Geodetic Measurements along the Rose Canyon Fault

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Abstract

This grant has supported the initial phase of a long-term study of earthquake hazard in the cities of San Diego, CA, and Tijuana, Baja California. The Rose Canyon Fault, a minor fault in the San Andreas System of faults in southern California, runs through the region from north of La Jolla, past Mount Soledad, and on to downtown San Diego. From there the fault location is not known, but two possibilities are commonly mentioned: the fault may across Coronado island and then offshore to the international border, eventually coming back on land south of Tijuana, or it may continue southeast from downtown San Diego eventually linking with the Vallecitos Fault east of Tijuana. Paleoseismic studies have show this fault is active and accumulating crustal deformation at a rate of about 1-2 mm/yr. We have established a survey-mode network of GPS sites designed to accurately measure this deformation and have conducted the first set of occupations of this network; repeat occupations will be conducted several years in the future (perhaps 5) after a sufficient signal has accumulated. There are several innovative aspects to the way these surveys have been conducted including: (1) each ''site'' in the network is actually composed of 3-5 individual monuments all located within a few hundred meters of one another; this cluster of monuments averages the affects of monument instability and produces a more stable combined GPS reference point by effectively monitoring a few-hundred meter sized piece of crust, (2) very high accuracy fixed-height antenna poles have been specially designed and used to ensure that the antenna phase center can be positioned above each individual monument at about the 0.15 mm level of accuracy—an order of magnitude better than most previously existing systems, (3) the position of the phase center of all antennas used in the study have been determined to about the 0.15 mm level through an exhaustive inter-comparison on a short baseline test range at UCSD; because of this, when future measurements of the network are conducted we need not use the same set of antennas, nor even GPS if some more advanced system is developed. These extreme measures were undertaken because the deformations expected from the Rose Canyon Fault are very small. The techniques developed will be useful in other situations where GPS measurements must be pushed past their typical level of accuracy.

Geodetic Measurements along the Rose Canyon Fault

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1. Introduction

This grant provided funds to build a small network of survey sites in the San Diego/Tijuana area and to conduct the first round of measurements at these sites with GPS. The goal of the project is to quantify the level of earthquake hazard in the region posed by the Rose Canyon Fault and also to determine exactly where this fault is located south of downtown San Diego. Previous studies have determined that this fault is active at a slip-rate of 1.5 ± 0.5 mm/yr (Lindvall and Rockwell, 1995). Because this is a small rate of deformation we have had to develop several new strategies for making very high accuracy survey-mode GPS measurements. These include: monument clusters, discussed in section 2.1; a new fixed-height antenna pole, discussed in section 2.2; a method for determining the relative phase center offsets between GPS antennas, discussed in section 2.3, and a surveying strategy that relies on both very high accuracy short-baseline and longer-baseline measurements, discussed in section 2.4. Section 3 discusses the future of this project and the expected results.

2. Techniques

2.1. Monument Clusters

Several studies of GPS and EDM time series have found noise spectra that contain high levels of power at low frequencies in a form that is consistent with one or more power-law processes (Langbein and Johnson, 1997; Zhang et al., 1997; Mao et al., 1999). The GPS studies analyzed data embedded in a global reference frame and found a power-law signature consistent with ''1/f'' noise, while the EDM study found the signature of ''1/f^2'' (or random walk) noise. The GPS series are most likely also contaminated by 1/f^2 noise, but the 1/f noise is at a higher power level at this point in time; eventually the 1/f^2 signature will become evident. Random walk motions are exactly those expected from instability of the survey monumentation. When geodetic data are used to constrain site velocities the presence of these low-frequency noise sources proves to be the dominant source of uncertainty as shown by Johnson and Agnew (1995). When a random walk process is dominant the velocity uncertainty can be approximately computed analytically as,

$$\sigma_{vel} = \frac{\sigma_{RW}}{\sqrt{T}} \qquad 1$$

where σ_{RW} is the amplitude of the random walk noise (in mm/$\sqrt{\text{year}}$) and T is the overall duration of the measurements in years. Notice that the number (and spacing) of measurements is immaterial, only the experiment duration counts.

