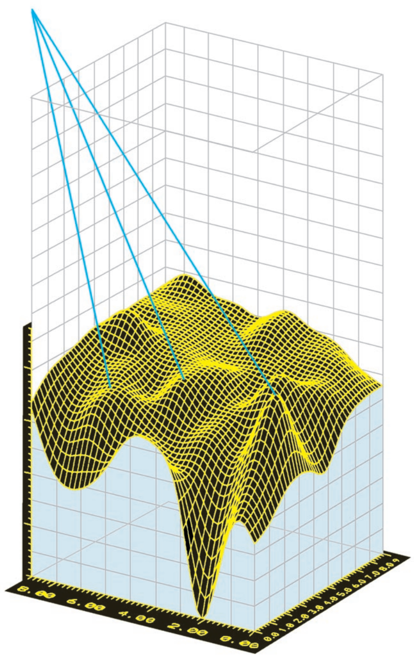

RTK GPS

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Novare, the Latin root of the word innovation, means to make new. And that is exactly what scientists and engineers working with the Global Positioning System have been doing ever since the conception of GPS in the early 1970s. Not only have they discovered many new GPS applications, they have devised new ways to use the GPS signals. One of their most recent innovations is RTK, real-time kinematic, GPS — a technique that provides position accuracy close to that achievable with conventional carrier-phase positioning, but in real time. In this month's column we'll briefly examine RTK GPS, emphasizing one of the system's critical components: the radio link.

"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.

During the past 15 years or so, the techniques involved with GPS use for surveying and navigation have continuously evolved. In fact, a convergence, of sorts, has occurred between these two major application areas. Before we examine this evolution and convergence, though, let's first distinguish the requirements for these two main GPS applications.

A FIX ON ACCURACY

In surveying, we are usually interested in determining the position of one or more (relatively) fixed points, which are usually monumented — either permanently or temporarily. Often, we are primarily interested in the horizontal coordinates of points, a two-dimensional application, but might alternatively be interested only in heights, a one-dimensional application, or in all three coordinates, a three-dimensional application.

Surveyed positions are usually relative, that is, surveyors determine them with respect to the coordinates of one or more other points. The required accuracy typically depends on the distance to these other points and could range from millimeters, in the case of very short distances, to tens of centimeters over distances as far apart as hundreds of kilometers or more.

In many cases, the positions of points need not be determined in real time, which has made data postprocessing fairly common. This involves generating the actual coordinate information back in the office after collecting survey data at project and reference sites. Some survey tasks, however, require real-time positioning. When setting out, for example, surveyors or construction engineers establish ground marks to enable construction works to be correctly located in plan and elevation.

Craft Positioning. Navigators, on the other hand, need to know where they are and where they are going — usually in real time. Bowditch (the common name for the *American Practical Navigator*, the Bible of navigation, first published by the nineteenth century American mathematician, shipmaster, and insurance company president, Nathaniel Bowditch) defines navigation as "the process of directing the movements of a craft, expeditiously and safely, from one point to another."

Although navigation originally referred to guiding ships (the word navigation comes from the Latin words *navis*, meaning ship, and *agere*, meaning to direct or drive), the term applies to any craft, whether on land, on or below the sea's surface, in the air, or in space. To guide the craft from one point to another, we need to know the positions of those points and usually the route between them. The positions — particularly in the marine environment and if determined without reference to any former position — are known as *fixes*. Useful ancillary information includes the craft's speed or velocity (speed plus direction of motion).

The required position accuracy (or acceptable error) depends very much on the application. For ships navigating in mid-ocean, safety typically requires a minimum accuracy (2drms [distance root mean square] or within about 95 percent probability level) of 2–4 nautical miles (3.7–7.4 kilometers), although 1–2 nautical miles (1.8–3.7 kilometers) is desirable. Ideally, the vessel's position should be determined every 15 minutes or less, but a fix interval of as long as two hours may be acceptable. For ships on inland waterways, the accuracy requirement is around 2–5 meters (2drms), with fix updates every second or so.

Aircraft similarly have different needs depending on where they are. Over the North Atlantic, aircraft must maintain a cross-track position accuracy of 12.6 nautical miles (23.3 kilometers), 2 sigma or at the 95 percent probability level, and a height accuracy of 350 feet (107 meters), 3 sigma or at the 99.7 percent probability level. To conduct a Category III precision approach to a runway, however, the cross-track accuracy at the runway threshold must be better than 4.1 meters (95 percent), with vertical accuracy better than 0.6 meters (95 percent).

