Continuous Monitoring of Crustal Deformation

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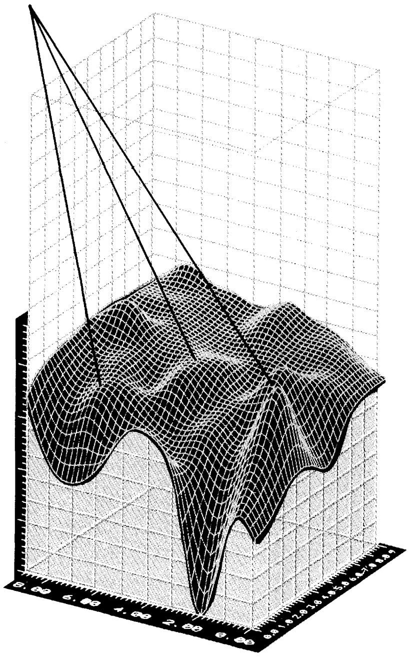

"Innovation" is a regular column in GPS World *featuring discussions on recent advances in GPS technology and its applications, as well as on the fundamentals of GPS positioning. This month, in a departure from our usual format, we feature an in-depth article on an application of GPS that is of great significance not only to scientists but to society as a whole: the monitoring of earthquake fault motion. The author is Dr. Yehuda Bock, an associate adjunct professor at the Scripps Institution of Oceanography in La Jolla, California, and staff scientist at the Jet Propulsion Laboratory in Pasadena, California.*

This column is coordinated by Richard Langley and Alfred Kleusberg of the Department of Surveying Engineering at the University of New Brunswick. As always, we welcome your comments and suggestions of topics for future columns.

The theory of plate tectonics tells us that the earth's surface is composed of about 10 large plates that are in relative motion. The plates move in three primary ways: (1) they slide past each other, (2) they pull apart, or (3) they push into each other with one being pushed underneath the other. The movement of these plates gives rise to large-scale features on the earth's surface, such as continents, ocean basins, mountain ranges, and volcanoes.

Earthquake belts coincide with the plate boundaries; for example, the boundary between the North American and Pacific plates in California produces as its primary expression the famous San Andreas Fault. This fault moves in the first way described earlier: one side slides past the other — a motion that is referred to as *strike slip* — at a rate of as much as 35 millimeters per year.

A geologic fault is a line of weakness in the rocks that make up the earth's crust. Rocks near the fault are under extreme stress. When these rocks fail, an earthquake occurs. That is, the elastic strain that has accumulated in the rocks is suddenly converted into ground motion, which often has catastrophic effects.

Earthquakes are therefore directly related to tectonic motion and crustal deformation. Space geodetic techniques, including very long baseline interferometry, satellite laser ranging, and, most recently, GPS, have been able to confirm by direct measurement the rates of motion of the tectonic plates inferred from geological observations. These rates can be as large as 150 millimeters per year in some parts of the world. Although the plates are rigid in their interiors and very little deformation occurs there, along their boundaries the plates are not rigid.

GPS has been particularly useful in measuring the more complex deformation patterns across plate boundaries. In California, for example, the plate boundary is not a single feature but a broad zone of deformation several hundred kilometers in width. Although much of the deformation — and more than 60 percent of the total motion between the North American and the Pacific plates — is taken up by the San Andreas Fault, numerous other active faults exist in California. Knowledge of these large-scale and regional-scale secular strain rates is important; however, it provides only an incomplete record of the earthquake process, because near the plate boundaries the deformation is not steady but cyclical in nature due to the buildup and release of stress.

THE EARTHQUAKE PROCESS

The accumulation and release of strain along a strike-slip fault is described as the earthquake cycle and is distinguished by two primary phases. In the first phase, the *coseismic,* the fault breaks during an earthquake, releasing the elastic strain accumulated since the last earthquake. The ground near the fault may move as much as several meters during large earthquakes. This part of the cycle has been best measured by seismic instruments that can determine the precise location (depth and fault geometry) and magnitude of the earthquake.

In the second phase of the cycle, the *interseismic,* the strain begins to accumulate again until the next earthquake. According to the elastic rebound model of the earthquake cycle, the ground near the fault moves very little during the interseismic period but moves dramatically during the coseismic period, while the ground away from the fault moves at a steady rate and is nearly unaffected during the earthquake.

Earth scientists would like to believe that there are two more distinct phases to the earthquake cycle. The *postseismic* stage, in which inelastic effects in the region near the fault cause crustal motion that is different from that during the interseismic period, immediately follows the earthquake. This kind of deformation gives insight into the rheology of the crust and the underlying mantle and may be crucial to understanding the physics of earthquakes.

The fourth, and most elusive, stage in the earthquake cycle is the *preseismic,* which occurs toward the end of the interseismic period and is manifested by anomalous variations in strain. These anomalies, if they exist, may serve as precursors in the prediction of earthquakes.

Geodetic instruments are restricted to measuring the surface deformation resulting from the subsurface movements of the crust associated with earthquakes. Nevertheless, the measurement of ground deformation across active faults is a direct way to observe and understand the different stages of the earthquake cycle. With this knowledge, earth scientists will be better able to forecast earthquakes and provide warning of impending seismic risk. Obtaining this insight into the earthquake process is the primary scientific motivation for continuous monitoring of deformation with GPS.

