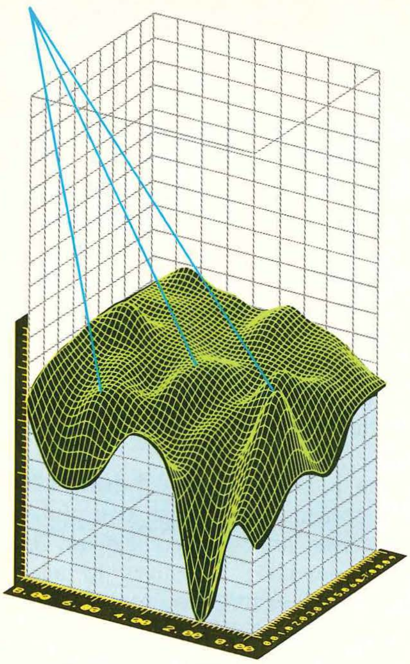

Measuring Velocity Using GPS

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Naval Command, Control and Ocean Surveillance Center

"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. In this month's column, we feature an article on a subject that has received little scrutiny outside military circles: the measurement of velocity using GPS. Our author, Marvin May, is a navigation systems engineer with the U.S. Navy's Research Development Test and Evaluation Division Detachment of the Naval Command, Control and Ocean Surveillance Center (NCCOSC) in Warminster, Pennsylvania.*

This 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 and suggestions of topics for future columns.

The classic first page of Global Positioning System (GPS) executive briefings heralds an era of 16-meter (spherical error probable) position performance, 100-nanosecond (one sigma) time transfer capability, and 0.1 meters/second (root-mean-square) per axis velocity accuracy available continuously in an all-weather, dynamic environment. For the most part, the claims for position and time transfer accuracy and environmental capabilities have been or will be validated and are virtually universally accepted. Velocity performance, which often gets tertiary billing, is subject to considerable interpretation. GPS, which was initiated by the Department of Defense (DoD) largely to reduce the proliferation of positioning systems, is also the first long-range radionavigation system to advertise a velocity capability. In this article we'll investigate, in a tutorial manner, the measurements a GPS receiver makes to provide the indicated velocity, the principal contributors to velocity error, and some examples of velocity performance.

VELOCITY USERS

Navigators often require the knowledge not only of where they are presently — their position — but also of where they are going and how fast they are getting there — their velocity. In considering how well GPS may meet one's velocity requirements, it is important to keep in mind the specific application for which the GPS-indicated velocity will be used. Consider Figure 1, which could represent the one-dimensional motion of a slowly moving vehicle experiencing a high-frequency vibratory motion together with a lower-frequency attitude motion and an acceleration beginning eight seconds after the vehicle starts moving. Note that the variation in position shown in Figure 1 (top) is about 13 meters, or about twice the nominal GPS precision-code-range error budget. In contrast, the velocity variation shown at the bottom of Figure 1 is about 5 meters per second or about 50 times the nominal one-dimensional velocity error expectation.

Although the number of applications of GPS velocity measurement is large, we can broadly classify GPS velocity users into five groups according to their levels of tolerance of delay or latency in availability of the velocity data and distortion in the data caused by filtering. We define a "Type A" user as one who requires an instantaneous real-time knowledge of total velocity in an application such as providing an initial velocity estimate for a projectile launch computation. Latency or distortions due to filtering must be minimized. "Type B" users also desire total velocity with minimum distortion, but can accept a limited amount of latency as long as the data received from GPS are accurately time tagged. An application might be sending a GPS velocity to an inertial navigation system for resetting the inertial navigator.