CARRIER-PHASE POSITIONING

Relatively recently, scientists and engineers developed a new positioning technique that any application, including surveying and navigation, can take advantage of for increased accuracy. Real-time kinematic GPS employs a method of carrier-phase differential GPS positioning whereby users can obtain centimeter-level position accuracies in real time.

The carrier phase is the more precise sibling of the pseudorange. It is the phase of the received carrier with respect to the phase of a carrier generated by an oscillator in the GPS receiver. That carrier has a nominally constant frequency, whereas the received carrier is changing in frequency because of the Doppler shift induced by the relative motion of the satellite and the receiver. The received carrier's phase is related to the phase of the carrier at the satellite through the time interval required for the signal to propagate from the satellite to the receiver.

So, ideally, the carrier-phase observable would be the total number of full carrier cycles and fractional cycles between the antennas of a satellite and a receiver at any instant. Unfortunately, a GPS receiver has no way of distinguishing one cycle of a carrier from another. The best it can do, therefore, is to measure the fractional phase and then keep track of changes to the phase; the initial phase is undetermined, or ambiguous, by an integer number of cycles. To use the carrier phase as an observable for positioning, this unknown number of cycles, or *ambiguity*, must be estimated along with the other unknowns — the receiver's coordinates.

If we convert the measured carrier phase in cycles to equivalent distance units by multiplying by the carrier's wavelength, we can express the carrier-phase observation equation in a form very similar to the observation equation for the pseudorange. The major difference (apart from the sign of the ionospheric propagation delay term) is the ambiguity term's presence. In fact, the carrier phase can be thought of as a biased range measurement just like the pseudorange.

Using the Carrier Phase. Although all GPS receivers must lock onto and track the signal's carrier to measure pseudoranges, they may not record carrier-phase observations for external use. Some, however, may use carrier-phase measurements internally to smooth — reduce the high-frequency noise of — the pseudorange measurements. The carrier phase's rate-of-change is related to the Doppler shift, which is used to determine velocity. Incidentally, in comparison with the carrier phase, pseudoranges, when measured in code wavelength units (about 300 meters for the C/A-code and 30 meters for the P-code), are sometimes referred to as code-phase measurements.

For high-accuracy position determination, carrier-phase measurements made by one receiver are typically combined with those made simultaneously by another receiver to form double differences in which the effects of satellite and receiver clock errors are essentially eliminated. The double differences are then processed using a least-squares filter of some kind to estimate the relative coordinates of one receiver (actually, its antenna) with respect to the other. If the coordinates of one of the receivers is well known in some coordinate frame, for example, it occupies a geodetic control point, then the coordinates of the second receiver can be determined in the same frame.

Postprocessed. The first uses of carrier-phase measurements for precise static positioning in the early 1980s required observation spans lasting many hours to achieve the required accuracy levels. With relatively few GPS satellites in orbit, the long data spans enabled resolution of the carrier-phase integer ambiguities. Various modeling errors, such as those of the satellite orbits, also necessitated the lengthy observations.

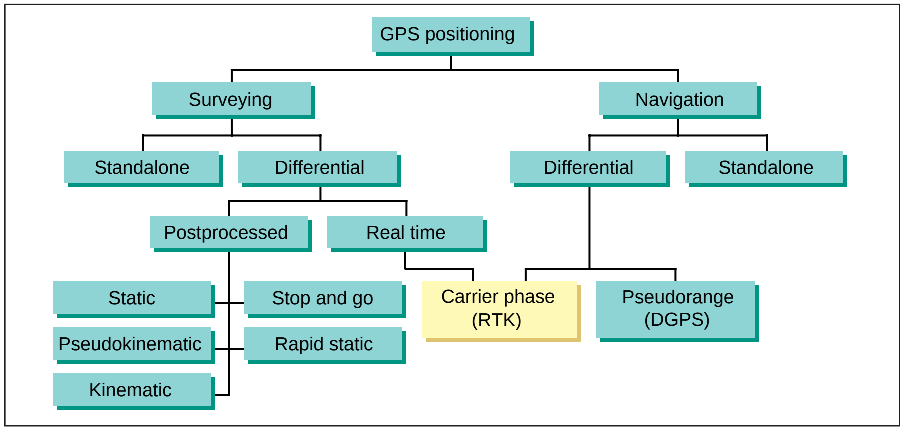

Figure 1. As GPS applications have developed, so too have the methods used to employ GPS technology. To meet the accuracy requirements of real-time surveying and high-precision navigation, scientists and engineers developed real-time carrier-phase differential GPS, better known as real-time kinematic (RTK) GPS.

