New Technology Aids Geophysicists

Geophysicists are listening in on a new military satellite system to determine precise positions on the earth with unprecedented ease

The Navstar Global Positioning System (GPS), a military satellite system intended to guide machines of war, has spawned the ultimate piggyback experiment. Civilian geophysicists have learned how to use the military satellite signals in a way unintended by the system's creators who still foot the $6 billion development bill and a $250 million annual operating budget. The technique allows the determination of relative positions across 1 kilometer or 1000 kilometers with a precision of 1 part per million. That is a 1-centimeter error in measuring the distance between points 10 kilometers apart. Researchers expect to have that error down to 0.1 centimeter in 10 kilometers within the next year or two. Such precision would be superior to that of classical surveying techniques, although costs based on the use of GPS should be only 1/20 as much.

With such precision, low cost, and mobility, geophysicists will be able to monitor the straining of the crust that precedes earthquakes, the shoving and wrenching that accompanies movement at tectonic plate boundaries, and the bulging that results from subterranean magma movement. Instead of making one measurement across the slowly spreading Atlantic, they might go to the spreading center itself on Iceland and map the changing strain on the rift as it pulls apart. Rather than being limited to showing that India is colliding with Asia, they might detail the way the rock responds kilometer by kilometer across the Himalayas.

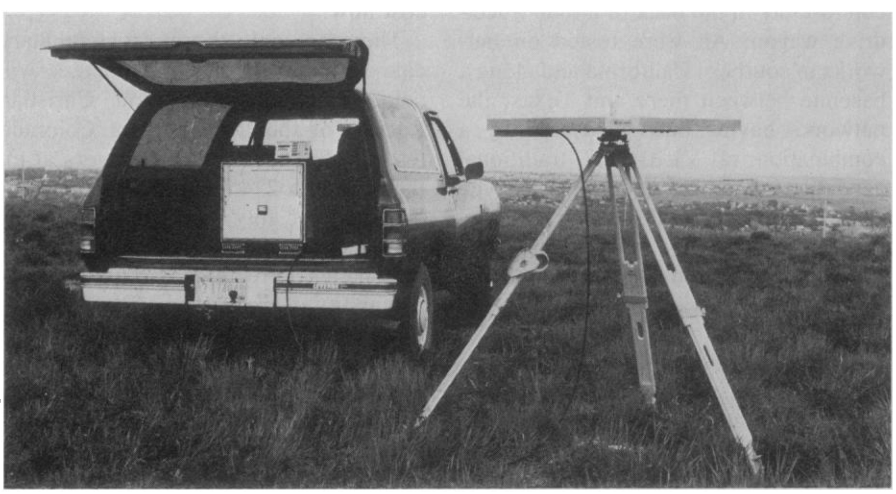
The Global Positioning System, as it is being developed by geophysicists and geodesists, is a low-cost hybrid of two complex and very expensive techniques for determining where you are on the face of the earth. The Navstar (Navigation Satellite Timing and Ranging) GPS, as the U.S. military will use it, will be a stunning achievement but will be of little use to geophysicists. Anyone having the proper satellite receiver—a bomber pilot, tank driver, or ship captain—will be able to determine his latitude, longitude, altitude, and velocity instantaneously at any time and at any place, usually with a position error of 10 meters. With that error, geophysicists would have to wait hundreds of years to measure changes along the San Andreas fault.

The other system contributing to the hybrid—very-long-baseline interferometry (VLBI)—is more than precise enough. It can measure between points a few thousand kilometers apart with a precision of 1 to 5 centimeters. But VLBI typically uses massive and quite immobile radio telescope dishes in order to pick up the faint signals of quasars at the edge of the known universe. Mobile VLBI's are used for geophysical positioning, but they are not all that mobile or inexpensive.