GPS MONITORING

The use of GPS to continuously monitor crustal deformation involves a fixed network of receivers tracking the GPS satellite constellation 24 hours a day. A central facility monitors the performance of the receiver network remotely and automatically collects data

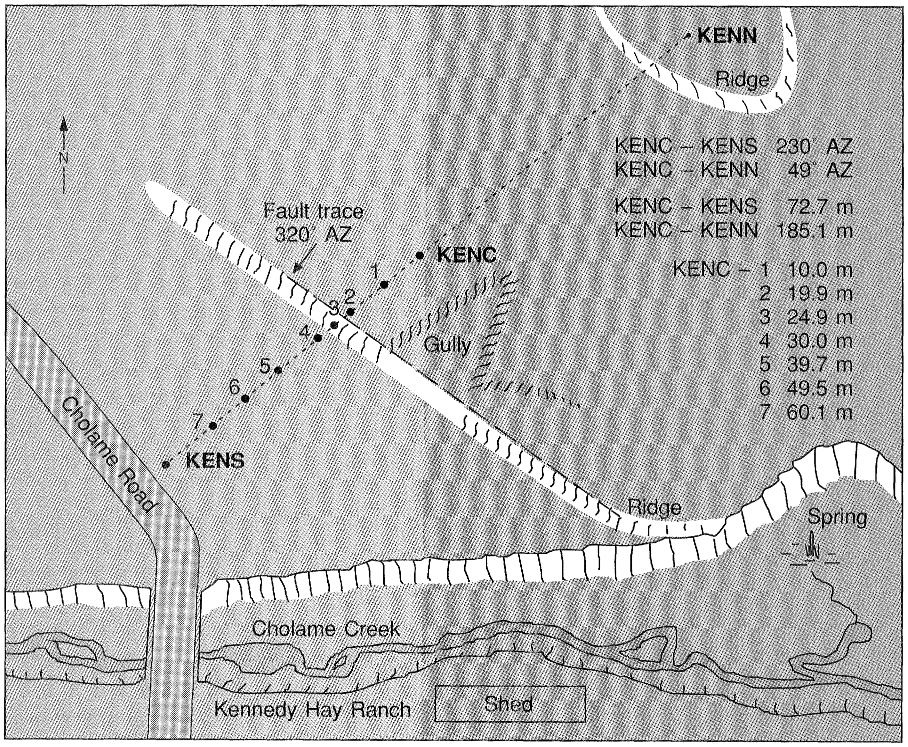

Figure 1. Sketch of the USGS Kennedy Ranch House alignment array, consisting of a 258-meter-long line of 10 points crossing the San Andreas Fault at a right angle

from all the sites via a high-speed communications link. The data are analyzed at the central facility to obtain accurate "snapshots" of the relative positions of the network stations. Significant variations in these positions indicate deformation within the network. The most fundamental challenge in operating such a network is to rapidly analyze and correctly interpret the data collected so that system operators can distinguish between actual crustal deformation and measurement noise due, for example, to systematic errors in modeling the GPS phase observables or to monument instability.

Continuous monitoring of deformation uses the same principle as the kinematic GPS technique. In kinematic GPS surveying, once integer-cycle ambiguities in the GPS signals are resolved between two receivers, one receiver remains fixed and the second receiver moves to a series of new points, which are surveyed very precisely with, typically, several minutes of observations. At each new site, only three parameters representing the three-dimensional position of the site need to be estimated from the accumulated series of doubly differenced (between satellites and between receivers) phase observations.

This technique is useful as long as four or more satellites are observed simultaneously and phase continuity is maintained. In continuous monitoring, all receivers are held fixed. Once the integer-cycle phase ambiguities are resolved, the kinematic problem becomes one of estimating the record of the earth's deformation by computing the changing positions of the stations very frequently. Thus, a fixed, continuously monitoring GPS baseline can operate as a meter to detect crustal strain.

This approach is very appropriate for small-scale networks spanning active geologic faults, because millimeter-level precision can be obtained for baselines of less than several kilometers in length. Although antenna multipath effects can cause excursions of several millimeters in positions determined from a few minutes of data, they tend to average out over several hours of measurements. Moreover, the multipath signature repeats from day to day so that it can be modeled and removed, as we show later on in this article. As the scale of the network increases, errors begin to accumulate primarily due to uncertainties in the satellite orbits and to tropospheric and ionospheric refraction.

The GPS orbital errors can be virtually eliminated by monitoring the orbits from regional and global tracking networks consisting of stations whose coordinates are well known (the fiducial tracking concept). Ionospheric effects can be removed by forming the ionosphere-free linear combination of L1 and L2 phase measurements (see "Ionospheric Effects on GPS" in the April 1991 issue of *GPS World*).

Tropospheric effects, particularly those due to water vapor in the atmosphere, are the most problematic, although they affect primarily the vertical component of the baseline. Stochastic modeling of tropospheric refraction, which takes into account the refraction's partially random behavior, has been useful in reducing the effects of this error. In the future, dense, continuously tracking networks of regional extent will be used to calibrate tropospheric (and ionospheric) errors. The data set collected by San Diego County, which surveyed a countywide high-precision network for three days in April 1991 using 32 simultaneously tracking GPS receivers, will be invaluable for testing this concept.