Attempts to make GPS surveying more efficient resulted in such techniques as stop-and-go kinematic, pseudokinematic, and rapid-static positioning (see Figure 1). Researchers also devised various clever methods to determine the integer ambiguities at the start of a survey.

Real Time. In all of these GPS surveying modes, either the receiver or an external device records the data for postprocessing. The coordinates of the points visited by a roving receiver or the track it followed cannot be determined to the requisite accuracy until its data are combined with those from a reference receiver. Many applications, however, could clearly benefit from obtaining the receiver's coordinates in real time rather than waiting.

To accomplish this, the reference receiver data can be relayed to the moving receiver using a suitable radio link. Of course, real-time differential GPS (DGPS) has been around since the mid-1980s. However, that technique uses pseudorange data, rather than carrier-phase data, with resulting 2drms horizontal position accuracies of a meter or so at best. Pseudorange DGPS entails a reference station transmitting pseudorange *corrections* to user receivers, which combine those data with their own pseudorange measurements to produce corrected pseudoranges. A user receiver then processes these in the usual fashion to determine its coordinates.

Correction Message Formats. In 1985, the Radio Technical Commission for Maritime Services (RTCM) suggested a standard format for coding and transmitting such corrections. Although other proprietary formats have been devised, the RTCM format remains the mostly widely used. For example, member agencies of the International Association of Lighthouse Authorities, such as the U.S. and Canadian Coast Guards, employ the RTCM format for DGPS correction transmissions broadcast by selected marine radionavigation beacons.

Researchers had shown by the early 1990s that is was possible to improve on the accuracies afforded by DGPS by transmitting carrier-phase data to user receivers, permitting real-time, high-accuracy positioning even if the receivers were moving. They christened the technique real-time kinematic, or RTK.

In response, RTCM Special Committee 104 (SC-104), which devised the DGPS message format, added four new message types to Version 2.1 (published in January 1994) to handle RTK requirements. The four message types consist of two message pairs. Message Types 18 and 19 contain the raw carrier-phase and pseudorange measurements, respectively, made at the reference station. The measurements may be L1 or L2 and are accompanied by a high-precision time stamp.

Message Types 20 and 21 contain corrections to the corresponding measurements based on the reference station's known position, the satellite's position, and the behavior of its clock as determined from the broadcast navigation message. The corrections are adjusted for reference receiver clock offset but not for ionospheric or tropospheric delay. In other words, the pseudorange correction of Message Type 21 is very similar to a Message Type 1 or 9 correction used for DGPS but has additional measurement quality information and can be used to support dual-frequency receivers.

To avoid large biases, the integer whole

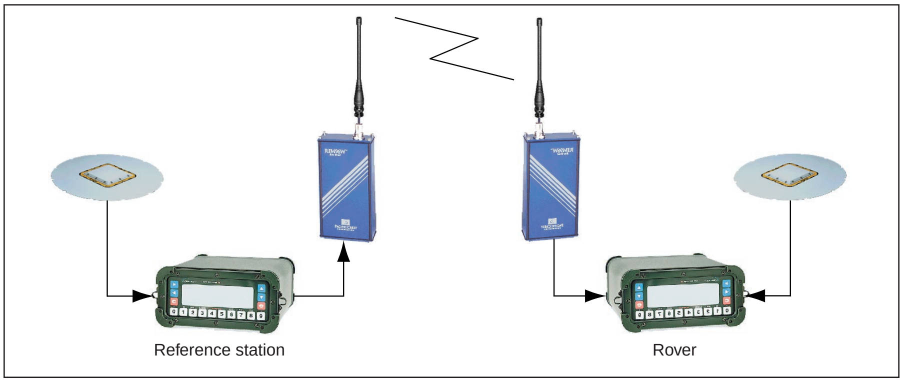

Figure 2. In RTK positioning, a GPS reference station transmits carrier-phase and pseudorange data over a radio link to a roving station. Either single- or dual-frequency GPS receivers can be used, with the dual-frequency systems typically affording faster ambiguity resolution and higher positioning accuracies over longer distances. (For more information about radio link and RTK GPS equipment manufacturers, consult the *GPS World* Buyers Guide, June 1998, or online at <http://www.gpsworld.com>.)

cycle carrier-phase ambiguity at the initial epoch is reduced to a small value in the Message Type 20 carrier-phase corrections.

