COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

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☐ SMALL BUSINESS ☐ MINORITY BUSINESS
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☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **PBO Nucleus: Support for an Integrated Existing Geodetic Network in the Western U.S.**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 4,462,906	43 months	03/01/05	

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

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☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C)
☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.B, II.C.1.d)
☐ HISTORIC PLACES (GPG II.C.2.j)
☐ SMALL GRANT FOR EXPLOR. RESEARCH (SGER) (GPG II.D.1)
☐ VERTEBRATE ANIMALS (GPG II.D.5) IACUC App. Date ________
☐ HUMAN SUBJECTS (GPG II.D.6)
Exemption Subsection ________ or IRB App. Date ________
☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.g.(iv).(c))
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A. PROJECT SUMMARY

Intellectual Merit: Tectonic and earthquake research in the US has experienced a quiet revolution over the last decade precipitated by the recognition that slow-motion faulting events can both trigger and be triggered by regular earthquakes. Transient motion has now been found in essentially all tectonic environments, and the detection and analysis of such events is the first-order science target of the EarthScope Project. Because of this and a host of other fundamental tectonics questions that can be answered only with long-duration geodetic time series, the incipient 1400-station EarthScope Plate Boundary Observatory (PBO) network has been designed to leverage 432 existing continuous GPS stations whose measurements extend back over a decade. The irreplaceable recording history of these stations will accelerate EarthScope scientific return by providing the highest possible resolution. This resolution will be used to detect and understand transients, to determine the three-dimensional velocity field (particularly vertical motion), and to improve measurement precision by understanding the complex noise sources inherent in GPS.

Proposed Work: In this proposal, we request support to operate, maintain and upgrade a subset of the six western U.S. geodetic networks until they are subsumed by PBO. Uninterrupted data flow from these stations will effectively double the time-series length of PBO over the expected life of EarthScope, and create, for the first time, a single GPS-based geodetic network in the US. Other existing sites will remain in operation under support from non-NSF sources (e.g. the USGS), and EarthScope will benefit from their continued operation.

On the grounds of relevance to EarthScope science goals, geographic distribution and data quality, 209 of the 432 existing stations have been selected as the nucleus upon which to build PBO. Under a current grant we have begun converting these stations to a PBO-compatible mode of operation; data now flow directly to PBO archives and processing centers while maintenance, operations, and meta-data requirements are currently under upgrade to PBO standards. These upgrades have to date been performed under an existing NSF grant that extends only through March 1, 2005. This proposal seeks funding for their continued operation, evolution to PBO technical standards, and final integration into a single network entity between March 2005 and September 2008. At the end of this period, all 209 stations will be fully incorporated into PBO, and will be the nucleus for PBO. Funding for continued operation of these instruments is not included in current EarthScope PBO budgets. Funds for operation of these stations have been included in planned budgets for PBO after the construction phase ends and PBO begins an operational phase in 2008.

Broader Impacts: The research community has only begun to understand the pervasive effects of transient creep, and its societal consequences remained largely unexplored. For example, one open question is whether slow faulting pervasively moderates earthquake nucleation. The existence of slow earthquakes will impact seismic hazards estimation, since these transients are now known to 'absorb' a significant component of total slip in some regions and trigger earthquakes in others. The data from these stations serve a much larger audience than just the few people who work to keep them operating. Nearly half of the 146 publications that have used data from these stations were published by a lead author who was not directly associated with the operation. This project is now collecting the data that will be used by the next generation of solid-earth researchers for at least two decades. A web-based curriculum will be developed by education professionals to enable teachers to bring the newest developments in tectonics research into the K-12 curriculum.

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Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

C. PROJECT DESCRIPTION

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1. Overview

1.1 Introduction

In this proposal, we describe the role of continuous GPS in energizing and reshaping the debate about the fundamental controls of plate boundary deformation, and describe a detailed plan to optimize integration of the previous decade of continuous GPS observations into EarthScope. Specifically we propose a temporally seamless transformation of the six existing continuous GPS networks in the western states, which have operated with disparate equipment and standards of data acquisition and processing, into a single network. In addition to realizing significant economies of scale, the standardization of equipment and data acquisition procedures will result in enhanced capability to explore processes that may be occurring at scales larger than a single network. At the end of this performance period, the continuous networks will constitute the nucleus of the PBO continuous GPS network, thus extending the time series of a subset of PBO sites by at least a factor of two. Our goal in operating the Nucleus stations is to ensure that the scientific goals of EarthScope are met, and to enhance EarthScope performance. Scientific results already produced from these stations, some of which are described in this Section, demonstrate that we can achieve that goal.

The continental-scale, instantaneous velocity field of the Earth's surface is one of the main predictions of many physical models of plate boundary tectonic processes. Large-scale tectonic processes have traditionally been investigated using various geophysical and geological methods that reveal kinematic behavior at either the relatively short timescales of earthquakes and volcanic eruptions (seconds to weeks), or the relatively long timescales of the seismic cycle (hundreds to thousands of years). Over the last decade, continuously operating GPS networks have led the way in investigating previously inaccessible temporal and spatial scales of motion of the Earth's surface (seconds to decades).

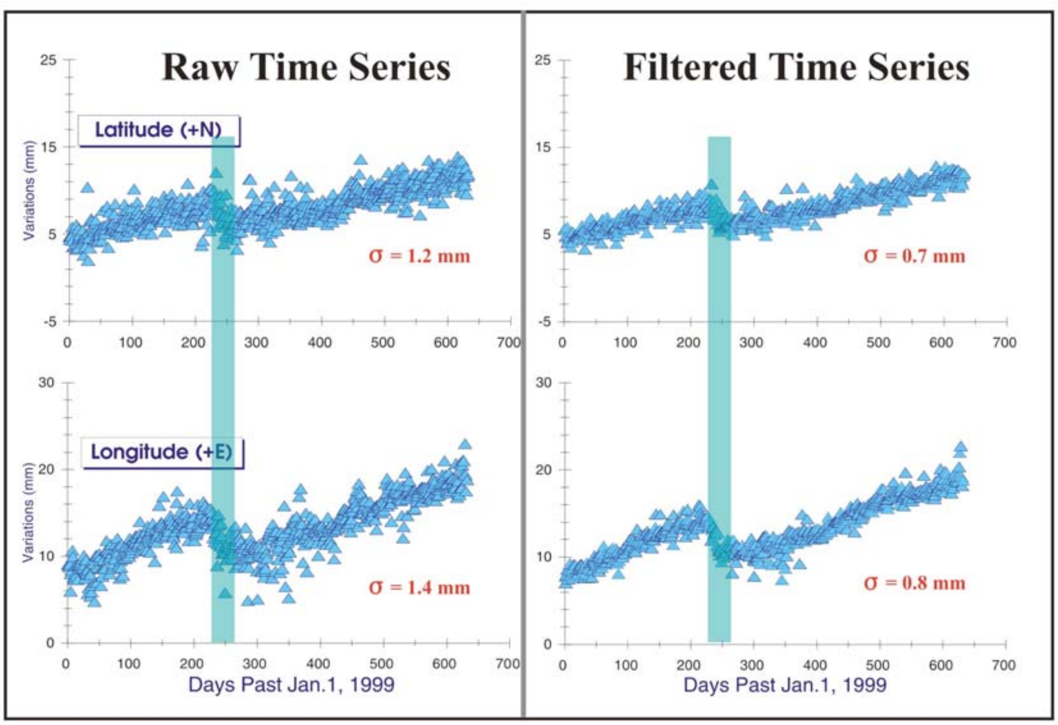
The results from these continuous networks reveal a rich variety of unexpected behaviors. Contrary to the classical notion of the earthquake cycle as a steady-state process, the precision and data continuity of continuous GPS networks have demonstrated that non-steady-state motions are measurable and in some instances may be the norm rather than the exception. Although the ultimate accuracy of GPS data are a topic of vigorous investigation, it is clear that "secular" velocities, as might be deduced through relatively infrequent campaign GPS measurements, are in many instances unsatisfying averages of complex transient motions with periods of a few seconds to as much as a decade or more. The relatively high precision of continuous GPS has also shown that in some instances relatively steady short-term deformation rates are significantly different from rates measured on geologic timescales (up to the level of differences in sign), suggesting transient behaviors at periods longer than the decade or so of continuous GPS measurements.

Data from these networks will extend PBO time series and provide critical data bearing on three fundamental, and still controversial, questions critical to EarthScope science: (1) Transient detection. How widespread are significant deformation transients at timescales of days to decades, or longer when compared with geological velocity estimates? (2) Three-dimensional velocity field. Will the accuracy and precision of the relatively uncertain vertical component be sufficient to yield the fully three-dimensional velocity fields that best discriminate among geophysical models of earth deformation? (3) Instrumentation performance and discrimination between tectonic and non-tectonic signals. To what degree are geodetic time series affected by low-frequency noise, and how well can we discriminate between tectonic and non-tectonic sources of signal?

