GPS: A Multipurpose System

David Wells and Alfred Kleusberg

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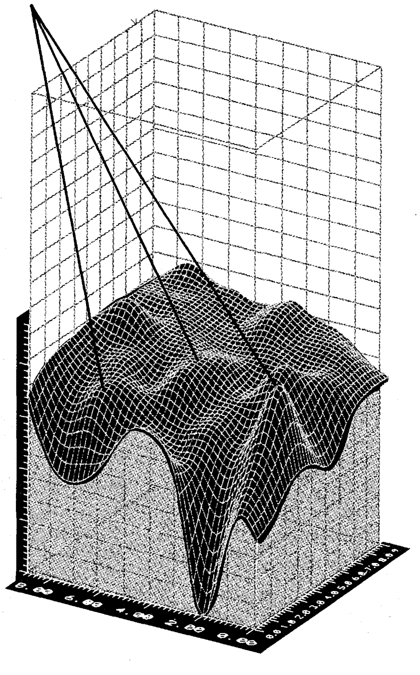

"Innovation" will be a regular column in GPS World *and will comment on GPS technology, product development, and other issues and needs of the GPS community. Coordinating editors are **Alfred Kleusberg**, PhD, and **Richard Langley**, PhD both of the Department of Surveying Engineering at the University of New Brunswick in Fredericton, New Brunswick, Canada, as is **David Wells**, PhD, co-author of this initial column.*

The first few columns will introduce GPS World *readers to GPS technology. This first column focuses on the many capabilities of GPS. The next column will look at the flip side – what are the limitations of GPS? "Innovation" will discuss some intriguing questions in future columns: Why is the GPS signal so complicated? How have surveyors been able to use it to get such accurate results? How serious is selective availability? We will also devote columns to exploring in depth some of the issues raised in this column: GPS and electronic charts; GPS and geographical information systems; and prospects for using GPS and GLONASS together. We welcome readers' comments and topic suggestions for future columns.*

GPS: A Multipurpose System

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Although the global positioning system was designed to meet some specific military requirements, it can be used in all sorts of unexpected ways. Here are three examples.

■ Consider the maiden voyage of the fictional *Exxon Valdez II,* built to demonstrate that her namesake's tragedy of March 23, 1989, need never happen again. We join the vessel a few years from now, as it approaches Europort, the port of Rotterdam and the busiest harbor in the world.

The navigating officer on the bridge is carefully watching an electronic chart display system, which is linked to a state-of-the-art GPS system. She can call up on the display a look-ahead prediction of the ship's track, based on GPS-measured position, speed, and heading of the ship, and can see how far the ship is from each of the known navigation hazards. The channel into Rotterdam is shallow, but the navigating officer can assure herself that the ship's keel will clear a certain shoal by finding out how much the ship is heaving up and down due to ocean swell and what the present tide reading is at the ship, both provided by GPS.

As the ship nears her berth, the officer calls up an enlarged display of the dock showing the position of both the bow and the stern of the ship. On a whim, she finds out from GPS how much the ship is rolling and pitching. Meanwhile, in a port administration building ashore, a vessel traffic controller watches a display showing all this information about the *Exxon Valdez II* and all other ships in Europort, obtained via radio links from each ship.

Is this maiden voyage of the *Exxon Valdez II* a pipe dream? Not at all. GPS has already been shown to be capable of providing each of these pieces of information, except for the tide reading. And the U.S. Army Corps of Engineers is currently sponsoring a project to show that tide readings accurate to better than a decimeter *can* be obtained from GPS. To make this fictional voyage of the *Exxon Valdez II* possible, all these features of GPS will have to be packaged into a state-of-the-art system like the one described here.

■ On October 18, the day after the Loma Prieta earthquake near Santa Cruz, California, GPS receivers were at work in the San Francisco Bay Area, measuring with centimeter accuracy how much the earth had moved. The California fault system is only one of several earthquake-prone areas around the world where scientists have been using GPS for the past four years, preparing to "capture" an earthquake like Loma Prieta. They use GPS to measure precisely the distances between a set of survey markers securely anchored in the ground on each side of a fault line. These measurements are repeated on a regular schedule before any earthquake occurs, to monitor very small changes in the local shape of the earth. Remeasurements immediately after the earthquake show just how the earthquake changed the shape of the earth.

