GPS SURVEYING TECHNIQUES

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GPS surveying is no longer a method of the future. The new generation of GPS instruments is bringing about a price revolution. As these more reliable and less expensive instruments become available, their cost and accuracy will challenge that of conventional control surveying. The time to understand this new technology has arrived.

DURING THE past three years, the Global Positioning System (GPS) has been used by the U.S. National Geodetic Survey (NGS), the Texas Highway Department and at least two private firms to establish thousands of high-order geodetic control points. Even though the cost of most GPS equipment is high (over $100,000 each), the technique is so highly productive that the per point cost for establishing control is a fraction of the cost of conventional surveys.

The first GPS instrument to be used for control surveying was the Macrometer™ V-1000. This instrument has the capability of determining a point's precise co-ordinates without relying on any of the special codes broadcast by the GPS satellites and is therefore often referred to as a codeless receiver. For the past year, the TI 4100 GPS instrument has also been used for precise control surveys.

Unlike the Macrometer instrument, the TI 4100 instrument relies on the codes broadcast by the GPS satellites and, for this reason, is classified as a code-correlating receiver. In fact, the TI 4100 instrument receives and decodes the P-code or precise code emitted by each satellite and is therefore strictly a P-code (correlating) receiver.

A third, lower-cost type of GPS instrument is now being introduced to the market. This new instrument is classified as a CA-code receiver because its operation depends on decoding the clear access code broadcast by the GPS satellites.

More detailed information about these receivers will be given in this article, but, first, a brief description of how GPS works is given for those readers who are unfamiliar with this new system.

How GPS Works

The concept behind GPS is quite simple even though some of the practical details are complicated. In reality each of the 18 satellites that will orbit the earth by the late 1980s is a "flying control point". The instantaneous X, Y and Z co-ordinates of each satellite can be computed with a moderate degree of accuracy (± 10 meters) using the satellite ephemeris associated with each satellite. More will be said about the ephemeris in the next section.

Because the X, Y, Z co-ordinates of each satellite are known (by computation), the co-ordinates of a ground point can be determined by measuring the ranges to at least three satellites. In practice, the ranges to a minimum of four satellites are measured because of the measuring technique used. When only one receiver is used to range to the satellites, a single or point position is determined. This is why the use of a single receiver is called point positioning. The accuracy of point positioning with GPS averages ± 10 meters, depending on a number of factors.

Most surveyors are interested in a second technique called differential positioning or translocation. When this method is used, one satellite receiver is placed over a point whose position is known while a second receiver is placed over a point whose co-ordinates are to be determined. The difference in co-ordinates between these two points can be determined to centimeter accuracy (plus 2 ppm of the distance between points) when sufficient data are observed.

Both the point positioning and translocation methods involve measuring the ranges to a number of satellites over a series of intervals from 2 seconds to several minutes. The point's co-ordinates or difference in co-ordinates are then computed by standard resection techniques. The various processing techniques will be covered in a later section.

The GPS satellites broadcast a spread spectral signal on two separate frequencies with wavelengths of 19 and 24 centimeters. The spread spectrum broadcast technique is used so the transmissions cannot be easily jammed. The system was designed by the military to modulate the base carrier with two codes that would contain ephemeris and time information. These modulations are the CA-code, which is available to all users, and the P-code, which will be restricted to military users.

GPS Orbital Data

Today, the greatest single problem in using the Global Positioning System is the uncertainty of receiving timely satellite orbital data (ephemeris). Two types of orbital data are currently in use: the broadcast ephemeris and the precise or post-fitted ephemeris. To compile these ephemerides, the Department of Defense (DoD) tracks the GPS satellites and computes a "best-fit" orbit by averaging several days' observations. The orbital data are periodically "injected" into each satellite's computer that, in turn, rebroadcasts a navigation message to users on the CA- and P-code modulation. This navigation message can then be used to compute accurate X, Y, Z satellite coordinates for any desired time, i.e. time of each observation. The formulas for computing the satellite orbits are the same as those discovered by Johannes Kepler in 1600. So although satellite surveying is new, its mathematical basis is quite old.

The X, Y, Z co-ordinates computed from the GPS broadcast navigation message are presently accurate to about ± 20 meters. The DoD has published a policy stating that they reserve the right to degrade the broadcast (CA-code) message so that the co-ordinates will be accurate to only ± 200 meters. The same policy also states that the P-code navigation message will maintain its present accuracy but access will be limited to specially authorized users.

The post-filled ephemeris determined by DoD uses several days (usually seven) of orbital data in a least-squares fit to compute the "best-fit" orbital elements. This GPS orbit data will be available to U.S. users through NGS for a nominal fee. At present, there is a two-week time lag before NGS receives the DoD data, so a three-week time lag before the information is available to the general public is likely.