The ability of the scientific community to address all of these issues depends on uninterrupted measurements; the most information can be gleaned from those stations with the longest time period of unbroken observations. The work proposed here will allow PBO's observations to be extended back in time by 10 ten years or more. Specific examples below, drawn from recent publications, highlight how long-duration time series play a unique and irreplaceable role in quantifying these transients, the discovery of which is arguably the most exciting development in crustal deformation since the discovery of elastic rebound by H.F. Reid after the 1906 San Francisco earthquake.

1.2 Geodetic Imaging of Transient Slow Faulting

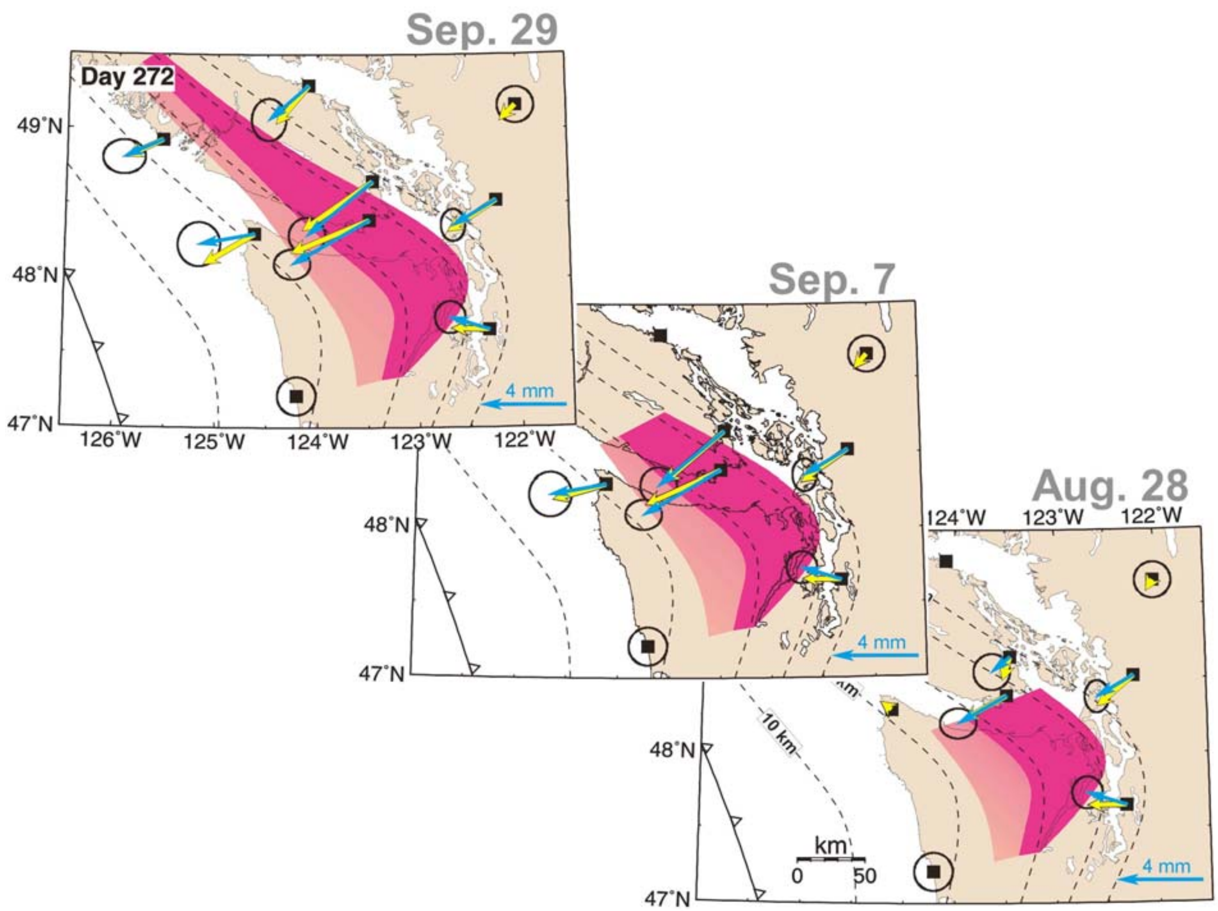
Earthquake research is largely a data-driven science, and discoveries have consistently followed the deployment of new instrumentation. In particular, as GPS cost and measurement and processing technologies have improved over the last decade, researchers have imaged widespread transient creep which has, in turn, forced a reappraisal of earthquake nucleation mechanisms. Subduction zones originally led the way, displaying a complex suite of previously invisible preseismic, postseismic, and transient aseismic slip behavior, but we now recognize similar transients in essentially all active tectonic environments. Dynamic feedback from seismogenic and transient creep is almost certainly responsible in part for the deterministically chaotic behavior of nearly all faults; this fundamental paradigm shift has been spawned in large part by PBO Nucleus time series whose continued support is requested here. To further our understanding of these phenomena will require continuing the observations that have proven themselves to be so valuable to date.



***<u>Figure 1.</u>* A systematic re-analysis of 1999 GPS data resulted in a significant reduction in the daily scatter of the time series (shown as "raw" time series) which was even further reduced by removing common day-to-day variations across the network (shown as "filtered" time series). The new analyses clearly revealed a reversal of motion at ALBH in late Aug. 1999 (Dragert et al, 2001).**

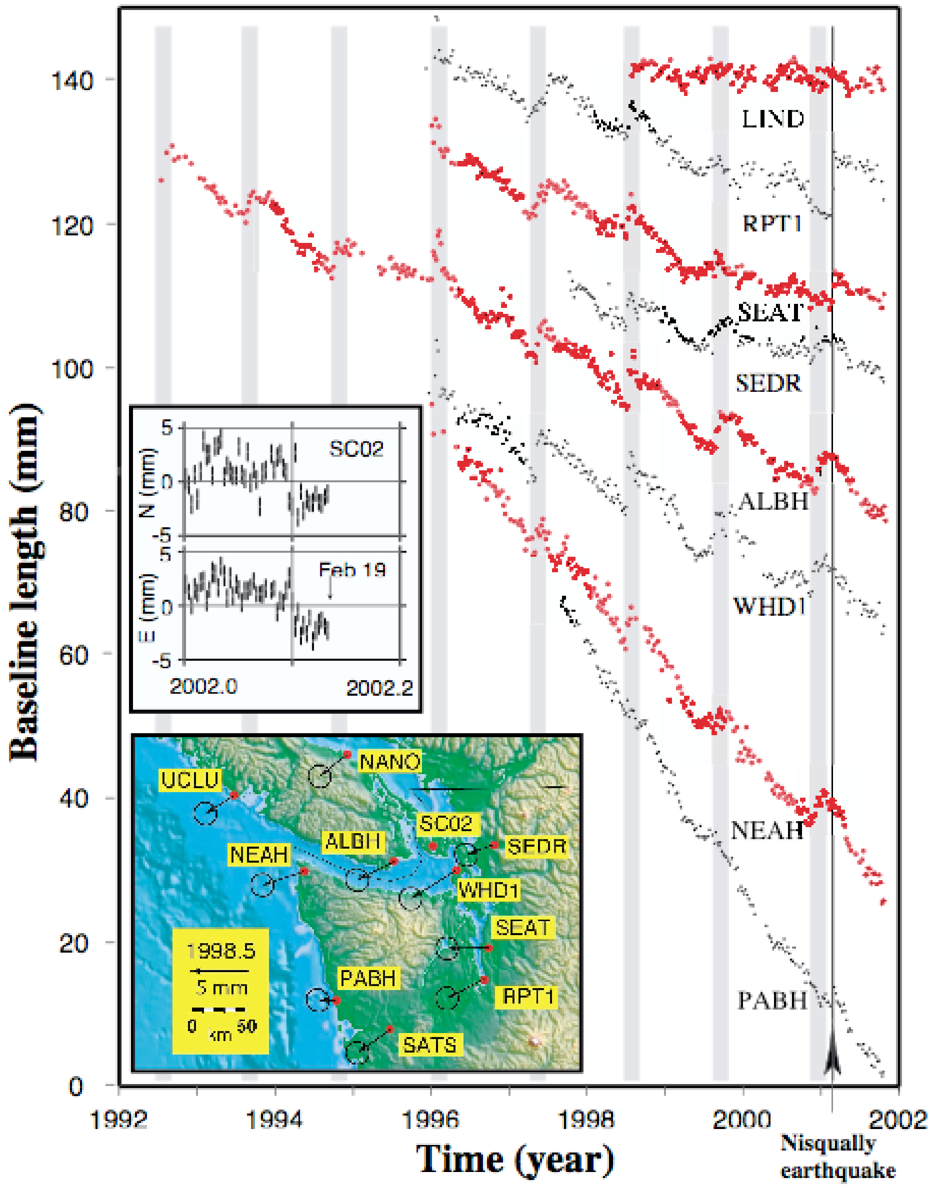
This is particularly well illustrated by the episodic slow earthquakes in the Cascadia subduction zone. These events occurred regularly every 15 months throughout the 1990's before enough data, roughly a decade's worth, had accumulated to allow confident discrimination of slow faulting signals from GPS noise. In evaluating the importance of these uninterrupted time series, it is important to appreciate how the duration of the observations factored into this discovery that is revolutionizing our understanding of subduction zones.