From learning more precisely what actually happens just before and during earthquakes, scientists someday may be able to predict when the earthquake danger is high by analyzing the small "precurser" movements immediately before the earthquake. Continual monitoring of the network of survey markers by GPS could then become an earthquake-alarm system.

■ A call comes into Gotham City Emergency Central. There is a suspected gas main leak. A field team is dispatched with gas detectors and GPS receivers, both connected back to Emergency Central, via a dedicated radio link. There, the Emergency Response Controller turns to his geographical information system (GIS) computer graphics display.

The controller studies the network of gas mains in the area of the suspected leak. As the gas level and GPS position reports come in from the field team, the gas readings show up on his display. He locates the joint that is leaking and forms a plan of action. First he displays all the other utilities in the area: the rapid transit system, underground electrical power and telephone cables, water mains, sewers, traffic signal control cables, and the surface streets, sidewalks, curbs, and poles. The controller sees that only one place can be excavated near the leak that would leave all other city services undisturbed. He places a call to the excavation team and dictates precise instructions.

GPS has played two essential roles in this emergency response. When each of the utility networks were being assembled into the GIS, it was found, as usual, that each of the utilities had been mapped in a different way. For example, the set of survey markers used by the Gotham Power Company to survey its underground cables was not the same as the set used by the City Water Department, and later construction projects have destroyed most of the markers in each case. Simple resurveys using GPS were used to relate the different utility networks precisely to each other. The second role of GPS was to position precisely the gas detector readings from the field team in the same mapping system as the utilities, allowing the gas readings to be displayed directly on the GIS, greatly speeding up the response time.

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Although these three examples look to the future, each is based on capabilities that GPS has already demonstrated. GPS works by simultaneously measuring the distance from a GPS receiver to each of several GPS satellites. A variety of ways of making and using these measured distances have been developed, differing in accuracy and complexity. In the rest of the column, these capabilities of GPS are described as answers to a series of questions.

"Where Am I?" Military use of the GPS system employs the precise positioning service (PPS). PPS tells us where we are with errors less than 20 meters horizontally and 30 meters vertically, 19 trials out of 20. PPS also tells us how fast we are travelling and in which direction, with errors less than 0.1 meter per second, 19 trials out of 20. PPS is available to U.S. and allied military forces and to other authorized users under special conditions.

Anyone, authorized or unauthorized, is able to use the GPS standard positioning service (SPS). SPS is capable of telling us where we are and what our speed and direction is with errors that are about twice as large as the PPS errors. However, this is thought to be too high an accuracy to make available to any unauthorized user (including unfriendly military forces). Consequently, U.S. Department of Defense policy calls for SPS errors to be increased deliberately until they are up to about five times as large as PPS errors: errors of approximately 100 meters horizontally and 156 meters vertically, 19 trials out of 20. This process of deliberately increasing SPS errors, euphemistically called "selective availability," was seen by users for the first time during 1989.

SPS, like PPS, is available worldwide, 24 hours per day, under all weather conditions. This fact, together with its guaranteed 100-meter accuracy, is the main advantage of SPS compared with other navigational systems. Small, lightweight, relatively inexpensive SPS receivers are already available. At that level of accuracy, SPS is adequate for en route air navigation and for most ocean and coastal marine navigation, including recreational boating. When less expensive receivers are available, SPS should find wide use for other recreational activities such as hiking and biking.

"Where are you?" The SPS user is asking GPS to answer the question "Where am I?" With some help from a radio link to report GPS positions to a central office, SPS (and PPS) can also answer the question "Where are you?" Managers of transport fleets (of trucks, ships, planes, and boxcars, for example) want this question answered. The vessel traffic controller in Rotterdam wants to know this information as the *Exxon Valdez II* appears over the horizon.