NGS is also considering developing its own ephemeris service. The NGS would use two-frequency phase data collected at their Very Long Baseline Interferometry (VLBI) sites and compute its own GPS orbits, so there would be a delay of only a few days before data were received.

At present, Aero Service computes orbital data from a private tracking network and sells GPS ephemeris data to users of their Macrometer system. These data are generally available after a one-week delay. Aero Service has indicated it plans to have ephemeris data available with only a few days' delay.

To the author's knowledge no comprehensive test has been performed to compare the Aero Service ephemeris with the DoD ephemeris. The very limited comparisons performed by Geo/Hydro show that Aero Service ephemeris quality is at least as good and sometimes better than the DoD's precise ephemeris.

Instrumentation and Observations

There are currently three basic techniques for measuring from one to several centimeters using GPS. These are:

1. Precise-code ranging to satellites.
2. Radio interferometry or ambiguous pseudoranging.
3. Reconstructed modulation code (SERIES).

The first technique is conceptually the simplest. The GPS satellites broadcast the P-code at specific regular time intervals so that, in a sense, they broadcast precise time signals. If the land-based GPS receiver were connected to an atomic clock set to Universal Time (UT), the true range to each satellite could be computed by multiplying the elapsed time between a pulse transmission and its reception by the speed of light. In practice, GPS receivers employ a crystal oscillator (clock) that keeps highly accurate time but has a constant offset to UT. These receivers measure the true range plus some unknown constant length (called pseudo range). This pseudo range is converted to a true range by measuring the distance to four satellites. These four pseudo ranges produce four equations in four unknowns (X, Y, Z and time offset) which can be solved by standard mathematical techniques.

An example of this type of receiver is the TI 4100 which receives the precise P-code clock pulses. Because it is able to decode the P-code, the TI 4100 can receive these time pulses on both the high- and low-frequency channels and thus is able to compute ionospheric corrections (the propagation delay due to the free ions in the outer part of the earth's atmosphere) to its ranges. This two-frequency capability is considered necessary for obtaining the best results over long (1000 km) lines. The major disadvantage of the TI 4100 is that access to the P-code will be denied in the next year or two (Block II satellites), a fact that obviates the instrument's advantages.

The second technique has been successfully used for the past three years. The Macrometer™ Interferometric Instrument employs the ambiguous pseudoranging principle. The Macrometer measures the instantaneous fractional phase of the 19 cm carrier broadcast by the satellite. This measurement is essentially an ambiguous pseudo range since it is composed of an unknown number of whole cycles plus a fractional (measured) cycle. When a large number (200) of these observations are made, a series of equations can be formed and the small number (seven) of unknowns solved for.

The Macrometer instrument operates in a codeless mode since is does not use any of the GPS broadcast codes. Observation periods of one hour typically yield results accurate to a few centimeters over ten-kilometer lines. It should be noted that the TI 4100 can also measure ambiguous pseudo ranges and produces results similar to the results obtained using the Macrometer.

The latest entries to the market are the CA-code receivers. These receivers decode the CA-code, which has an effective wavelength of 300 meters compared to the 30-meter length of the P-code. The present point positioning of these receivers is ± 20 meters; however, when they are used in the translocation mode, accuracies comparable to the Macrometer and TI 4100 are obtained. The CA-code receiver locks on to the 19 cm carrier and measures its instantaneous phase as well as recording the time. This time-tagged phase measurement is identical to the phase measured by P-code receivers and the Macrometer instrument. The advantage of the CA-code receiver is that precise (0.1 microseconds) time can be obtained from the coded time message, whereas the codeless instruments (clocks) must be synchronized prior to and checked after the observation period.

At the present time, the only operational CA-code receiver is the Trimble 4000S instrument. Testing by the Federal Geodetic Control Committee (FGCC) was held from February 11 to 28, 1986 and results of the test can be obtained from the National Geodetic Survey.

A second CA-code receiver (WM 101) was promised by Wild/Magnavox for delivery in January 1986 and had not yet been delivered as of this writing. The prototype instrument appears to be very well designed and is briefcase size for ease of transport.

The third technique was developed at the California Institute of Technology's Jet Propulsion Laboratory and is fully described in JPL Publication 84-16. A commercial version of the JPL SERIES receiver has been produced by ISTAC, Inc.

The SERIES technique essentially collapses the broadband spectrum of the GPS signal by a delay and multiply technique. This process recovers the P- and CA-code chipping rates so that phase-resolving circuits can measure their instantaneous phase. The SERIES technique requires no prior knowledge of the GPS coding; however, precise UT time and time synchronization between instruments (similar to Macrometer) are required. The equipment presently used (GPS 1991 and Model 2002) requires that the broadcast ephemeris be collected by a separate receiver such as the Trimble 4000A.