"Type C" users also desire total velocity with minimum distortion due to filtering, but can accept an unlimited amount of latency, assuming the data are accurately time tagged. An application might be range tracking in which the velocity information is used for postmission data reduction. A "Type D" user desires a smoothed velocity output and can accept some limited latency. A Type D user wouldn't be concerned with the vibratory or attitude motions shown in Figure 1 and might only need to know the "speed made good." A "Type E" user requires knowledge of velocity only within some low-frequency bandwidth of motions and can accept an unlimited amount of latency. A Type E user might be a geophysicist who is compensating a gravimeter output for apparent vertical accelerations due to Coriolis effects (the Coriolis acceleration is an apparent acceleration exhibited by bodies moving in a rotating coordinate system such as one attached to the earth). In this application, primary concern is with velocity changes that lie within the same spectral

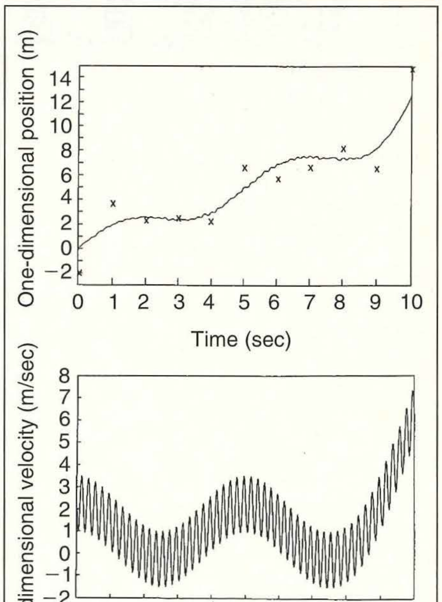

Figure 1. (top) One-dimensional position of a slowly moving vehicle; and **(bottom)** corresponding one-dimensional velocity of the slowly moving vehicle

band as the gravity signal; latency is not an issue because the data are reduced in postmission. Users have successfully applied GPS velocities in each of the above situations, but the quantitative contribution of individual error sources mentioned below is considerably different for each user.

Velocity performance is clearly a function of receiver measurement (pseudorange and the change in range over some time interval — delta range), accuracy, satellite–user geometry, satellite and user clock stability, platform dynamics, receiver processing algorithms, selective availability status, aiding configurations, sampling, senescence, and latency factors. In contrast to velocity, GPS position accuracy can be reasonably quantified, with some level of fidelity and with some qualifications, by the product of a satellite–user geometry parameter with a measurement error statistic. For example, a user may quantify the three-dimensional root-mean-square GPS position error as the product of the position dilution of precision (PDOP) and the user equivalent range error (UERE) (see "Innovation," *GPS World*, July/August 1991, for further details on position accuracy measures). For velocity, although tempting for managers, engineers, and theoreticians alike, the use of an analogous generalized simple relationship can lead to serious misestimations of the actual velocity errors. More often, users must quantify GPS velocity errors on a case-by-case basis.

BASIC CONCEPTS

GPS positioning capability is often introduced as the instantaneous measurement of pseudoranges to four satellites and the solution of the four equations for the three position variables and the unknown user clock bias. In addition to providing the pseudoranges, we can initially consider a GPS receiver as also providing four independent pseudorange rates representing the instantaneous range rates of change plus a clock drift term. The simultaneous solution of the eight equations resulting from the four pseudorange and four pseudorange rate equations can be solved in a receiver's microprocessor for the three position coordinates, three velocity components, user clock bias, and drift. We note that pseudorange rate measurements depend not only on the relative velocity between the satellite and user, but also on their positions.

The maximum sensitivity of pseudorange rate to position is about 0.19 meters per second (Doppler frequency shift of the L1 carrier of about 1.0 Hz) per kilometer of position uncertainty, and the sensitivity to velocity uncertainty is naturally 1 meter per second of range rate per meter per second of velocity uncertainty (about 5.2 Hz of L1 Doppler shift). The above sensitivities permit use of the pseudorange measurements to eliminate most of the effect of the position uncertainty within the pseudorange rate equations. A receiver then can use the pseudorange rate measurements to solve for the velocities and clock drift. The geometric relationships between position accuracy and pseudorange errors represented by the familiar dilutions of precision are also approximately applicable to the relationship between velocity accuracy and effective pseudorange rate error.