In summary, we expect that it will be possible to determine nearly instantaneous positions at several-millimeter accuracy for networks approaching regional scales (several hundreds of kilometers). The following example demonstrates the potential of continuous monitoring of crustal strain.

PARKFIELD ALIGNMENT ARRAY

The town of Parkfield, California, sits directly on the San Andreas Fault in a transition zone between the central creeping section and the southern locked portion of the fault. (Creep is near-fault motion that takes place in the interseismic period.) The Parkfield area has been the site of frequent quasiperiodic moderate earthquakes. Magnitude 5.5–6 earthquakes occurred in this region in 1881, 1901, 1922, 1934, and 1966, or, on average, every 22 years.

The next similar event has been predicted to occur in 1988, ± 5 years. Other investigators have estimated the earthquake time to be March 1991, ± 1 year, based on decreases in the rate of seismicity and geodetic baseline shortening since 1986. Consequently, Parkfield is an area of intense geophysical and geodetic investigation led by the U.S. Geological Survey (USGS).

During the last few years, the USGS has measured several alignment arrays along the fault near Parkfield using conventional surveying measurements. An alignment array is a line of closely spaced monuments crossing the fault at about a 90° angle. Such arrays are periodically surveyed to measure fault creep.

The Kennedy Ranch House alignment array 10 kilometers southeast of the town of Parkfield is shown in Figure 1. We surveyed the 10 points of this array with kinematic

GPS measurements in November 1990 and February 1991. We operated two receivers at the two ends of the array and used a third roving receiver to survey the intermediate points.

The receivers at the endpoints sampled dual-frequency phase measurements every second of a one-hour window during which more than five satellites were visible simultaneously. We used the full observation set to determine the integer-cycle phase ambiguities and the relative positions of the two endpoints. We then held these ambiguities fixed to integers and determined the relative position of the two points from each 1-second sample. That is, we used 10 to 12 doubly differenced measurements (5 to 6 each on L1 and L2) at each sampling instant to determine the three components of position.

The time series of positions is plotted in the upper panels of Figure 2 in terms of length and vertical components. We see clear systematic behavior in the positions, on which are superimposed higher-frequency fluctuations. The systematic signature is primarily due to antenna multipath effects, while the superimposed higher-frequency fluctuations are due to receiver measurement noise.

Because GPS orbits have periods of 12 sidereal hours, we view the same constellation of satellites every day, approximately four minutes earlier each successive day due to the difference between the civil 24-hour day and the sidereal day. By shifting the time series of positions by four minutes, we get almost complete correlation between the systematic signatures observed on successive days.

In fixed-point networks, therefore, we can easily remove most of the multipath contribution to position changes by correlating the daily time series. We have done this for the endpoints of the Parkfield alignment array. The remaining position changes are plotted in the lower panels of Figure 2. The fluctuations in position are now fairly random, with a root-mean-square (RMS) deviation of less than 1 millimeter for all three baseline components over the 15-minute interval displayed in Figure 2. The magnitude of these fluctuations is consistent with (double-differenced) receiver noise, which we know to be below the millimeter level.

The position measurements in November and February agree at the submillimeter level, indicating that over the three-month period between the surveys, the fault appears to be locked at the Kennedy Ranch House alignment array. Near the town of Parkfield, 10 kilometers to the northwest, however, fault creep is observed.

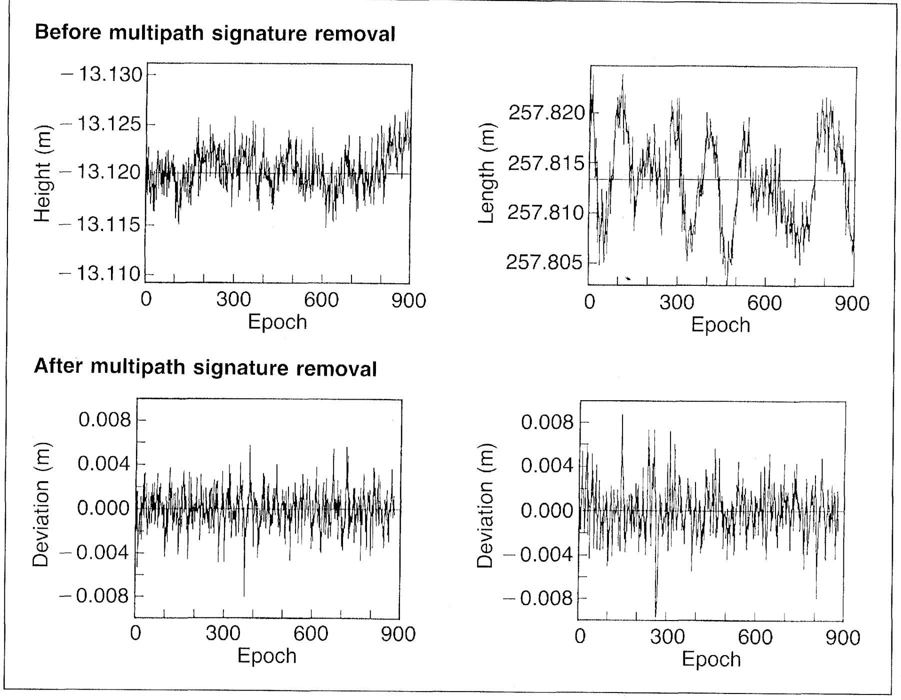

Figure 2. Variations in position every 1 second for the line between the endpoints of the Parkfield alignment array, for height and length before (top) and after (bottom) the multipath signature has been removed

