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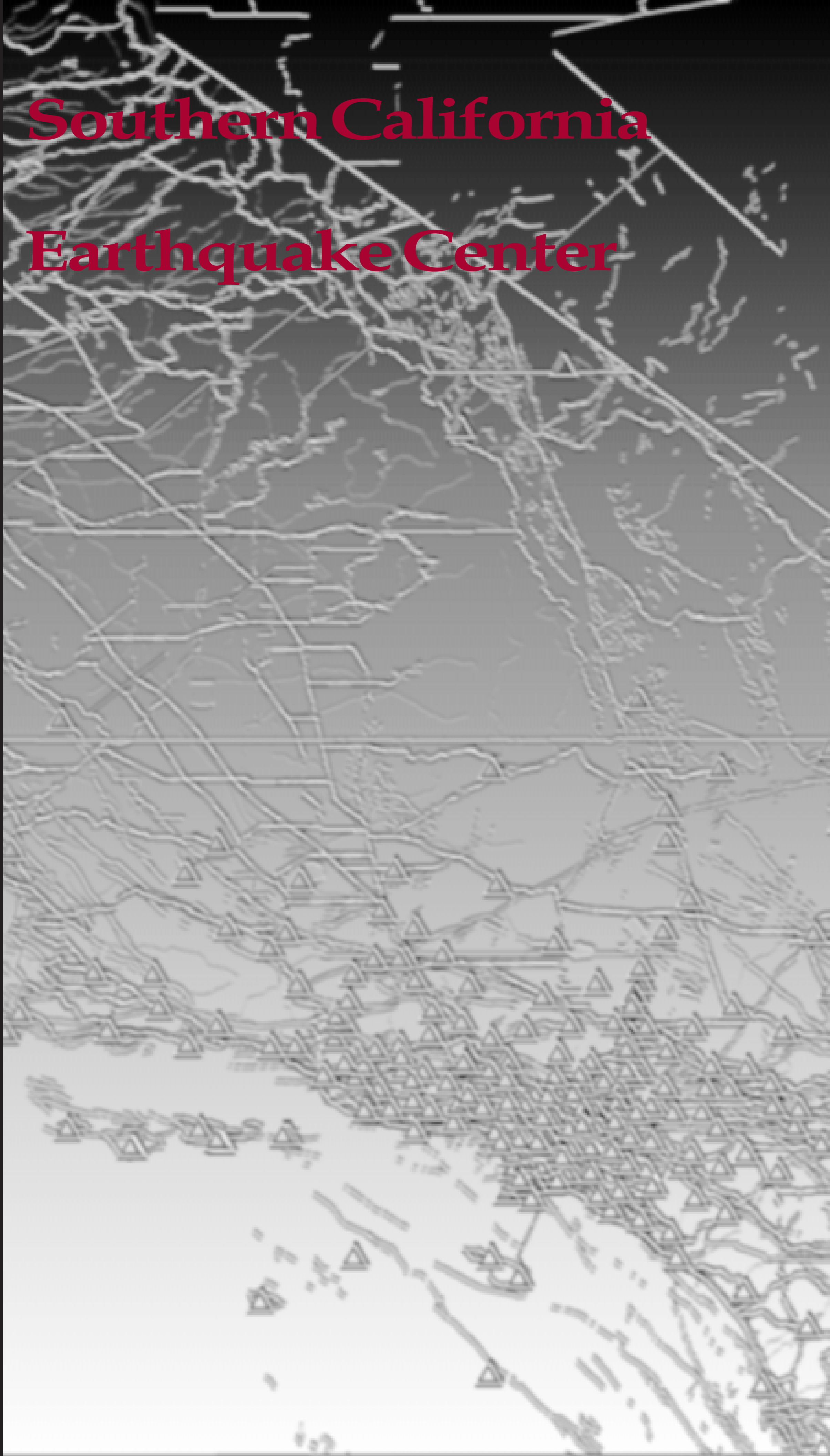
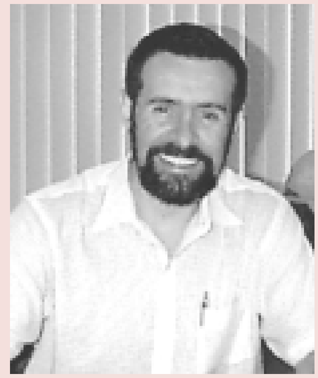
Southern California Earthquake Center



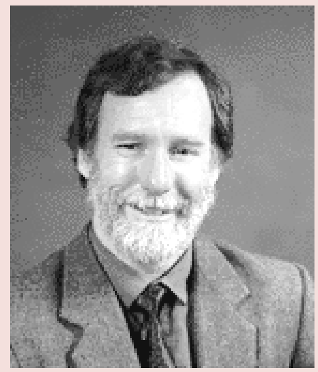
SCEC

Attitude Matters: SCIGN's Technical Achievements

David D. Jackson



Bernard Minster
Acting Science Director



David Jackson
Former Science Director

Thomas Henyey
Center Director

SCIGN began in 1996 with ambitious scientific objectives, described in the proposal to the Keck Foundation as follows:

1. To provide regional coverage for estimating earthquake potential throughout southern California

2. To identify active blind thrust faults and test the "thin-skin" and "thick-skin" hypotheses of fault behavior in the greater Los Angeles region

3. To measure variations in strain rate to reveal the mechanical properties of earthquake faults

4. In the event of an earthquake, to measure the response of major faults to the regional change in strain

5. In the event of an earthquake, to measure permanent crustal deformation that is not detectable by seismographs

At this time, there is already substantial progress on the first two objectives. SCIGN data have contributed strongly to the SCEC Horizontal Deformation Velocity Map (www.scecdc.scec. org/group_e/release.v2/) and recent publications based on SCIGN data have shown that strike-slip faulting around the Los Angeles basin is as important as shallow thrusting. However, SCIGN is young yet, and completion of the scientific objectives awaits more data (and earthquakes).

The SCIGN team recognized early that these challenging scientific objectives would demand improvements in GPS measurement and processing technology. They built technological development into the plan. The efforts, stemming from an attitude that only the best will do, are now paying off in fundamental ways.

SCIGN has pioneered the development of drilled, braced monuments for mounting GPS antennas in a wide variety of surface materials. Though these monuments are more expensive than those used in most previous GPS studies, they have proven to be vastly more stable than others, so much so that the design is being copied for many other GPS experiments. Experiments in designing stable monuments, once challenged as excessively expensive, have proven their exceptional value.

SCIGN has carried out experiments on the effects of the radomes covering the antennas to protect them from the elements. After finding that these domes may cause significant errors in GPS data, SCIGN staff designed and manufactured an improved radome, which is now the standard for high-precision permanent GPS stations.

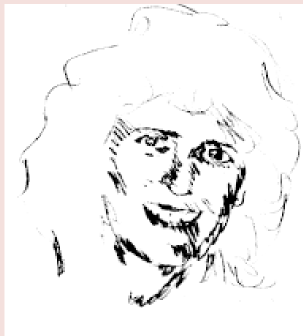
SCIGN personnel have studied the effects of trees and fences on GPS data, providing guidelines for avoiding multi-path errors that arise from these common field impediments.

Processing of data for very short baselines has shown that distances can be measured with uncertainties well below the millimeter level under carefully selected field conditions. These short baseline controls also allowed analysts to distinguish measurement errors caused by soil-induced monument motions for the first time.

Independent processing of GPS network data by three analysis centers using different techniques has revealed significant discrepancies. Although the cause of these differences is yet to be fully explained, their discovery is an important step in developing more accurate analysis. Only with dense, highly accurate data can the nature of these discrepancies be determined. At one time the proposal for multiple, redundant processing needed vigorous defending. Now it is evident that with this strategy, SCIGN is resolving questions that no other institution can.

These technical improvements and discoveries will improve GPS measurements everywhere and lead to a better understanding of the relationship between tectonic deformation and earthquakes. Without a concentrated effort to build the best possible GPS array, these developments would be a long time in coming. Thanks are due to the entire SCIGN staff for their hard work and their uncompromising attitude. ■

by Susan Hough



Back in the Old Days . . .

Nancy King, USGS
Guest Columnist

Upon being informed of plans to devote an entire newsletter to the SCIGN project, I knew I'd have to lean on my friends to fill this column. I approached fellow USGS scientist Nancy King and asked if she might have any amusing tales of SCIGN-related fieldwork. Nancy laughed and told me that, while her involvement with the project has involved more meetings and WWW work than fieldwork, she certainly could share some stories from the old days of GPS campaigns. If the SCIGN project is a torch lighting the way to the future of GPS science, this is perhaps a fitting time to share the kinds of fieldwork adventures that, for better and maybe for worse, will be rendered mostly obsolete by permanent GPS networks.

—SEH

"Campaign-mode GPS" means using a surveyor's tripod to precisely center a GPS antenna over a geodetic monument, babysitting the equipment for several hours, taking it all apart and driving away, and then doing it all over again the next day. Large-scale GPS campaigns in southern California began in the late 1980s, when the National Geodetic Survey (NGS), the USGS, and the University NAVSTAR Consortium (UNAVCO) joined forces for several major campaigns.

GPS campaign work, carried out by various agencies, continues to this day in southern California. Campaign-mode GPS field teams have the usual problems faced by all surveying crews: finding stations, permitting, driving on poorly maintained dirt roads, getting through locked gates, avoiding landowners' dogs, bulls, and geese, and carrying multiple loads of heavy equipment up and down hills.

These measurements, taken only with flashlight illumination by people who were bleary-eyed and usually bone-cold, were probably not the most reliable.

We also faced some special situations that were unusual, dangerous, or entertaining. In the first UNAVCO campaign, we discovered that one of the monuments on San Clemente Island was in the skip zone of the Navy's shelling range and that the zone was inhabited by wild pigs. We were able to observe there, but eventually switched to a less potentially lethal observation point.

In addition, on San Clemente Island, we stayed at the wildlife biologists' field station. It was a congenial group of scientists who promptly labeled each other: a woman doing the annual gray whale census (the whale lady), entomologists (the bug people), botanists (the plant people), wildlife biologists (the cat people), and ourselves (the satellite people).

The cat people got their name because on that trip to the island, their mission was to reduce the population of feral cats in order to protect the San Clemente Island fox. Their method was to catch dozens of cats, sterilize them, and release them. It was a sterilization factory, with cages full of angry cats all over the floor. They were doing cats as we satellite people left late at night to go to our station. They were still doing cats when we returned around dawn, although they swore that they had been to bed while we were gone. The program was decidedly involuntary in the opinion of the cats, and there was a lot of yowling and spitting from the patients. The cat people anesthetized them by attaching a syringe to a long stick and poking it inside the cages.

On Santa Barbara Island, we had to brace our tripod against strong winds. The usual method is to place sandbags or rocks against the tripod legs. Our hosts, the National Park Service, forbade us to move any rocks in the area because they were home to an endangered species of snail. We improvised by lashing the tripod legs to our extra water jugs. Although proud of our ingenuity, we weren't inclined to feel charitable towards gastropods—endangered or not—after carrying six gallons of water a mile uphill.

Field crews working in urban areas had different problems. A USGS person doing post-Northridge observations set up at a monument in the middle of an intersection. The equipment was stolen right in front of him. The thief stopped his pickup truck, threw the receiver in the back, and drove off before the field technician could stop him.

Tales *continued on page 24*

A SCIGN before Its Time

A History of the Southern California Integrated GPS Network

Ed Hensley

A number of astronauts, and then all of us who saw the photography from space, marveled at how much the Florida peninsula, the meandering Mississippi, the islands of Britain, and the boot of Italy resembled the maps everyone had grown up with. We had taken it for granted that maps were faithful reflections of reality; but we were somehow amazed when reality turned out to be true to the maps.

—John Noble Wilford
The Mapmakers

Human history is plotted and punctuated by maps. Changes in maps change how people see their world. Eras end and begin when blanks on maps are filled. By that criterion alone, we are on the edge of a new era and new ways of seeing, thanks to a combination of technological and scientific advances. And right at the forefront of producing this era's new maps and that new vision is SCIGN—the Southern California Integrated GPS Network.

That network is a perfect example of the conjoining of time and space, technology and science, progress and insight, preparation and chance. Its history is one of persistent attempts finally coinciding with the development of the right technology at the right time.

You would be right if you said that SCIGN dates back to the likes of Isaac Newton and Euclid because the use of satellites for geodesy owes so much to centuries of earlier science and mathematics. However, the more direct history of SCIGN began in the late 1980s in the usual way: meetings and proposals.

A core group of geodesists from MIT, Scripps, Caltech, UCLA, and JPL believed in the potential of the Global Positioning System (GPS) for detecting minute movements of the crust, but not just in the way it had been used until then. Previously, GPS receivers had been hauled out into the field to establish point-in-time locations for sites. Later campaigns would then establish whether those locations had changed. This new gathering of scientists believed in the value and feasibility of a permanent network of continuously operating GPS stations.

Yehuda Bock moved from MIT to Scripps in 1989 for just this kind of work. He spent his first two years in southern California shuttling between joint appointments at Scripps and JPL to work on establishing the first continuous GPS stations. At the same time, Ken Hudnut was a post-doctoral fellow at Caltech. Frank Webb was one of the graduate students who had to haul around GPS receivers in field campaigns. Duncan Agnew and Will Prescott were more established voices in the field of crustal motion. All these individuals would eventually help steer the SCIGN program. They and many others shaped the early proposals and projects that would eventually become SCIGN.

The Early Proposals

Researchers have been submitting proposals for continuous, space-based geodetic measurement for more than 20 years. Ideas of using GPS in a continuously operating network, similar to a seismographic network, have been around for at least 13 years, as GPS gained accuracy and respect. Webb remembers attending a meeting of the Crustal Dynamics Project—a NASA-sponsored program of investigators from around the world who used VLBI (very long baseline interferometry) and SLR (satellite laser ranging) for crustal deformation observations. "Brad Hager showed a map of southern California's seismic network," Webb said, "and proposed that there should be a continuous GPS network of the same density in the area. That was in 1987 or 1988."

We are on the edge of a new era and new ways of seeing, thanks to a combination of technological and scientific advances.

The main obstacle back then was the high cost, especially when combined with the unproven nature of the technology in competition with the more established techniques of VLBI and SLR.

GPS geodesy eventually won that competition, however. As Webb explained, "While the GPS satellite constellation filled, the ground network grew, processing techniques improved, and the precision in

GPS improved, eventually equaling the precision of VLBI and SLR. That, combined with the much lower cost of the equipment, the portability of the systems, and the less complex analysis made GPS accessible to a broader community of researchers and applicable to a broader range of problems."