Cascadia Subduction Zone. For more than two decades, seismologists puzzled over the episodic occurrence of "noise" appearing simultaneously on seismographs from stations located over the Cascadia subduction zone in southwestern British Columbia. With the 1992 initiation of continuous GPS monitoring in Victoria, B.C., another puzzle presented itself in an inexplicable 5-mm westward displacement of the then solitary regional continuous GPS monument over a period of about a week in October 1994. These observations remained unexplained (and unrelated) until recently. As a result of improvements in GPS orbits and regional densification of continuous GPS networks around the world, transient aseismic crustal motions lasting from periods of a few days to over a year were starting to be recognized, particularly in Japan. For the Pacific Northwest, detailed analyses of continuous



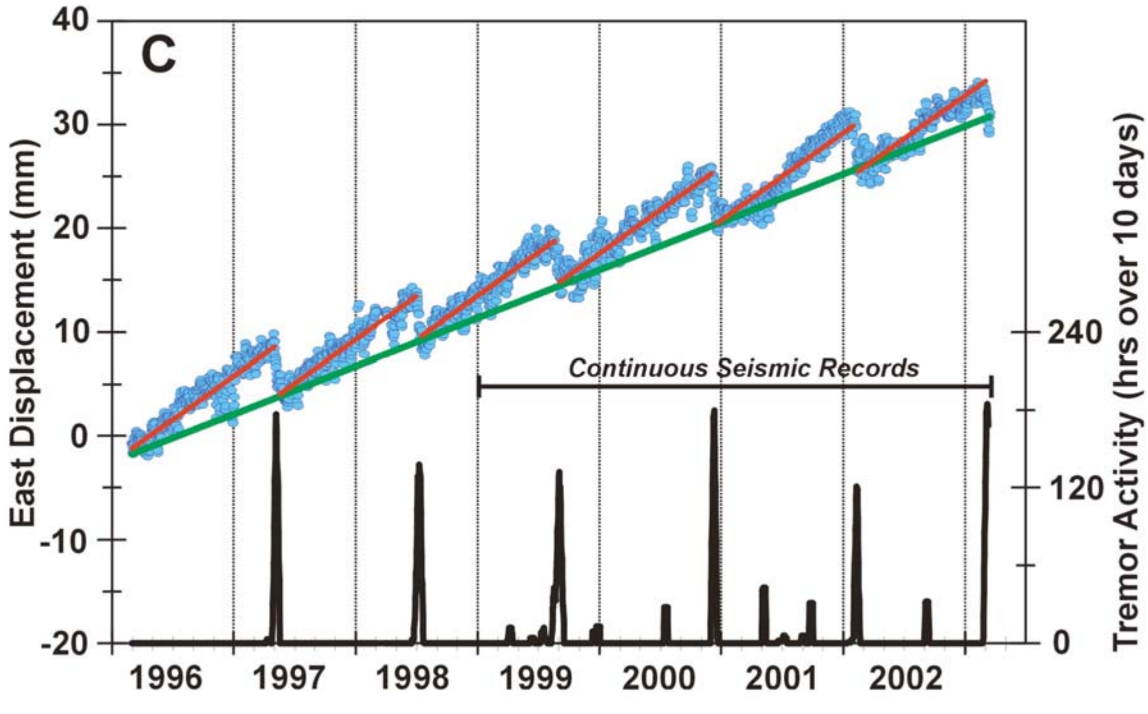
<u>Figure 2.</u> The observed migration of the slip was modeled in three steps. 10 days into the slip event, only the southern portion of the slip zone was involved. This slip zone then expanded northwest along the subducting interface, smoothly or in discrete steps, until 40 days later it had extended to over 300 km. (Dragert et al, 2001)

GPS data by scientists at the Pacific Geoscience Center successfully resolved a spatially coherent, transient signal that occurred in August 1999 (Figures 1 and 2) (Dragert et al., 2001). Unrelated to after-slip that can follow great thrust earthquakes or to shallow slow-slip “tsunami” earthquakes, this signal, detected at 7 contiguous GPS sites, was characterized by a change in site positions ranging from 2 to 5 mm over a period of 6 to 15 days in a direction opposite to long-term deformation motions. This brief reversal was modeled by ~2 cm of slip on the plate interface, providing the first evidence for discrete "silent” slip events occurring on the deeper Cascadia subduction zone (Dragert et al, 2001).



<u>Figure 3</u>. GPS baseline measurements from Cascadia forearc stations to a stable station in the back-arc clearly show episodic transitions from secular E-W dominated contraction to transient extension. The extension events propagate across the GPS network and last between 1-2 weeks at any given station. The most recent ETS event occurred in July, 2004 (not shown), and the average recurrence interval over 10 events is 14.5$\pm$2 months (Miller et al., 2001).

In early 2002, researchers at Central Washington University established the surprising regularity of Cascadia slip events on the plate interface underlying southern Vancouver Is. and northwestern Washington State (Figure 3) (Miller et al, 2001). Eight slip events were identified between 1992 and 2002, with a recurrence interval of 14.5 +/- 2 months and an equivalent moment release of M*w*=6.7-6.9. The recognition of this stunning regularity was made possible uniquely due to long time series, which allowed the tectonic signal to be distinguished from the noise. Next, Japanese scientists discovered the episodic occurrence of unique, non-volcanic tremors at average depths of about 30 km along the Nankai Subduction Zone (Obara, 2002). The similarity of the average depth of slip and the migration velocity of slip for the GPS-determined Cascadia slip events, to the depth and migration velocity of the Japanese tremors triggered the search for seismic signatures for the Cascadia slip events. An examination of seismic records from 1996 to 2002 for sites on Vancouver Is. revealed that what had previously been deemed surface noise was signal from seismic tremors that accompanied slip events. The Cascadia tremors were found to be similar in character to the Japanese deep tremors. In addition, their source region was found to coincide with, or directly overlie, the region of the subducting slab interface where transient slip occurs. The close correlation of tremors with slip coined the naming of the phenomenon as Episodic Tremor and Slip (ETS) (Figure 4a) (Rogers and Dragert, 2003). In the context of seismic hazard,



<u>Figure 4a.</u> The examination of the past 6 years of digital seismic records revealed a remarkable correlation of tremor activity with slip events observed in the Victoria region. The black graph shows the total number of hours of tremor activity in a sliding 10-day period (a 10-day window was used since it was the nominal duration of a slip event.) Tremors were also found to occur at times between slips, but tremor activity at such times was substantially less (Large peaks tremor duration is ~15 days; small peaks tremor duration is typically < 2 days). The graph ends with the initiation of the tremor & slip activity which was predicted for the Spring of 2003. It was this strong correlation that prompted Rogers and Dragert (2003) to name this phenomena "Episodic Tremor & Slip".

the ETS zone may mark the down-dip limit of coseismic rupture of the next M*w*=9.0 megathrust earthquake. Also, since it is conceivable for a slip event to trigger a large subduction thrust earthquake, the onset of ETS activity could identify times of higher probability for the occurrence of megathrust earthquakes.

ETS activity has now been found beneath northern California, along the Gorda-North America plate interface (Figure 4b), again employing time series that had been collected without interruption for nearly a decade. Eight ETS events have occurred since 1997, only here, intriguingly, the recurrence period is 10.8 $\pm$ 2 months, as opposed to 14.8 months in then Northern Puget Basin (Szeliga et al, 2004). Given comparable rates of convergence, there currently is no explanation as to why their ETS recurrence rates differ.

The most recent 2004 Cascadia slow earthquake appears at the present time to have been a compound event, which nucleated in May in the southern Puget Basin, showed up on five stations, and then stopped for a month before resuming in the northern Puget Basin in late July (PANGA Geodesy Lab, www.geodesy.org). The two-stage ETS has not been seen before in Cascadia, but this new complexity can be appreciated only in the context of the decade of previous measurements recording nine other slow earthquakes.