The expected motion on the Rose Canyon Fault is 1.5 ± 0.5 mm/yr. If we hope to monitor this small deformation we must attain an uncertainty in site velocities considerably less than ±1.5 mm/yr (like half this value, or ±0.7 mm/yr). Using equation 1 we can determine an appropriate experiment duration for any level of velocity-uncertainty if we know a value for σ_{RW}. The study of Langbein and Johnson (1997) found pier-type monuments at Parkfield, CA, showed a range of instabilities, with an average value of about 1.3 mm/$\sqrt{\text{year}}$. Using this value for σ_{RW} and an experiment duration of 5 years we get σ_{vel} = 0.6 mm/yr and a resulting 95% confidence ellipse of about ±1.4 mm/yr.

To lower the size of the error ellipse to 0.7 mm/yr we could either let the experiment run longer (20 years would be required!) or we can do something to reduce σ_{RW}, either by constructing more elaborate monuments (expensive) or by relying on cheaper multiple monuments. We choose the latter route in order to make the experiment-cost smaller and also to make the monument array less vulnerable to vandalism; destruction of an individual monument does not then mean that the site is lost. If the individual monuments of a cluster are independently affected by monument instability, then there is a numerical averaging effect from making measurements to all sites; that is, making measurements to four monuments will reduce the collective value of σ_{RW} by a factor of $\sqrt{4} = 2$. Evidence from Piñon Flat Observatory suggests that nearby monuments are indeed independently affected by monument instability. This technique relies on the ability to determine the individual σ_{RW} values for each monument in a cluster so that the aggregate value can also be determined. Normally this would require a large number of points in the time series for each monument because the positioning uncertainty (white noise) must be separated from the monument instability (random walk). However, over baselines of about 100 meters GPS can be used in its relative (baseline) mode with an accuracy of about 0.15 mm because all atmospheric effects are common. Because this is 10-times better than the accuracy of GPS in its positioning mode it is much easier to quantify monument instability. Effectively, the inter-cluster distances can be measured very accurately and the stability of each mark determined.

The new monument cluster sites established for this study are located at (see Figure 1),

Cowles Mountain: Four sites were established at the top of this peak northeast of downtown San Diego. The mountain is located in the Mission Trails regional park operated by the City of San Diego and is thus immune to future development. The four monuments are set in large rock outcrops near the top of the mountain. Cowles Mountain is approximately 8 miles east of the Rose Canyon Fault. Vehicle access is restricted through a locked gate and about 1.5 miles of steep dirt road. The mountain is a popular hiking destination and traffic is high; the sites cannot be left unattended.

Sweetwater County Park: Four sites were established on the top of a small hill south of the Sweetwater reservoir due west of downtown San Diego. The monuments are set in large rock outcrops at the surface. Sweetwater park is located about 10 miles east of the Rose Canyon Fault. Vehicle access is through an unlocked gate and about 0.5 miles of dirt road. The park has a resident ranger at all times who monitors activity in the area, but the number of hikers is still too high to leave equipment unattended.

Point Loma/SPAWAR: Five sites were established on US Navy property on the western slope of Point Loma, due east of downtown San Diego. Four of the monuments are set in massive buried concrete structures which were built during World War II to mount coastal artillery guns; the fifth site is set into the retaining wall of a buried equipment bunker. Point Loma is located about 3 miles west of the Rose Canyon Fault. Access is through Navy-controlled checkpoints and security badges are required. Equipment can be left unattended at these sites.

Border Field State Park: Three sites were established at the top of a hill along the international border with Mexico about 1.5 miles from the coast and approximately 30 miles south of downtown San Diego. The State Park is surrounded by the Tijuana River National Estuarine Research Reserve and patrolled by both state park rangers and national border patrol personnel. The monuments are set in massive buried concrete structures which were built during World War II to serve as spotter's bunkers for coastal artillery guns. The site is either several miles west of the Rose Canyon Fault (if that fault continues southeasterly from downtown San Diego), or several miles east of the fault (if the fault runs off-shore south of downtown San Diego). Access is along 2 miles of dirt road which becomes quite steep for the last ¼ mile (4wd often required). These sites cannot be left unattended despite the presence of (many) border patrol officers.

Isla Los Coronado, Mexico: After more than a year of effort (especially by a colleague at CICESE in Ensenada, Mexico) we have finally received verbal permission to install four sites on this island about 10 miles off shore from Tijuana, Mexico. We have made one reconnaissance trip and located suitable sites along the rocky spine at the north end of the island. Once official papers are in hand we will install and survey these sites using funds from other sources. The island is farther west than any other possible site in the region and will provide an important test of where the Rose Canyon Fault is located. The island is controlled by the Mexican Navy who maintain a small station of 5-10 people at all times. Access is either by helicopter or boat. Equipment can be left unattended.