The most recent history of continuous GPS-based geodesy that resulted from the developments that Webb describes brought a flurry of proposals—modest compared with today's 250-station configuration of SCIGN—in 1990 and 1991. The two organizations at the forefront were Scripps and Caltech-JPL.

In 1990, for example, a proposal by Hudnut and others at Caltech requested $109,000 from the Caltech President's Fund for "Crustal Deformation Studies in the Los Angeles Basin." Their summary proposed that their work would help answer "the major, unresolved question of whether Los Angeles should be bracing for a M >7 earthquake produced by faults directly underneath it."

Processing the data was so laborious and slow that people didn't believe we could do continuous monitoring and keep up with the data.

The five "part-time monitoring" sites they proposed to supplement the one existing JPL receiver would be able to produce the "required millimeter-level positioning accuracy" because of JPL's existing work in producing high-accuracy satellite orbits.

"From geological studies, the geometry of the detachment faults beneath Los Angeles has been crudely estimated. . . . We propose to determine whether portions of these deep faults are 'locked' and accumulating stress or whether they are moving aseismically." Their focus was localized in the basin, and their assumption was that patterns of small differences in the motion of the Earth's surface would allow them to tell the type of motion.

A proposal in the same year by Bock and others reflects a broader regional approach to GPS monitoring. They proposed to expand the NASA-funded existing four-receiver Permanent GPS Geodetic Array (PGGA), a joint project of JPL and Scripps. "Our long-range goal is a dense network covering the entire state to supply geodetic baseline data of several millimeter accuracy for the detection and analysis of both steady and transient crustal strains. . . . We envision a reference network with a 100-km grid spacing with

History *continued on next page*

Archiving and Using Data

Archiving data is not something that SCIGN takes lightly. Scripps, and specifically the Scripps Orbit and Permanent Array Center (SOPAC), is the archiving facility for all SCIGN data. Although the task of downloading data from the stations is divided between the USGS and SOPAC, all data are moved automatically after downloading to SOPAC for analysis and archiving. The data are also moved automatically to JPL for separate analysis there.

The total volume of continuous GPS data is more than 1 gigabyte per day coming into SOPAC. The data are not merely stored. They are always online and available via FTP and the Web (HTTP://LOX.UCSD.EDU). SOPAC uses the latest storage and retrieval technologies available, from large arrays of hard drives to "juke boxes" that sort through storage media such as optical-magneto disks and bring online a certain data set in real time when a user requests it. Those actions are so fast that the user notices only a slight delay before receiving data.

SCIGN data are accessible by external users via anonymous FTP from the SOPAC archive within minutes of download and entry into the database. The retrieval of SCIGN and other continuous GPS data from SOPAC is increasing dramatically. An additional 1 terabyte of storage media has been recently acquired to keep up with the growing volume and demands.

The director of SOPAC is Yehuda Bock, and his data management and analysis team includes Jeff Dean, Peng Fang, Paul Jamason, Michael Scharber, and Matt van Domselaar. Jeff Dean is responsible for database development and management at SOPAC. Dean pointed out that the SOPAC archive is being designed as a repository for any type of GPS data. "The SOPAC archive is not just for SCIGN data. We're setting up the database so we're not limited by program type or data collection methods. For example, SCIGN data are collected once a day. We want to be ready, if necessary, to collect real-time data and to handle different data types, such as data from old campaign data sets. At this point, we're not even limiting it to GPS. We're also including metadata about other types of data, such as synthetic aperture radar (SAR) data downloaded by Scripps. But the main data collection and processing is tuned for continuous GPS data, and SCIGN is the largest generator of continuous GPS data. We're allocating considerable resources to develop Web-based user applications so that people can make the most effective use of the database. Several of these applications are online, but we still have a long way to go."

Currently SOPAC is developing and testing a GIS (geographical information system) interface for the GPS data, making it more useful and accessible to a wider variety of users, especially those interested in geodetic control, such as the newly formed California Spatial Reference Center (CSRC).

"There's a big spin-off from SCIGN in the form of the California Spatial Reference Center," said Bock. He ought to know. He's not only the director of SOPAC, he's also the director of CSRC.

Archiving *continued on next page*

History

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densification along a number of active faults."

Also in that same proposal is a revealing description of the purposes of the project, clearly showing the origins of what would become SCIGN. The proposal lists among its purposes "developing the GPS technique, refining its operational aspects, and improving our understanding of the nature and source of the GPS error spectrum." The proposal promised that the program would be "an example of how to make, comprehend, and archive a large body of highly accurate measurements of crustal deformation."

The Northridge earthquake opened the door, no doubt about it.

Today, operating a few GPS sites may not seem like a major accomplishment. But as Bock pointed out, "Back in the days of campaign GPS [see Nancy King's description in the "Tales from the Front" column], the task of setting up the stations was difficult enough, but the processing of the data was laborious and slow. It was so painful to do the processing even for something that you measured once a year that people didn't believe we could do continuous monitoring and keep up with the data."

That disbelief showed itself in reactions to several early proposals. A modest Caltech proposal was for intermittent GPS readings to "differentiate seismic versus aseismic fault behavior." The proposal went on to say that the project would be "an ambitious test of new systems that hold great potential for densification of permanent GPS geodetic networks." That proposal was seen as too ambitious and was rejected.

An unsuccessful joint four-year 1991 proposal called for spending a total of under $1 million for all four years and increasing the existing PGGA network by two stations each year, for a total of 12 stations in 1995.

Another relatively modest ($422,900 for four years) proposal from Caltech and JPL investigators was unsuccessful, rejected by a peer review committee.

Unsuccessful proposals from those days generated responses such as these from review panels:

- "The large number of surveys which were proposed were not adequately justified, nor is that great a commitment of resources plausible. . . . The . . . technique has a lesser precision, and thus is not appropriate for looking at the very small signals which you plan to investigate."

Archiving

Continued from previous page

Bock summarized the origins of CSRC: "The surveying community initiated it as a grass-roots effort to meet California's needs in spatial referencing and geodesy. SCIGN's work and experience in high-precision geodesy was the perfect vehicle, and SCIGN's network was the perfect foundation for a high-accuracy geodetic grid for California. It's an example of the nontraditional—or at least the nonscientific—application of and support for SCIGN-like efforts."

But CSRC grew to encompass more than surveying needs. All the different interests in California for GPS data—surveying, engineering, geology, water infrastructure, GIS, coastal environment, disaster preparedness and relief, etc.—will be represented on the board of CSRC.

CSRC is two things: an operational center and a board representing the groups who have interests and responsibilities in the area. Bock is the director of the operations center, and Bill Young, a surveyor who was involved in founding and shaping SCIGN (see "A Marriage Made in Space" in this issue), is the chair of the board.

After two years of organizing efforts, a memo of understanding identifies CSRC as the National Geodetic Survey's partner in California, taking over geodetic control responsibilities for the state. NGS will still provide all geodetic coordinates for the U.S., but CSRC will do all the work in California.

"It's working now," said Bock; "we've received our initial funding from NGS and Caltrans. They're funding the first two years of operation." The operation center is at SOPAC for now, and CSRC work is being handled by SOPAC staff on a part-time basis as the new center develops. Bock expects that the CSRC will soon have its own full-time staff. "But we will probably still have considerable overlap between SOPAC and CSRC," he added.

The CSRC is also working with the GIS community to use GPS as the backbone for managing other kinds of information—planning, emergency response, subsidence, water systems. Eventually, GPS info along with all other related information will be GIS-based. "We're developing GIS software here at SOPAC, sponsored by CSRC," said Bock. "I call it wide-area or precise GIS. Now individual organizations, such as cities and counties, maintain their own GIS, but they're not always compatible with each other. The wide-area GIS is based on a statewide infrastructure that incorporates all this info into a common reference so that cities can tap into that reference frame and be assured that they are compatible with every other city in California."

How will perpetually strapped cities and counties fund conversion and participation? Bock hopes to keep the financial burden off the users. "We do not plan to charge the individual user for the services, but we'll try to get federal and state funds and fee support. Up to now, everything's been very open, and there have been no charges for any of the data that we provide."

Asked about the difference and possible conflicts between being a major participant in both SCIGN and CSRC, Bock said he sees the two functions as both different and compatible. "SCIGN's ability is very limited, both in funds and resources, to support anything beyond its primary purpose, which is academic and scientific. The motivation for the CSRC is to for-

- "The expected deformation signal is very faint indeed, making it questionable whether any tectonic movements would be detected within a four-year program, let alone with seven times per year monitoring."

- "A very costly proposal relative to expected return."

- "A more modest effort would be justified. The issue of whether NASA should be involved in such studies, given USGS and NSF programs, is crucial."

Nevertheless, there is generally a time at which such proposals catch that peak wave when technological advances begin to meet general awareness, revealing the previously hidden value and possibilities in proposed applications. The early 1990s turned out to be the beginning of that wave for the application of GPS to geodesy.

Southern California is the premiere place in the world where significant tectonic problems exist and have been solved in large part by GPS. This is a natural place to extend what we've already done and try to do more with it.

The decade of 1985-95 was the one in which not only was the GPS constellation completed but the precision of the GPS technique increased exponentially, and the price of receivers decreased dramatically.

The experience, feedback, and even the rejection of many early ideas and proposals gave the GPS advocates the foundation they needed when the technology was right, the price was right, and the funds and interest came together following the Northridge earthquake in 1994. At that point, when GPS technology was proven, the constellation complete, and the need to know what was happening in detail below Los Angeles was a gut-level reality, they had a tested prototype network, and they had their ideas and proposal language ready.

Early GPS Work

Early geodetic work using GPS was done by campaigns in which receivers were hauled out into the field along with all the other equipment needed to make them run. The stations were set up in a chosen location and readings taken during the time when the satellites were in the sky.

History *continued on next page*

malize this additional service so that we have staff and resources to provide the geodetic and other services. That way we can respond as service providers rather than as scientists who may or may not have time."

To optimize efficiency, the services are designed to be Web-based and driven by user applications that guide the user through getting appropriate data. Therefore funds and resources can be focused on what everyone wants: the data. The plan is for the full database and GIS interface to be available through the Web.

"Up until now you established three-dimensional geodetic coordinates by whatever means were available at the time and published those, including staking out monuments as reference points on the Earth's surface," Bock said. "For most of the country that works fine, but not for California, where crustal motion and earthquakes change the surface constantly. Here in California, you must have the fourth dimension of time for complete accuracy. And adding that fourth dimension is the strength of a continuous GPS network."

Bock pointed out that a great deal of current GIS work is based on readings from hand-held GPS receivers, which are accurate only to 10-30 meters. "Surveyors are doing centimeter-level work with GPS, so there's a disconnect between the GIS people and the land surveyors. Using traditional methods, surveyors 100 years ago could do more accurate surveying than modern hand-held GPS receivers can. Another contribution that the CSRC can make is to work to improve the quality of hand-held instruments."

For CSRC to work, said Bock, "we need coverage all over California. We certainly need denser coverage of areas that are more populated and where resources are important. We don't need the kind of density that we've established in the L.A. area for SCIGN, since that has a different purpose. For CSRC, it would be better to have a fairly uniform coverage of California with concentration in areas of large population of some particular interest."

The state transportation department, Caltrans, for example, has an obvious need for a precise statewide geodetic backbone.

"There was a difference of opinion within SCIGN concerning whether to focus on a particular area or problem or whether to spread out the resources because we don't have a very good idea of where we're going to have seismic activity," Bock said. "I think we've come to a fairly nice compromise in SCIGN. We are focusing on the L.A. basin, but there are more sites than originally planned being installed in the periphery, which helps CSRC and those larger purposes."

On what's needed to expand SCIGN-like coverage statewide for CSRC purposes, Bock said, "In central and northern California, there are still some gaps that we need to fill somehow, probably initially by piggybacking on scientific projects. If CSRC grows sufficiently, perhaps we'll be able to install our own stations in areas that are not covered. The recent Hector Mine earthquake has helped in this regard by increasing the awareness that uniform spatial coverage makes practical as well as scientific sense." ■

SCIGN PROFILE

Kenneth W. Hudnut

Geophysicist
Earthquake Hazards (Pasadena)
U.S. Geological Survey

- Member of SCIGN Coordinating Board and Executive Committee since project's inception (1994); Vice Chair, Coordinating Board, 1998-1999; Chair, 1999-present
- Current leader, SCIGN-USGS operations group
- Led SCIGN radome development and production effort
- Member of several SCIGN committees, including the earlier-stage site selection ("Dots") committee
- Co-wrote all major SCIGN project proposals and reports produced since 1994
- As chair of SCEC Crustal Deformation Working Group (July 1996-October 1998), oversaw production and release of first and second version of SCEC Crustal Deformation Velocity Map

Education

A.B., earth sciences, Dartmouth College

M.A., geology, Columbia University

M.Phil., geology, Columbia University

Ph.D., geology, Columbia University

Professional Highlights

Board of Directors (USGS representative), SCEC, 1998-present

Steering Committee member, Plate Boundary Observatory, 1999-present

Elected member of UNAVCO Steering Committee, 1995-1997

Committee member, GPS Continuously Operating Reference Stations (CORS), American Congress on Surveying and Mapping

Committee member, California CORS

Associate editor (geodesy), *Journal of Geophysical Research*

History *Continued from previous page*

Frank Webb's experiences in the early days were typical. "When we started doing geodesy in southern California in 1986," Webb said, "I was a graduate student, and there were six GPS satellites in the sky. They were only over North America for about six hours a day.

"A single GPS receiver at that time cost $150,000," he recalled. Nevertheless, scientists wanted to use them. They had seen the potential value of such geodesy work because of the similarities to VLBI, in which radio telescopes and quasars are used instead of receivers and satellites. The problem was that radio telescopes are expensive, huge, and stationary.

The U.S. military was in the process of completing the 24-satellite GPS constellation. Webb: "Scientists wanted to use GPS to measure small-scale deformation in southern California where there weren't VLBI antennas, so the NSF purchased three receivers—$450,000—in 1986."

The NSF also set up the University NAVSTAR Consortium (UNAVCO) to maintain and coordinate the sharing of GPS equipment for research. UNAVCO started as an organization that lent out equipment for GPS campaigns all around the world. As receivers became less expensive, UNAVCO bought more receivers until the equipment became so inexpensive that individual investigators could buy their own.

"Now UNAVCO represents the broader GPS community when it comes to GPS scientific work," explained Webb. "It provides forums for GPS people to make presentations and discuss technology and science." It maintains an archive of GPS data and still plays a role in campaigns and continuous GPS in other parts of the world.

Also in those early days (1992), an international GPS-related organization grew more directly involved in overseeing working networks and in gathering, processing, and disseminating data. The International GPS Service for Geodynamics (IGS) is made up of agencies and individuals from around the world. The IGS provides global standards and infrastructure for GPS work worldwide. Part of that infrastructure is providing accurate orbit calculations daily to the worldwide GPS community.