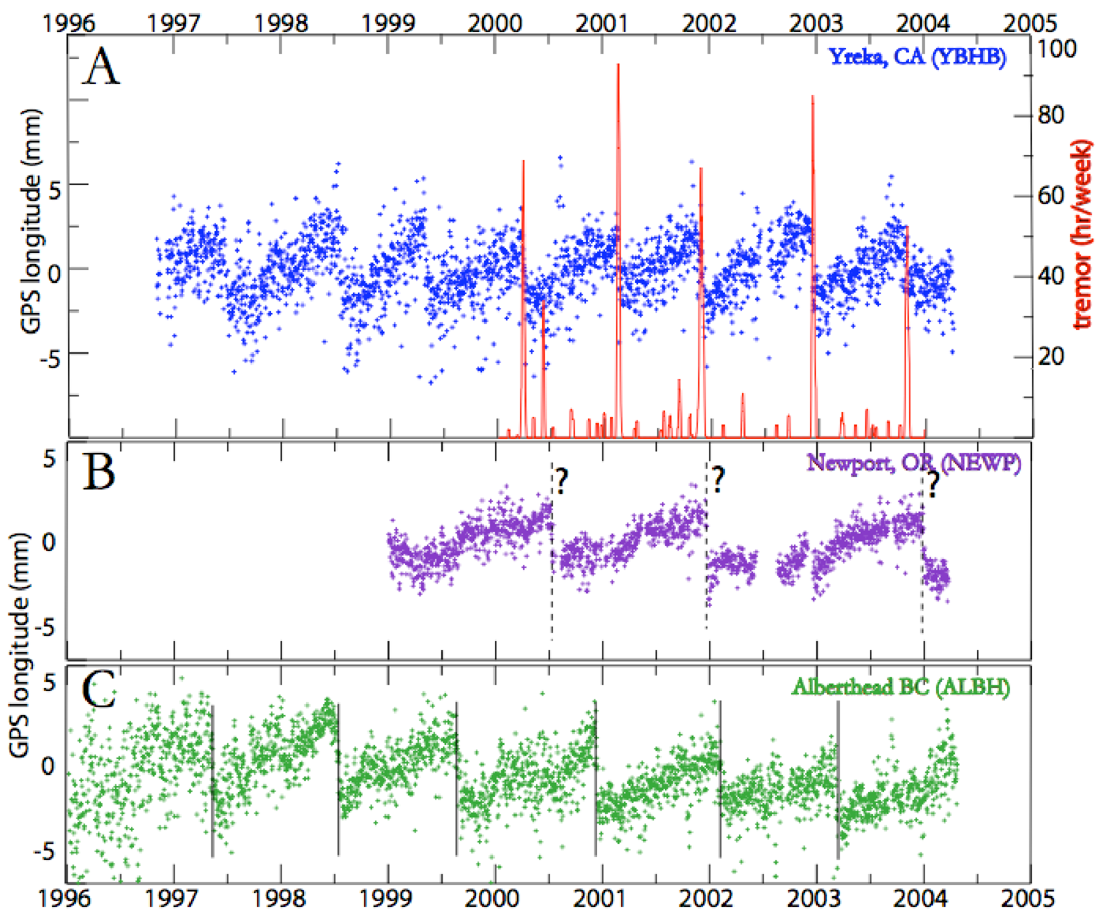


***Figure 4b**. Correlation of GPS reversals with seismic tremor from northern California, where slow earthquakes occur every 10.8 $\pm$2 months. Despite comparable rates of convergence, the recurrence interval here is significantly shorter, for reasons as yet unknown. (Szeliga et al., 2004)*

A different sort of aseismic slip event has been observed in Alaska, where a single very large event lasting 2.5-3 years occurred in the area north of Anchorage. This event, with a total maximum slip of roughly 10 cm and magnitude M_W~7.2 was detected based on repeated campaign GPS measurements and the record of the Alaska Deformation Array (AKDA) site ATW2 (Freymueller pers. comm.). This site was installed several months after the beginning of the slip event, and is part of the PBO Nucleus. Based on similarities between the Alaska event and a slow slip event still underway in the Tokai region of Japan (Ohta et al., in prep), this event can be expected to repeat in the future, but whether it occurs regularly or not is not known. Whether Cascadia-type events occur in Alaska as well is also unknown, but PBO will provide enough sites to determine whether frequent repeating events are characteristic of the Alaska subduction zone as well.

Eastern Sierra, CA. Hybrid transients are not limited to subduction zones, but in fact almost certainly occur throughout greater western North America. Now that the research community knows what to look for, their rate of identification has jumped dramatically. Smith et al. (2004) recently reported an unusually deep swarm of 1611 earthquakes that occurred in late 2003 at Lake Tahoe, California (depth 29-33 kilometer; Richter Magnitude [M_L] < 2.2; sum of the moment magnitude of all events is M_w 3.1). This swarm was coeval with a GPS transient displacement of 6 ± 0.3 mm horizontally outward from the swarm and 7.9 ± 1.0 mm upward measured at the GPS station on Slide Mountain, Nevada (SLID) 18 km to the northeast. SLID is a part of the 53-station Basin and Range Geodetic Network (BARGEN) network, continuously operating since 1996 and one of the PBO Nucleus stations.

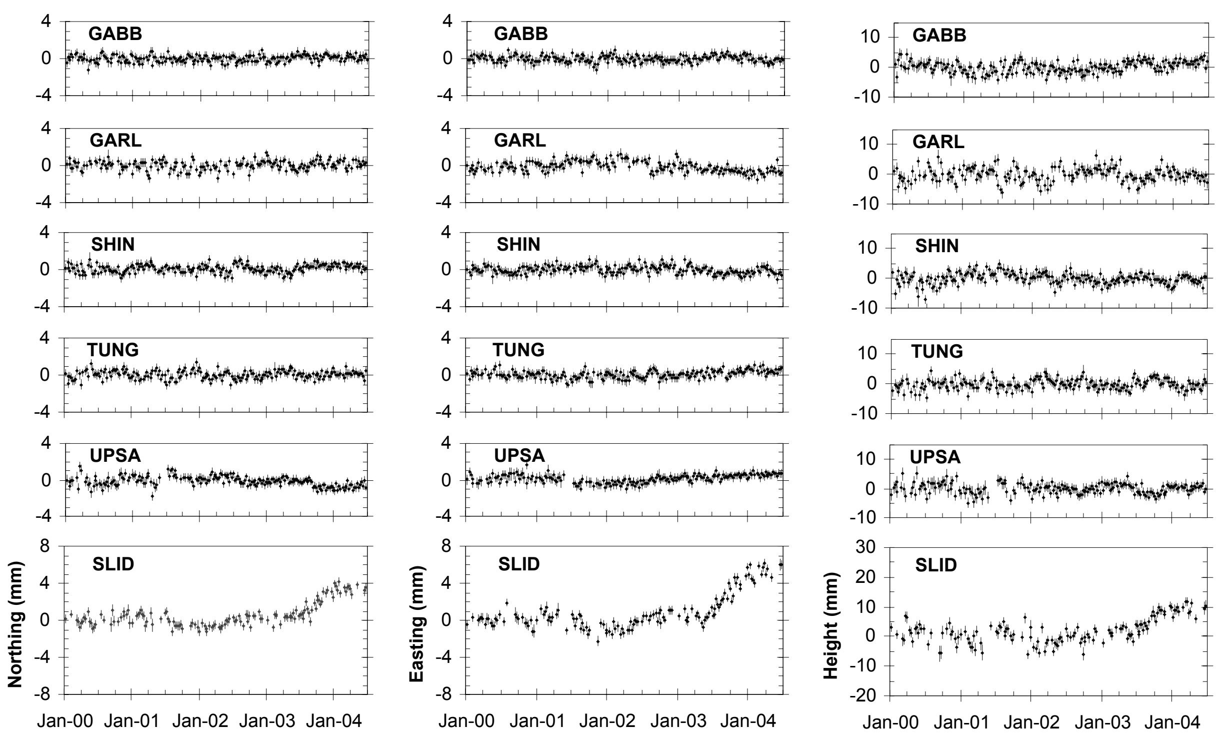


Figure 5. ***Transient displacement detected in GPS coordinate time series for SLID, coeval with a deep microseismicity. Also shown are time series for other BARGEN stations within 200 km of SLID (Smith et al., 2004).***