Besides these new survey-mode sites there is also a continuous GPS site at Scripps Institution of Oceanography, about 15 miles north of downtown San Diego and 1 mile east of the fault. This site serves as our local tie to the permanent GPS network in California and the global reference frame. A second continuous GPS site (part of the SCIGN network) is in the works for the San Diego region near Brown Airfield which is located about 25 miles south of downtown San Diego, two miles north of the international border, and about 10 miles inland from the sites at Border Field State Park. We considered placing survey-mode sites at this facility, but decided to wait for the continuous site instead. This site is being developed by the Southern California Integrated GPS Network (SCIGN) and should be operational by the summer of 1999.

2.2. Fixed-Height Antenna Mount

In order to take advantage of the very high accuracy of GPS baseline measurements over short distances (0.15 mm) we must be able to position an antenna above the mark on the ground to this level of accuracy as well. Typical antenna setups using tripods and optical plummets are accurate at only about the 1 mm level, even when extreme care is taken during setup and when using well calibrated plummets[1]. In addition, tripods have a tendency to move slightly under adverse conditions such as wind. To alleviate these problems we have designed a fixed-height antenna post that can achieve the desired level of precision and which is kinematically mounted to the ground so that small perturbations in its position, from being bumped, or from wind load, will not affect its position above the mark (Figures 2a and 2b). This is accomplished by using large diameter ground stainless steel rod for the vertical pole. These rods are manufactured to be linear over their length to less than the 0.15 mm necessary. The posts are attached to the ground using three chains. The chains attach to a spring-loaded

[1] We have made several tests of this at Piñon Flat Observatory using an EDM between a benchmark "farm" of NGS-class monuments. The scatter in distances between these marks shows that positioning above a monument using a tripod and plummet is only good to about 1 mm accuracy.

collar on the post which makes the setup elastic. Turnbuckles in each length of chain allow the post to be leveled and once this is done the turnbuckles are locked in place with nuts. A separate leveling device is clamped to the post during setup. This device can be spun around the post to verify verticality and also to check its own calibration (by swinging through 180°). The bubbles on this leveling device are ultra-sensitive to ensure the antenna phase center is within 0.15 mm of the desired position. At first this style of setup is more difficult than a typical tripod arrangement, but after some training it can be done as easily (and almost 10-times more accurately). In controlled tests in our lab two people have been able to do independent setups of this equipment to better than 0.1 mm accuracy.

The monuments in the ground (Figure 3) are 2 inch diameter stainless steel plugs which are set in drilled holes in solid rock (or concrete) with epoxy. The mark has an internally-threaded cap in the top end which can be removed using a specially designed wrench (to prevent tampering). When not in use this cap is flush on top and has a standard surveying mark (circle with dimple) machined into its surface. For surveying with the fixed-height post the insert is removed and another insert put in its place that has a cone-shaped surface on top that mates to a hemi-spherical projection on the bottom of the post; there is only one way these two pieces can mate (assuming they have not been damaged and are clean). If either piece is damaged it can be removed and easily replaced with duplicate fittings.

Besides the main mark each monument requires three points for the hold-down chains. These are placed about 2 feet away from the central mark and spaced at 120° azimuthally. Each point is a threaded insert that accepts an eye-bolt when surveying; a locking hook connects the eye-bold to the chain. When not in use the eye-bolts are removed and allen-head bolts are inserted (again to minimize vandalism).

2.3. Antenna Offset Calibrations

Every GPS antenna has a slightly different location for its phase center with respect to its mounting threads. When GPS data are processed into baseline distances it is the vector between the phase centers of two antennas that is actually being measured. To relate this to points on the ground requires that the position of the antenna mounting threads be know (thus the fixed-height design discussed above) and also that the position of the phase center with respect to these threads be known. The orientation of the antenna with respect to north must also be known since the phase center will normally be offset from the rotation axis. We have dealt with these issues in several ways. First, we always use the same antenna at each individual monument in a cluster; this is not necessary, but makes later corrections easier. Second, we always orient the antennas to north to within a few degrees using a hand-held compass; this way the rotational asymmetry of each antenna is constant for all surveys. And most importantly, we have conducted an exhaustive inter-calibration of all antennas used in the study to determine the relative differences in phase center location for all possible antenna pairs; this allows us to correct the baseline lengths to absolute vectors that will be comparable to future measurements even if different measurement equipment is used.