Of the receivers discussed, the TI 4100, Macrometer, WM 101, and Trimble 4000S all provide the time-tagged (20 cm) carrier phase as an output observable. The next section will discuss how geodetic co-ordinates are obtained from this measurement.

Computations

There are a number of mathematical models that can be used to solve the difference in co-ordinates (vector) between the GPS points. One method that has been employed for the TRANSIT satellite system of the past decade is to use the integrated Doppler count produced by the moving satellite. Although this Doppler solution produces reasonable (± 20 cm) results, the various solutions that use the instantaneous received carrier phase are much more accurate (± 1 cm).

There are three basic solutions that use the phase observable: the single- double- and triple-difference techniques. The single- and double-difference solutions yield the most accurate results (millimeters) but are also the most labour intensive.

Single-differencing subtracts the received phase of a given satellite between survey sites. Double-differencing subtracts the received satellite phases between sites and between satellites. Triple-differencing additionally subtracts the phase between epochs. A more complete description of these techniques can be found in *Surveying With GPS*, Monograph 9, School of Surveying, The University of New South Wales, Kensington NSW, Australia.

When obstructions at a survey site or equipment malfunctions cause a loss of lock of the satellite signal, a cycle slip occurs. These cycle slips must be manually (interactively) corrected during processing when the single- or double-difference technique is used. This procedure can be quite time consuming and significantly increases the difficulty of processing GPS data. Some efforts have been made to automate this process, but none are in common use today.

The triple-difference technique generally produces less accurate results (1:100,000) than the single- and double-difference techniques. This disadvantage is offset by the fact that the triple-difference technique is insensitive to cycle slips so that data can be processed in a "hands-off" batch mode. For large projects, a first-pass processing by the triple-difference technique to obtain relatively good site co-ordinates followed by a single-difference solution will yield optimum results for a minimum of effort.

Practical Considerations

The visibility of the GPS constellation varies widely throughout the world. In some areas, it may be possible to obtain only one point per day with a pair of receivers due to the limited time the satellites orbit that area. Fortunately, the satellite coverage in the U.S. is excellent so that the maximum number of points can be established.

Consider that there are three GPS instruments available for a given project. At the beginning of the survey, one receiver would be placed over a point of known co-ordinates while the other receivers would be placed over points whose co-ordinates were to be determined. These two receivers are often called "roving" receivers in contrast to the fixed receiver placed over the control point. With the present satellite constellation, two to three points can be established per day per roving receiver. In the three receiver case, six new points could be established in a day if the drive times between points were limited to 30 minutes or less. To accomplish this level of productivity, the first and last observation periods may be one hour or longer while the mid period would be 30 minutes.

When equipment manufacturers quote performance specifications, they normally describe accuracy and length of observation for the mid time of the GPS constellation passage. This optimum time with the greatest number of satellites gives the best results for the briefest observation times. During the early and late portions of the constellation passage, there are periods when only three satellites are available. If the proper software is used, centimeter accuracies can be obtained during these (suboptimal) periods by extending the observation period. Care must be exercised since some software in present use provides a solution only if four satellites are observed.

In my opinion, software is the most critical part of any GPS system. Naturally, instruments are important but as time passes, I believe that the hardware will improve faster than the software.

Summary

The new generation of CA-code receivers now being introduced will bring about a price revolution in the GPS field. More reliable and less expensive instruments that output the time-tagged carrier phase will provide results comparable to the accuracies achieved by current more costly receivers.

The present per point cost for establishing second-order horizontal control with GPS is between $500 and $800 per point. As more satellites become available and equipment costs decrease, this cost will dramatically decline so that GPS is cost competitive with conventional control surveying. We still have a long way to go, but the pace of technology seems to increase with the passage of time.

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Antennas Now Critical

With the advent of CA-code receivers that output the carrier phase, the accuracy of the antenna being used has become critical. The reason for this is that these instruments are virtually capable of millimeter accuracy; however, some antennas' electrical centers vary by as much as a centimeter from the geometric center. This may not seem too important unless one considers that the azimuth between two closely spaced (1000 m) points can be accurately determined by GPS if the proper antenna is used.

Three basic antenna types are presently being used by various GPS instrument manufacturers; the dipole, the helix, and the micro-strip. The dipole antenna used by the Macrometer instrument is probably the most accurate one in use, and tests show its electrical center is virtually identical to its geometric center. A number of helix antennas are presently being used. The type used by Trimble Navigation for their 4000A receiver has demonstrated a variability of about one centimeter between the electrical and geometric centers.

Finally, the micro-strip antenna has been extensively tested (by an independent testing laboratory) and found to have a stable electrical center (within a few millimeters).

The antenna system that produced the best results included a 60 cm x 60 cm absorbing material collar that surrounds the antenna. This micro-strip antenna system (including absorbent collar) is less bulky and lighter than the rather cumbersome dipole antenna.

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