Though UNAVCO and IGS were created before the SCIGN acronym was coined, they owe much of their present structure and experience to the people who formed SCIGN and to the projects that eventually became SCIGN. There has been a significant amount of cross-involvement among SCIGN, UNAVCO, and IGS.

PGGA

In 1988, work began on the first permanent GPS network in southern California. Up until then, there were some isolated individual stations only. Caltech, MIT, Scripps, UCLA, and JPL received funding for the first four stations that formed the Permanent GPS Geodetic Array (PGGA). Installation occurred in 1989, and operations began in April 1990.

The goal of the PGGA was a statewide 100-km grid of GPS stations to function primarily as a reference frame to improve the accuracy of campaign GPS.

The founders of what would become SCIGN, in other words, did not see campaign versus continuous GPS as a core issue. They assumed that the two methods would have to coexist, primarily because of the expense of the receivers and the untested nature of managing a continuous network.

JPL and Scripps collaborated on the first four continuous stations in southern California. Two were operated by JPL—the ones at JPL and Goldstone, part of NASA's Deep Space Network. Two were operated by Scripps—the ones at Piñon Flat Observatory and on the Scripps campus. During the years leading up to 1994, other sites were added for various purposes. For example, there's one on an oil platform and one at a site on Vandenberg Air Force Base. A few more sites went in for geodetic measurements at Monument Peak (a NASA satellite laser ranging facility), Coso volcanic field in the southern Owens Valley, Parkfield, and Lake Mathews. (The latter site, at a water reservoir operated by the Metropolitan Water District and funded by the Riverside County Flood and Water Conservation District, was the first one installed in collaboration with the surveying community in southern California.)

Each site was added for its own individual purpose, but together they also broadened the network, thus providing a more complete view of crustal motion. From 1990 through 1993, the network grew to 12 stations, reaching as far north as Parkfield.

I compare the situation to building a better telescope. We don't know what we're going to see, but if we don't build it, we're never going to know.

The scientists of PGGA participated in the creation of UNAVCO and the IGS. JPL and the Scripps Orbit and Permanent Array Center (SOPAC) were instrumental in developing software for analyzing GPS data as well as in calculating more exact orbits for the satellites to improve the accuracy of the entire GPS system worldwide.

PGGA scientists also participated in and learned from earlier and ongoing experiences of the Japanese in developing a large nationwide GPS network. The Swedes and the Australians were also working on continuous networks. The SCEC scientists shared their experiences and expertise as well as learning from the experiences of those in other countries.

In the very early days—1990 or even 1989—of what would eventually become the SCIGN project, there were two independent and complementary GPS-based approaches being proposed. One group, prominently represented by Yehuda Bock at Scripps, wanted to do continuous GPS on a sparse network, primarily for broad-scale geodesy. The other, driven by Hudnut of Caltech, wanted to apply the same technology on finer-scale problems—the L.A. basin in particular—with earthquake hazards as the focus.

The two types of proposals were different in design, focus, and cost. Each group had been submitting proposals, some successful and some not, for a considerable time. Each had the experience of having made several such installations. Each had co-investigators from the other group. Eventually, they combined forces.

The Northridge Earthquake

On January 17, 1994, SCIGN's pivotal shaping event occurred. Bock put it this way: "The Northridge earthquake opened the door, no doubt about it. Northridge gave the impetus to increase the number of stations."

The nature of the fault on which the Northridge earthquake occurred spurred increased interest in and funding for research into the "hidden" faults below L.A., which had been the goal of some of the proposals of Caltech back in 1990 and 1991.

Before Northridge, according to Bock, the PGGA scientists had written a white paper in which they proposed expansion to 50 sites, with increased density in the L.A. basin because of the complexity of its underlying geology and tectonics. Part of the justification of the larger number was the nature of the area around the L.A. basin—geologically and tectonically complex, pushed and pulled by plate motions, and distorted by the Big Bend in the San Andreas fault. As Bock pointed out, "The Northridge earthquake generated interest in an even larger number than we had proposed."

Immediately after the Northridge earthquake, there was a focus on the L.A. area. A group of SCEC scientists began work on what they called the Dense GPS Geodetic Array (DGGA), a tight-knit network of receivers entirely in the L.A. area that was planned from the start to be 250 stations.

At some point DGGA was essentially SCIGN but without the name. Its main difference was that its first iteration focused more exclusively on the L.A. basin. As SCIGN evolved, the array spread to include all of southern California with an emphasis on L.A. SCIGN combined the PGGA and DGGA—that is, it folded together the ideas of a broad regional array with the very dense array. The region is all of southern California. The dense part is in the L.A. basin.

The geodesists of SCIGN were then able to think in completely unlimited terms of what they would need to do a thorough study of crustal motion and ended up proposing 250 sites—at that point largely in the L.A. basin and surrounding area—to capture the details of crustal motion and strain build-up.

Since there was a great deal of overlap between the participants in the PGGA and the DGGA (which was never quite institutionalized as an official name), the SCEC geodesists had experience in both dense and regional continuous GPS when the Northridge earthquake occurred. After Northridge the PGGA and DGGA combined and formed SCIGN. That name became official in 1996.

Webb remembers the time and the circumstances of that January vividly: "Several of us from JPL and Scripps were in Japan participating in the development of the Japanese network. We returned to California and were supposed to go back a week later. On the first day back, I was lying awake in bed with jet lag when the Northridge earthquake happened.

"Some of us went back to Japan to continue our work, and while we were there, we began thinking that we should be building a network like [the Japanese one] in Los Angeles. When we returned from Japan, other people were thinking the same thing. After some conversation, our sponsor at NASA headquarters, John LaBrecque, managed to leverage enough money to buy about 15 GPS receivers—but no money to install them." Nearly simultaneously, Jim Mori at the USGS approved the use of Northridge earthquake funds for GPS implementation. That total of $500,000 was at the time a generous amount to start what would rapidly become SCIGN.

Those involved started working through SCEC to get NSF money to install those stations. Meanwhile, "we started pitching to ourselves and to others that we should try to build a bigger network of 250 stations," said Webb. The group that would eventually coalesce as SCIGN was loosely knit and trying to get funding for the larger, denser network that they increasingly knew was feasible and desirable. In their efforts to find new money, they tried nontraditional sources. In one case, Andrea Donnellan made a presentation at the annual meeting of a reinsurance organization in the East, pitching not only the scientific benefits but the larger societal and economic benefits. That one didn't work out.

The velocity field that comes out of the GPS network should help us identify active structures and understand which are the most hazardous ones in southern California.

However, others did—most notably among the less traditional sources of research funds—the W. M. Keck Foundation. The Keck Foundation saw the merits, not only in the proposed network, but also in supporting a consortium of institutions in southern California with a common purpose. That consortium turned out to be a formal marriage of SCIGN and SCEC, with SCIGN operating under the SCEC umbrella. "This leveraging of our funding," said Webb, "was one of the key successes of SCIGN."

Webb explained why Northridge's blind thrust fault gave new purpose to geodesy in the L.A. basin: "One of the things that we're trying to do with SCIGN is make the array dense enough to show how the surface is deforming in a more detailed way than ever before. We then use those measurements and our understanding of the subsurface geology to establish the slip rates on these faults and infer which faults are active and which faults are not." This of course is one of the principal goals of SCEC and its mission to develop a better seismic hazard model for southern California.

Campaign vs. Continuous

Hudnut, the current chair of SCIGN, pointed out that SCEC had sponsored a great deal of survey-mode GPS research and that SCEC research produced a coherent crustal motion map of southern California. When asked the question of whether a network of continuous stations is necessary in light of the success of those campaigns, he said, "When we set out to frame the scope of the SCIGN project, the crustal motion map work [using campaign GPS and high-precision non-GPS data] was not complete. Therefore, at the same time that we were raising the funding for a continuous GPS network, we were also raising the standard that such a network would have to meet. To make a significant improvement over that standard, SCIGN is going to have to do one heck of a job."

Besides the quest for increased precision, Hudnut believes there's another convincing argument for a continuous network—one of discovery. "I think we needed to try out this new technology that was available to us and see if it's going to help us with earthquake research in general," he said. "Southern California is the premiere place in the world where significant tectonic problems exist and have been solved in large part by GPS. As a result, southern California has drawn in a lot of the major talent in this field. This is a natural place to extend what we've already done and try to do more with it.

"I compare the situation to building a better telescope. We don't know what we're going to see. We have some ideas about what we might see, but if we don't build a better telescope, we're never going to know for sure."

Much of what we think we know about earthquake mechanisms is not yet supported by direct observation, Hudnut pointed out. "All this stress change modeling is just that—modeling. We don't have an observational basis that says what is really happening. GPS gives us the potential to do that, but only if we have it in a continuously operating network."

Do We Need an Earthquake?

Will SCIGN reach its full potential only if a significant earthquake hits? Hudnut's response was refreshingly human: "Oh, that would be lovely. If we were able to record data from the full network for five years and then we had a magnitude 7.2 or higher, especially within the dense part of the network, and then we kept the network running for an additional five years—that would be beautiful. We would have such a great data set for being able to tell for sure whether there had been anything precursory. We've never had a data set anywhere close to that.

"That in itself is reason enough to try to perpetuate this network beyond a seven-year lifespan. The longer we keep it going, the more we increase our odds of capturing a big event and seeing whether stress interactions are accompanied by measurable strain changes. Although it's not an event we can count on, and therefore we can't make it a primary purpose, when you ask what would it take for this network to realize its full *scientific* potential, then an earthquake would be necessary.

"In the case of a future earthquake, we can have the trap set and ready to capture something interesting. In the meantime, geodesy is at its best in between the times of big earthquakes, because that's when its capabilities are shining. You're measuring the interseismic deformation field without the perturbations of earthquakes." In effect, SCIGN is measuring the distribution of strain across southern California and how fast individual pieces of crust are moving due to the inexorable motion between the Pacific and North American tectonic plates.

Bock's experience with PGGA showed the value of having a continuous network in place during an earthquake. "The Landers earthquake happened two years after we started PGGA monitoring," he noted. "It was smack in the middle of the few sites that we had, so it was perfect for us. We learned a lot of things from the Landers earthquake.

"It certainly would be a benefit to have an earthquake," Bock said. "But there are several things that we're studying. The first order question is how the strain is distributed over the region. The two plates are moving with respect to each other; how is the total motion of about 45 mm/yr distributed over southern California?"

However, he added, "We don't need an earthquake for the data to be of value. Contraction of the L.A. basin is going on constantly at 7-8 mm/year and nobody knows how that strain is distributed across the basin.

"Is all the strain accumulating underneath downtown L.A., or is it being distributed among small strike-slip faults over the basin? What is the role of thrust faulting? Is most of the contraction taken up by vertical thrust faults, some of which you can't see? Is some of it taken up by the squeezing out to the sides on strike-slip faulting? Where is that 7 mm/yr?"

What's needed, Bock said, is to understand the different parts of the cycle of deformation. Seismic deformation will be different from secular deformation, he said, and it's not necessary to have an earthquake to understand that. In fact, for the study of secular deformation, Bock noted that an earthquake "resets the clock," and it can take several years before all seismic deformation stops.

Administering SCIGN

SCIGN is officially administered by the Southern California Earthquake Center, but has its own operating structure consisting of a coordinating board (representing all the relevant

History *continued on page 25*

SCIGN PROFILE

Frank H. Webb

Research Scientist
Satellite Geodesy and Geodynamics Systems Group
Jet Propulsion Laboratory

- Chair, SCIGN, 1998-1999
- Member, SCIGN Executive Committee, representing JPL, the Satellite Geodesy and Geodynamics Systems Group, and Section 335
- Member, SCIGN Siting Commitee
- Liaison between SCIGN and JPL group members
- SCIGN representative on SCEC Steering Committee

Education

B.A., geology, UC Santa Barbara

M.S., geology, California Institute of Technology

Ph.D., California Institue of Technology

Professional Highlights

Member, Technical Staff, JPL, 1990-1996

Senior member, Technical Staff, JPL, 1996-1999

JPL Program Element Manager for SCIGN, June 1999-present

JPL task manager for integration of GIPSY into the 1060- and 20-station Japanese GPS networks of GSI and GSJ, 1994-present

Development of stochastic baseline estimation techniques for addressing high strain rate geophysical problems with GPS and the development of routine GPS analysis software, 1992-present

A lead team member in the expansion of the Los Angeles GPS network for daily monitoring of spatial and temporal strain signals in the Los Angeles area, 1994-present

Panel member reviewing proposals for USGS NEHRP program

A SCIGN for the Times

Karen Brown

The term "win-win" isn't often applied to scientific projects, but it has been invoked in connection with the Southern California Integrated GPS Network, and all involved agree it fits.

That is because both scientists and other groups connected with SCIGN—principally ones with a surveying role—see nothing but benefits flowing from it both now and upon its full completion.

Scientifically, the project's main purpose is to improve hazard maps, points out USGS geophysicist Ken Hudnut, the chair of the SCIGN Coordinating Board. But everyone will benefit, he says, from better information about strain loading on faults and, therefore, potential hazards.

Looking beyond pure science, however, to who might benefit in a pragmatic, day-to-day sense, Hudnut points to the surveying and civil engineering communities in particular, as well those doing geographic information system (GIS) mapping of such things as the locations of gas pipelines and telephone wires.

"The surveying community in particular demands high accuracy in GPS results, and the infrastructure from this network will help them," Hudnut says.

Michael A. Duffy, manager of the geometronics section of the Metropolitan Water District of Southern California (MWD), is fully aware of how SCIGN helps him in his work providing primarily horizontal and vertical "control"—geodetic control—for all MWD construction projects to ensure, among other things, that water runs downhill. Some pipelines run 40, 50, or 100 miles.

Duffy says the SCIGN expanding network of Continuously Operating Reference Stations (CORS) is critical for the future geodetic management of all MWD projects. Data obtained are saving time and money and providing the section with more precise results, he says.

Integral to everything the section does, Duffy explains, is an approximately 70-year-old system known as State Plane Coordinates. This system was devised by the federal government so surveyors and engineers could use geodetic control on a plane surface rather than having to take into account the curvature of the Earth.

Duffy says the global positioning system (GPS) allows very precise measuring between different units, "but it doesn't place you on the coordinate system that most surveyors use: State Plane Coordinates. To get us on that system we had to find reference points that already had established coordinates on them." SCIGN does that for his organization through its network automatically.

As an example of how such direct, on-site project control can save time and money, Duffy says it took several years to provide the control network for construction of the Colorado River aqueduct in the 1930s using old-fashioned tools of the trade such as theodolites, sighting at night and building towers on high points of ground. With GPS, the control network could have been complete within two weeks, he says.