The inter-calibrations were done in La Jolla at a test range atop the SIO library where we have two monuments (SIO2 and SIO4) attached to the same concrete wall of the building. As long as the building does not experience any non-linear (with respect to time) motions during the month-long calibration then the fact that over the longer term (years) most buildings are not really stable will not be of concern. The calibrations proceed as a number of swaps between antennas at SIO2 and SIO4. For instance, with antenna #1 at SIO2, two other antennas (#2, and #3) are placed sequentially at SIO4 over a several-day period. As long as antenna #1 does not move during this time then the vector difference between the SIO2/SIO4 baseline tells us the vector difference between the antenna phase centers for antennas #2 and #3. With this information we can correct all antenna #2/#3 baselines measured in the field to their absolute values. However, this correction only applies to the antenna #2/#3 baselines. We must repeat the calibration for all other antenna combinations. There are a maximum of five monuments in any cluster and so there are a total of 10 combinations of two antennas. The last step was to determine the number of days of measurements for each SIO2/4 combination necessary to achieve an uncertainty in phase centers of ±0.15 mm; our calculations showed that three days were necessary.

If we knew the absolute distance between SIO2 and SIO4 then our calibrations would be much easier, but to know this distance accurately enough would require a large number of ''antenna rotation'' tests since all antennas seem to have the rotational asymmetry problem at the 0.15 mm level. In the end either approach would probably require the same number of days of measurements to achieve the same level of understanding to correct the field measurements.

2.4. Survey Strategy

There are two parts to conducting the field surveys for this project: the inter-site distances at each cluster of monuments must be accurately determined, and then the clusters themselves must be tied together to get the geophysically interesting distances. Our initial plan was to conduct these two sets of surveys at the same time by setting one receiver at each cluster for many days in a row, and then moving three other receviers from one cluster to the next. In this way there would be a direct tie between the two sets of measurements. Instead, the two parts of the survey were conducted separately because of limits on available equipment and also because of our desire to minimize the total number of antennas used so that their inter-calibrations were as simple as possible. Because the two sets of measurements were not actually done at the same time we had to be concerned about the possibility of large instabilities within each cluster during the intervening time. However, as long as these instabilities are smaller than the uncertainty in cluster- to-cluster distance measurements (about 1.5 mm) this turns out not to be a problem. Each intra-cluster survey was conducted three times to make sure the resulting baselines were known to about the 0.15 mm level of accuracy. Three measurements are the minimum necessary to correct for possible blunders in measurement; if the first two distances between two monuments don't agree then the third can (hopefully) determine which was in error. For the same reason the inter-cluster surveys were also repeated three times.

All data have been archived at the Southern California Earthquake Center (SCEC) Data Center. Until a second round of measurements are made in the future there can be no geophysical interpretations from this data. We do hope to continue, on an irregular basis, making intra-cluster surveys to monitor the stability of the monuments. Because all sites (except Isla Coronado) are within a half-hour of our lab these can be done at very small cost in conjunction with other on-going projects in the area. We are particularly interested to see how the massive buried concrete structures behave. Because these were all built over 50 years ago we can hope that the back-filled material around them has stabilized and that they will provide a good platform for GPS observations, but we are not sure.

3. Future Surveys and Expected Results

We do not plan to make another inter-cluster survey for about 5 years. At that time we will make another three distance measurements between the five sites using whatever technology is most appropriate (most likely this will be GPS, but perhaps not). In the meantime we hope to continue occasional intra-cluster surveys to learn more about the stability of the monuments used. The results of these stability studies will hopefully have an affect on the design of other high-accuracy survey-mode GPS networks as well as continuous GPS networks. The stability values we find will also have an affect on our decision as to when it will be appropriate to do another inter-cluster survey. If the values individually turn out to be about like those found at Parkfield for pier-type monuments (1.3 mm/$\sqrt{\text{year}}$) then about five years in the future would be the right time. If the monuments are found to be more stable than this (and we are hopeful that this will be the case) then a survey slightly sooner might make sense. Either way, we can only wait for time to pass so that the geophysically interesting signals have time to stand out from the background of noise sources, both monument-related and GPS-related.