The Message Types 18 and 19 pair is intended for use in double-differencing algorithms, whereas the 20 and 21 pair is meant for processing undifferenced data. Although there are several advantages to its use, this latter pair of message types seems not to be used as much as the former.

RTCM SC-104 published Version 2.2 of its standard in January 1998. Message Type 22 was added to further support RTK. This message type provides additional corrections to the reference station antenna information provided in Message Types 3 and 32 used for pseudorange differential GPS and GLONASS operations respectively. Some GPS receiver manufacturers have also devised their own proprietary formats for RTK use as an alternative to the RTCM SC-104 standard.

RTK SYSTEM ARCHITECTURE

In an RTK system, both the reference station and roving station consist of a single- or dual-frequency GPS receiver, the associated antenna, a data radio (sometimes called a radio modem), and its associated antenna (see Figure 2). Typically, users employ identical GPS receivers and data radios at the base and roving stations, although one must obviously use the reference station data radio for transmitting and the roving station data radio for receiving. High-power transmitters and less costly receive-only radios are available. Often, the transmitting antenna has higher gain than the receiving antenna, although it is common for both to be omnidirectional whip antennas. Sometimes users opt for "rubber duck" (helical, quarter-wavelength) antennas for receiving and low-power transmitting.

Some RTK systems integrate the GPS receiver and data radio into one package, with the GPS and radio link antennas even sometimes sharing a common enclosure.

To achieve the best results, the reference station GPS antenna should be mounted in a location free, as much as possible, of multipath and, as we'll discuss in the next section, the radio link antennas should be as high as possible to maximize the link's coverage.

Some RTK installations use combined GPS/GLONASS receivers at the reference and roving stations. Using GLONASS data in addition to GPS can provide faster ambiguity resolution and higher positioning accuracies. We'll discuss this a bit more later on.

THE DATA LINK

The data link used to support RTK operations is usually a radio channel of some sort, although an optical data link could conceivably be used in some environments. For RTK operations that carry out double differencing using Message Types 18 and 19, the data must be updated every 0.5–2 seconds, rather than the more leisurely 10 seconds or more used with code differential operation. So, whereas the RTCM SC-104 messages for code DGPS are typically transmitted by marine radionavigation beacons at 200 bits per second (bps), the data links for RTK use need data rates of at least 2,400 bps and preferably 9,600 or even 19,200 bps. The bandwidths required to support such data rates can be found in the VHF and UHF part of the radio spectrum.

In North America and in some other jurisdictions, frequencies in the VHF band from 150 to 174 MHz and in the UHF band from 450 to 470 MHz may be licensed for RTK radio links. Typically, narrow-band FM and some kind of frequency-shift-keying is used with packetized data transmission. Both 2-watt and 35-watt transmitters are commonly available. In North America, the 902–928-MHz (Industrial, Scientific, and Medical — ISM) band can be used without a license, but transmitter output is limited to 1 watt with restrictions on maximum antenna gain. In this band, the typical transmission mode is phase-shift-keyed direct sequence or frequency-shift-keyed frequency-hopping spread spectrum.

Propagation Distances. Because RTK data links operate at VHF/UHF frequencies, their use is limited, for the most part, to line of sight with the maximum distance, *d*, in kilometers that can be theoretically achieved given approximately by

$$d = 3.57\sqrt{k}\left(\sqrt{h_t} + \sqrt{h_r}\right)$$

where h_t and h_r are the heights in meters of the transmitting and receiving antennas above their common horizon. In many cases, the heights may be approximated as heights above average terrain. The term k is the effective earth radius factor that accounts for the fact that the distance to the radio horizon is normally longer than the distance to the geometric horizon because of atmospheric refraction. A typical value for k in temperate climates is 1.33 (k depends on the vertical gradient of refractivity near the earth's surface and normally varies from about 1.2 to 1.6, depending on weather conditions).