One might ask if using consecutive pseudorange measurements would provide the velocity capability, thereby obviating the need for processing pseudorange rates. In Figure 1 we have simulated high-frequency random noise pseudorange errors typical for a GPS P-code tracking receiver. By connecting the "X" points in Figure 1 (top) derived from the pseudorange "measurements" and considering the extrapolated slope of the line as the estimated velocity, one can see that the pseudorange-derived velocity estimate would be noisy and useful only as a coarse estimator in a benign environment.

Most GPS dynamic positioning applications are based on the measurement of times-of-arrival of a certain point of the code; that is, really code-phase measurements (pseudoranges). Accurate dynamic velocity, however, relies primarily on the carrier-phase measurements. Phase-measurement errors on the carrier-phase loop are multiplied by the 19-centimeter wavelength to arrive at an effective biased range error, whereas code-phase measurements are multiplied by 30 meters for the P-code phase (or 300 meters for C/A-code). This means that the improved

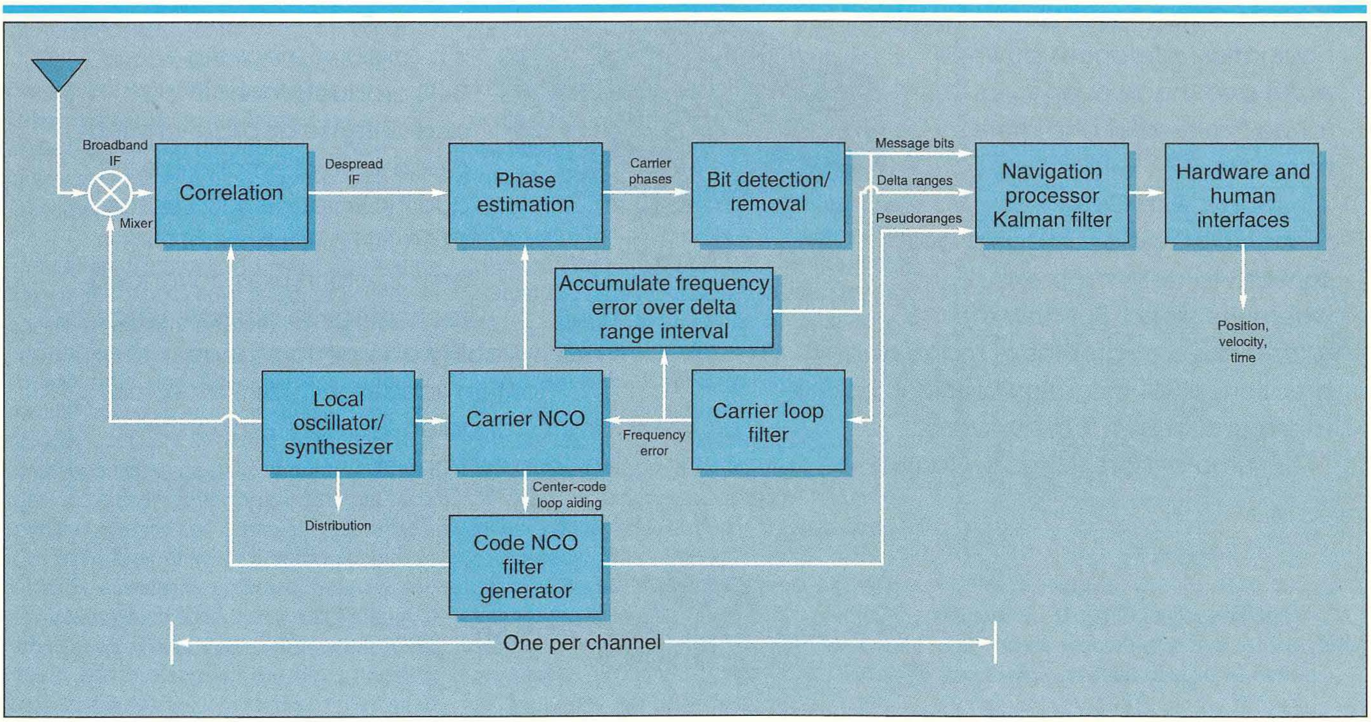

Figure 2. Block diagram of a simplified generic GPS receiver

accuracy obtained using the carrier-phase measurements for velocity is necessary for most velocity measurement applications.