The criteria for siting SCIGN stations are "very stringent," Duffy says, adding that MWD is still "very much in favor" of having stations at its facilities, which include five large and complex water treatment plants, earthen dams and reservoirs, and concrete dams.

There are two main reasons for having the stations at its facilities, Duffy says: "We get free information that helps us save approximately 20 percent on any kind of survey we do that uses GPS." Current savings could total tens of thousands of dollars.

Second, MWD wants to see SCIGN seismic data results after an earthquake near one of its facilities. "We could respond more quickly in terms of damage assessment; that's going to help us."

Duffy is working with Hudnut and others on emergency response—another key potential benefit of SCIGN. Duffy is particularly keen to help streamline a reliable and direct communication network link that could receive geodetic and geotechnical data from the USGS shortly after an earthquake in southern California.

Hudnut says that an earthquake that comes close to the surface and has a large amount of slip close to the surface can disturb pipelines and actually cause water to flow the wrong way in sewer lines or water delivery lines.

Warping of the ground surface can also produce compression in some places and extension in others, he says, which can either pull apart or compress pipeline joints.

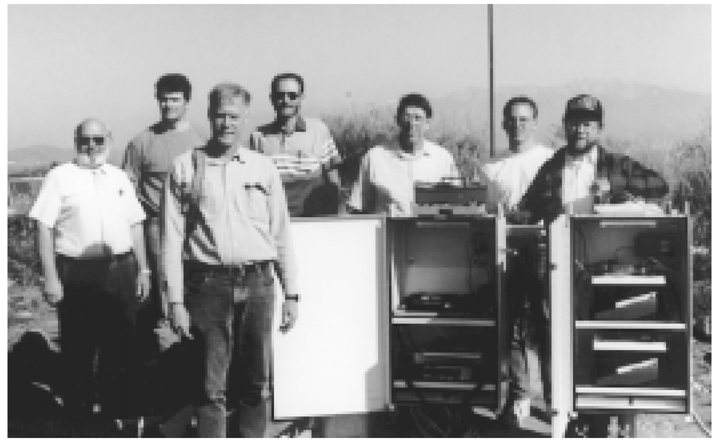
What scientists intend to do through SCIGN, Hudnut says, "is very rapidly provide an estimate of how the ground has been displaced, how the tilt pattern has occurred across a whole region, and also how the strain pattern has occurred on a regional scale. We want to be able to provide that directly to the emergency response community." High-water-pressure valves could be shut off automatically as soon as damage or problems were indicated.

Real progress has been made in monitoring individual large civil engineering structures, and civil engineers are among the groups he and colleagues aim to help in an emergency response sense, Hudnut says.

He says scientists want to provide such information within a useful time frame—a few hours or, ideally, in "real time," meaning less than 10 minutes after an earthquake. "There are GPS technologies coming along that we're testing that we think we can do that with," he says. Some operators of large dams in southern California also are interested in using GPS for real-time detection of problems.

Longer term, scientists are considering monitoring the "health" of engineered structures: using GPS and seismic equipment with a computer system hooked up to a tall building or large concrete dam.

A SCIGN *continued on next page*



Inauguration of the PGGA site at Lake Mathews reservoir, April 1993. In front is Yehuda Bock, Scripps Institution of Oceanography. In the back from left to right are Gerald Stayner, Riverside County, Ken Hudnut, USGS, Gerald Doyle and Bill Young, Riverside County Flood and Water Conservation District, Keith Stark, Scripps, and an unidentified electrical contractor. Lake Mathews is a water reservoir operated by the Metropolitan Water District. This construction was the first joint effort on a continuous GPS site by the scientific community and southern California surveying groups, a collaboration that continues to grow within SCIGN and the California Spatial Reference Center.

A Marriage Made in Space

Karen Brown

Earthquake researchers and surveyors have been working together on understanding earthquakes and earth deformation for a long time, but it took GPS technology to marry the two groups in a way that is set to benefit both.

Surveyors had problems with the changing shape of the Earth right from the time of the establishment of California's own Washington's Monument, in 1852. The structure is not, of course, in Washington, D.C. but atop West San Bernardino Peak in the mountains east of San Bernardino.

Surveyors know this as the Initial Point from which all the land surveys in southern California were done. It was named after a surveyor called Washington.

USGS geophysicist Ken Hudnut relates that Washington and his party climbed the peak, chopped down a tree and hewed it into a 30-foot-high timber pole from which they hung metal plates.

The original surveyors intended to return to the valley floor surveying as they went, establishing distance and shooting back up to the Initial Point using the sun's reflections on the plates to establish the orientation of their transect lines.

It didn't work; they couldn't see the monument from the flatlands. Some went back and lit a fire behind so it could be picked up at night.

Hudnut says they were thus able to site onto the point and make measurements from the valley below, establishing what is now known as Baseline Road running all the way from San Bernardino to Pasadena on a direct line of sight and an east-west orientation.

Washington Monument is placed at the intersection of the Base Line and the San Bernardino Meridian, which is the north-south oriented line that splits the boundaries into those east and west of it.

"All the properties to the north of that line are north and all to the south are called south," Hudnut explains. "That's how the property boundaries are all defined."

Survey monuments, or benchmarks, were thus established in the valley floor. Several decades later, when surveyors tried to close their survey loops back to the Initial Point, they noticed larger-than-standard survey errors.

Hudnut says it was never resolved as to why the surveys did not close correctly. He says there is speculation that the 1857 earthquake "may have caused enough deformation across those networks so that by the time they crossed the San Andreas fault and then came back over it again, the property boundary baseline surveys may have just all been offset by movement on the fault."

In the 1906 earthquake the ground deformed noticeably, and surveying instruments picked up the deformation away from the fault. Hudnut says it was those early surveying instruments that were used as a basis for the work of H. F. Reid, who is credited with formulating the elastic-rebound theory, which is "fundamental to our understanding of earthquake occurrence and recurrence even today."

At least since the turn of the century, therefore, geodetic data have had an important role in understanding earthquakes, Hudnut says.

Marriage *continued on next page*

A SCIGN continued from previous page

The computer system would be highly sensitive and capable of deciding whether the structure had sustained enough damage, for example, to sound an alarm or dump water.

In addition, Hudnut says civil engineers are interested in SCIGN for information on land subsidence (monitored with a combination of synthetic aperture radar interferometry, leveling, and GPS), and slow deformation and fault creep.

Caltrans

Reaping similar rewards as MWD and looking to the future is California's Department of Transportation (Caltrans), the agency responsible for the state highway network.

Caltrans also uses State Plane Coordinates extensively, in this case to control state highway corridors and provide a framework for surveys, says Adrian D. Davis, Caltrans' geometronics branch GIS/GPS coordinator.

"Everything we do is based on the State Plane Coordinates system: where we locate a highway or develop right-of-way lines for highways facilities," Davis says.

"Traditionally the points that have had State Plane Coordinates on them were on mountaintops, because you had to see from mountaintop to mountaintop.

"GPS enabled us to bring the control down to the job site. We can bring State Plane Coordinate geodetic control into our job sites more effectively and cheaply than we could in the past."

Davis says Caltrans is anticipating the expansion of SCIGN and similar networks because some present stations may not be in areas where the agency has projects.

"As the SCIGN network is built up, there will be more stations throughout southern California and they'll just be more accessible. They will be closer to our jobs," he says.

"We are supportive of SCIGN and its endeavors because the sites they are establishing will be beneficial to Caltrans now and in the future. It will enable us to develop project control on our project sites more economically."

The Surveyors' View

SCIGN volunteer and retired Los Angeles city chief surveyor Robert F. Packard agrees that ultimately the benefits of SCIGN boil down to economics.

"The benefits to the surveying community will be the ability to refer to a continuously operating station that is relatively close to any survey made in the southern California area," he says. "This will improve the accuracy of the local survey.

Marriage continued from previous page

Following the 1906 quake, the U.S. Coast and Geodetic Survey, which later became the National Geodetic Survey, established profile networks across the San Andreas fault system. "Sure enough," Hudnut says, "they saw the deformation going on across the fault system.

"Since the 1906 earthquake, but even before that and certainly from that time up through the mid 1960s or so, there was a generally rising appreciation of how much the ground was deforming between earthquakes."

The debate intensified, Hudnut says, over what was known as the Palmdale Bulge, or the southern California uplift.

Then and on through the mid-1980s, he says, "There was a general appreciation of the fact that the earthquake researchers were using data collected by the surveying community to conclude things about the earthquake hazard problem."

In my career we've moved from steel tapes to satellites. What's going to happen in the next 50 years? I don't know.

Hudnut says the USGS Geodolite Program in the 1970s, which involved earthquake researchers in high-precision laser-distance measuring along faults, was an indication of earthquake research putting resources increasingly into geodetic measurements to study earthquakes.

"This marriage that's come about now between the surveying community and the earthquake research community has been coming along for decades and now, finally, with GPS—boom—everything meshed," he says.

With the SCIGN network, Hudnut says, instead of just positioning points at one time the way they used to, surveyors will have a control network that is constantly being positioned on a daily basis.

"So as the whole network deforms, they're keeping track of that, and they can modernize the way property boundaries and all kinds of other surveying work are done. Things will be based off a network that moves with the deformation of the ground rather than a network that's defined at a point in time and then becomes outdated within a matter of years."

Says surveyor and SCIGN volunteer Robert F. Packard: "SCIGN has the potential to move the surveying community into the space age as far as its measuring ability goes."

Packard says the legal aspect of surveying will continue the way it has for centuries, but that measurement-taking will change with a network that will allow the local surveyor to tie to a global system.

"In my career we've moved from steel tapes to satellites," he says. "What's going to happen in the next 50 years? I don't know."

Packard estimates that it will take 15 or 20 years, however, before the majority of surveyors are using GPS regularly.

"Ultimately I see economics as the chief driving force, whether you're public or private. The private practitioner has to deliver the best product for the most reasonable price. The public surveyors are continually constrained by budget requirements, so economics will drive the process."

By having a SCIGN site close by, Packard says, "it means that your organization, public or private, does not have to maintain one of its own. And that has advantages in that all the technical expertise of SCIGN is available—for free—for anybody who wants to use the system. The price is right."

William (Bill) H. Young, fellow surveyor, SCIGN volunteer, member of the SCIGN Executive Committee and Coordinating Board, goes further from his perspective as chair of the board of the newly formed California Spatial Reference Center, an agency looking to take on full GPS-based geodetic control responsibility for the state.

Young says that the National Geodetic Survey (NGS)—builder and guardian of the National Spatial Reference System—continues to shrink in size.

"It can no longer maintain the national network of horizontal and vertical control points that makes up the National Spatial Reference System," Young told the latest SCIGN annual meeting.

A SCIGN *continued on next page*

Photo by John Galetzka

GPS technology has enabled scientists and others to monitor motion in large structures such as Pacoima Dam in Los Angeles. Ken Hudnut, of SCIGN and USGS, says Los Angeles County wanted monitoring at the dam to know how much it had moved right after an earthquake. SCIGN scientists helped the county install two GPS stations. The scientists detected 16 mm in annual deformation that they related to thermo-elastic motions. "As the dam warms and cools each year, the concrete expands and contracts so that the dam flexes like a diaphragm," Hudnut says. "The GPS picks up these small motions. Nobody had ever observed this subtle motion of the dam before. So GPS provides a very sensitive monitoring method."

"Visionaries" is the label Hudnut applies to Packard and several other surveyors and SCIGN volunteers—Bill Young, John Canas, Larry Cotton, Bob Smith, and Bob Reader. From positions high in their organizations, they recognized early on how important GPS would be and worked with earthquake researchers on surveys.

It was Packard who, outlining the benefits to a group of the siting of a SCIGN station on their property, first applied the term "win-win." He was referring to the advantages of surveyors working with earthquake researchers.

Hudnut says the term might sound like a cliche, "but when it comes out of Bob Packard, you buy it because it comes across so convincingly. It comes right from his heart."

Hudnut also recalls hearing Bill Young crediting SCIGN on behalf of surveyors: "We'd be in deep Bandini without you." Hudnut asked him afterwards and found out that Bandini was a brand of lawn fertilizer.

Hudnut says he smiled at this, because the earthquake researchers looked at it the other way around—as the surveyors having helped *them* so much.

The likes of Packard and Young had some hard sell on GPS within their own organizations, however, because of the profession's natural tendency to work within the established system, using equipment they already owned and were familiar with.

Surveyors had already faced change in the form of total station instruments (combination of previously separate angle-measuring and distance-measuring gear in one electronics-based package) and were just getting familiar with them when along came GPS, which was even more foreign and expensive.

Some of the resistance to GPS, until the late 1980s when things came together, concerned the GIS user community. Hudnut says with GPS the potential is there for anyone who doesn't understand surveying or its principles to go out and position any point on the ground within a centimeter with GPS.

"There was never any technology before that let you do that, especially not $100 pocket-size technology," he says. "To the surveying community, that can either be seen as a threat or an opportunity, because you've got this huge GIS mapping community saying, 'We don't need the surveyors any more. We know how to position ourselves within a centimeter or two.'

"Well, the problem then comes immediately, because once they try to register what they get with the GPS unit to this historical property boundary surveying information, there is a misrepresentation. The data don't fit."

Hudnut says the surveyors understand how to work that out into legal descriptions of property boundaries. He believes that is where licensed land-surveying professionals will be able to use GPS to work their way into a whole new job sector—working with GIS mapping groups and "helping them figure out how to do it right." ■

SCIGN PROFILE

Yehuda Bock

Research Geodesist
Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography

- SCIGN Executive Committee and Coordinating Board, 1994-present
- Director, Scripps Orbit and Permanent Array Center (SOPAC): Permanent GPS Geodetic Array (PGGA), 1989-present; UNAVCO Orbit Facility, 1992-present; IGS Global Data Center and Global Analysis Center, 1992-present
- Principal investigator for the creation of the first permanent GPS array in the U.S., eventually folded into SCIGN
- Instrumental in founding the California Spatial Reference Center (CSRC) and currently serves as its director

Education

B.A., mathematics, New York University

B.S., geodetic engineering, Technion-Israel Institute of Technology

Ph.D. (M.S.), geodetic science, Ohio State University

Professional Highlights

SCEC Crustal Deformation Working Group, 1991-present

California Geodetic Control Committee, 1993-present

IGS Steering Committee, 1991-1993; Governing Board, 1993-present; and Executive Committee, 1995-present

Editorial Board, *Manuscripta Geodaetica*, 1992-1995

Editorial Board, *Journal of Geodesy*, 1996-present

Convener, UNAVCO/IRIS Workshop on Geophysical Observatories and Regional Networks, Scripps Institution of Oceanography, 1994.