For a transmitting antenna at 30 meters above the terrain and a receiving antenna at 2 meters, the computed maximum propagation distance is 28 kilometers. It can be difficult to achieve such maximum distances in practice. Any obstructions along the propagation path will affect the signal's range. Signals might be blocked or reflected by buildings or other objects, diffracted over and around mountain peaks and ridges and the corners of structures, or even travel much longer distances than normal because of anomalous atmospheric ducting.

Predicting Signal Path Loss. Furthermore, even in the absence of obstructions, the signal suffers an attenuation, according to the inverse square law, as it spreads out from the transmitting antenna. This is the so-called *free-space loss*. But in addition to the direct path signal, the receiver often obtains a signal that is reflected from the ground and combined with the direct-path signal. So, the total signal path loss depends on several factors, including ground reflection characteristics, terrain, and the presence of buildings and other structures.

It is difficult to accurately predict the path loss unless one has a detailed description of the environment through which the signal travels. Researchers have, however, developed a number of empirical models that attempt to predict path loss. One of the simplest and often used comes from John Egli, a radio engineer who worked at the U.S. Army Signal Engineering Laboratory at Fort Monmouth, New Jersey, and who introduced it in 1957. The predicted loss in dB is given by

$$L = 88 + 20\log f - 20\log h_t - 20\log h_r + 40\log d$$

where the frequency, *f*, is given in MHz, the antenna heights in meters, and the distance in kilometers. Note that the signal power decays with the fourth power of distance.

Using the antenna heights of our earlier example, a 450-MHz signal is attenuated by about 146 dB at a distance of 10 kilometers. This means that the received signal is some 146 dB weaker than the transmitted signal. If the transmitter has an output power of 2 watts to an isotropic antenna, the received power at an isotropic antenna 10 kilometers away is –143 dBW, or 5×10^{-15} watts. Power losses in the antenna cabling at the transmitter and receiver sites also affect the received signal strength. And whether or not a received signal can be successfully detected and used depends on receiver sensitivity.

Continuing with our example, let's say that the antennas used are omnidirectional with 3 dB effective gain and that the cables between the transmitter and its antenna and the receiver and its antenna both have losses of 1.8 dB. If the receiver sensitivity is 12 dB SINAD (the ratio of signal plus noise plus distortion to noise plus distortion — a common sensitivity measurement associated with FM receivers; 12 dB characterizes a nominally healthy signal) for a 0.45-microvolt signal delivered by the antenna, the required signal level is –144 dBW.

Analyzing the Link's Viability. In determining whether or not a link can be used reliably, one must take into account the fact that various parameters governing the received signal strength may fluctuate, which could result in fading. If the signal becomes too weak, then bits in the digital message will be lost (although forward-error-correction techniques can be used to help overcome brief signal dropouts). To compensate for such an eventuality, link analysis computations include a conservative fade margin — 18 dB is typical for digital links.

So, continuing once again with our example, can our 2-watt transmitter reach a distance of 10 kilometers with a usable signal? Let's add up the gains and losses:

$$\begin{aligned} P_r &= P_t - C_t + G_t - L - FM + G_r - C_r \\ &= 3\text{dBW} - 1.8\text{dB} + 3\text{dB} - 146\text{dB} \\ &\quad - 18\text{dB} + 3\text{dB} - 1.8\text{dB} \\ &= -158\text{dBW} \end{aligned}$$

where P_t and P_r are the transmitted and received powers respectively, C_t and C_r are the cable losses at the transmitter and receiver respectively, G_t and G_r are the transmitting and receiving antenna gains respectively, L is the path loss, and FM is the fading margin. This signal is some 15 dB below the sensitivity threshold of the receiver and so, while the link might work some of the time, it would not be considered reliable. The maximum distance over which it can be considered reliable (with a path loss of 131 dB) is actually only 4.3 kilometers.

This range could be increased by boosting the effective radiated signal power by increasing the transmitter power, using a directional transmitting antenna, or increasing the antenna heights. A directional receiving antenna, although not always practical, could also help. Repeater stations can also be employed to extend the radio link's range.

The successful application of RTK hinges on the radio link's viability. In addition to possible dropouts caused by signal blockage, the signal might be lost because of interference from other users of the radio spectrum on or near the frequency of the link. Users can detect such interference by checking whether the rover's data radio status light is blinking when the reference station is not transmitting. One can also monitor the link frequency aurally with a scanner radio.