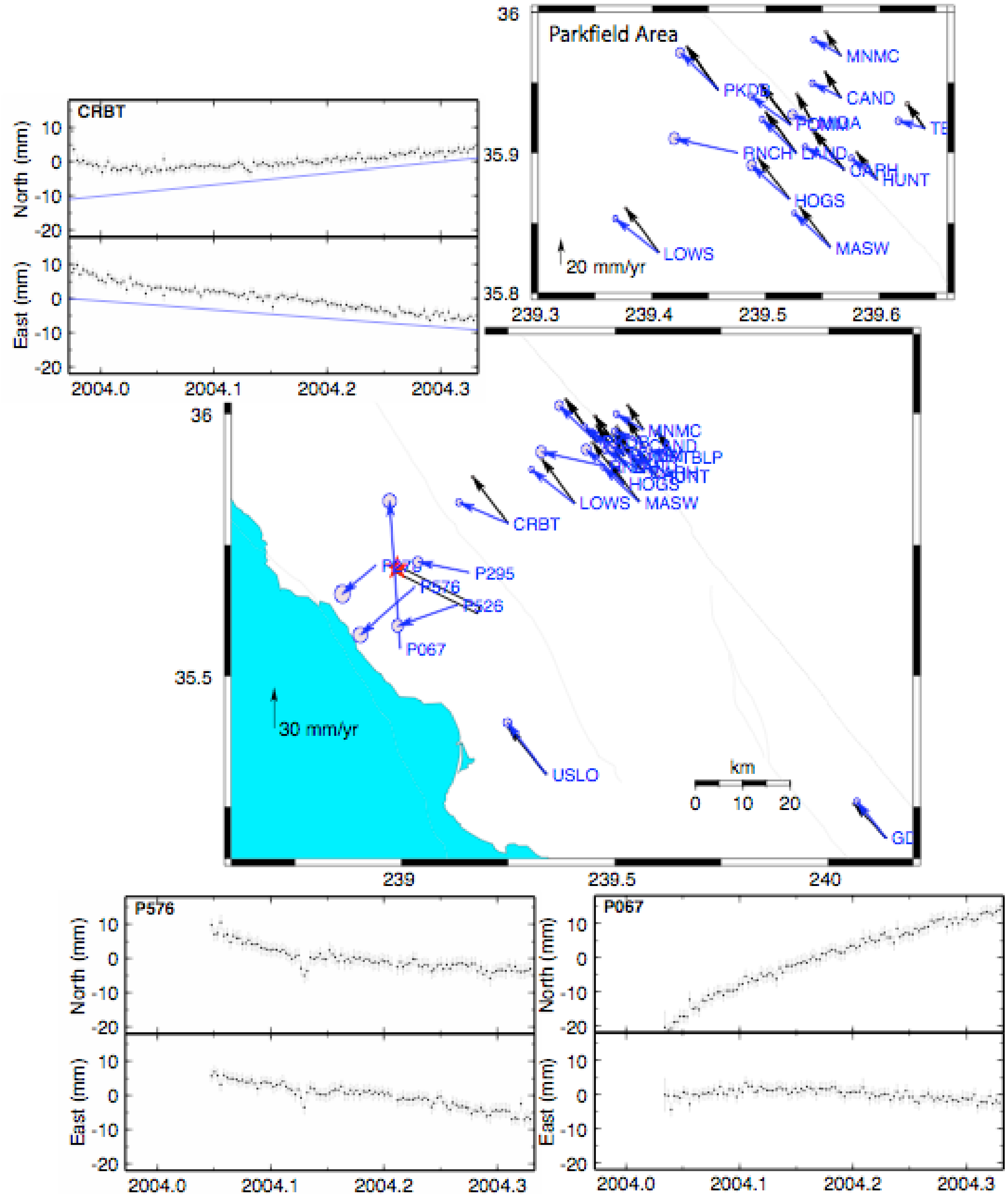
Figure 5 shows the results of a geodetic analysis for SLID, and other BARGEN stations within 200 km of SLID, starting on 1 January 2000, and including data through 28 June 2004. The next closest station, UPSA, is 100 km further from the event. The SLID transient displacement is 9.8 mm in a direction normal to the planar structure defined by the deep earthquake swarm, spanning the same time period of the swarm.

The geodetic displacement here is too large to be explained by the elastic strain from the cumulative seismic moment of the sequence, suggesting an aseismic forcing mechanism. Aspects of the swarm and SLID displacements are consistent with lower-crustal magma injection under Lake Tahoe. During the first 23 days of the swarm, hypocentral depths migrated at a rate of 2.4 millimeters/second up-dip along a 45 kilometer^2 structure striking N30°W and dipping 50°E. The area of the planar structure at depth (45 km^2), assuming a stress drop of 10 MPa (reasonable for upper crustal earthquakes), would cause a seismic moment equivalent to a moment magnitude (Mw) 6.0 and displacement of ~1 meter at the source. Applying Okada's model for a tensile crack at 28 km depth in the source region, a potency equivalent to a volume of 3.7 x 10^7 m^3, or volumetric moment equivalent of Mw 6.4, fits the SLID observations. Smith et al. (2004) suggest that this magmatic phenomenon should not be viewed as a likely precursor to volcanism, but rather as part of the tectonic cycle of lower crustal evolution, perhaps providing a mechanism to sustain crustal thickness and crustal strength in zones of extension.

Whether the transient deformation will continue is a clear issue of key scientific importance, as it constrains whether the lower-crustal magma inference is correct and, if so, whether this is only one episode of a longer-duration steady-state process. Keeping SLID and other sites in the area running contributes not only to transient detection but also to understanding lower-crustal dynamics and continental volcanism.

1.3 Postseismic Transient Deformation

2003 San Simeon, CA. Another class of fault behavior that can only be imaged with long-duration, uninterrupted time series is postseismic creep. Many of the largest earthquakes trigger slow slip either along the mainshock rupture or along adjacent regions of the fault that did not rupture during the mainshock. A recent example of such behavior comes from the Mw=6.5 earthquake that struck the central California coast on December 22, 2003. The event was located 11 km NE of San Simeon, where the brunt of the damage and casualties occurred. The earthquake was a reverse event that uplifted the Santa Lucia mountains and triggered a vigorous aftershock sequence. A model for the San Simeon mainshock, derived from both seismic and GPS observations of the event, indicates that over 200 mm of slip occurred on the fault plane during the event (Hardebeck et al., 2004). Illustrating the interplay between faults, the San Simeon mainshock also triggered a small amount of right-lateral creep on the San Andreas Fault near Parkfield. In turn, creep on the San Andreas fault reloads the San Simeon fault (Hardebeck et al., 2004). For GPS sites that existed before the mainshock, the postseismic motion is in the same direction as the co-seismic motion, suggesting possible afterslip. Shortly after the earthquake, PBO installed five sites that had been planned for this area (Figure 6). Their installation was advanced to capture possible postseismic motion. The new PBO sites show very rapid and complex motions and at this time the mechanism that is producing these motions is not obvious. Assuming the pre-existing instruments continue running, the San Simeon earthquake will provide an excellent case for studying postseismic