A SCIGN continued from previous page

"This is not as bad as it might seem, for the satellite-based Global Positioning System has come to our rescue. By the year 2005, NGS plans to switch from the brass disk and concrete monument to Continuously Operating Reference Stations for the National Spatial Reference System."

Elaborating on the problems connected with maintaining the critical state spatial reference system, Hudnut says that in most of the U.S., if a highly precise survey were done and monuments or benchmarks set in the ground, someone returning a century later would find them still there relative to a station hundreds of kilometers away.

In California, however, "there's this particular problem that stations keep moving at a rate of up to a couple of inches a year. Six years go by and you've moved a foot over to the northwest."

Traditionally, surveyors have referenced property boundaries in California and elsewhere back to a control network based on brass disks on mountaintops to which every other measurement is tied.

"Meanwhile," says Hudnut, "this whole control network is deforming through time and so are property boundaries.

"You can imagine how, through time, this led to a creeping, horrendous problem in terms of defining where things are, and that's what property boundary surveying is all about. Property boundaries end up overlapping in some cases. It just makes for a mess."

Surveyors in California had historically dealt with the issue but had had more help from NGS. An agreement now in place meant that state and county surveying organizations would take on more responsibility to maintain the spatial reference system.

Young, former Chief of Surveying and Mapping for Riverside County Flood Control, represents the League of California Surveyors on the SCIGN Coordinating Board. He says Riverside was installing CORS before SCIGN came along. Eventually, his county and others would probably have installed enough CORS, he says, but not as many or as quickly as SCIGN.

Having SCIGN installing the CORS is saving the surveying community and the national government millions of dollars, Young says.

"SCIGN is really filling a tremendous gap that was being created in the surveying community because we didn't have the funds to update the existing coordinates or spatial reference system."

Young adds: "The general public does not realize that the Spatial Reference System that we had was deteriorating to a position that it was next to useless."

Benefits of SCIGN will be far-reaching, he says. He adds that the main users of GPS technology will be nontraditional and in real time. Among these are agriculture, auto navigation, trucking, aircraft (both private and commercial), trains, boating, earthmoving, and marine shipping.

"They're equipping tractors with GPS units," Young says. "They will map their fields, outline the different soil types and then when they get ready to fertilize the fields, the information's put into a computer on the tractor, and it will only dispense fertilizer where it's needed. GPS allows them to know exactly where they are.

"Also, when they spray pesticides, it allows them to spray the pesticides only in the areas where they're needed."

The construction industry is also putting GPS equipment on tractors and graders, which could then automatically dig or deposit earth.

Young guesses, however, that the transportation sector—already set to be a major user of GPS—will get the largest benefits and payoff by being able to know exactly where trucks, shipping, trains, cars, and airplanes are at any given time.

Adds Packard: "The application to various kinds of construction and civil engineering projects will only be limited by the imaginations of the folks who do those kinds of things."

With SCIGN stations going in at the rate of two per week, the remaining approximately 130 are expected to be installed in about 15 months. But the benefits are already being felt. Surveyors, for example, have filed records of survey for many of the stations established in 1994 and 1995 after the Northridge earthquake.

Hudnut says that as a result, the positions of those continuously operating stations have become official through the NGS, meaning surveyors can now use the data as legally binding data when they are submitting a survey for public record.

Education

Education is yet another sector that has been quick to appreciate the benefits that "hosting" a SCIGN station at a school can bring.

El Camino College in Torrance responded enthusiastically when it was approached in January 1998. The college is adjacent to the Newport-Inglewood and Palos Verdes faults, and the USGS saw the school as an ideal site for a station, says Dean of Natural Sciences Joy Albert.

"I thought it was a good idea, and I phoned our resident geologist, Joe Holliday. He was very excited about getting the equipment on campus," she says.

Albert says Holliday, who knew about GPS and its applications, saw it as a way of working the subject into homework assignments and also of teaching students about how to get on the Internet to obtain information.

The SCIGN installation is located at the college planetarium. An outside display

Off-Scale

"The Flames Will Be Here in Fifteen Minutes"

Not in history has a modern imperial city been so completely destroyed. San Francisco is gone. Nothing remains of it but memories and a fringe of dwelling-houses on its outskirts. Its industrial section is wiped out. Its business section is wiped out. Its social and residential section is wiped out. The factories and warehouses, the great stores and newspaper buildings, the hotels and palaces of the nabobs, are all gone.

Within an hour after the earthquake shock the smoke of San Francisco's burning was a lurid tower visible a hundred miles away. And for three days and nights this lurid tower swayed in the sky, reddening the sun, darkening the day, and filling the land with smoke.

There was no opposing the flames. There was no organization, no communication. All the cunning adjustments of a twentieth century city had been smashed by the earthquake. The streets were humped into ridges and depressions and piled with the debris of fallen walls.

Dynamite was lavishly used, and many of San Francisco's proudest structures were crumbled by man himself into ruins, but there was no withstanding the onrush o' the flames. Time and again successful stands were made by the firefighters, and every time the flames flanked around on either side, or came up from the rear, and turned to defeat the hard-won victory.

On Thursday morning, at a quarter past five, just twenty-four hours after the earthquake, I sat on the steps of a small residence on Nob Hill. I went inside with the owner of the house on the steps of which I sat. He was cool and cheerful and hospitable. "Yesterday morning," he said, "I was worth six hundred thousand dollars. This morning this house is all I have left."

He pointed to a large cabinet. "That is my wife's collection of china. This rug upon which we stand is a present. It cost fifteen thousand dollars. Try that piano. Listen to its tone. There are few like it. The flames will be here in fifteen minutes."

—Jack London, Collier's, *1906*

case contains the equipment and information about it to tell students what they are looking at: high-technology equipment in operation.

"It cost them [SCIGN] $30,000 to install the equipment and they're going to maintain it free of charge," Albert says. "So we have this wonderful, currently in use equipment which is all free, and that's something we couldn't have purchased. It makes students more aware of the scientific basis of earthquakes, and the more information I think you have about a subject the less frightening it is."

Downey High School also has a SCIGN station up and running, situated in an outdoor-classroom-type area that features a half-acre vineyard. A weather station is also planned.

Vice-principal Tom Houts, who has a science background, says SCIGN was keen on the school as a possible equipment site because of a fault it was interested in that "pretty much runs under Downey High School. "

"I thought it was a wonderful idea," he says. Two other science teachers also were receptive, and the equipment went in about six months ago.

Recently the school found out that it had been selected as a Digital High School (a state program that offers funding to help schools catch up technologically); Houts says that beginning next year every classroom will have Internet access.

Information available on the Internet through the SCIGN connection will become part of class work: "We can get away from textbooks and look at real data as it's happening, live."

Downey science teacher Greg Pittenger says that when more SCIGN stations are installed and downloading data, the data are going to be useful.

"We have access to all their data, so in our earth science classes, we can start using some of that to talk about earthquake epicenters and fault line tracing. We'll be able to bring down the data and look real time or archive the data and see what's happened over a longer period of time."

Really Big Picture

Among so many pluses, what SCIGN spin-off matters most personally to Hudnut? "I guess the overall big-picture best reason to do it is that we have the technology to do precise geodesy in a continuous mode now. This is how seismic networks have operated for a long time. In geodesy, we've never been able to do that before.

"I have the real strong sense that what we're doing is going to improve our ability to quantify the earthquake hazard, respond to future earthquakes and get good information out after future earthquakes.

"I think it is going to definitely benefit a lot of people, partly just by virtue of the fact that this network is planted right on top of 15 million people; it's got to help people." ■

SCIGN PROFILE

William H. Young

President, Board of Directors
Analytical Photogrammetric Surveys, Inc.

- Member, SCIGN Executive Committee; liaison for surveying, engineering, and scientific communities
- Since SCIGN's inception, has participated in efforts to locate permanent sites for its network of Continuously Operating Reference Stations (CORS)

Education

Graduate, Harbor College, Harbor City, California

Graduate study in photogrammetry, Loyola University, and in geodesy, UCLA

Certificate, Advanced Management Program, UC Riverside

Professional Highlights

Chair, California Spatial Reference Center

Chief of Surveying and Mapping, Riverside County Flood Control and Water Conservation District for 39 years (ret. 1996); spearheaded the district's development of, and transition to, fully integrated Geographic Information System

Instructor, Engineering Photogrammetry, University of California, Riverside, and Pasadena City College

Licensed by the State of California as a land surveyor, photogrammetric surveyor, and consulting engineer

Member, National Academy of Sciences
—Member, NAS Research Committee of Geodesy

I Try to Keep Up with John Galetzka

Sara Tekula

Photo by Tom Rockwell

John Galetzka moves. Constantly. Even when he's standing still, he makes you think of motion—clearly a man ready for anything, whenever and wherever it shows up. And chances are, if it doesn't show up, John will go out and find it. Even when he's not physically in motion, you know his mind is leaping ahead and around, curious about his world and what's next in store.

Personal Profile

John Galetzka

"Every day is like a new life."

–J. Galetzka

Born
San Luis Obispo, California

Raised
Oregon

Education
University of Oregon, B.S., Geology, 1995.

Philosophies
Keep the mind open, think about your buddy, eat right (and include some good chocolate now and then!), recycle, and make every day count.

This is a good thing for SCIGN. Because to wear the number of hats issued with the job of SCIGN network coordinator, he needs plenty of energy—on any given day, the job title can shift from Negotiator, to Mountain Climber, to Geologist, to Carpenter, to Outreach Professional. John doesn't even blink.

Consider the first time I caught John actually at rest. Early in the morning on the first day of the 1998 SCEC Annual Meeting, I found him on a couch in the hotel foyer, struggling to stay awake.

Photo by Sara Tekula

When I asked him why he was so tired, he explained that, rather than spending the previous night in a comfortable Palm Springs hotel room, he'd been out in the desert searching for future SCIGN sites before unrolling his sleeping bag on the desert floor and sleeping under the stars.

It's this kind of enthusiasm and immersion in his work that gives rise to such questions as "Does he ever sleep?" (Answer: sometimes; see above) and "Where does he get his energy?" (Answer: I wish I knew; see below).

First: Coffee
In mid-March, John was supervising and coordinating the installation of a GPS monument at El Camino College in Torrance, so I decided to join him to see if I could uncover the source of the dynamo that drives him. In the days leading up to my field trip, I received several warnings from my colleagues. "Make sure you get enough caffeine in your system" was the most common. I boasted that I wouldn't need it. My confidence didn't last long—on the way meet him at the site at 6 a.m., I decided to stop for coffee.

I spent the first half of the day observing the process of SCIGN monument installation. It's really much simpler than I expected, with everyone working in a professional but informal atmosphere.

On a mountaintop in China, he met an English geologist/stockbroker, who got him thinking about land in a new way.

Mr. Coordinator
Building a GPS station requires finely tuned synchronization among many contractors, and it's here that John's skill at changing hats is most apparent. As SCIGN Network Coordinator, he oversees the project from beginning to end. First, he has to locate potential sites—meaning he does a lot of driving around. When he finds a potential site, he begins the work of getting the permits to build the station—often a lengthy process, especially when a SCIGN monument is to be built on city or county property. When the permits are secured, he moves into the next phase—working with contractors to build the sites (the phase I observed on this field trip).

John Galetzka (far right) and Sara Tekula (in front) along with the drilling crew that was installing a GPS receiver for SCIGN at El Camino College in Torrance.

Once the search for new sites slows down, John will focus more on keeping tabs on each site and participating in research and development, including assisting in research dissemination for SCIGN-generated data.

History over Lunch

After I ate a breakfast burrito for my lunch and watched John eat from a bag of nuts and berries for his, we sat for awhile and talked about the road he's been on that led him to SCIGN.

John attended high school in Oregon, and upon graduation, he decided that he didn't want to go to college. Instead, inspired by President Reagan's call for support and the Cold War that was still in progress, he felt called to, as he says, "protect the country and do public service through military service." So, right out of high school, John and four friends became Army Rangers, whose mission for four years was to parachute into enemy airfields, capture and secure the land, then continue to infiltrate the country, controlling traffic in and out of the area. John enjoyed his army experience ("it was lots of fun," he says), and when it was over, it was time for what he calls "new fun."

His field partners report that they can't keep track of John. One moment he's right beside them. The next moment he's up a tree, on a rooftop, or on top of the next hill.

"New fun" was traveling the world with a hometown friend and fellow Ranger. The two spent a year in East and South-

"Geologic Forces and Human Will"

Field Notes

Excerpts from John Galetzka's field notebook from another day, earlier this year, showing how this man gets around...

0810 hrs, near Rose Valley Road and Hwy 33

Dang! I'm really getting a late start today!

Although I didn't mind the air temperature hovering at 32 degrees or the lumpy ground under my sleeping bag, my subconscious was evidently uncomfortable being in a bivouac site so close to the highway. I had nightmares all night of being raided by evil travelers who happened to catch sight of my vulnerable white USGS vehicle.

But now it was the start of a beautiful day made all the better by a refreshing head dunk in Sespe Creek. Breakfast consisted of dried mangos, a Balance Bar, and water.

0900 hrs, farther up Hwy 33

After thanking the officer, I walked up the road to the ranch to see things for myself. The place had several small houses and mobile homes spread around. Each was abandoned, and there were no fresh vehicle tracks on the dirt road. Very eerie…

1110 hrs, old gas station at turn-off to Carrizo Plain from Hwy 166

The journey north out of Ventura County is an amazing spectacle of geologic forces and human will. Hay farms and pistachio orchards nestled in valleys bounded by slopes of steeply dipping sedimentary rocks.

The next destination was the Carrizo Plain, but before I started this next leg I wanted use this rare-for-this-part-of-California pay phone to check in with the office. Linda Curtis, the psychic secretary at our USGS Pasadena Field Office, is always a friendly voice to hear and is quick to relay all my messages. Without her, I am dust.

1200 hrs, Goodwin Education Center, Carrizo Plain

We ended up finding a spot suitable to all parties and came up with a plan of how to handle the permit process. What a wonderful place this is with its wide-open landscape and big sky! Truly one of my favorite places in southern California.

1850 hrs, Blue Moon Café in Ojai

I also took the time to pull into a viewpoint alongside Hwy 33 at the head of Matilija Canyon to watch the sunset and admire the incredible view of the Pacific and Santa Cruz Island far to the south. It was dark by the time I pulled into Ojai and found the Blue Moon Café. My routine is to put down some hot chow and compile notes onto my laptop computer while enjoying dessert and coffee.