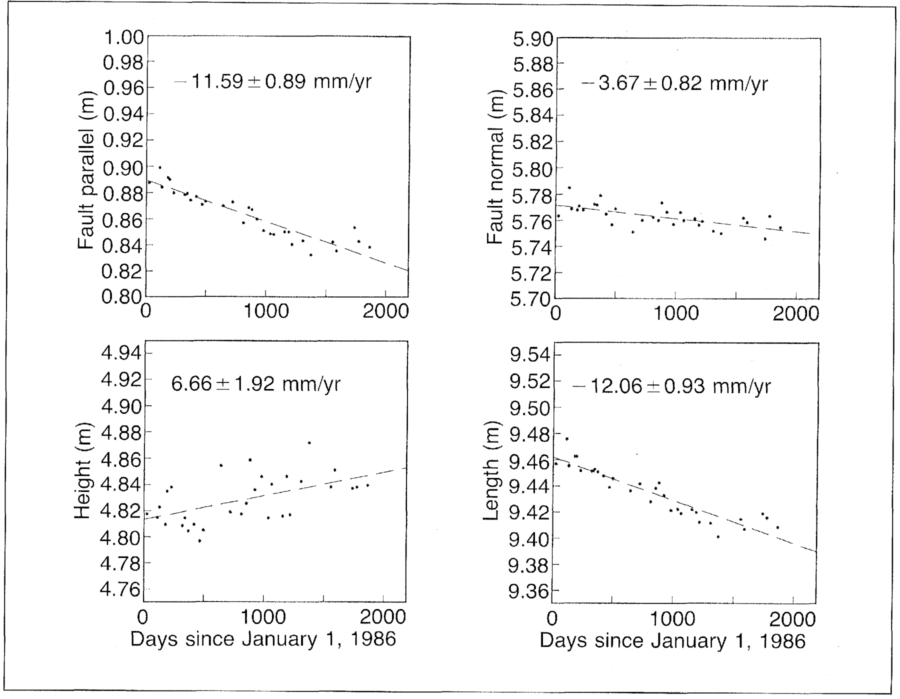

Figure 3. Time history of position for a 6.7-kilometer line across the San Andreas Fault from 1986–1991, for fault-parallel and fault-normal components, height, and length (leading digits are not shown in the vertical axis)

Creep on this segment of the fault occurs at a rate of about 10 millimeters per year. Figure 3 shows a time history of position for a 6.7-kilometer line across the San Andreas Fault from 1986 to 1991, for fault-parallel and fault-normal components, and height and length (the leading digits are not shown in the vertical axis). Each point has been determined from about 6 to 8 hours of GPS observations collected by the USGS since 1986 and by Scripps Institution of Oceanography (SIO) since 1990. Note the primarily fault-parallel (right lateral strike-slip) creep of 11.6 mm/yr, the smaller fault-normal rate of 3.7 mm/yr, and the height change of 6.7 mm/yr.

The results at the Parkfield alignment array are quite remarkable considering that — although we were very careful with tripod setup, tribrach calibration, and antenna orientation — we needed to break down the equipment between surveys. Furthermore, the measurements were performed with two types of dual-frequency C/A-code GPS receivers (and antennas). For fixed-point networks, the setup does not change and the monuments are more stable and permanent. This example demonstrates why earth scientists are so excited about using continuously monitoring GPS instruments for studying the earthquake cycle.