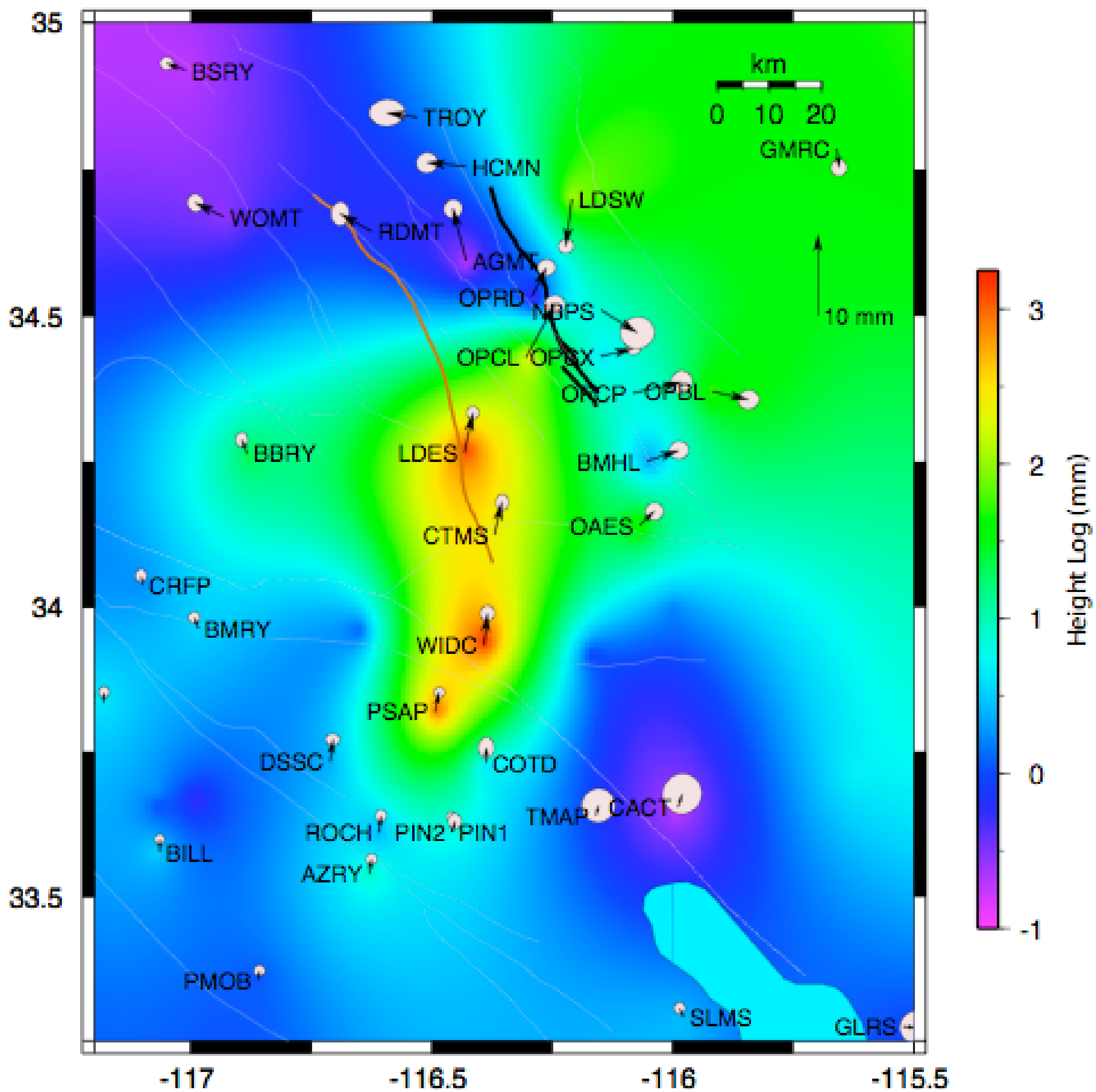


<u>Figure 6.</u> PBO and PBO Nucleus data from central California show rapid postseismic motion following the 2003 San Simeon Mw=6.5 thrust earthquake. Pre-existing sites show postseismic motion in the same direction as coseismic, suggesting afterslip to be the predominant cause. For PBO stations installed shortly after the event, the data are clearly not linear and the underlying cause is not obvious.

processes through the combination of the long time series available from pre-existing sites and the new time series for sites that are effectively on top of the rupture zone.

1999 Hector Mine, CA. The Hector Mine earthquake occurred on October 16th, 1999. Consequently, there is a longer record of post-seismic displacement available for examination.

This event displaced GPS sites within 430 km of the epicenter by more than 1 mm and up to 200 mm for the Southern California Integrated GPS Network (SCIGN) site closest to the epicenter. The continued operation of the GPS sites in Southern California and the installation of new sites in the region have allowed the temporal behavior of the postseismic deformation and the relationship between the pre- and post-event velocities to be studied (Hudnut et al., 2002). It is by no means simple. The analysis of SCIGN data has suggested a logarithmic time dependence for the postseismic deformation, as has been found elsewhere, but the physical mechanism that gives rise to this decay is not known (Figure 7).



<u>Figure 7.</u> Horizontal estimates of log coefficients of postseismic motion after the 1999 Hector mine earthquake, vectors with 95% confidence ellipses, and interpolated height motions, color background. The median standard deviation of the height estimates is 0.3 mm. The thick black and red lines are the surface ruptures of the Hector Mine and Landers earthquakes. The thin grey lines are quaternary faults in the region. Many of the sites near the Hector Mine rupture were installed after the earthquake. The largest horizontal amplitude is 7.3±05 mm (OPCL) and the largest vertical amplitude 3.2±0.8 mm (WIDC).

However, the logarithmic form has long-term implications for the relationship between instantaneous geodetic velocities and long-term interseismic rates. It predicts that the instantaneous velocity of the site most affected by earthquake about 5 years after the earthquake will still differ from its long-term velocity by 1.5 mm/yr. Similar behavior also occurred after the Landers earthquake, and the expectation is that residual velocity effects of at least 1 mm/yr are still ongoing at sites near that rupture. A complete understanding of the mechanism and consequences of postseismic deformation requires combination of short-term and long-term measurements. Curvature in the time series of the short-term measurements immediately after an earthquake constrains the time constant, while long-term measurements spanning an earthquake allow the relationship between pre- and post-event velocities to be determined. For Hector Mine in particular, the predicted viscous relaxation time constants for the mantle differ from that of the lower crust (Pollitz et al., 2001), and differentiating between these two mechanisms will be a direct product of uninterrupted Nucleus time series.

2002 Denali AK. Arguably the most stunning example of postseismic deformation, however, comes from the November 3, 2002 Denali Fault Earthquake (M_W 7.9), which was the largest on land strike-slip earthquake in the US since at least 1857. It ruptured more than 300 km of the Denali, Totschunda, and Susitna Glacier faults. The earthquake caused measurable displacements across much of Alaska, and displaced all Continuous GPS (CGPS) sites in Alaska except for the site in Barrow (SG27). Because of the sparse CGPS coverage, no sites were located within 50 km of the rupture and coseismic displacements at CGPS sites were modest in magnitude. Under separate NSF support, the University of Alaska Fairbanks, Purdue University and the University of California, Berkeley established 15 additional CGPS sites and carried out GPS survey-mode measurements to measure both coseismic displacements and postseismic deformation, with the aim of understanding postseismic deformation mechanisms triggered by this earthquake. Five of these new sites are becoming PBO sites, but the other ten sites were installed too recently to meet the standard of "Existing Networks" that was agreed upon for this proposal

The pre-existing CGPS sites, that are part of the PBO Nucleus, provide a means to separate coseismic from postseismic deformation. It took several days for survey teams to reach all of the survey-mode sites displaced by the earthquake, and only the pre-existing CGPS sites provided data on the immediate postseismic deformation; at survey mode sites this cannot be separated from the coseismic signal. At CLGO, postseismic displacements in the first two weeks after the earthquake amounted to 10-15% of the coseismic displacement. Furthermore, because of their long time history, these CGPS sites provide a very accurate means of measuring even small postseismic displacements, relative to a precisely known pre-earthquake velocity.

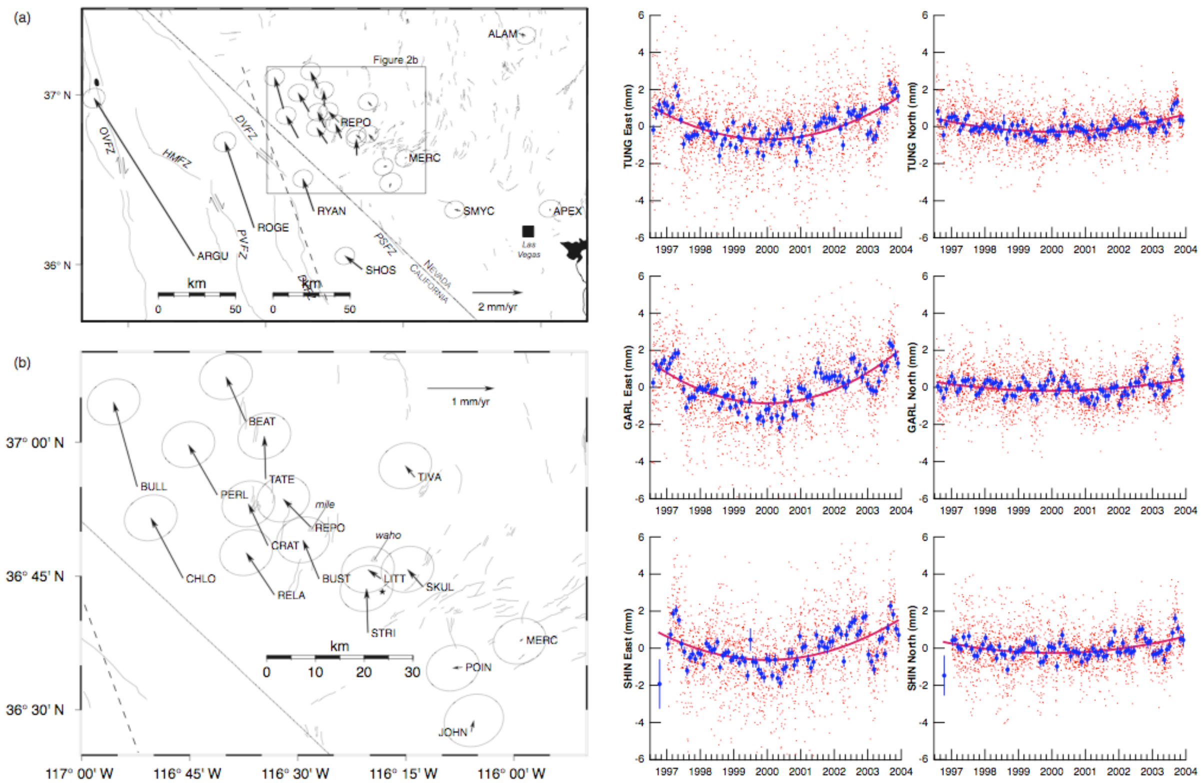
Operation of these Nucleus sites until the postseismic signal decays to nearly zero will be of critical importance in understanding the long-term decay of postseismic processes. The more numerous survey-mode sites provide a less-precise measure of pre-earthquake velocity. The 10 new post-Denali continuous sites, several of which have recorded more than 15 cm of postseismic deformation, have pre-earthquake velocities based only on survey mode data or based on model predictions fit to other survey mode data. Current Denali post-seismic deformation, suggests this signal will be measurable for several years and possibly several decades. The large signal produced by the Denali earthquake will allow discrimination between afterslip and viscous relaxation of the mantle or lower crust.