We can draw some limited analogies between velocity measurement and precise surveying, both of which largely depend on carrier-phase measurements. Precise relative surveying requires accurate relative position with respect to a base station whose coordinates are known a priori, whereas velocity determination, for very small time intervals, requires relative position with respect to the previous point in time. As a matter of fact, several of the differencing operations familiar to GPS surveyors are implicit in velocity determination, making wavelength count ambiguities, constant control segment errors, and some environmental and user and satellite clock error effects negligible.

GPS RECEIVER MEASUREMENTS

In actuality, GPS receivers do not measure instantaneous pseudorange rates, because this would imply the ability to instantaneously measure frequency. In addition, a receiver can employ a Kalman filter using an underlying platform dynamics model for an unaided set to compute velocity from the measurements. The Kalman filter lessens the effects of measurement noise while still minimizing velocity distortion and allows improved operation during times of reduced satellite availability. Figure 2 is a simplified diagram of a generic GPS receiver highlighting the carrier-tracking loop function, which is nested within the code-tracking loop. Subsequent to code lock, the code-tracking loop strips off (despreads) the spread-spectrum code modulation in the down-converted received intermediate frequency signal, leaving phase modulation due to the relative motion of the satellite and user (Doppler effect) and biphase digital message modulation. The carrier-tracking loop measures the phase of this signal with respect to a local oscillator by adjusting the carrier numerically controlled oscillator (NCO) output phase to track the incoming signal phase. GPS receivers use either analog, hybrid, or wholly digital phase-tracking loops as a servomechanism to track the phase difference under the inherently low carrier signal-to-noise levels.

The NCO has, as an input, the frequency error of the carrier loop–generated frequency with respect to the incoming signal's frequency. Because the frequency generated by the NCO with no input error signal is nominally equal to the carrier frequency, the frequency error input signal represents the Doppler frequency shift. The overall effect of the tracking loop is a low-pass filtering of phase changes. Thus, when the NCO aligns its phase with that of the incoming signal, it tracks the more-slowly varying phase changes below the low-pass bandwidth cutoff of the carrier-loop filter. The loop filter and the integrating effect of the NCO attenuate phase changes that vary more quickly, and these appear as errors in the loop.

The selection of a bandwidth and type of carrier-tracking loop mechanization for an unaided GPS receiver is a tradeoff. One must strike a balance between tracking high-dynamic platform maneuvers, which would call for a wider bandwidth, and the attenuation of noise and jamming effects, which would dictate a narrower bandwidth. A typical implementation would have a 5-Hz bandwidth with a "third-order tracking loop," allowing tracking of most high-dynamic aircraft maneuvers under nominal noise conditions. The third-order tracking loop incorporates a filter that allows tracking of user-to-satellite motions, which appear as constant accelerations without steady-state errors (errors that remain after any transients die away). We should note that phase dynamics are primarily a function of the user motion, because range rate changes due to