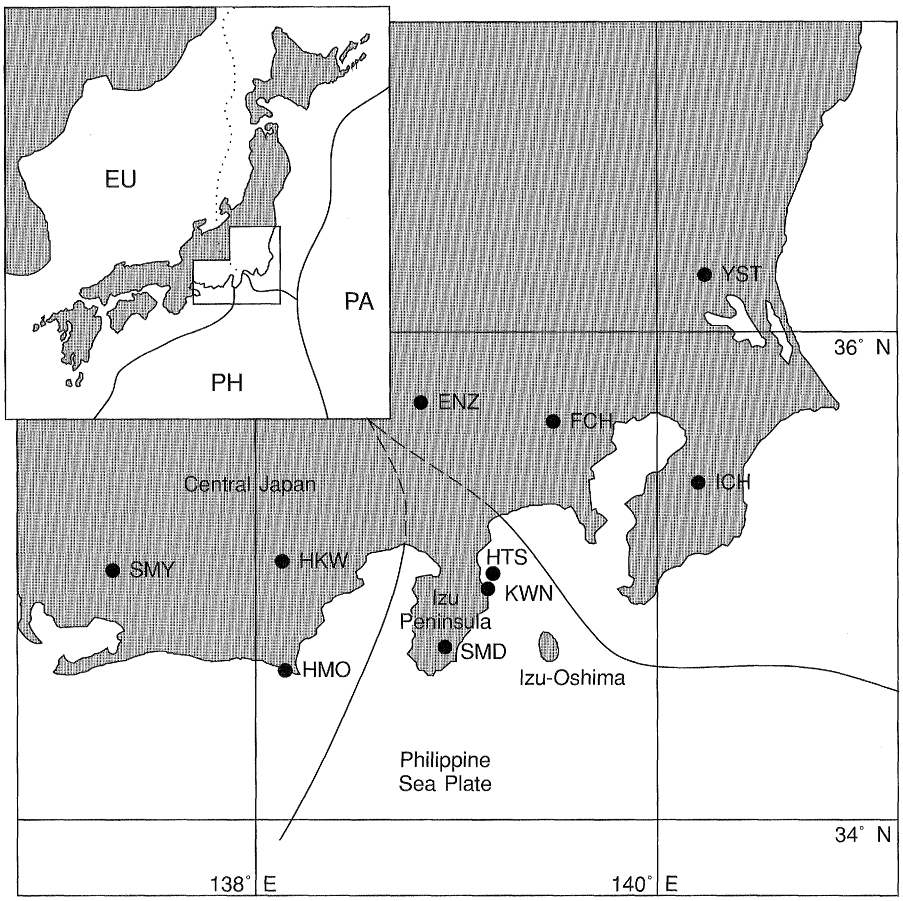

Figure 4. The 10-station NIED GPS fixed-point network in the Kanto-Tokai region of Japan where the Pacific, Eurasian, and Philippine Sea plates converge

A JAPANESE GPS NETWORK

Japan lies in the boundary zone between the Eurasian, Pacific, North American, and Philippine Sea plates. In the Kanto-Tokai area of central Japan, which includes the Tokyo metropolitan area, the Philippine Sea and Pacific plates converge against the overriding Eurasian plate. Two large earthquakes of magnitude 7 or greater are expected to occur along the boundary with the Philippine Sea plate in the next few years.

A 10-station GPS fixed-point network was established in April 1988 in Kanto-Tokai to monitor crustal deformation and the earthquake cycle. The network, established by the Japanese National Research Institute for Earth Science and Disaster Prevention (NIED), was the first continuously monitoring GPS array in the world. The stations are distributed with a spacing of approximately 100 kilometers over three different plate segments (Figure 4).

A GPS receiver at each site tracks all visible GPS satellites automatically every day. A comparison of 32 biweekly positions of the NIED network over a 16-month period between April 1988 and August 1989 reveals a clear pattern of crustal deformation associated with the subduction of the Philippine Sea plate in the Izu Peninsula. Remarkably, these results have produced estimates of significant deformation at a level of 1–3 cm/yr along regional-scale baselines with only 16 months of data. (Regional orbit improvement techniques were used to strengthen the precision of a very weak GPS satellite constellation over Japan — four satellites simultaneously visible with one visible only at a low-elevation angle.) These results indicate the benefit of frequent sampling of deformation.

The time series of positions measured over a typical baseline is shown in Figure 5. Note that there is no significant motion of the north and length components. There is a significant −30 mm/yr deformation in the east component. This indicates the westward movement of the Izu Peninsula related to the subduction of the Philippine Sea plate beneath the Eurasian plate.

In addition to tracking regional plate movement, data from this network revealed a precursory crustal deformation prior to a 1989 underwater volcanic eruption east of the Izu Peninsula. A deformation of about 14 centimeters was observed over a 10-kilometer baseline one week before the eruption. This is the first recorded precursory deformation observed with GPS.

SOUTHERN CALIFORNIA ARRAY

A Permanent GPS Geodetic Array (PGGA) has been operated as a NASA pilot project since the spring of 1990 by Scripps Institution of Oceanography and the Jet Propulsion Laboratory (JPL), with assistance from the California Institute of Technology, the Massachusetts Institute of Technology, and the University of California at Los Angeles. The PGGA network is designed to monitor crustal deformation continuously, in near real-time and with millimeter accuracy, using a fully automated and economically feasible system. The PGGA also provides reference sites for more-detailed GPS geophysical surveys and supplies precise GPS orbital information.

Every day at 00:00 UTC (Universal Time Coordinated) a personal computer at SIO invokes a series of programs that dial up the PGGA stations using high-bit-rate modems