A more detailed technical report on this project, including reduced data values, site descriptions, and machine drawings for the fixed-height antenna post, is being prepared so that everything of possible use for a future survey is documented. This report will be submitted to the Scripps Institution of Oceanography library for archival storage. The data have already been archived at the SCEC Data center.

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High Accuracy GPS Sites Near San Diego

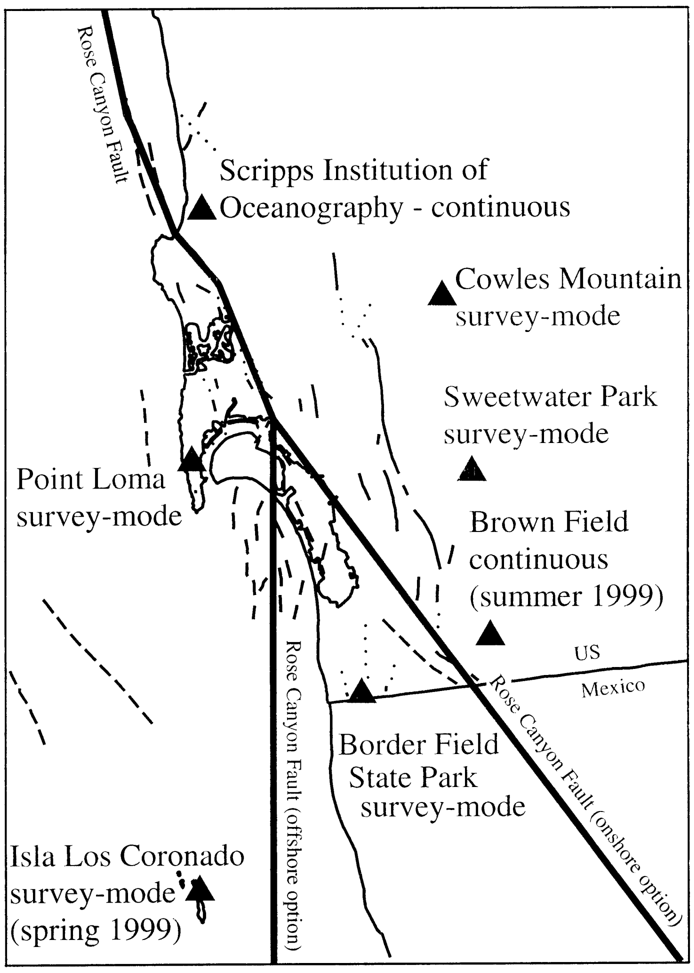

Figure 1

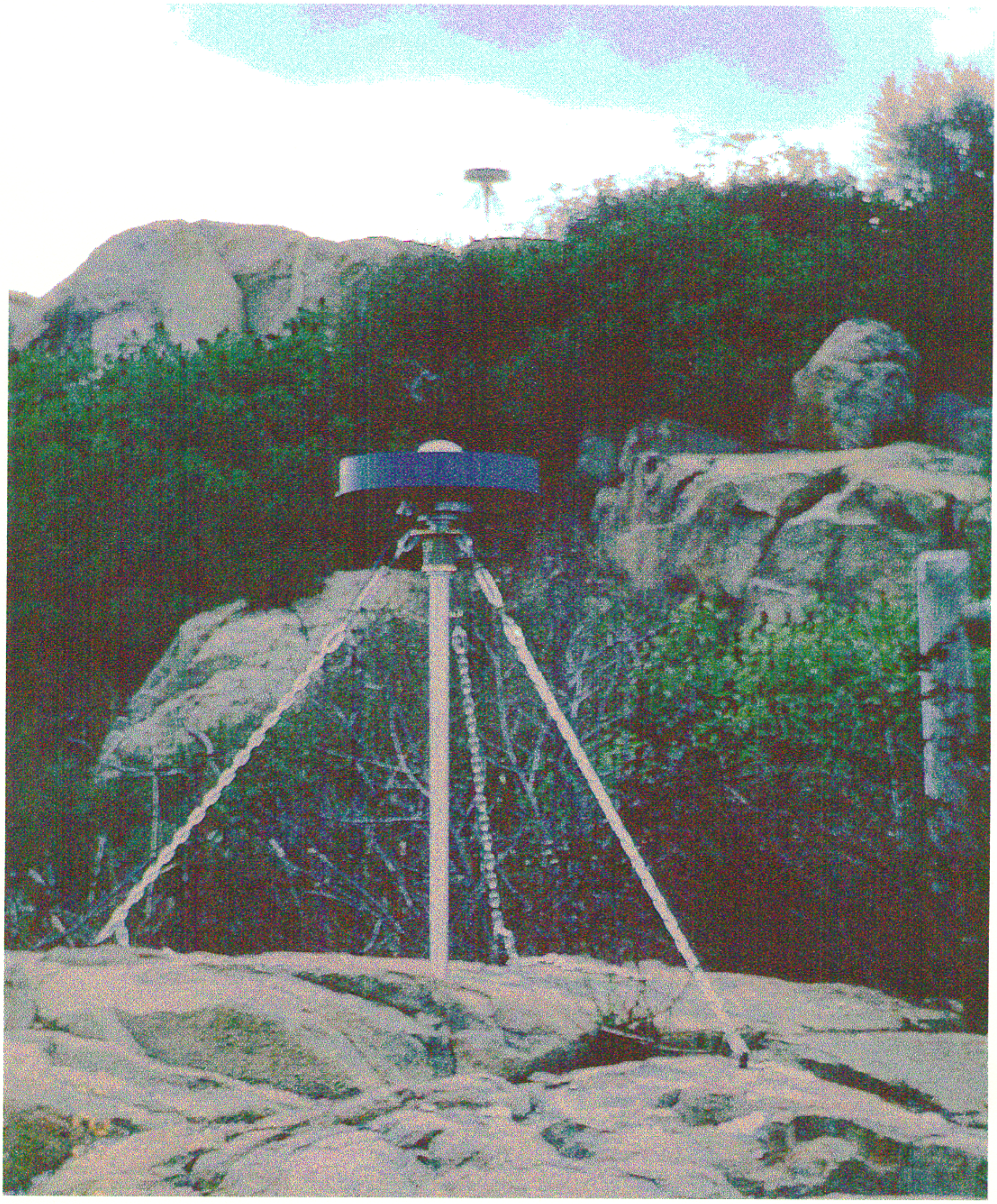

Figure 2a

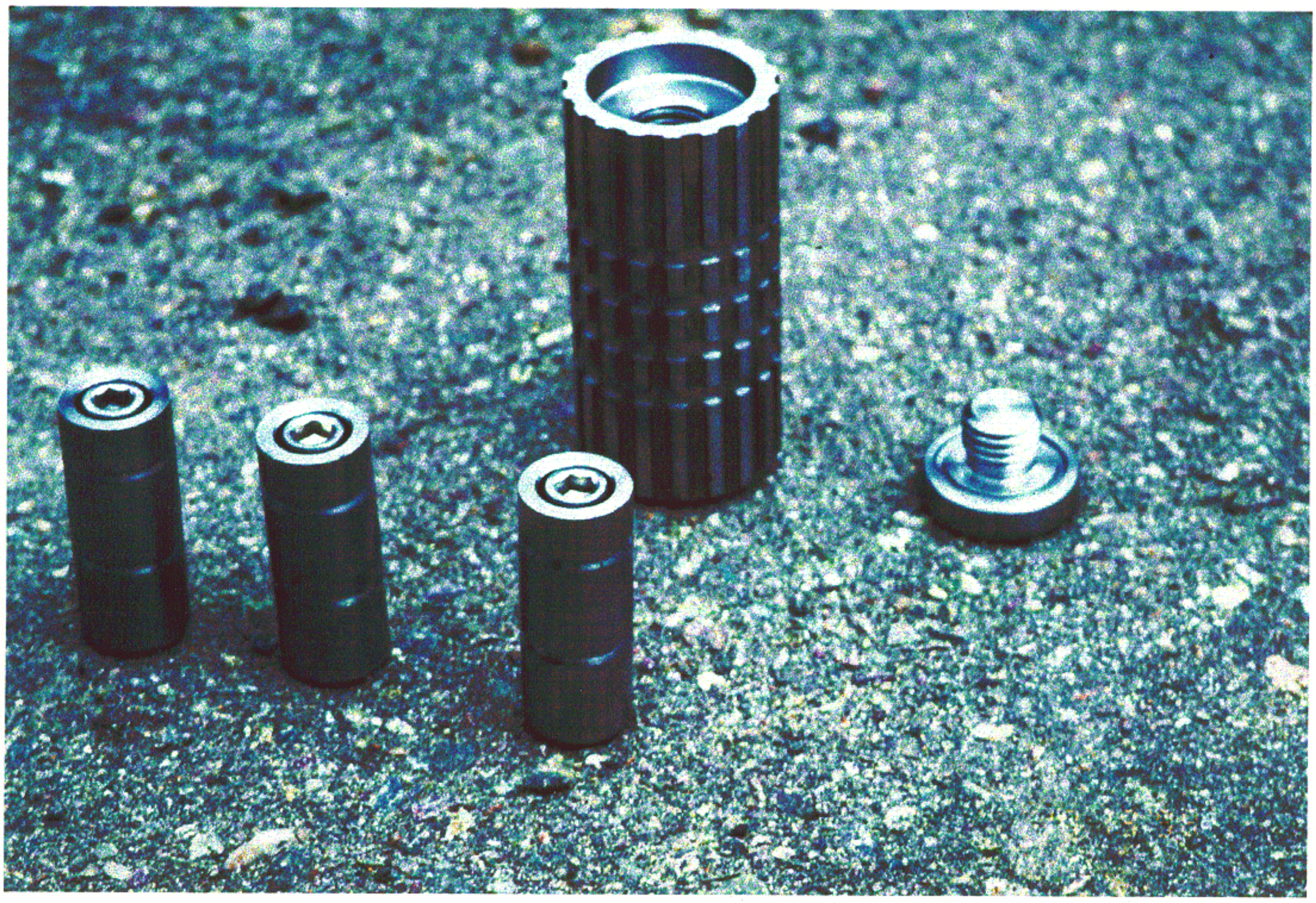

Figure 3

1434-HQ-97-GR-03142
GEODETIC MEASUREMENTS ALONG THE ROSE CANYON FAULT

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TECHNICAL ABSTRACT

This grant has supported the initial phase of a long-term study of earthquake hazard in the cities of San Diego, CA, and Tijuana, Baja California. The Rose Canyon Fault, a minor fault in the San Andreas System of faults in southern California, runs through the region from north of La Jolla, past Mount Soledad, and on to downtown San Diego. From there the fault location is not known, but two possibilities are commonly mentioned: the fault may across Coronado island and then offshore to the international border, eventually coming back on land