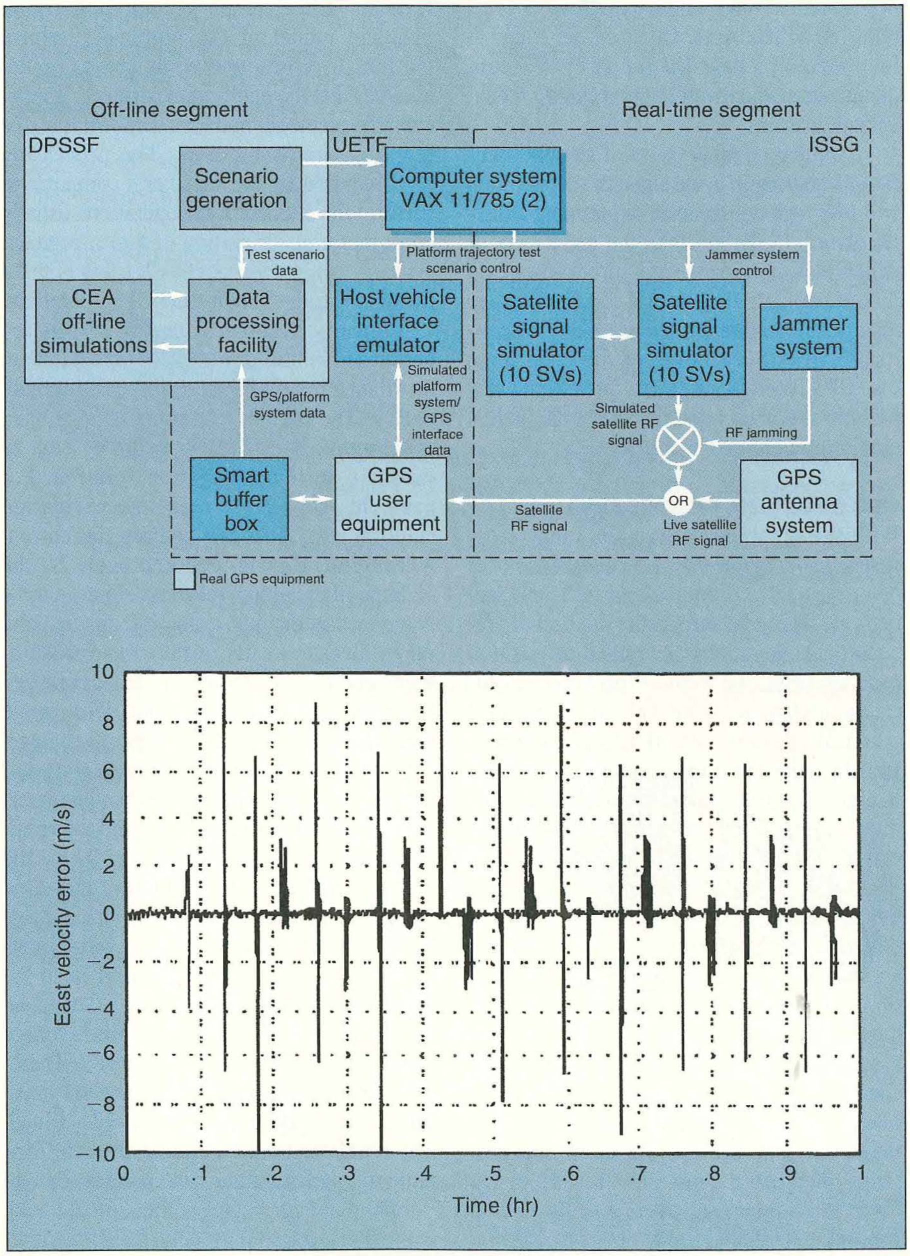

Figure 3. (top) CEA user equipment test facility; and **(bottom)** GPS east-velocity errors during laboratory testing

satellite accelerations are smaller than 0.175 meters per second per second (less than 1 Hz per second), and higher-order derivatives of satellite motion are negligible. The 50-Hz biphase digital message modulation is beyond the bandwidth of the tracking loop and is extracted from the loop error signal for subsequent message decoding.

A phase measurement ideally represents the number of carrier-cycle wavelengths within the distance between the satellite and receiver antenna phase centers. Because the receiver can only make phase measurements unambiguously within one wavelength, one can consider the phase measurement, in the absence of all errors and time offsets, as a biased range measurement with the bias equal to an integer number of carrier wavelengths expressed in units of distance. The delta range, which is the primary quantity used by the Kalman filter in the GPS receiver to compute velocity, represents the difference of phase measurements (or average Doppler frequency) over a time interval called the *delta range dwell interval.* The delta range represents the change in satellite-to-user range over the delta range dwell interval and is thus proportional to the average line-of-sight velocity of the user with respect to the satellite during the interval. The differencing operation eliminates the integer wavelength ambiguity and satellite-to-user clock bias, and a clock bias drift (or frequency bias) term appears in the delta range measurement. The GPS receiver estimates this bias drift term within the Kalman filter. Typical delta range measurement intervals vary from 200 milliseconds to two seconds; significantly smaller intervals are impractical due to increased computational load and the lack of independence of the phase measurements at tracking loop bandwidths.