The Scripps PGGA monument at La Jolla

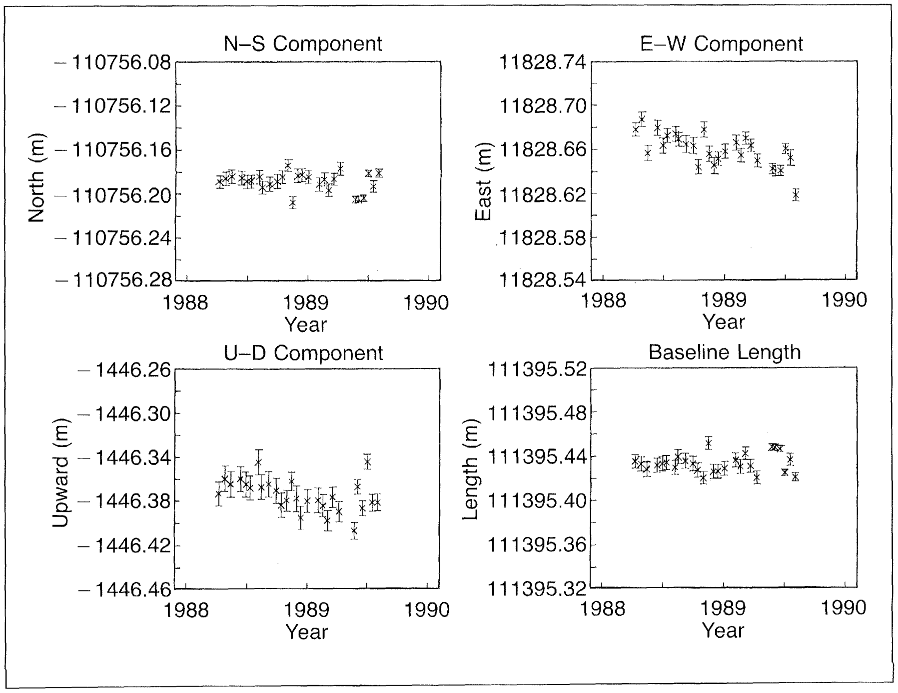

Figure 5. Biweekly time history of position for the ENZ-to-SMD baseline of the NIED network from April 1988 to August 1990

over commercial telephone lines, download the previous 24 hours of data, uncompress and reformat the data, and copy the data to a magnetic disk residing on a network of scientific workstations and to an optical storage device for archiving. Every day at 02:00 UTC one of the workstations invokes a program that copies, via electronic links, orbit-tracking data from the Cooperative International GPS Network (CIGNET) Data Processing Center at the National Geodetic Survey in Rockville, Maryland.

When all PGGA and CIGNET data reside on the magnetic disk, the same workstation invokes a series of programs that performs a simultaneous least-squares estimation of station positions and satellite orbits and plots the time series of changing site positions, including those from the last 24 hours of data. This process, which is described in more detail later, is performed automatically without any human intervention.

Network description. The 1991 configuration of the PGGA, including operational and planned sites, is shown in Figure 6. Each site consists of a GPS receiver system, a high-bit-rate modem, telephone and power lines, a backup battery on continuous charge, a shelter, and a stable monument.

We have chosen to use P-code GPS receivers for the network. The precise measurement of P-code pseudorange allows for automatic cycle-slip detection and repair in undifferenced phase measurements. This capability greatly enhances the efficiency of data processing because the data can be edited automatically site by site, satellite by satellite. In contrast, dual-frequency C/A-code receivers require a more cumbersome process of data editing that involves differencing phase measurements between satellites and stations. This process is difficult to automate thoroughly and often requires extensive human interaction.

P-code observations also allow for higher temporal resolution of position on regional-scale baselines, which is an important consideration for detection of anomalous strain events. Unfortunately, P-code operations will not be possible if the Department of Defense implements antispoofing. In that case, in lieu of a P-code receiver, we need a receiver that will not cycle-slip in fixed, unobstructed locations and that can measure full-wavelength L2 phases. I leave this as a challenge to GPS receiver manufacturers.

At present, JPL operates a receiver capable of both P-code and codeless dual-frequency operation, which provides excellent data. However, it is large, heavy, and power-hungry (about 500 watts); requires a relatively benign environment in which to operate; and is limited in internal RAM storage (currently 1 MB). Second- and third-generation versions of the receiver that will address these limitations are currently being developed and should provide data with the same excellent quality.

GPS sites at SIO, Parkfield, and the Pinyon Flat Observatory (PFO) operate C/A-code receivers with codeless L2 capability, and the National Geodetic Survey operates a codeless dual-frequency receiver at the Mojave CIGNET site, located at NASA's Goldstone Deep Space Network tracking complex. We expect to deploy and evaluate two P-code receivers at SIO and PFO in June 1991. Those compact and lightweight P-code receivers will contain 6 MB of internal RAM for data recording and require only 12 watts to operate.