2315 hrs, my home in South Pasadena

Took Hwy 126 for a quiet night ride home. Looking forward to a good night of sleep and meeting tomorrow with incredible SCIGN volunteers Bill Young, Bob Packard, and Art Varon.

east Asia, "exploring," he says, "new lands, new cultures, foods, peoples, and political ideas." On a mountaintop in China, he met an English geologist/stockbroker, who got him thinking about land in a new way. And his new acquaintance said something that stayed in John's mind: "You go to school to learn how to think, how to solve problems."

Soon after this meeting, however, John became very ill. Discovering he had tuberculosis, he returned home to Eugene.

Fortuitous Juncture

He took a year to recover, and when he was well again, he felt, he says, as though he had "a new lease on life." Remembering what his mountaintop friend had said, John studied for two years at a community college, then transferred to the University of Oregon to study geology with Ray Weldon. A course in field geology convinced John he had found his niche, and his enthusiasm led his professor to suggest he apply for an internship with the USGS.

John interned with Ken Hudnut (USGS geodesist and current SCIGN chair) during the summer of 1996. At that time, John says, SCIGN was "baby sized,"

I've spent a fifth of my nights during the last year out under the stars. It's hard to get back to being in the office.

and was known as DGGA—the Dense Geodetic GPS Array. At the end of the summer, Ken asked John to stay and work for the USGS and SCIGN project as the network coordinator. "To this day, I still don't know what that means, exactly," says John, "but it definitely involves getting things done."

This past summer, SCIGN's "Energizer Bunny" took some time off to do a different kind of fieldwork. John went to Sumatra (on the western end of the Indonesian archipelago). Kerry Sieh of Caltech invited him to collect large coral head samples, survey and map research sites, and compile data.

Photo by Sara Tekula

Finishing the Job

On his return, he came back to SCIGN. "I want to see SCIGN's five-year [funding] lifetime go as planned," he tells me, "though I'm sure it will live much longer than that because the network is so valuable."

And after that? John thinks a Ph.D. in geology is a possibility. Definitely not geophysics, though—"that requires being indoors too much. I've spent a fifth of my nights during the last year out under the stars. It's hard to get back to being in the office.

"Or I could go off and do something completely different. There are so many exciting things; who knows? I don't worry; there's always something interesting around the corner."

One thing's certain: Whatever he does, wherever he lands, having John around makes it mighty interesting for the rest of us. Just bring coffee. ■

SCIGN's Secretary of Energy

John Galetzka—An Appreciation

Nancy King

John Galetzka works out of the USGS Pasadena office. He supervises field technicians, oversees station maintenance, and works tirelessly on station reconnaissance and installation. He has done splendid work and has earned the liking and respect of all his colleagues.

We are all astounded by his energy. John never seems to stop working. He comes to work early with the morning people and leaves late with the night people. He may work a long day in the office and then drive out to the desert for evening station reconnaissance. His field partners report that they can't keep track of John. One moment he's right beside them. The next moment he's up a tree, on a rooftop, or on top of the next hill.

When John does stop working, he doesn't just go home like most people. It is nothing for John to casually mention, after a day in the field that would exhaust most people, that he's going to relax by going out to dance the tango. If he's not tangoing, he's hiking. He leads hikes for the Sierra Club but doesn't have many takers since people have learned that John's hikes are way too hard.

John meets many people while doing his job, and all of them like him. We hear constant comments on his cheerfulness, competence, and, of course, his energy. John can talk to anyone and often enlists people in SCIGN's cause. When the station at Compton College was in the way of road construction, John persuaded the construction crew to move the road. A forest ranger who started by asking John if he needed help ended up helping him with reconnaissance. John, in turn, often stops to help put out fires, free stuck vehicles, or render first aid. SCIGN is fortunate to have such an ambassador.

Passing along the Spirit of Inquiry

Sara Tekula and Jill Andrews

When earth scientists first decided to use the "eyes in the sky" (Global Positioning System satellites) to study minute changes in the Earth's crust, they were surely embarking on a project that feeds the imagination and opens doors to new possibilities for Earth science researchers. To pass this spirit of inquiry on to younger generations thirsty for knowledge, in 1996 SCEC's education program director designed a summer internship project to create an educational product that could promote understanding of the scientific basis of the Southern California Integrated GPS Network (SCIGN).

"Exploring the Use of Space Technology in Earthquake Studies" is an online tutorial that teaches the basic concepts of earthquake science and the Global Positioning System.

The result of that summer internship was the launching of the SCIGN Education Module, "Exploring the Use of Space Technology in Earthquake Studies." Since the first module was created for accelerated high school students and community college students, SCEC recruited an advisory team to align the modules to National Education Standards, beta test them in their classrooms, and begin translating them into products appropriate for middle school students. The teacher-advisors work with the module creators (scientists), combining weekend workshops with online feedback. We call this project, created to enhance the existing module, Development of Earth Science Curricula (DESC) Online.

"Exploring the Use of Space Technology in Earthquake Studies" is an online tutorial that teaches the basic concepts of earthquake science and the Global Positioning System, highlighting SCIGN's contributions to measuring ground motion in southern California. The module is divided into sections that introduce material and activities focusing on plate tectonics, earthquakes, GPS, and space technology at work.

The first three sections highlight satellite technology and tectonic phenomena; the final section serves to integrate knowledge learned in the first three by allowing students to use real SCIGN data in their investigations. There is an inventive "Activities" section that accompanies this module, which poses such questions as "How many earthquakes does it take to make a mountain?" and "How long will it take for San Francisco and Los Angeles to meet?" ■

Education Module Overview

Exploring the Use of Space Technology in Earthquake Studies

Appropriate Grade Levels
High school and college undergraduate

Design of the Module
This educational module was designed to allow students to explore interactively the use of SCIGN and its data in earthquake studies. It is divided into four major sections: Plate Tectonics, Earthquakes, GPS, and Space Technology at Work. All the sections include background material and activities.

Principal Authors
Maggi Glasscoe, Anne Mikolajcik, Andrea Donnellan, Mike Watkins, and Mark Smith with funding provided by the JPL, SCIGN, and SCEC

Example Activity
The following is the beginning of one of the activities included in the SCIGN Education Module. The illustrations and data referred to are provided online.

How long will it take for Los Angeles and San Francisco to meet?

The crust in southern California is constantly changing due to tectonic movement. The San Andreas fault, which is the main surface evidence of the plate boundary between the North American and Pacific plates, is allowing most of the movement of these plates as they grind past each other. This sort of boundary is known as a transform boundary.

Some day in the distant future, the movement of the Pacific plate along the San Andreas fault will eventually lead to Los Angeles and eastern San Francisco meeting and becoming neighbors. How long is that going to take?

We can figure this out by looking at two different SCIGN stations, one on each side of the San Andreas and use their relative motion to determine how long it will take for Los Angeles and San Francisco to meet.

First, let's use the accompanying graphic to find where the SCIGN stations are located so we can choose two appropriate stations. To determine the relative motion of the North American and Pacific plates, we will need to choose stations that are on each of these plates.

For the rest of the activity and accompanying materials, see: http://scign.jpl.nasa.gov/learn.

SCEC Intern Was Pivotal in Project

Developing the SCIGN Education Module

Maggi Glasscoe

If someone had told me that the little Web-based project that I started as a SCEC intern would develop into the full-fledged education module that it is today, I would not have believed it. The little Web project went from a lot of text on a gray background to an interactive Web site, complete with graphics and animation. More than two years of effort have been completely worth it, especially when teachers and students say that they are excited about the project as well. Such feedback helped drive the development of this module.

It is hard to believe that a little over two years ago I was consulting a book entitled *Learn to Program HTML in 14 Days* and struggling with just getting text onto the Web. Today, I worry that the text I am putting up for the world to see is accurate and insightful and meets education standards.

Working with the teachers and hearing from students who have been inspired by the module and the topics of GPS and earthquakes has made every bit of developing this module worth it.

This whole project was born from an idea shared by Mark Smith and Andrea Donnellan, who were directly involved in SCIGN activities at JPL. Mark was working with schools early in SCIGN's history, trying to find possible sites for the SCIGN stations. When he spoke with school officials, they often commented that it would be nice to have educational materials to help explain the SCIGN sites on the school campuses. He shared this with Andrea, who then spoke with Curt Abdouch (the former education director at SCEC) about the possibility of finding a SCEC intern interested in developing these materials. I happened to be applying for a SCEC internship that year and was interested both in Web design and GPS, and the rest is history.

The project continued even after my summer internship ended, and the module continued to evolve. I worked closely with JPL scientists who were involved with SCIGN, including Andrea, Mike Watkins, Ken Hurst, Mike Heflin, and a student from Occidental College, who is now at the University of Washington, Anne Mikolajcik. We also kept in touch with SCEC and worked closely with Meridith Osterfeld, an educational consultant working on the state systemic initiative in science, who worked as a reviewer on the project.

In 1998, we met with Jill Andrews and Sara Tekula of SCEC Outreach and started to gear the module up for public release. This now meant that educators would be looking at the module and helping us with the review process so that it would meet education standards. Meridith began to work closely with Jill and Sara, and the SCIGN module became a part of SCEC's new DESC Online program. This was a very exciting time for me, because I was working on making the site more interactive by adding animation and other graphics. Anne and I had already written the bulk of the text, so this meant that the module would soon be ready for public release.

It is hard to believe that a little over two years ago I was consulting a book entitled Learn to Program HTML in 14 Days *and struggling with just getting text onto the Web.*

In August 1998, we released the module to the public in its beta form (HTTP://SCIGN.JPL.NASA.GOV/LEARN). We have received a great deal of feedback that has been helpful in developing and refining the module. Currently, we are working closely with SCEC to review the module and bring them into compliance with educational standards so that they will be useful at the high school and middle school levels. I am also continuing to develop more informative animation and activities to be used in the classroom.

All in all, this process has been extremely exciting and fulfilling and has been a great deal of fun as well. I am excited and pleased to have been lucky enough to have stumbled into the SCEC office two and a half years ago and been awarded the SCEC internship that started me on this project.

Working with the teachers and hearing from students who have been inspired by the module and the topics of GPS and earthquakes has made every bit of developing this module worth it. The next step in the process is going to be the most critical, I think. Once the review is complete, the module will be ready for use in the classroom, which is our ultimate goal. ■

Tales continued from page 3

The antenna and tripod, attached to the receiver by the cable, were dragged down the street until the cable broke. The field tech called 911 and was put on hold. We never got the receiver back.

In the early days, we also had problems unique to GPS. At the time of the first UNAVCO campaigns there were only seven GPS satellites. They rose over California in the middle of the night, so we often began tracking at midnight. Finding stations and setting up is, of course, much more difficult in the dark. The early UNAVCO observing protocol also required us to measure temperature, pressure, and humidity every 30 minutes. These measurements, taken only with flashlight illumination by people who were bleary-

We were always staggering around carrying batteries in and out of motels. Our rooms often looked like battery warehouses.

eyed and usually bone-cold, were probably not the most reliable of scientific observations and turned out to be unnecessary anyway.

Hanging out in vehicles in remote areas at night also tends to look suspicious, and our activities often attracted the attention of the police. Although most people have heard of GPS today, in those days it was almost unknown. The police sometimes had a hard time accepting our explanation that we were out tracking satellites in the wee hours of the morning because we wanted to study earthquakes.

Finally, when we weren't on station, we were charging

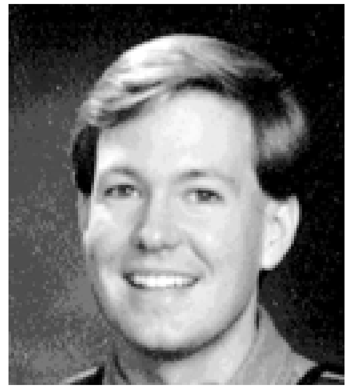
We discovered that one of the monuments on San Clemente Island was in the skip zone of the Navy's shelling range and that the zone was inhabited by wild pigs.

batteries. The early GPS receivers were power hogs and required two heavy deep-cycle marine batteries that were drained every night. We were always staggering around carrying batteries in and out of motels. Our rooms often looked like battery warehouses, which must have puzzled the cleaning staff.

The 200 new SCIGN stations require a huge reconnaissance and installation effort. A project of this magnitude inevitably leads to its own set of associated field tales. Those of us who remember campaign-mode GPS are happy to see the new state-of-the-art array. However, as we hunch over our workstations, we fondly remember our old adventures and sometimes wonder if those days weren't more fun. ■

Interested in sharing a field-work story of your own?
hough@gps.caltech.edu
www-socal.wr.usgs.gov/hough/

SCIGN PROFILE



Michael Heflin

Senior Member, Technical Staff
Jet Propulsion Laboratory

- Interprets data from SCIGN and derives GSP time series, positions, and velocities
- Discussed recent SCIGN results published in *Geology* on the NBC Nightly News with Tom Brokaw and on Los Angeles local news broadcasts on channels 2, 4, 7, 9, 11 and 13

Education

B.S., Miami University, Oxford, Ohio

Ph.D., Massachusetts Institute of Technology

Professional Highlights

Member, American Geophysical Union

Member, Sigma Xi

NASA Tech Brief Award for innovative technology

NASA Group Achievement Award

GIPSY Software Award

JPL Award for Excellence

History

continued from page 11

participating organizations), and an executive committee headed by a chairperson.

The first chair of SCIGN was Duncan Agnew by virtue of his being the head of the SCEC Crustal Deformation Working Group. After Agnew came Will Prescott, Yehuda Bock, Frank Webb, and the current chair, Ken Hudnut.

As currently funded, SCIGN has a lifetime of seven years. The first two years were devoted to implementation and the remaining five to operation, under the assumption, Webb said, that five years would be enough time to gather the data necessary to understand tectonics in southern California.

The SCIGN operations plan went through development and revision throughout 1996 and into 1997. Before the current full funding was secured, the plan called for installation in phases. Hudnut remembered, "At that time, we were thinking in terms of how to install the network in stages, depending on how the money came in." However, with nearly full funding following the Keck Foundation grant and a supplementary NSF award, the phases changed significance. They now indicate simply when installation contracts will be let.

Phase 1 was a kind of shakedown that involved installing three stations and writing eight site evaluation reports. Phase 2, now finished, called for installing 100 stations. Phase 3, scheduled to be finished by the end of the year 2000, will complete the total of 250 stations. Siting and permitting had been envisioned as part of the contract work, but to keep contract costs down, SCIGN staff led by John Galetzka, network coordinator, took on that major task.

Originally, the division of responsibility between Scripps and USGS was planned along the PGGA/DGGA lines, reflecting the two original networks that merged to form SCIGN. However, in practice, it's turned out that Scripps maintains the southern sites and USGS maintains the sites in the north end of the SCIGN array, which includes the entire L.A. basin. Some original PGGA sites, such as Vandenberg Air Force Base, were transferred to USGS responsibility and vice versa. In the final configuration, Scripps will be responsible for 50 sites and USGS will be responsible for 200 sites. Maintenance means both physically maintaining the site as well as downloading the data.