1.4 Interseismic Transient Deformation

Northern Hayward Fault, CA. PBO Nucleus stations in the San Francisco Bay area also have proven to be a powerful tool for investigating crustal deformation processes along the splinter faults of the San Andreas. As with the Cascadia events, and the afterslip and viscous relaxation that follow large conventional earthquakes, continuous observations conducted here over many years have enabled transient deformation to be isolated from long-term tectonic motions, seasonal effects and other temporally correlated sources of noise. These observations have led to identification of a complex suite of faulting behavior along the Hayward fault that bisects the greater San Francisco metropolitan region. The southern section of this fault ruptured in an M7 earthquake in 1868, but paleoseismic investigations suggest that the most recent earthquake along the northern section occurred between 1640 and 1776. Given long-term slip rate estimates of ~10 mm/yr, this suggested that 2.2-3.6 m of seismic slip potential may have accumulated. As a result, the Hayward fault, combined with the locked Rodgers Creek fault zone to the north, was commonly assumed to pose the highest earthquake probability of any fault in the San Francisco Bay area.

However, aseismic creep of 5-6 mm/yr along the surface trace of the Hayward fault, and the unknown depth to which that creep extends, complicate the estimation of seismic hazards, which depends in part on depth of seismic coupling. To better constrain its depth, observations from continuous and survey-mode GPS, InSAR, and surface creep were used to constrain models of slip-rate on the fault (Bürgmann et al., 2000). Furthermore, about 20 continuous GPS stations, some of which are PBO Nucleus stations, provided a primary constraint on inferred deep slip rates on the major faults of the San Andreas system in this area. The measured deformation is best modeled by a locked segment along the southern Hayward fault and an absence of locking along a 20-km-long segment of the northern Hayward fault. The portions of the fault that show surface creep at rates less than the long-term slip rate are expected to catch up during and in the aftermath of 1868-type southern Hayward fault earthquakes or earthquakes on the Rodgers Creek fault to the north. These results therefore show that the northern segment of the Hayward fault should not be considered as an independent source region of large earthquakes for hazard estimation in the San Francisco Bay area, at least for now. One intriguing aspect of creeping faults, and also one of the most important reasons for maintaining PBO Nucleus sites, is that creeping faults often change their rate of creep, as has been seen to south along the San Juan Batista and Parkfield regions of the San Andreas (Linde, et al., 1996 and Gao, et al., 2000). A change in creep rate might indicate relocking at depth or a change in seismic moment accumulation rate.

Basin and Range, NV. A final example of how uninterrupted, long-duration time series offer a unique window into transient detection involves PBO Nucleus stations in Nevada which have shown departures from linearity that suggest long-term, multi-year accelerations in deformation rate. The BARGEN network has provided the PBO Nucleus network with a dense array constructed using highly stable deep-anchored monumentation with existing time series spanning up to seven years for the northern part of the network. Across a dense cluster in the Yucca Mountain area, the north components of velocity increase from east to west, reflecting NNW right-lateral shear across the array (Figure 8a). The longest of all the BARGEN time series, in the northern Basin and Range, shows how deviations from linearity that appear to be well above the accuracy in velocity on a 2 to 3 year time frame (Wernicke, pers. comm.). Figure 8b shows time series of the east and north components of three sites in northwestern Nevada, all of which exhibit curvature, especially in the east components. It is not yet known whether these effects are truly tectonic or related to uncertainties in reference frame; several years of additional data will answer this question definitively. Examination of all sites in this cluster at the present time, using the available seven-year time series (Figure 8b), shows that there is a general tendency for deceleration of sites in Nevada while sites in Utah tend to have more linear time series. If these effects turn out to indeed be tectonic and not in some way a result of GPS error, it will be quite exciting and undoubtedly lead to a rethinking of current models.

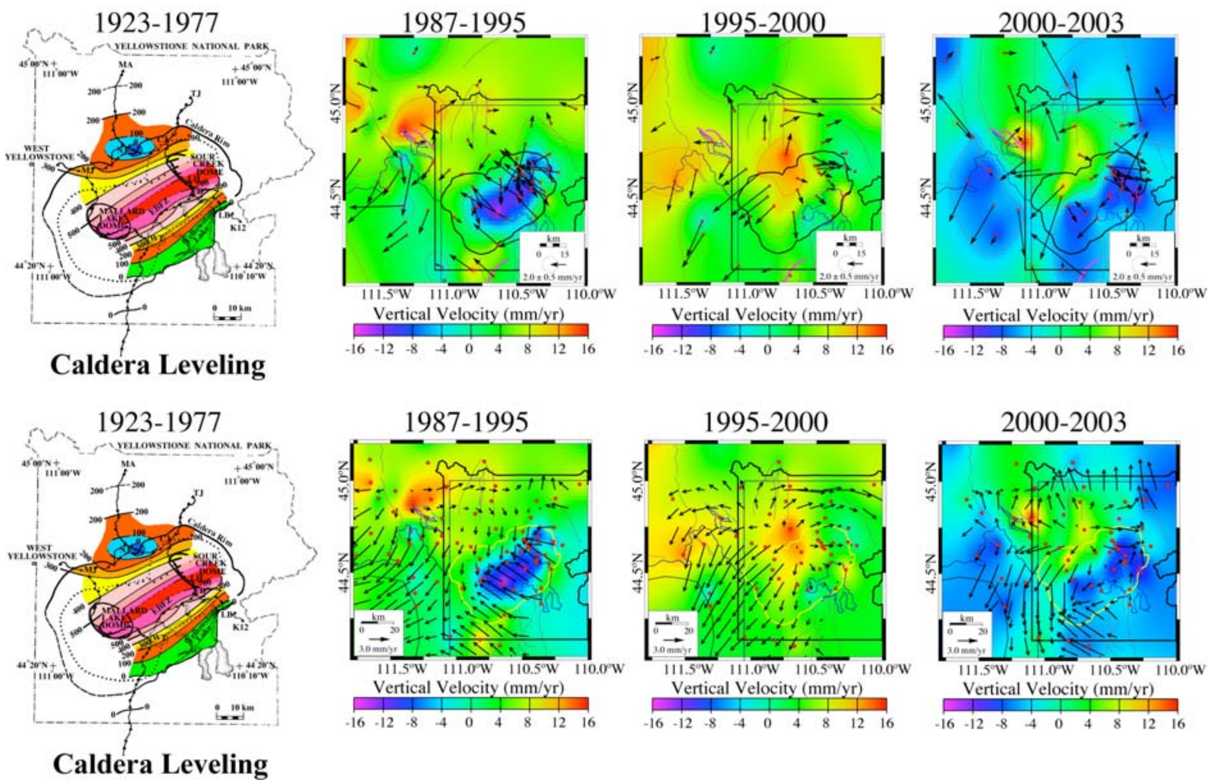


<u>Figure 8a. (Left).</u> Shaded relief map showing the horizontal velocity field for the Yucca Mountain GPS network. Sites are located at the base of the velocity arrows, shown with 95% confidence ellipses. Quaternary faults are shown with thin lines. (b) Inset showing details of the horizontal velocity field for the Yucca Mountain cluster. Star indicates the epicenter of the 29 June 1992 M_s 5.4 Little Skull Mountain earthquake. B. Acceleration field of the northern part of the BARGEN network, based on second order polynomial fits to the data. Note relatively coherent pattern of westward slowing of the three sites SHIN, GARL and TUNG, which are similar to many other sites in Nevada.

<u>Figure 8b. (Right).</u> Acceleration field of the northern part of the BARGEN network, based on second order polynomial fits to the data. Note relatively coherent pattern of westward slowing of the three sites SHIN, GARL and TUNG, which are similar to many other sites in Nevada.