GPS works by simultaneously measuring the distance from a GPS receiver to each of several GPS satellites.

"How far am I from you?" What happens if the question asked of GPS is "How far am I from Los Angeles?" GPS users in San Francisco are 35 times closer to Los Angeles than they are to the nearest GPS satellite. Even users in New York are five times closer. Many GPS errors, including selective availability, will be almost the same for users in all three cities, and can be made to cancel each other out. Thus, GPS can tell us how far we are from Los Angeles (or anywhere else) much more accurately than just simply telling us where we are, as long as we are able to use GPS measurements made in Los Angeles (or elsewhere), which contain errors similar to those in our measurements.

This way of using GPS is called differential GPS — we end up differencing the Los Angeles measurements from our own. Differential GPS positioning is up to 10 times more accurate than SPS, depending on how far apart the two GPS receivers are.

The *Exxon Valdez II* probably doesn't need anything better than SPS as she crosses the Atlantic Ocean. However, as Rotterdam looms on the horizon, the question "How far am I from Rotterdam?" becomes important. This example of differential GPS requires a radio broadcast from a fixed GPS monitor near Rotterdam, sending error correction information out to all approaching ships. This technique could also be used by aircraft on approach to land. An example for which neither receiver is fixed would be two ships approaching a midocean rendezvous, each asking the other "How far am I from you?"

"How far are you from me?" As the *Exxon Valdez II* moves closer to the approach channel into Rotterdam, the vessel traffic controller will want to know her position more accurately than 100 meters. If the GPS information radioed from the ship is changed from GPS positions to GPS measurements, those measurements can be combined with measurements being collected at the Rotterdam GPS monitor to obtain the 10-meter accuracy of differential GPS positions for the ship. The Gotham City gas leak field team used this method of GPS positioning as well. Similar applications of GPS have been proposed for both in-air and on-ground operations at airports.

"How far am I from you? Give it your best shot. I'm willing to wait." One of the reasons PPS is more accurate than SPS is that the electronic ruler built into PPS to measure distances to the satellites is 10 times as finely marked as the electronic ruler built into SPS. However, GPS has an even finer electronic ruler, called the "carrier phase," which is marked 150 times more finely than the PPS ruler. Although this ruler is very fine, the marks are not unambiguously numbered, as are the SPS and PPS rulers. This makes it complicated and time-consuming to use carrier phase measurements. The differential GPS technique is always used.

Until recently, many minutes or even hours of GPS measurements had to be collected without moving either antenna, in order to find out how to correctly mark values on the carrier phase ruler (technically known as resolving the carrier phase integer ambiguity). Surveyors have been using GPS carrier phase measurements for several years —