While a link typically ceases to work because its viable range has been exceeded, it may also not work properly if the rover is so close to the base station that its link receiver experiences signal overload. When initially testing a link, one should use a low transmitter power (if there is an option) with the rover a few tens to a hundred or so meters away.

RTK SOLUTIONS

Although the processing of the measurements made by the roving receiver and those received by way of the link could be carried out in an external computer, several manufacturers have programmed their receivers to produce RTK solutions internally.

When carrying out a double-difference solution, whether one uses pseudorange or carrier-phase data, processing software must match the time tags of the data from the reference station and the roving station. This does not pose a problem when postprocessing, because all of the data are available in computer files. However, in real-time operation, the data collected at the reference station reaches the rover after some delay. The data must be formatted, packetized, transmitted over the link, decoded, and passed on to the roving receiver's software. This cannot all occur simultaneously and so there is some delay, called latency, which, depending on the link data rate, might be upward of two seconds. This delay might be acceptable for some static-point surveying applications, but

Further Reading

For discussions about carrier-phase positioning including RTK operation and on-the-fly ambiguity resolution techniques, see

■ *Global Positioning System: Theory and Practice,* 4th revised edition, by B. Hofmann-Wellenhof, H. Lichtenegger, and J. Collins, published by Springer-Verlag, Vienna and New York, 1997.

For one of the first papers about RTK positioning, see

■ "Centimeters in the Field, a User's Perspective of Real-time Kinematic Positioning in a Production Environment," by N.C. Talbot, published in the *Proceedings of ION GPS-93, the 6th International Technical Meeting of the Satellite Division of The Institute of Navigation,* Salt Lake City, Utah, 22–24 September 1993, pp. 1049–1057.

For a more recent discussion of RTK positioning using the RTCM standards, see

■ "Real-time Carrier Phase Positioning Using the RTCM Standard Message Types 20/21 and 18/19," by J.B. Neumann, K.J. Van Dierendonck, A. Manz, and T.J. Ford, published in the *Proceedings of ION GPS-97, the 10th International Technical Meeting of the Satellite Division of The Institute of Navigation,* Kansas City, Missouri, 16–19 September 1997, pp. 857–866.

For a description of RTCM standards, see

■ *RTCM Recommended Standards for Differential GNSS (Global Navigation Satellite Systems),* Version 2.2, RTCM Paper 11-98/SC-104-STD, by RTCM Special Committee No. 104, Radio Technical Commission for Maritime Services, Alexandria, Virginia, January 1998.

Past "Innovation" columns on the topic of carrier phase ambiguity resolution include

■ "Why On-the-Fly?" by S.R. DeLoach, D. Wells, and D. Dodd, published in *GPS World,* Vol. 6, No. 5, May 1995, pp. 53–58.

■ "Comparing GPS Ambiguity Resolution Techniques," by S. Han and C. Rizos, published in *GPS World,* Vol. 8, No. 10, October 1997, pp. 54–61.

For a Web-based introduction to RTK GPS with application to hydrographic surveying, see

■ <http://www.usahydrosoc.org/RTK.htm>.

it might not be for some kinematic surveys or for vehicle navigation.

In situations requiring minimal data latency, such as high-speed navigation and machine control, the rover can extrapolate reference station measurements to the epoch of its own current measurements with an appropriate filter before carrying out the double-difference algorithm. This approach induces errors in the double differences at the centimeter level for data link latencies of one second. Alternatively, an approach similar to that used for standard differential pseudorange positioning can be used where the reference station transmits carrier-phase *corrections*. Because the corrections change much more slowly than the raw phases, an error in the correction caused by its delay is less serious. Using this method can reduce solution latency to less than a quarter of a second, but accuracies are typically limited to a few centimeters at best.

Any cycle slips occurring in carrier-phase data will degrade positioning accuracy. The roving receiver software should contain algorithms to detect and repair these in real time.

Resolving Ambiguities On-the-Fly. The key feature enabling the high accuracies afforded by RTK operation is the ability to determine the carrier-phase integer ambiguities while the rover is in motion. If the processing software simply estimates the ambiguities as real values, that is, floating point numbers, the resulting so-called float solutions will have accuracies that can range from the meter level to the decimeter level depending on how long the rover has been tracking the GPS signals. Researchers have devised a number of algorithms for determining or resolving these ambiguities "on the fly (OTF)." Generally, pseudorange observations are used to narrow down the ambiguity search space. This procedure reduces the number of integer combinations to be tested. The more precise, or low noise, the pseudorange values are, the smaller the search space and the faster the solution.