south of Tijuana, or it may continue southeast from downtown San Diego eventually linking with the Vallecitos Fault east of Tijuana. Paleoseismic studies have show this fault is active and accumulating crustal deformation at a rate of about 1-2 mm/yr. We have established a survey-mode network of GPS sites designed to accurately measure this deformation and have conducted the first set of occupations of this network; repeat occupations will be conducted several years in the future (perhaps 5) after a sufficient signal has accumulated. There are several innovative aspects to the way these surveys have been conducted including: (1) each ''site'' in the network is actually composed of 3-5 individual monuments all located within a few hundred meters of one another; this cluster of monuments averages the affects of monument instability and produces a more stable combined GPS reference point by effectively monitoring a few-hundred meter sized piece of crust, (2) very high accuracy fixed-height antenna poles have been specially designed and used to ensure that the antenna phase center can be positioned above each individual monument at about the 0.15 mm level of accuracy—an order of magnitude better than most previously existing systems, (3) the position of the phase center of all antennas used in the study have been determined to about the 0.15 mm level through an exhaustive inter-comparison on a short baseline test range at UCSD; because of this, when future measurements of the network are conducted we need not use the same set of antennas, nor even GPS if some more advanced system is developed. These extreme measures were undertaken because the deformations expected from the Rose Canyon Fault are very small. The techniques developed will be useful in other situations where GPS measurements must be pushed past their typical level of accuracy.

NON-TECHNICAL ABSTRACT

This grant has supported a high-accuracy GPS survey in the San Diego, California, area to begin to quantify the earthquake hazard posed by the Rose Canyon Fault. Five new survey sites were established for this purpose at: Cowles Mountain, Sweetwater County Park, Border Field State Park, Point Loma/SPAWAR, and Isla Los Coronado (Mexico). There are also two high-accuracy continuous GPS sites in the area at Scripps Institution of Oceanography and near Brown Field on Otay Mesa (operational in summer 1999). Because the fault motion on the Rose Canyon Fault is small (1-2 mm/yr of slip) these surveys were conducted to much higher accuracy than typical, but we will still need to wait several years (5 or more) before re-surveying, at which time enough deformation will have accumulated to be measured.