Funding SCIGN

SCIGN organizers tried to get funding from the state of California and other sources that don't typically support this kind of research, but nothing was working. "The main thing that we wanted was to bring in new money so that we would not compete for existing funds with colleagues doing related research," explained Hudnut.

They succeeded when they received $5.6 million in funds from the W. M. Keck Foundation. "That large amount of money from a private source really set our project apart," said Hudnut. "It allowed us to match federal funding with a degree of comfort and flexibil-

SCIGN PROFILE

Andrea Donnellan

Research Scientist
Satellite Geodesy and Geodynamics Systems Group
Jet Propulsion Laboratory

- Member, SCIGN Coordinating Board (SCEC representative, 1994-1998; NASA representative, 1999-present)
- Convened first network design workshop at JPL (1995) and co-convened (with Yehuda Bock) second workshop at Scripps (1997)
- Member, SCIGN "Dots" committee (phase I of the network)
- Development oversight of SCEC DESC online Web-based educational modules for SCIGN

Education

B.S., geology, Ohio State University

M.S., geophysics, California Institute of Technology

Ph.D., geophysics, California Institute of Technology

Professional Highlights

Pacific Plate Boundary Observatory steering committee, 1999-present

General Earthquake Models (GEM) program planning committee co-chair, 1998-present

AGU 2000 and 2001 Spring Meeting program committee geodesy section chair-elect (2000) and chair (2001)

GEM Data committee co-chair, 1999-present

SCEC Crustal Deformation Working Group, 1993-present

Member, American Geophysical Union, 1986-present

AGU Geodesy Section educational outreach representative, 1999

Recipient, SCEC Outreach Award for Education, 1998 ity that we would never have achieved otherwise. The Keck Foundation award was pivotal to the success of SCIGN.

"The main thing that helped us, overall, was the occurrence of the Northridge earthquake," said Hudnut. NASA and USGS immediately offered support for putting in more GPS stations.

It also helped that the group was experienced at writing and submitting proposals. Their work was respected and well known to the funding agencies by the time of Northridge.

However, full funding didn't just fall into their laps even after the Northridge earthquake, Hudnut pointed out. "We'd been out there pounding the pavement for quite some time before the Keck funding came through."

SCIGN's advisory council has strongly urged the group to find funding sources that would continue operations to ensure that each station in the network produced at least five years' worth of observations. Hudnut believes that even if current funding sources run short of that goal, others are likely to follow.

"I think we're going to be able to keep it going," he said. "The California Spatial Reference Center is a potential revenue generator. We may be able to draw upon the surveying organizations in southern California once they become reliant on the data from the stations. My guess is that they'll be able to help us out with personnel in order to keep the network running."

Bock pointed out that local and state agencies have a stake in an ongoing permanent GPS network. "SCIGN received funds from several counties in our area, some flood control districts, and Caltrans. They recognized the benefits and wanted sites in their locations."

In the future, Hudnut expects that funding agencies will look at SCIGN to justify funding or not funding similar arrays, particularly in urban areas along the plate boundary. However, he is also confident of the SCIGN approach. "I think that this is a globally applicable approach to better evaluating seismic hazards."

If we were able to record data from the full network for five years, and then we had a M 7.2 or higher, and then we kept the network running for an additional five years—that would be beautiful.

Bock added, "I'd also give credit to SCEC for organizing and providing the umbrella to allow these groups to work productively together. Without SCEC, we wouldn't have had SCIGN the way it is today."

The Equipment

"The first meeting I went to where people were talking about GPS was in 1984," remembered Hudnut. "At that time people were talking about the very best you could do with high precision GPS was 6-10 cm. Now we're down to 3-4 mm." The decade from 1985 to 1995 was the period in which GPS hit its fastest growth spurt and in which it matured into a scientifically precise and economical tool. "Now we're getting out there onto the tail of the exponential where we're having to work harder to get every little bit more in terms of precision," Hudnut said.

In 1995 the current type of receiver and antenna cost about $25,000. Hudnut expects that in a few more years "we're going to be able to buy the top of the line geodetic receiver and antenna for something like $5,000."

Although almost every aspect of the SCIGN program reflects the need for precision, a few early decisions stand out as critical shapers of the project's success. First, and most fundamental, is the design of the monuments on which the receivers are mounted. SCIGN developed its own specifications for the monuments, based on a design by Frank Wyatt at Scripps, including blueprints for the welded stainless steel tripod that each receiver is mounted on and the adapter ring that connects the base with the receiver. The purpose of the design was not only to ensure a stable monument that was well attached to the Earth's crust, but a monument that would have a useful life of 50 years.

SCIGN's work with the manufacturers of GPS equipment ensured that each station would have the best equipment available and that each station was fully tested before and after installation. In many cases, receivers, antennas, and other parts had to be returned because they did not meet SCIGN's rigid specifications and testing.

Fairly early in the process, it became clear that the antennas and their choke rings (concentric metal rings at the base of the antenna that prevent duplicate signal reception) needed protection from the elements and that no available covering was adequate. The solution? SCIGN scientists designed their own "radomes" and had

How SCIGN Is Funded

The Southern California Integrated GPS Network is administratively a part of the Southern California Earthquake Center, which is an NSF-sponsored science and technology center for coordinating earthquake research. In the case of SCIGN, however, special funding sources came together to make it happen. Early support from the USGS and NASA provided startup monies, and subsequent major grants from the Keck Foundation, NASA, and the NSF ensured its continuation and completion.

them manufactured. To support that additional cost, they now also sell those domes to other GPS networks.

In the case of a future earthquake, we can have the trap set and ready to capture something interesting.

In the future, anyone wanting to install a dense network will have to look carefully at the experience and data from SCIGN. Although appropriate alternatives to the SCIGN choices are possible if a high degree of precision is not needed, Hudnut is confident that if a network needs to be within a mm/yr, then it must use drilled-braced monuments of the type SCIGN is using—or something better, if available. "For any geophysical application, you want as high a signal-to-noise ratio as possible," said Hudnut. "The cost of good monuments is going to prove very worthwhile for getting the best science from these new networks."

Strain Meters

Though SCIGN is primarily a GPS project, there are also laser strain meters in three southern California locations; two are at Piñon Flat Observatory in the San Jacinto Mountains and another is at Bombay Beach near the Salton Sea. A third site is being developed in the L.A. basin, along the Glendale Freeway near the San Rafael Hills. The strain meters, installed and maintained by Duncan Agnew and Frank Wyatt, provide an independent check on the data from the GPS network. The laser is shot a few hundred meters through a vacuum from one monument to another and provides a more accurate measurement of ground motion than is possible with GPS. The strain meters measure how the ground is moving all the time and therefore how strain is building very precisely over a relatively short distance—down to near a thousandth of a millimeter—about two to three orders of magnitude more sensitive than GPS.

Keeping It All Going

Judging by the paperwork alone—the official plans, reports, papers, press releases, and presentations—SCIGN seems like a huge organization. In reality, it involves a relatively small number of people, almost all of whom have other projects or responsibilities. Therefore, when something goes wrong, it can have a significant effect on the project and the people.

When sub-millimeter precision is your goal, you have to have the best, and it has to be reliable. If previous SCEC work and SCIGN's own goals set high standards for the project, those standards necessarily had to be passed along to all others associated with the project, including the equipment manufacturers. Almost every aspect of SCIGN was innovative. Despite the best-laid plans, not everything worked right the first time. Hudnut reluctantly mentioned one example: "The antennas—what a nightmare—we all spent a lot of time on that. The company we bought them from eventually had to recall them.

"You set a goal, make a list of all the things you have to do to get there, and then plan out your time accordingly," said Hudnut in describing the obstacles SCIGN encountered. "Then—boom—the first thing pops up that you hadn't planned on, so you have to deal with that. Then—boom—the next thing pops up. By the time you've dealt with all the little problems—and some of them aren't so little—you start getting behind schedule and getting frustrated and realizing just how severely you are understaffed. It starts getting to be a serious weight on your shoulders instead of being something you can just breezily toss off. You start feeling as though you're slogging along rather than walking along and whistling."

The cost of good monuments is going to prove worthwhile for getting the best science from these new networks.

Why SCIGN?

The technical goal of SCIGN is to achieve sub-millimeter-per-year precision in crustal motion. Where does it stand in 2000 on its way to that goal? "It's still a goal," said Webb, "because that goal is based on five to seven years of operation. As time goes on, we will accumulate more data, increase our knowledge, and the long-term velocities will get more accurate."

Hudnut summarized the overall scientific purpose of the part of the SCIGN array in the L.A. basin, the part where receivers are installed with the greatest density as determining "how the crustal motion between Mt. Wilson and Palos Verdes is distributed." The total movement is about 7 mm/yr; therefore, "we knew that our accuracy level had to be within a millimeter a year or we'd fail," he said. High precision had to be the standard from the outset.

"When we were discussing and developing a rationale for SCIGN," recalled Hudnut, "we wanted to contribute to improving the SCEC estimates of earthquake hazards in southern California by adding GPS data to the hazard maps."

"We know where many of the faults are in southern California," explained Webb, "and the faults represent hundreds if not thousands of earthquakes averaged over, say, a million years. For some faults, we know the most recent earthquake history, say the last two or three earthquakes. The velocity field that comes out of the GPS network will tell us what's going on right now. It should help us identify active structures and understand which are the most hazardous ones in southern California."

Bock believes that the line of receivers across the L.A. basin (part of the densification plan) should be beneficial, but that there could be limits to its significance. "The whole idea of this profile through the basin is to find out where the strain is concentrated and to determine the nature of the deformation," he said. "There are models of detachment faults and blind thrusts, but there is disagreement about their geometry. The idea behind a dense profile is to be able to pick out subtle changes that will allow us to differentiate between those models. That's if there's a single fault that's causing this build-up of strain. The more faults that are involved, the more difficult it is to differentiate between them using surface measurements.”

Bock said that one basic scientific question is whether the basin's contraction is being taken up by vertical faulting or by a combination of vertical faulting and strike-slip faulting. “The jury is still out,” he said, “but as the network gets denser, and as we look at the data in more detail, we'll have a better handle on that.”

Because of its origins in both a dense network and a broad regional network, there are divergent objectives for SCIGN. The network configuration that has emerged is a compromise between different goals, reflecting the different questions that scientists want to answer.

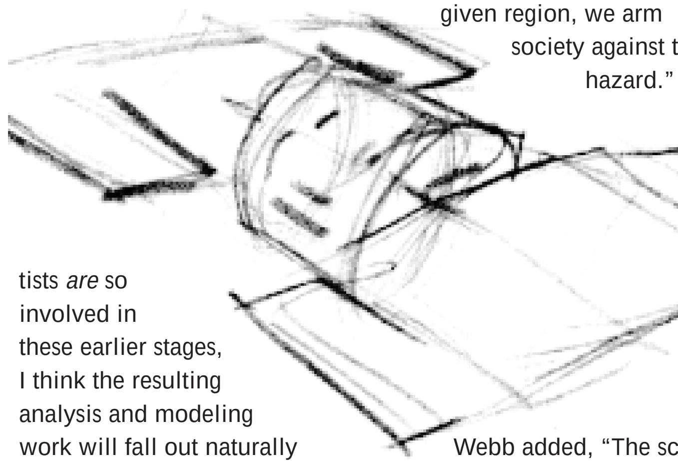
Though he sees great value coming from the increased number of stations and data, Bock, perhaps reflecting his broader, regional approach to GPS monitoring, believes that there is benefit to what is already in place. “Even if we just stopped everything right now and just analyzed all the data that we've collected up to this point, we'd get a pretty good answer to this first-order problem—how the strain is distributed in the L.A. basin.”

Even if we just stopped everything right now and just analyzed all the data that we've collected up to this point, we'd get a pretty good answer to how the strain is distributed in the L.A. basin.

There has been and continues to be debate among SCIGN participants and even on the Advisory Council about SCIGN's ultimate scientific role. Some argue that SCIGN should just be a network operator and produce positions for the stations, which would then be available to the entire scientific community. Others argue that SCIGN should itself come up with a model of how the L.A. basin and southern California are moving.

Bock believes that procedural question needs no solution. “I'd say the most basic purpose of SCIGN is to put in the infrastructure and accumulate enough data to produce some results in answer to the fundamental problem of how strain is distributed in southern California,” he said. “Since so many people involved in SCIGN are scientists, I take the broader view that SCIGN is really a community of scientists that shouldn't stop at collecting data but should also produce a model.

“A scientist who's spending a lot of time working on infrastructure alone is a scientist who could be doing other things,” Bock noted. “But we have to get the infrastructure in place, and it has to be done appropriately for the scientific goals. Therefore, scientists have to be involved. But since scientists *are* so involved in these earlier stages, I think the resulting analysis and modeling work will fall out naturally as the project matures.”



A secondary, but important, purpose of SCIGN involves reversing the position calculations to determine the locations (i.e., the orbits) of the satellites in the GPS constellation. That reverse measurement is done daily and fed back into the calculations of the receivers' positions, ever increasing the accuracy of the data. SOPAC, JPL, and others have been feeding precise orbit information back to the IGS ever since the international group began. The more stations there are around the globe, the more precise the orbit information. The more precise the orbit, the more precise the locations for all receivers.

Societal Benefits

“Earthquakes pose a risk to society in regions worldwide,” said Webb. “I think it's a worthwhile investment by society to try to understand the physical process of earthquakes so that we can prepare ourselves against the hazards. You can't stop the plates from moving, but you can certainly obtain more information about where and how they're moving. By translating that information into a statement of the hazard for a given region, we arm society against the hazard.”

Webb added, “The scientist's job is to inform people, not to set public policy.” However, he went on to say, “There has to be some translation for and education of the public about what we're finding, especially when those results have societal consequences.”

Bock compared earthquake research to cancer research, pointing out that it's sometimes difficult to tell what's “pure” and what's “applied.” “There's a certain purely scientific interest in understanding how the Earth works. In purely scientific terms, the answer is that knowing is a goal itself.”

He went on to point out that GPS has a range of applications beyond detecting crustal motion. An example is the proposed work of the California Spatial Reference Center in creating a statewide grid of GPS stations for surveying and other geodetic purposes. “Even if we learn nothing from SCIGN—which I'm sure will not be the case—we will have an infrastructure that we can use in day-to-day life. It's like a utility, like electricity. It's how we know where we are.

"One of the most satisfying things for me in the SCIGN project is knowing that whatever developments we make can be spun off into many other applications. Determining the precise location of something is becoming increasingly a fundamental piece of information. It's a unique situation in which we're able to study fundamental science in addition to developing something that will be of practical use to society in general."