Traditional geodetic methods are less precise, more labor-intensive, and slower than VLBI, and they require that one point be visible from the other. To determine height differences, a surveyor sights a vertical bar 60 meters away through a telescope and then extends the leveling line 60 meters at a time, kilometer after kilometer. For horizontal distances, a network of surveyed triangles would be laid out away from a baseline measured by a metal tape. If trees or anything else blocked the view, observation towers would have to be built. The precision is 10 parts per million. Modern devices that measure distance with lasers can achieve better precision but are also limited to line-of-sight measurements.

The version of GPS most useful for geophysicists achieves high precision at low cost by ignoring the information in the satellite signals that is vital to their intended use and treating the signal almost as if it were the radio noise of a quasar. A conventional Navstar receiver decodes a satellite signal, determines from the signal exactly when it left the satellite (which carries four atomic clocks), and compares that time with the signal's time of arrival, which the receiver measures with its own clock. Given the speed of light, the distance between satellite and receiver is calculated. Observations of several satellites, 18 of which will be in the system by 1988, provide the receiver's position within 10 meters.

Instead of comparing time of transmission and time of reception, a pair of global positioning receivers intended for geodetic work compares the phases of a signal from the same satellite as received at two different sites. The phase difference between the signals is proportional to the separation of the sites. The time of broadcast need not be determined from the signal, so the instability of the satellite's clock cannot limit accuracy. This is the type of comparison made in VLBI between the radio noise received at two sites from a quasar, but in GPS the sources are far stronger (thus easier and



Aero Service

Plugging into the Global Positioning System

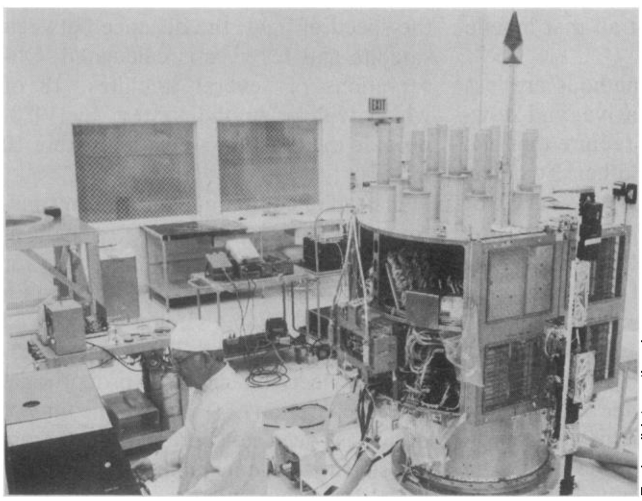
This Macrometer^{TM} surveying system manufactured by Aero Service can determine its position in three dimensions relative to a reference site to within 1 millimeter if the reference site is 1 kilometer away and to within 10 centimeters at a distance of 100 kilometers. The tripod holds an omnidirectional antenna for reception of GPS satellite signals.

cheaper to detect) and in 12-hour orbits about the earth. A pair of GPS receivers will usually make such observations of four or more different satellites in order to determine the relative positions in three dimensions of the two receivers.

Researchers are busily assembling GPS receiver systems and testing them in the field. One of the more comprehensive experiments was run by a group of U.S. agencies to test four different makes of civilian receivers. The tested models included the Macrometer™ receiver made by Aero Service, the first on the market; two receivers developed by the Jet Propulsion Laboratory, the prototype SERIES and the SERIES X; and the Texas Instruments TI4100, a commercial receiver that decodes the signal to provide absolute position in addition to high-precision relative position.

veyors who might otherwise have to inch through Amazonian jungles using traditional methods to lay out a road, but it will not do for geophysicists measuring crustal motion. They have a few problems to overcome yet. One of them is the signal's passage through the atmosphere, where its speed and thus apparent distance is altered depending on the signal's particular path through the moist lower atmosphere.