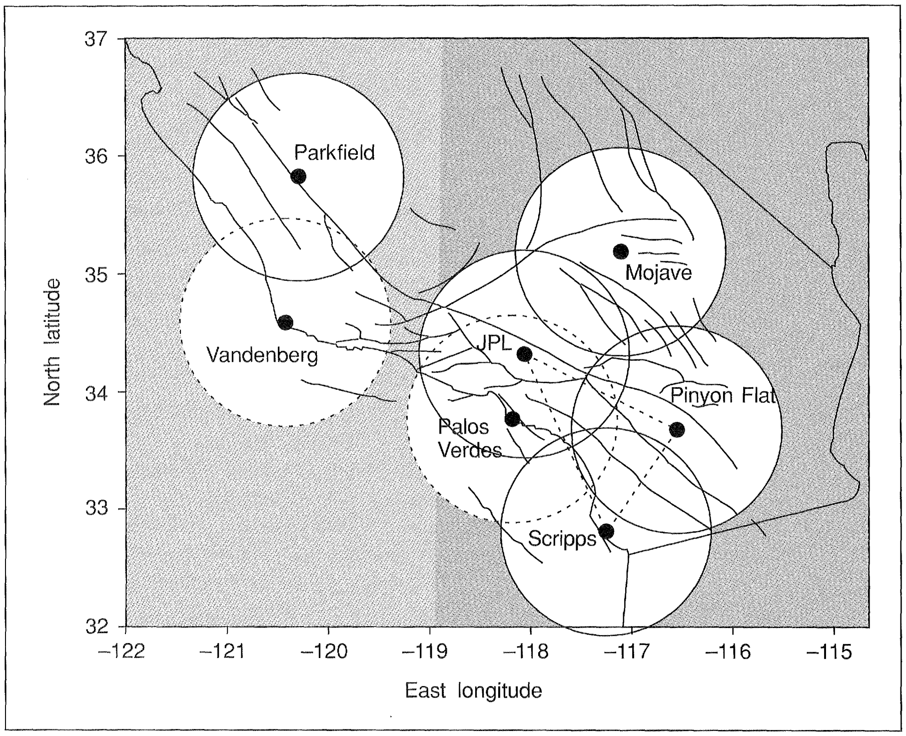

Figure 6. Map of the Permanent GPS Geodetic Array (PGGA) in Southern California; solid circles (100-kilometer radii) indicate stations currently in operation; dashed circles indicate stations that will be established in 1991; irregular solid lines represent geologic faults

A highly stable GPS monument for use in the network has been designed at SIO based on experience gained in building monuments for strainmeters at Pinyon Flat Observatory. The monuments are designed to have two parts: a ground-level base that is anchored at depth and decoupled from the surface as much as possible, and a removable antenna mount that can be precisely positioned on this base and can also support other types of measurements by being able to be precisely reset. We expect to have six well-monumented sites with power and telephone lines installed by this summer, including a line across the Los Angeles Basin.

HANDLING THE DATA

The SIO system is set up to collect data remotely and automatically from the receivers. We use a personal computer to download data over commercial telephone lines via high-bit-rate modems (with a maximum 19,200 bits per second [bps]). We download the data using either the CONAN software developed at JPL or the software provided by the receiver manufacturer. Both software packages allow for convenient remote control of their respective receivers and for automatic downloading. SIO downloads data daily seven days a week from all operational receivers.

All the receivers store data internally in compressed format. One type of receiver takes about two minutes to download 24 hours of data sampled at 1-minute intervals (at a rate of approximately 16,000 bps); the other type's data transfer is about half as fast.

Once the data are downloaded to the PC, they are uncompressed and translated into the Receiver Independent Exchange (RINEX) format conceived by Dr. Werner Gurtner of the University of Bern. All major receiver manufacturers support the RINEX format, and translators are available for all geodetic GPS receivers. The PC is connected directly to a ring of workstations. After translation, the data are copied to the hard disk of one of the workstations for analysis and to an optical storage device for archiving.

In order to eliminate orbital errors for the California baselines and to make the automatic analysis more robust, we collect data from a global network of tracking stations in the United States (Mojave, Westford, Richmond, Kokee Park), Canada (Penticton), Japan (Tsukuba), Germany (Wettzell), Australia (Townsville, Hobart), and New Zealand (Wellington). All global tracking data except the Penticton data (courtesy of the Pacific Geoscience Centre of Energy, Mines and Resources Canada) are collected daily via electronic links from the CIGNET Data Processing Center at the National Geodetic Survey, usually within 24 hours of collection of the data by the tracking stations. The Penticton data are downloaded daily in the same way as the PGGA data.

Data storage and dissemination. SIO uses a state-of-the-art optical storage system for archiving the raw and RINEX PGGA data. The optical storage device has 300 GB (gigabytes) of on-line WORM-type optical disk storage, using a jukebox arrangement. The system is accessible through the workstations and the Internet computer communications network. In one year of PGGA operations, we have used less than one 5-GB WORM platter on the optical storage device; so data storage is not a problem, even with a much-expanded network.

We store the PGGA data in a simple, hierarchical tree structure on the optical storage device. Our basic mechanism of data dissemination is by means of computer-to-computer communications using FTP (File Transfer Protocol — a standard communications protocol distributed with most computer workstations) over Internet. Any Internet user can access PGGA and CIGNET data in this way. This method has proven efficient in current PGGA operations. The data are available to scientific users as soon as they are archived on the optical disk, usually within several hours for PGGA data and within one to three days of collection for CIGNET data.

Data processing and software development. Once the PGGA and CIGNET data are collected on magnetic disk at the workstations, a sequence of batch files automatically invokes a daily, simultaneous least-squares adjustment. We use the GAMIT GPS software package developed at MIT and SIO, which includes GPS orbit refinement and network-based ambiguity resolution methods. The time series of daily station positions provides a record of crustal deformation. A by-product of these daily solutions is precise GPS satellite orbital parameters, which are at least an order of magnitude better than the broadcast ephemerides.

We have developed a completely automated analysis package that generates daily solutions without any human intervention. However, in order to achieve full automation we have taken a less-than-optimal approach. The main problem is cycle-slip detection, primarily for the non–P-code CIGNET data collected by dual-frequency receivers with codeless L2 tracking. All cycle slips need to be fixed in order to achieve the best solution, and this is difficult to achieve without human interaction. Instead of fixing all slips, we introduce a new ambiguity parameter whenever a possible slip is detected.