The Data
The typical SCIGN field site contains the antenna mounted on a tripod. Connected to the antenna by cable is a box containing the receiver that gathers and stores the information through the antenna. Also in the box are the means of transferring the data once a day. Depending on the services available at the site, that could be an Internet connection, a modem and telephone line, a cellular phone/modem combination, or radio telemetry.

Each day, the USGS in Pasadena downloads the sites around and to the north of the L.A. area. SOPAC at Scripps downloads the more southerly sites. Automatically and immediately, all data are transferred via FTP on the Internet to SOPAC for archiving. The raw data are in RINEX (receiver independent exchange) format, the standard for GPS data.

Almost immediately, the complete raw data set is available for processing. The USGS makes rapid position calculations immediately after the data are retrieved. If an earthquake occurs, the USGS will provide static displacement data. Later, after calculating final, precise orbits, both SOPAC (using GAMIT) and JPL (using GIPSY) analyze the data and produce location information for each site, indicating how each site is moving in relation to an international reference frame. That positioning information along with other information about each site is available within hours via the Web. From the beginning, SCIGN was designed to include the two analysis centers. Both are world leaders in GPS-based research and data analysis. In addition, both analysis centers calculate precise orbits for the satellite constellation daily and feed that information back into the global network.

As former SCEC Science Director Dave Jackson, an early participant in GPS research, put it, "We are lucky to be able to have two such organizations at work on this project. The fact that they might disagree in their results is a sign of our success since that's how we planned it at the beginning: two analysis centers using different approaches gives us the chance to put the entire system to a full test, from individual receiver placement to the details involved in final data processing."

In the first year or so of analysis, the results from the two centers did not agree, and there was no way to merge or average the results. "The point of the dual analysis centers is to assure that the project as a whole is producing a good product," said Webb. "And one measure of whether the product is good is how close those analysis center results are. Each of us is going to learn a lot about the other group's analysis techniques and strategies. We'll learn something about our own analysis methods and their strengths or weaknesses.

"I don't think SCIGN will decide which software package or data processing method is best. It will decide which solution we're confident in and is true to the data."

Bock pointed out the dynamic nature of data processing. "As the hardware and techniques improve, the analysis improves. It's not a one-time thing; we've already been through the entire data set at least two times. Every time we develop an improvement to the analysis techniques, we go back and reprocess the data. In addition, every year a new set of global coordinates is published. So going through the data once is not sufficient. We'll go through the data several times over the years—as analysis improves and as we understand the nature of the data better."

Looking beyond the calculation of station locations alone, current chair Hudnut pointed out that the freely available data are an open door for many potential users. "Between the raw data files and whatever somebody wants to get out of them, there's a huge space that can be filled by clever people writing programs and getting out there and working on problems that they want to solve. I think there's a lot of potential, and it hasn't really started yet."

There has to be some translation for and education of the public about what we're finding, especially when those results have societal consequences.

Real-Time Data
The focus of the GPS portion of SCIGN is gathering continuous data for the study of crustal motion. But that focus doesn't always meet the needs of the data's potential users.

For example, the data from a typical receiver is downloaded once a day and sampled at a rate of once every 30 seconds. For geodetic purposes, where the concern is long-term motion, those choices are fine. But the surveying community, which eventually stands to benefit in the form of nearly instantaneous precision surveying, the sampling rate and daily schedule are not frequent enough. The same could be said for the emergency response community as well as potential users such as utilities, transportation agencies, and dam owners.

Bock: "The surveyors have always pushed us, even back in the PGGA days, to use a higher sampling rate. Some of their kinematic surveys are sampled once a second. If we sample once a second, we'd have 30 times more data. It's not impossible, but we have to strike a balance. They want us to sample at least every 5 seconds. They want to go out into the field and stay at each survey point a minute or two, get their fixes, and move on, saving them time and money. They would even like some of the sites to broadcast data to people in the field."

Mostly that level of concern is related to the needs of surveyors (see "Archiving and Using Data"), but there are scientific reasons for having such a capability. For example, SCEC still does survey-mode GPS. For such campaigns, a near-real-time GPS backbone would make the survey easier and faster to conduct and would make the data processing easier and faster.

"The longer you wait to process data," said Bock, "the more likely you are to make a mistake. The closer you can get to real time in processing data, the more beneficial to the quality and accuracy of the final data. There is some discussion in SCIGN of considering data from a survey site as a temporary continuous site. The data from such a site would be plugged into the current daily data processing flow and processed along with all the other data. That way the data would be processed almost the same day it's collected. The difference between survey mode and continuous GPS is getting fuzzier and fuzzier."

Judging from the data we've collected and analyzed so far, I'd say that we're exceeding expectations.

The SCIGN plan includes a pilot test by the USGS of the feasibility of producing real-time data from a subset of receivers. The main drawback is the additional cost of sending out continuous data rather than storing it at the receivers and sending it once a day.

"If you want to triple the project's overall budget," explained Hudnut, "add a real-time telemetry component to every station. We're trying to keep this project relatively inexpensive, and one way of doing that is to run the telemetry as cheaply as possible. If we can, we use the seismic network telemetry and any other telemetry systems that we're allowed to. Some of our USGS office's receivers are piggybacked onto the military telemetry system. We are going to try to have some subset of data from the SCIGN network coming in here in real time as part of the earthquake response capability of SCIGN, but we're just now trying to develop that."

Integration of Data

"I don't think anybody thinks that geodesy will solve all the problems," Bock said about SCIGN's role in the bigger research picture, "but it can certainly be an important contributor to understanding the earthquake problem and building models of earthquakes."

He pointed out that the major benefit of SCEC is bringing different disciplines together. "The geologists and geodesists and seismologists weren't

SCIGN PROFILE

William H. Prescott

Senior Research Geophysicst
U.S. Geological Survey

- Member, SCIGN Executive Committee, 1996-1997
- Member, SCIGN Coordinating Board, 1995-present
- Chair, SCIGN Coordinating Board, 1996
  — SCIGN's first operating plan drafted, laying groundwork for strategy used to construct array
  — wrote "pro" portion of the *Eos* article on the proposed GPS network, defending concept of a continuous GPS array

Education

B.A., Middlebury College

M.A., mathematics, UC Berkeley

Ph.D., geophysics, Stanford University

Professional Highlights

Chief, Deformation Project, USGS, 1997-1999

Senior Research Geophysicist, USGS, 1995-1996

Chief, Branch of Earthquake Geology and Geophysics, USGS, 1993-1994

Chief, Branch of Tectonophysics, USGS, 1989-1992

Coordinator, Element II, National Earthquake Hazards Reduction Program, USGS, 1989-1992

Member, American Geophysical Union (president of Geodesy Section, 1998-2000)

Member, Seismological Society of America

Editor, *Manuscripta Geodaetica/Bulletin Geodesique*, 1991-present brought together before," said Bock. Now, he said, "All the information and insights of all the disciplines are brought to bear on the fundamental problems."

On the need to supplement GPS data to learn about the deeper structures, Bock said, "GPS is measurement at the surface, and we're trying to determine things that are about 15-20 km deep. You have only a certain sensitivity in translating surface conditions into conditions at depth. You'd have to cover every square meter of ground to begin to differentiate detachment faults from strike-slip.

You can't stop the plates from moving, but you can obtain more information about where and how they're moving. By translating that information into a statement of the hazard, we arm society against the hazard.

"That's why we want to use SAR interferometry (InSAR) as a way of getting a more dense picture of what's happening on the ground. That's why some of us, because of the development of InSAR, were even more adamant about broadening the SCIGN network.

"Since GPS on the ground provides a reference frame for InSAR, the idea is that if you broaden the GPS network and design it to be integrated with InSAR, then you could get a complete picture of deformation."

Bock believes the full scientific benefit will come only from a combination of regional, high-accuracy GPS and InSAR, a belief shared by most of the participants in SCIGN. "InSAR is not as accurate without a precise GPS backbone," Bock said, "and continuous GPS is not as thorough in its coverage as InSAR."

Future of SCIGN

The future of SCIGN can be summarized by geographical area: local, regional, state, and global. SCIGN clearly has a role in understanding the details of the seismic hazards in the L.A. basin and surrounding area. Those details, because of the composition of the network, will be understood in the context of all of southern California. Since SCIGN has already been recognized by the National Geodetic Survey as the foundation network for establishing a GPS-based surveying grid for all of California, SCIGN and its future incarnations will be the foundation of the future of how all surveying and precise locating is done in the state. And since SCIGN is one of the densest high-quality GPS networks in the world, it will continue to shape how geodesy is done and how much geodesy contributes to overall earth science programs worldwide.

Frank Webb: "SCIGN is a local network in southern California aimed at understanding the local tectonics. We have some scattered stations in the outlying areas to put those observations into a regional context, but the plate boundary is much broader than that and extends east through the Basin and Range and north into Canada and Alaska. Part of the future is to expand our observational strategy to understand how tectonic processes are deforming the entire plate boundary by linking the existing networks and filling the gaps in between. Certainly GPS will be a major component of that larger project."

After SCIGN, how will the sites be maintained? Of fundamental importance, said Bock, was the physical design of the network. "We chose our materials to last at least 50 years. That was an early decision, driven by surveyors and others, who are concerned about the longevity of the network. A broader plate boundary initiative is now on the drawing board; it is science-driven but could also maintain the GPS infrastructure. CSRC and a plate boundary initiative both have broader concerns than SCIGN, but SCIGN is a perfect test case and foundation for both."

To SCIGN or Not to SCIGN

In the early days of SCIGN, the American Geophysical Union's weekly newspaper, *Eos*, ran an article debating the proposed GPS network.

Will Prescott, chair of SCIGN at the time, wrote the "pro" piece. Jim Savage, a close colleague of Prescott's but a skeptic about GPS, wrote the "con" piece. In particular, Savage was skeptical about whether SCIGN was the best use of taxpayer support for earthquake research. Savage felt that it was going to be a waste of money.

We will have an infrastructure that we can use in day-to-day life. It's like a utility, like electricity. It's how we know where we are.

The debate, according to Hudnut, is not over yet. "A lot of people in our community of earthquake researchers would still favor Savage's arguments in that debate. We in SCIGN still have a lot to prove to ourselves and our colleagues—and to our funding agencies. The success or failure of the SCIGN project to some degree will determine how much the usual funding sources will be willing to fund more continuous GPS work.

"Judging from the data we've collected and analyzed so far, I'd say that we're exceeding expectations. So I think the prospects are incredibly good."

Just as SCIGN became a certainty, the *Eos* debate pieces appeared. That environment of both external and internal skepticism as well as the not-quite-fully-blended mix of advocates for dense versus broad arrays made for lively and ongoing discussions for the next several years. Those have already been productive years, partly because of the ongoing debates. The future promises no immediate end to the debates, but it does promise an ever-increasing flow of information, experience, and knowledge. ■

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Web Links

Participating SCIGN Organizations

Jet Propulsion Lab's Southern California Integrated GPS Network
http://scign.jpl.nasa.gov/

NASA Crustal Dynamics Data Information System
http://cddisa.gsfc.nasa.gov/

Scripps Orbit and Permanent Array Center
http://lox.ucsd.edu

Southern California Earthquake Center
http://www.scecdc.scec.org/

Southern California Integrated GPS Network
http://www.scign.org/

USGS Menlo Park
http://quake.wr.usgs.gov/QUAKES/geodetic/gps/

USGS Pasadena
http://www-socal.wr.usgs.gov/hudnut/

Other GPS/Geodesy Resources

American Geophysical Union Geodesy Section
http://www.grdl.noaa.gov/AGU/geodesy.html

Australian Surveying & Land Information Group
http://www.auslig.gov.au

Basin and Range Geodetic Network
http://cfa-www.harvard.edu/space_geodesy/BARGEN/

Bay Area Deformation Array—USGS/UC Berkeley
http://quake.geo.berkeley.edu/bard

Canadian Active Control System
http://www.geod.nrcan.gc.ca/html-public/GSDproductsGuide/CACS/English/cacstest.html

Crustal Dynamics Data Information System
http://cddisa.gsfc.nasa.gov/cddis_welcome.html

European Reference Frame
http://www.oma.be//KSB-ORB/EUREF/eurefhome.html

Geographical Survey Institute, Japan
http://www.gsi-mc.go.jp/

GPS—General GPS information
http://www.inmet.com/~pwt/gps_gen.htm

GPS Information and Observation System
http://gibs.leipzig.ifag.de/

International Association of Geodesy
http://www.gfy.ku.dk/~iag/

International Earth Rotation Service
http://hpiers.obspm.fr

International GPS Service for Geodynamics
http://igscb.jpl.nasa.gov

GPS & Geodynamics at MIT
http://www-gpsg.mit.edu

GPS World Online
http://www.gpsworld.com/

National Geodetic Survey (NGS)
http://www.ngs.noaa.gov/

NGS Continuously Operating Reference Stations
http://www.ngs.noaa.gov/CORS/cors-data.html

NGS Geodetic Resources
http://www.ngs.noaa.gov/geodetic_links.shtml

NGS Orbit page
http://www.ngs.noaa.gov/GPS/GPS.html

NOAA Geosciences Research Division
http://www.grdl.noaa.gov/GRD/

Northern California GPS Users Group
http://quake.geo.berkeley.edu/bard/ncgpsug.html

Pacific Northwest Geodetic Array, Central Washington University
http://www.panga.cwu.edu/

Pacific Northwest Geodetic Array, University of Washington
http://www.geophys.washington.edu/GPS/gps.html

Tom Herring's Continuous GPS Processing Results (MIT)
http://www-gpsg.mit.edu/~tah/cont98g/cont98.html

U.S. Coast Guard's Navigation Center
http://www.navcen.uscg.mil

U.S. Naval Observatory's GPS Data & Information
http://tycho.usno.navy.mil/gps_datafiles.html

University NAVSTAR Consortium
http://www.unavco.ucar.edu/

Western Canada Deformation Array
http://www.pgc.nrcan.gc.ca/geodyn/wcda.htm

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Jill Andrews, Outreach Director
213 / 740-3459 or jandrews@terra.usc.edu

Mark Benthien, Outreach Specialist
213 / 740-0323 or benthien@terra.usc.edu
(general information, publications, WWW)

Ed Hensley, Newsletter Editor
hensley@usc.edu

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Editor
Ed Hensley

Writing:	Photography:
Jill Andrews	John Galetzka
Karen Brown	Tom Rockwell
Maggi Glasscoe	Sara Tekula
David Jackson	
Nancy King	Assistant Editor:
Sara Tekula	Barbara Anderson

Cover and Incidental Illustrations:
Jim Hensley

Cover:
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Southern California Earthquake Center
University of Southern California
Los Angeles, CA 90089-0742

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