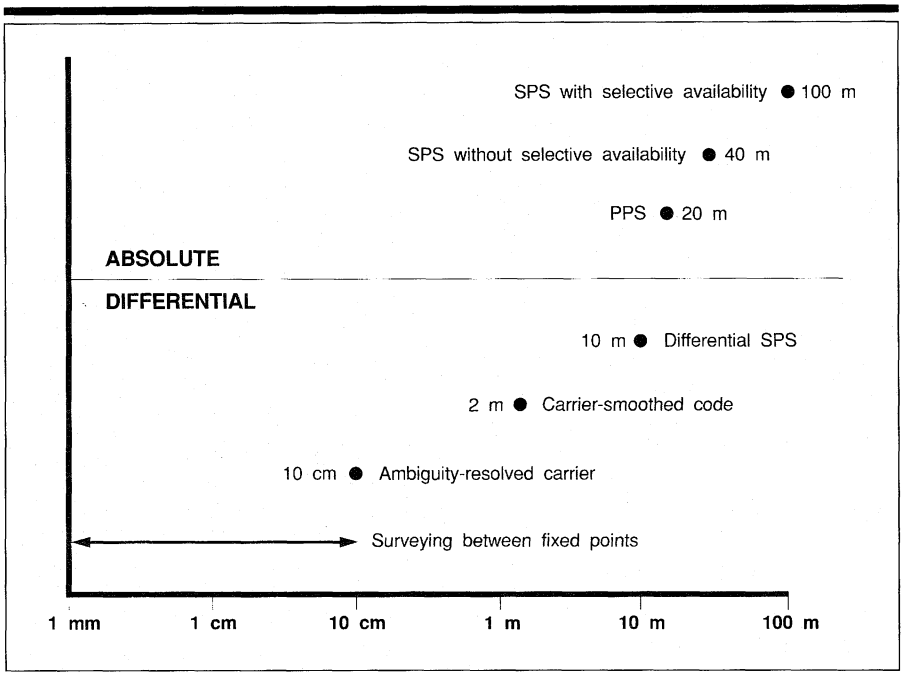

Figure 1: Positioning accuracies for different ways in which GPS can be used. Representative accuracies at the 95% confidence level are shown (typically 19 trials out of 20 will have accuracies better than the values shown). Accuracy of the differential techniques is dependent on the distance between the two receivers. The range of accuracies shown for surveying between fixed points represents various levels of care in accounting for errors.

for example, to position the networks of survey markers needed to map the utilities for Gotham City's GIS (typically centimeter accuracy over kilometer distances), to measure and remeasure the network surrounding the Loma Prieta earthquake (centimeter accuracy over tens of kilometers), and, in the future, to directly measure how fast the continents are drifting apart (centimeter accuracy over a thousand kilometers).

"How far am I from you? Give it your best shot. I need to know NOW." There are ways of partially using the fineness of the carrier phase ruler for navigation to help to smooth the coarseness of the SPS ruler. This improves differential SPS positioning accuracy somewhat, but does not approach the accuracy of carrier phase positioning itself. These techniques are called "carrier-smoothed code" positioning, and have been tested for some navigation applications such as hydrographic surveying — for example, to accurately map the channel which the *Exxon Valdez II* follows into Europort.

Recent ideas for resolving the carrier phase integer ambiguity without having to sit still for minutes or hours, if proven successful, will allow the accuracy of differential carrier positioning to be achieved immediately. Centimeter navigation will then be possible, permitting, for example, a GPS "tide gauge" to be carried on the *Exxon Valdez II.*

"Which way am I pointing?" If an array of three antennas is connected to an appropriately designed GPS receiver, the receiver becomes a three-dimensional orientation sensor. On the *Exxon Valdez II*, for example, the traditional gyrocompass has been replaced by such a GPS sensor for heading, roll, and pitch. Gyrocompasses are notorious for errors of as much as several degrees after a ship makes a sharp turn, but the GPS heading is always true to within a fraction of a degree. Other applications include determining the orientation of airborne and land vehicles.

GPS is the most accurate time transfer method available.

"What time is it?" One of the by-products of getting an SPS position fix is that a clock in the user's receiver is automatically synchronized to clocks in the GPS satellites to an accuracy of one ten-millionth of a second. Therefore, any GPS receiver is a very accurate time distribution device. Like differential positioning, differential time determination (called time transfer), using two receivers to measure GPS signals simultaneously, yields results that are about 10 times more accurate than those obtained from a single receiver. GPS is the most accurate time transfer method available, and has been used for several years to interrelate the time kept by the most accurate clocks in the world, located at national standards laboratories.

SUMMARY

At its simplest (and cheapest), GPS can tell us where we are on or above the earth's surface with an accuracy of about 100 meters. But GPS is capable of much more. The accuracies GPS can provide span five orders of magnitude, as shown in Figure 1. It will tell us how fast we are travelling, in what direction, and what time it is.

We can improve the accuracy of GPS by a factor of 10, if we are willing to make use of a second GPS receiver at a known fixed location. We can improve GPS accuracy by an additional factor of about 100 if we are willing to make use of the GPS signal carrier. Finally, we can precisely measure the attitude of our vehicle (pitch, roll, and yaw) if we are willing to use several GPS antennas mounted on the vehicle. ■