The error in the delta range measurement is a function of carrier-to-noise levels, local oscillator phase noise and acceleration sensitivity, carrier-tracking loop implementation, and vehicle dynamics. GPS receivers can maintain delta range accuracies to better than 1.5 centimeters (excluding acceleration-sensitive oscillator effects) down to carrier-tracking thresholds of about 26 dB Hz, even under high aircraft dynamics. Although the above figure includes GPS receiver oscillator phase noise effects of about 0.8 centimeters, crystal oscillators in GPS receivers experience frequency shifts when subjected to accelerations. Stabilities of about 0.5×10^{-9} per *g* (1 *g* is the nominal acceleration due to gravity at the earth's surface) would induce an effective range rate error of 0.15 meters per second for a 1-*g* acceleration. To the extent that this acceleration-induced frequency shift appears as a transient error within the tracking loop filter and Kalman filter, this could be a dominant error source.

Environmental errors due to ionospheric and tropospheric refraction potentially affect delta range measurement accuracy. Their effect on range rate is due to a combination of changing atmospheric effects and dynamic user-to-satellite geometry. Except under combined circumstances of low elevation angles, high user dynamics, and geomagnetic storm activities, these errors should have a negligible contribution to the nominal GPS velocity error budget. Delta range measurements, unlike pseudorange measurements, do not usually have environmental effects removed in real time. Other carrier-tracking loop errors include fractional cycle count quantization and dwell interval timing mechanization errors.

Assuming no other cause of signal obscuration resulting in cycle slips, the carrier loop will lose lock due to noise or jamming at levels about 10 dB less than the code loop, at which point delta range measurements are no longer available. This would disable message data demodulation and would likely discontinue carrier-loop aiding of the code loop. The GPS receiver's Kalman filter would still provide indicated velocities based on the less precise pseudorange measurements.

GPS RECEIVER PROCESSING

With the highly accurate delta range measurements of better than 1.5 centimeters over delta range dwell intervals of 200 milliseconds to 2 seconds, and similar dilution of precision considerations as applied to position measurements, we would expect commensurately highly accurate velocities. Several practical real-time considerations, however, tend to mute these expectations under non-benign dynamics. First, the duration of the dwell interval itself limits the GPS receiver to observing only an average range rate over the interval. In the case of switching (sequencing or multiplexing) GPS receivers that switch channel tracking from one satellite to another, measurements of the average line-of-sight range rates are only available to those satellites being tracked. This results in a *sampling* or *aliasing* effect. Even multi-channel, continuous-tracking GPS receivers often fail to make continuous delta range measurements, but operate in an *intermittently integrated Doppler* mode. Here the dwell interval is some fraction of the overall measurement cycle, again resulting in sampling or aliasing effects.

Although a delta range measurement is theoretically available at the end of the dwell interval, the receiver must accomplish considerable processing before a velocity in geographic coordinates becomes available to the user. The measurement (Kalman filter) and interface processing segments of the receiver software carry out these functions. The Kalman filter, in addition to transforming pseudorange and delta range outputs into position, velocity, and time outputs, reduces the effects of noise, enhances operation during underdetermined (fewer than four satellites being tracked) or overdetermined (more than four satellites) conditions, and performs time registration and/or extrapolation operations. To perform these operations, the Kalman filter employs an underlying dynamic model of the nominal platform motion. A representative dynamics model assumes that the platform experiences a near-constant acceleration over a data window of a few measurement cycles. The processing time required by the receiver's computer to perform the Kalman filter operations usually consumes a major portion of a measurement cycle — computer processor loading is still a major constraint in real-time GPS operation.