Many OTF implementations use the wide-lane combination of L1 and L2 carrier-phase data. Although noisier than L1 data, the wide-lane combination has an ambiguity of 86 centimeters, which is much easier to resolve than the L1 19-centimeter ambiguity. A resulting position from the wide-lane combination can be used to directly compute the L1 ambiguities. OTF approaches include the ambiguity function method, the least-squares ambiguity search technique, the fast ambiguity resolution approach, the fast ambiguity search filter, and the least-squares ambiguity decorrelation adjustment (Lambda) method. (See Hofmann-Wellenhof et al., and Han and Rizos, listed in the "Further Reading" sidebar, for details about these approaches.)

The speed with which ambiguities can be fixed depends on several factors, including the number of satellites tracked, satellite-receiver geometry, use of pseudorange data in addition to carrier phase, observation noise, and use of dual-frequency observations. Under good conditions, fix times can be shorter than one minute and optimally, less than 10 seconds.

GLONASS Advantages. Typically, the more common satellites the reference and roving receivers track, the faster the integer-fixing procedure and the higher the positioning accuracies. This benefits systems that use GLONASS signals in addition to GPS signals. However, dual-frequency GPS-only systems generally have the edge on single-frequency dual GPS/GLONASS systems on baselines longer than a few kilometers or so.

Dual GPS/GLONASS systems are also advantageous in areas with reduced sky visibility such as open-pit mines, urban canyons, and river valleys (although the radio link can require special attention in such areas).

One can achieve the best RTK results with the reference station and rover tracking the same eight or more satellites with a PDOP of 2 or less. Good results, however, can be attained with two receivers tracking five common satellites with a PDOP (position dilution of precision) of 4 or better.

Incidentally, RTK processing algorithms typically use a filter that requires an approximate estimate of the roving receiver's expected dynamics — velocities and accelerations. Sometimes these are expressed in such familiar terms as static, walking, automobile, and aircraft. Specifying an inappropriate value can result in less accurate solutions.

CONCLUSION

RTK GPS is one the latest additions to the kitbag of GPS positioning techniques. Almost any application requiring real-time positioning accuracy from millimeters to decimeters can benefit from this technique. Applications include aircraft navigation, machine control, and engineering, construction, and hydrographic surveying — to name but a few. Although RTK is the latest word, or should we say acronym, in GPS positioning, it will not be the last. Scientists and engineers will continue to invent faster, more accurate, more convenient, and more reliable ways to use GPS in navigation, surveying, and a host of other areas, some of which we haven't even dreamt of yet. ■

SYSTEM OPERATION

continued from page ***68***

Aviation Administration's GPS Wide Area Augmentation System, Local Area Augmentation System, and the European Geostationary Navigation Overlay Service.

The steps in recorded phase definitely appear to be satellite-related and confined to those GPS Block II SVs with SA.

SEEKING A SOLUTION

The oldest GPS Block II satellite is only nine years old, so we can expect these anomalies to persist for many years to come if no corrective action is taken. The anomalies are significant for any GPS users who require continuous service provision or near-real-time position, velocity, or time at the 1-meter accuracy level. When postprocessing differentially with no latency, the step effect will not be observed; but most differential GPS users rely on a real-time link that may have many seconds of latency. Loss of signal lock could pose a serious problem in applications involving real-time precision approach and landing, time transfer, and surveying, among others.

ISN has maintained GPS carrier-phase observation data using a receiver of its own design since January 1, 1995. The institute intends to publish a fuller account of its findings early in 1999. ISN has developed a method for identifying and excluding (in near real time) measurements affected by the phase steps and is willing to cooperate with the U.S. Departments of Transportation and Defense to explain and resolve these anomalies. ■

MANUFACTURERS

The **Institute of Satellite Navigation** at the **University of Leeds,** United Kingdom, made its observations using a 1 SPOT, 20-channel receiver from the University of Leeds, two Ashtech GG24 receivers from **Magellan**'s **Ashtech Division** (Sunnyvale, California), and a Trimble 4000 SSE from **Trimble Navigation** (Sunnyvale).