in the TDOP plot also indicate where constellation switches occurred: at about 2,500 and 3,800 seconds into the experiment.

The velocity and clock-rate data collected between these two times provide the strongest support of our phase wrap-up model. Figure 5b shows this with velocity in the upper plot and clock rate in the lower. Except for small transients (typically corresponding to less than 0.02 meters per second), the velocity solution was independent of rotation rate, as expected.

The plot of the receiver's estimated clock rate during this period clearly shows discrete jumps associated with changes in antenna rotation rate. Also, the clock rates corresponding to equal and opposite antenna rotation rates are themselves equal and opposite, as hypothesized. Arrows on the plot approximately match corresponding arrows on the rotation rate plot in Figure 5a, showing a clear cause-and-effect relationship.

## SUMMARY

We have introduced a theory that determines how rotating receiving antennas affect the GPS navigation solution. By tracking how each orthogonal polarization component contributes to the received phase, we have shown that circular polarization phase wrap-up effects depend on the antenna's geometry and phase configuration. We applied the theory to a common antenna type for two different mounting geometries and provided supporting data.

For antennas that can be modeled as crossed dipoles, both the base- and circumference-mounted cases have a common phase wrap-up term. The phase wrap-up error is the same on all channels for nontumble flight because it is independent of the depression angle. Because all channels have the same frequency bias, a single-point navigation solution with nonsingular geometry will place all of the phase wrap-up error into the clock-rate term. If fewer than four satellites are in view and the receiver uses the clock-drift model to predict the time error, then the fix during the outage period will have a position error that grows with time. Also, for a GPS channel attempting direct P(Y)-code acquisition, estimates of both translation along the antenna boresight and rotation about the boresight axis may be needed to correctly estimate where the receiver should initialize the Doppler frequency search.

Finally, any receiver that uses raw Doppler or a previously determined clock-rate term to align pseudorange channel data should subtract the rotation-error term. Typically, precompensation procedures that use raw Doppler or clock rate are performed to align channel data to incoming aiding data, or to align channel measurements with different data-bit boundaries to a common time point. For the circumference-mounted antenna case, additional spin-modulation terms exist that are different for each channel and can cause loss-of-lock problems.

We are continuing our phase wrap-up work and are now studying how elliptical polarization affects phase wrap-up. We are developing various antenna models, including the offset crossed dipole and quadrifilar helix. We also plan to investigate the effects of finite-length dipoles in the antenna models and large microstrip patch geometries. A general model resulting from these studies will allow GPS receiver and simulator manufacturers to account for the phase wrap-up effect in their products. ■

## Further Reading

This article is based on two papers presented at Institute of Navigation conferences:

- "Carrier Phase Wrap-Up Induced by Rotating GPS Antennas," by A.K. Tetewsky and F.E. Mullen, published in the *Proceedings of the 52nd Annual Meeting of The Institute of Navigation*, held in Cambridge, Massachusetts, June 19–21, 1996, pp. 21–28.
- "Effects of Platform Rotation on GPS with Implications for GPS Simulators," by A.K. Tetewsky and F.E. Mullen, published in the *Proceedings of ION GPS-96, The 9th International Technical Meeting of the Satellite Division of The Institute of Navigation*, held in Kansas City, Missouri, September 17–20, 1996, pp. 1917–1925.

For an introduction to GPS antenna properties, see

- "How Different Antennas Affect the GPS Observable," by B.R. Schupler and T.A. Clark, in *GPS World*, November/December 1991, pp. 32–36.

For an excellent, general reference on the theory and practicalities of antennas, see

- *Antennas*, by J.D. Kraus, 2nd Edition, McGraw-Hill Book Company, 1988 (and reprinted by Cygnus-Quasar Books, Powell, Ohio).

For an in-depth discussion of GPS signal propagation and GPS receiver and antenna operation, see the relevant chapters in

- *Global Positioning System: Theory and Applications, Vol. I*, edited by B.W. Parkinson and J.J. Spilker, Jr., Vol. 163 of *Progress in Astronautics and Aeronautics*, American Institute of Aeronautics and Astronautics, Inc., Washington, D.C., 1996.

For an example of how GPS is being integrated into munitions, see

- "An Integrated GPS/Micro-Mechanical IMU for 5″ Navy Shells," by J.R. Dowdle and K.W. Flueckiger, published in the *Proceedings of the 52nd Annual Meeting of The Institute of Navigation*, held in Cambridge, Massachusetts, June 19–21, 1996, pp. 207–212.