Typically, Kalman filter operations are performed in background processing and are distributed in time over several measurement cycles. The background processing is then synchronized with real-time processing to output a current navigation solution. For example, to obtain a real-time navigation solution valid at time t_1 within the current measurement cycle, denoted cycle N, the Kalman filter computations would have to be completed in the past cycle, N-1, using delta range measurements in previous measurement cycles (N-2 and N-3, for example). Receivers typically carry out delta range measurements over a delta range dwell interval within the measurement cycle time and use measurements from more than one interval to reduce the effect of noise and to extrapolate forward to current time. Thus the receiver effectively computes real-time velocity output at time t_1 from the average velocity computed over the delta range interval N-2 and extrapolated forward from the middle of the N-2 interval to t_1 using an acceleration computed from the average velocities over intervals N-2 and N-3. Therefore, in addition to receiver thermal noise errors, tracking-loop dynamic distortions, and oscillator-induced errors, the real-time velocity performance can degrade due to sampling and averaging effects of the delta range dwell process, as well as Kalman filter dynamic distortion and extrapolation errors. These latter errors, particularly for a Type A user under nonbenign dynamics, often dominate other error sources. Receiver designers have employed various methods, including decreased size of the delta range dwell interval, continuous delta range measurements, and less frequent Kalman filter gain computations (thereby reducing processing time consumption), to reduce these errors. GPS receivers can provide more accurate velocities if latent and/or smoothed velocities are acceptable.

Selective availability (SA) will have a significant effect on velocity accuracy achievable by "nonauthorized" users, meaning most civilian users. In addition to purposely degrading satellite orbit information in the navigation message, DoD manipulates or dithers the satellite clock frequency (see "Innovation," *GPS World*, September/October 1990). This dithering introduces errors in the computed pseudoranges and carrier-phase measurements. Differential GPS techniques, in which a reference GPS receiver at a known stationary location transmits range and range-rate corrections to a mobile GPS receiver, are forecast as saviors for some real-time commercial positioning applications. The broadcast range-rate signals will correct the SA-induced velocity error to the extent that the range-rate errors remain constant over the interval between broadcasts. For velocity, even with accurate differential broadcasts of range rate at 10-second intervals, much of the nominal GPS velocity error budget would be used up as a result of uncompensated range acceleration SA effects.

UNAIDED GPS VELOCITY RESULTS

The principal reason for the paucity of reliable test results for GPS velocity is the difficulty in ensuring an accurate independent reference. Even high-accuracy laser-tracking ranges have been unsuccessful in measuring velocity to the levels required of a reference for GPS evaluation. In this section, we briefly describe three tests specifically designed for unaided GPS velocity error assessment. The errors reported in all the tests represent a solution with a latency of about one second. The tests were performed using a five-channel GPS receiver.

The first test used the Central Engineering Activity (CEA) hardware-in-the-loop user equipment test facility (Figure 3, top), which employs a satellite signal generator to generate the received GPS signals according to a prescribed scenario. In this figure, DPSSF is the data processing and simulation software facility, UETF is the user equipment test facility, and ISSG is the integrated satellite signal generator. The test facility allows a cost-effective evaluation because an actual test platform is not required and the velocity reference is known perfectly (however, oscillator acceleration-sensitivity effects are not simulated). The true-east velocity profile is representative of a medium-dynamics aircraft east–west racetrack scenario with accelerations and decelerations along the racetrack legs. Figure 3 (bottom) shows the corresponding GPS east-velocity errors, where the spikes in the errors occur at the turns and times of the linear dynamics.

The second test occurred along an airstrip adjacent to the NCCOSC Warminster facility using the Mobile Navigation Test Facility van equipped with an unaided GPS receiver and two inertial navigation systems (INSs) as a velocity reference. A Kalman filter using zero velocity updates and position closure measurements yielded estimates of the predominant 84-minute period Schuler mode INS errors. The corrected INS velocity provided a reference for the GPS velocities, including lever arm and data senescence corrections — with an estimated error of 0.026 meters per second per axis independent of van dynamics. The overall root-mean-square GPS velocity errors were about 0.15 meters per second along each axis.