We plot as an example in Figure 7 the results of the daily solutions of the JPL-to-PFO baseline obtained from November 1990 through mid-February 1991. It should be pointed out that these solutions have been generated without human intervention, from data collection to data analysis. Although the automatic solutions are suboptimal, we can still see interesting trends in the data — for example, the clear linear trend in the north component of the JPL-to-PFO baseline.

Clearly, however, the fluctuations in position are due to the suboptimal way in which the data were analyzed and not to crustal deformation. We know from our earlier experience that this analysis can be refined so that virtually all GPS modeling errors can be eliminated. However, this requires considerable human interaction. We are working on a more-refined analysis of these data using a sophisticated interactive data editor and a recently improved automatic editor. The challenge to us is to perform the most refined analysis possible automatically and to build stable-enough monuments so that the remaining position variations are due to submillimeter random measurement error and to crustal deformation.

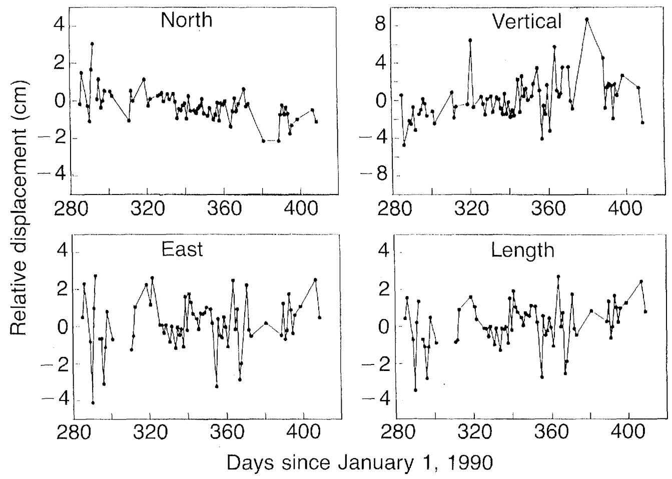

Figure 7. Daily time history of position for the JPL-to-Pinyon Flat baseline from November 1990 to mid-February 1991

PROSPECTS FOR THE FUTURE

Continuous monitoring of crustal deformation with GPS will definitely become an increasingly important tool for geophysical research into the earthquake cycle. The results on the Parkfield alignment array indicate that GPS baselines can be used as strainmeters for near-fault monitoring, and several groups are planning to do so. We already have the tools to operate these arrays automatically and efficiently, as has been demonstrated by the PGGA, although we expect to integrate new technological innovations as they become available. Regional-scale networks will clearly need more-refined analysis techniques to achieve the level of accuracy required to be useful scientifically, although the Japanese network is already producing significant results.

The support for continuous operation of the PGGA is growing. The newly established Southern California Earthquake Center has recognized the potential of continuous GPS measurements and has recently committed resources to expanding the PGGA. Six southern California county surveyor's offices have also initiated efforts to establish one continuously monitoring site in each county in collaboration with the PGGA. These sites would serve as reference sites for ongoing surveying operations. We anticipate a growing number of continuously monitoring stations in California. It will require many years of observations and several earthquakes to determine the significance of these measurements for our understanding of the earthquake cycle.

ACKNOWLEDGMENTS

Funding for the research described in this article was provided by NASA, the National Science Foundation, and USGS. The Parkfield research is being pursued with Jeff Genrich, a graduate student at Scripps, and with Dr. Daniel Rosenblatt. The Japanese results were obtained in collaboration with Seiichi Shimada of NIED, who analyzed these data as a visiting scientist at Scripps.

The PGGA is a collaborative effort of many investigators. I would like to single out the following individuals: Dr. Werner Gurtner, who was instrumental in designing and implementing the automatic operations while visiting Scripps; Keith Stark, who maintains the daily operations; Dr. Frank Wyatt and Prof. Duncan Agnew, who designed and built the GPS monuments at Scripps and Pinyon Flat; Dr. Ken Hudnut, who installed the Parkfield site; Dr. Peter Worcester, who made long-term loans of two receivers; Miranda Chin and Dr. Gerry Mader of NGS, who provided ready access to the CIGNET data; Dr. Herb Dragert, who provided access to the Penticton data; Dr. Bob King and his group at MIT, who provided GAMIT upgrades; Dr. Ulf Lindqwister and his group at JPL, who developed the CONAN download software; Steve Dinardo of JPL, who maintained some of the receivers; and Jonathan Ladd of Ashtech, Inc., who loaned receivers and download software.

When presenting research results, it is customary to cite referenced material. For the sake of brevity, I omit a long list of references. All these sources will be fully cited in a number of research papers now in preparation. In the meantime, the interested reader may wish to consult the paper "Continuously monitoring GPS networks for deformation measurements," by Bock and Shimada in *Global Positioning System: An Overview*, the proceedings of Symposium No. 102 of the International Association of Geodesy General Meeting, held in Edinburgh in August 1989. The proceedings were published by Springer Verlag, New York. ■