No one is certain whether water vapor will be a problem in high-precision GPS positioning, but most researchers are assuming that it will require a correction, at least under some circumstances. To make a precise correction they may need a water vapor radiometer that sights along the line to the satellite and measures the amount of microwave emission by the water vapor. One catch is that



Rockwell International

An artificial quasar for positioning

Eighteen of these 850-kilogram Navstar satellites will form the space component of the Global Positioning System. Much of its sophisticated equipment, including four atomic clocks, is superfluous when geophysicists use the satellite as a reference point for precise positioning, much as very-long-baseline interferometry uses distant quasars.

All the receivers consist of an antenna and electronics package, and all are easily transported, the Macrometer™ sitting comfortably in the back of a four-wheel-drive wagon. All were tested on networks in southern California and along a baseline between there and Texas, the networks having been measured by a combination of VLBI and traditional geodetic techniques. According to Clyde Goad of the National Geodetic Survey (NGS) in Rockville, Maryland, all the receivers measured distances ranging from 13 to 1300 kilometers—within observing periods of a few hours—with precisions of about 1 part per million. The results of most other experiments have been similar. With a special effort, William Strange of NGS has been able to obtain repeat GPS measurements in an experiment in Arizona that agree to within 1 to 2 centimeters over 45 kilometers, or 0.1 to 0.2 part per million.

A precision of 1 part per million obtained with GPS is exhilarating for sur-

such radiometers are still under development and cost about $150,000 each, which is as much as some GPS receivers cost now.

There are only the most preliminary data to suggest that radiometers will help. Randolph Ware and Christian Rocken of the University of Colorado tested radiometers with receivers at either end of a 22-kilometer baseline near Boulder last July while thunderstorms rattled through the area. Applying the radiometer corrections improved the repeatability of the baseline determination from 2 parts per million to 1 part per million, although longer observing periods might have accomplished the same error reduction. Whether water vapor radiometers will be useful under less unusual weather conditions remains to be seen.

The greatest limitation on GPS precision positioning is the less than optimum determination of the position of Navstar satellites. An uncertainty of about 20 meters in the position of a satellite 20,000 kilometers above the surface would seem quite precise, but that error limits positioning to the present 1 part per million level. Robert King of the Massachusetts Institute of Technology and his colleagues believe that they can improve the description of satellite orbits by reserving the VLBI technique. After precisely determining the relative positions of four VLBI sites by observing the fixed reference frame of the quasars, they are observing the satellites and fixing their positions relative to VLBI sites. When they reprocessed the interagency test data using the improved orbits, the precision improved from 1 to 0.3 part per million.

King and his colleagues believe that further refinements of satellite orbits can reduce the error to 0.1 part per million, the level geophysicists need to follow crustal deformation. The question is who will provide up-to-date, precise orbit information to civilian researchers. One possibility is a joint undertaking by the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, and the Defense Mapping Agency. A memorandum of understanding has been drafted and is now being reviewed by the agencies and the Department of Defense.

With increasing evidence in hand of sufficient GPS precision, geophysicists are putting together receiver systems intended for eventual fieldwork. A group at the Massachusetts Institute of Technology headed by Charles Counselman has six receivers on hand and plans tectonic studies here and abroad. The University Navstar Consortium, a group of university researchers chaired by Ware, expects to assemble three receiver-radiometer systems, test them, and make them available to the university community by 1987.

The U.S. Geological Survey is purchasing three receivers to test against networks now being measured by other techniques, primarily in seismically active parts of California. Testing will proceed without radiometers. And the Jet Propulsion Laboratory will be testing its SERIES X receiver and radiometers across the humid Gulf of California. JPL receivers will also be deployed to the Caribbean as part of a major tectonic study of the basin.—**Richard A. Kerr**

References

1. Abstracts for session G21, Intercomparison of Geodetic Measurements, of the fall 1984 American Geophysical Union meeting, *Eos* **65**, 853 (1984).
2. J. D. Bossler, *ibid.* **64**, 569 (1984).
3. C. C. Goad and B. W. Remondi, *Bull. Géod.* **58**, 193 (1984).