Researchers conducted the third test in February 1990 at Holloman Air Force Base, New Mexico, to quantify velocity errors under more severe land dynamics using an extremely accurate sled reference system. The GPS velocity error was again shown to be highly sensitive to changes in vehicle dynamics.

GPS/INS INTEGRATION

So far we have limited the discussion to the unaided use of GPS. The synergism between GPS and inertial navigation outputs, and their ability to mutually aid each other, is well documented. Much of the design tuning associated with an integrated GPS/inertial navigation system is directed at velocity performance, because position performance will be largely slaved to GPS when it is available. With inertial navigation system aiding, many of the aforementioned inherent limitations of the unaided GPS set regarding delta range integration, sampling, and extrapolation effects become less important if properly accounted for. This is because the potential high-frequency velocity accuracy of the combined GPS/INS is primarily the result of the inertial acceleration measurement. Accelerometer measurement bandwidths are typically wider than 100 Hz, and accelerations are integrated into velocities at rates of about 50 Hz with lags of less than a millisecond. Therefore, in the integrated system, the task of measuring the high-frequency velocities rests mainly with the INS, allowing the GPS to estimate the slowly varying INS errors.

CONCLUSIONS

We have examined some of the fundamental aspects of GPS velocity outputs. We have reviewed error budget considerations and discussed caveat emptor aspects of equipment specifications. As shown for nonbenign dynamics and real-time unaided operation, delta range integration, sampling, and extrapolation effects can outweigh phase-tracking loop errors. If users pay careful attention to latency, senescence, and filtering issues, they will be able to properly use the precise measurements that GPS affords. Where high-dynamic real-time velocity performance is important, inertial data integrated with GPS is indicated. An article by the author in the Institute of Navigation's 46th annual symposium proceedings offers further technical information on determining velocity using GPS. ■

For product information, turn to page 72 and see Manufacturers.

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Washington, D.C. Contact: Shirley Forlenzo, George Washington University, Continuing Engineering Education, Washington, DC 20052, USA, (202) 994-8530, (800) 424-9773 in the U.S., (800) 535-4567 in Canada, fax (202) 872-0645.

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ION GPS-92 — Institute of Navigation Fifth Annual International Technical Meeting
Albuquerque, New Mexico. Civil GPS Service Interface Committee meeting Sept. 14–15. Contact: Institute of Navigation, 1026 16th Street NW, Suite 104, Washington, DC 20036, USA, (202) 783-4121, fax (202) 347-4698.

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National Business Aircraft Association Annual Meeting and Convention
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OCTOBER 6-9

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OCTOBER 7-11

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OCTOBER 14

UK Civil Satellite Navigation Group One-Day Satnav Symposium
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OCTOBER 14-15

1992 GIS in the Rockies: GIS — Solutions through Cooperation
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OCTOBER 14-16

12th Annual Convention of Society for Photogrammetry and Remote Sensing
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OCTOBER 19-21

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MANUFACTURERS

Page 50. *Tracking Projectiles: The GPS Artillery Registration Fuze Program.* A **Magnavox 4200** receiver was used to monitor satellite ephemeris data during the field test. The projectile antenna was designed and build by **Ball Communications Systems Division**, Broomfield, Colorado. The data collection trailer was outfitted with both **Chu Associates** and **Adams Russell** GPS L1 antennas.

Page 58. *Measuring Velocity Using GPS.* The GPS receiver used in the three tests was a Navy Standard five-channel receiver from **Rockwell International, Collins Avionics and Communications Division,** Cedar Rapids, Iowa. The INS units used in the second test were LTN-72 manufactured by **Litton Aero Products,** Moorpark, California.

Manufacturer credits reflect the products used for the applications, as reported by the authors at the time the article was written.

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