1.5 Transient Deformation in Volcanic Calderas

Yellowstone, WY. PBO Nucleus stations located in volcanic centers show details of magmatic recharge not otherwise observable. For instance, the discovery at Yellowstone of unprecedented caldera motion of approximately 75 cm (at 14 mm/yr) over 50 years was originally observed with leveling surveys conducted in 1975, 1976, and 1977, and compared to the original leveling surveys of Yellowstone's roads in 1923. GPS methodology was employed starting in 1987 when campaign survey measurements were made. Beginning in 1996, six permanent GPS stations were installed adding additional high quality information. These stations are part of the PBO Nucleus network. While station velocities in the caldera are influenced by Yellowstone's volcanic system, stations surrounding the Yellowstone Plateau are dominated by SW-NE regional extension relative to the stable continental interior that reflect larger scale deformation of western North America. Measurements through 1995 within the caldera, however, revealed a surprising change to caldera subsidence, with radial motions toward the center of the caldera. This change was coincident with the occurrence of the largest historic seismic swarm in Yellowstone in 1985. The maximum subsidence rate was 10 mm/yr along the long axis of the caldera. However, for the 1995-2000 period, the caldera changed motion again to uplift, with an asymmetric pattern of NW caldera uplift and SE caldera subsidence. A maximum uplift rate of 12 mm/yr occurred in the NW caldera encompassing Norris Geyser Basin. During the 2000 - 2003 time period, uplift continued at 5 mm/yr in the northwest caldera area, but the main caldera deformation was dominated by subsidence at 5 mm/yr. These rapid changes lead to the idea of "a living, breathing caldera" (Figure 9).



***<u>Figure 9.</u>* Observed ground motion velocities (1st row) and interpolated velocity field (2nd row). Horizontal velocities are vectors and vertical velocities color contours. The panels on the left show uplift rates between 1923 and 1977 from leveling surveys.**

The unusual vertical and horizontal motions of Yellowstone were modeled by inverse methods to evaluate changes in volumetric strain. The inferred sources are concentrated in the upper crust at 0 to 6 km depths (Figure 2) and are attributed to Yellowstone's hydrothermal systems because the implied low viscosity and rapid reversals of motions. The initial uplift has been attributed to hydrothermal reservoir inflation, while the 1985 subsidence was related to hydrothermal fluid migration radially out from the caldera. Convective heat flux from the underlying magma body inferred between 6 and 18 km depth is thought to drive the overlying convective hydrothermal fluids and consequent large vertical surface motions. Clearly, long-duration time series without time gaps are of crucial importance for the scientific research into the Yellowstone volcanic system. Future observations will likely give rise to an equally diverse range of observations into this dynamic geophysical realm.

1.6 Tectonic Signal Discrimination

Since tectonic transients often produce small signals that are difficult to discriminate from noise in geodetic data, detecting and understanding transients requires very clearly understanding the character of the noise. Long time series from high quality stations are the only way to investigate these noise sources. The stations covered by this proposal are unique among PBO stations in providing these long time series. GPS data contain correlated errors as well as white noise (Johnson and Agnew, 1995; Langbein and Johnson, 1997; and Langbein and Bock, 2004), and we must characterize this noise both to determine realistic uncertainties for station velocities and to discriminate fluctuations from steady motion. Because the signal-to-noise level for slow deformations is often small, specialized filtering is typically needed to identify subtle features that indicate slow deformation. The evidence for periodic Cascadia slow earthquakes only emerges from a simultaneous analysis for interseismic strain, annual and semi-annual reference frame effects, and for offsets due to hardware upgrades and known earthquakes.

The longer the time series, the better we can identify and model such errors; it appears that series of at least 5 years length are required. The need for extended observation series makes the PBO Nucleus stations extremely important for EarthScope science; for some time to come, only these existing stations, with their long time series from sites with ultra-stable monuments, will be able to contribute to understanding noise sources. Knowledge gained from studying these observations will greatly improve the scientific usefulness of all PBO data.

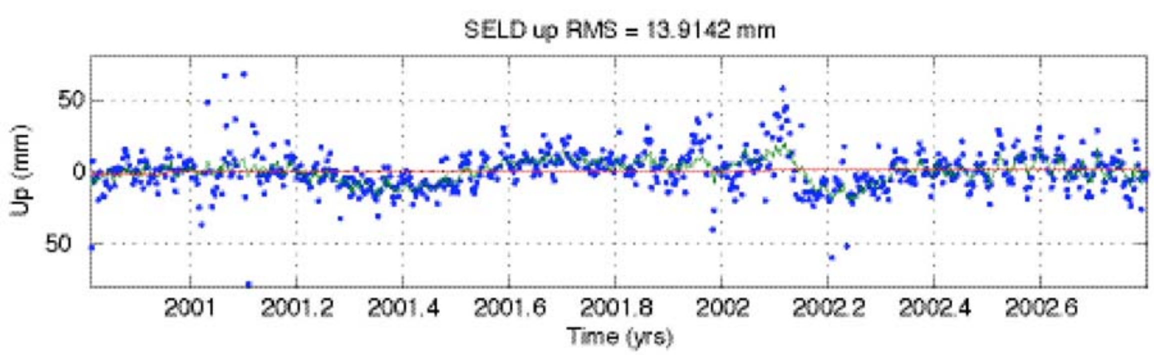
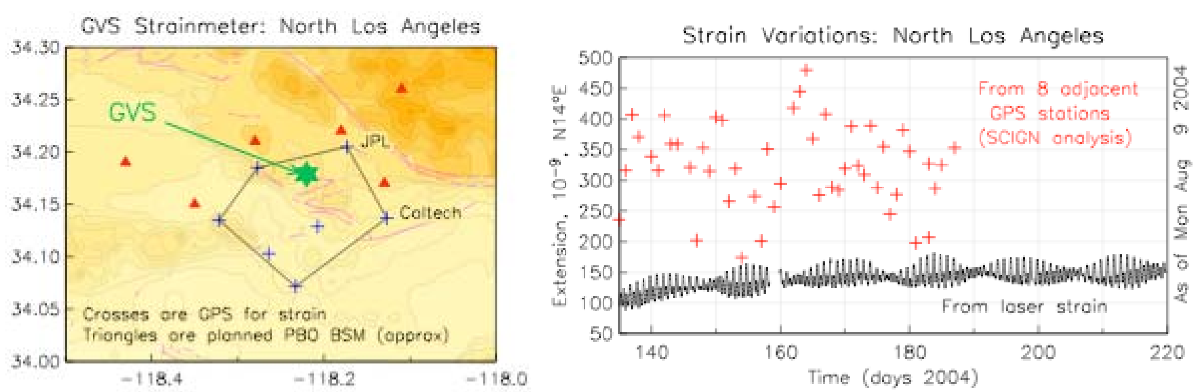


***Figure 10*. Vertical position time series for Seldovia, AK (SELD), with long-term trend removed. Blue points are individual days of data, and the green line shows the filtered time series based on principal component analysis. Note the prominent periodic residual, with a dominant period of 14 days. This signal results from modeling errors in ocean tidal loading. A strong annual component (high in middle of the year) is also seen.**

As an example of how we are still learning about noise sources, consider the periodic signals seen in many GPS series. Strong seasonal signals do not necessarily mean "bad sites";

in some cases, such signals reflect real ground deformation (Bawden et al., 2001) that must be understood even if not tectonic in origin. There is strong evidence for seasonal loading on global and regional scales (Blewitt and Lavallee, 2002; Blewitt, 2003; Blewitt et al. 2004, and Heki, 2003). Such signals constrain large-scale water redistribution and cryospheric variations. Another periodic signal has been observed in data from Alaska. Here, in addition to annual signals, there is a 14-day periodicity that is particularly strong in the vertical and at sites close to the southern coast of Alaska (Figure 10). Studies elsewhere show that errors in ocean tidal loading models will produce periodic position errors at periods of 14 days, 6 months and 1 year (Tsuji, 1995, and Penna and Stewart, 2003), but correcting for ocean tidal loading using current models improves this only nominally. We still have much to learn.

The PBO Nucleus network is especially well placed to enhance our understanding of GPS errors because it includes, almost uniquely in the world, an independent measurement of deformation over a frequency range overlapping with GPS. The Glendale-Verdugo Strainmeter (GVS) is a 560 m long interferometric laser strainmeter. GVS is installed in the middle of the densest part of the Southern California Integrated GPS Network (SCIGN) array in Los Angeles. Figure 11a shows the location of the GVS strainmeter, as well as nearby GPS sites. Figure 11b shows a time series of strain along the azimuth of the strainmeter, measured by fitting to the daily GPS displacements (red) and from the fully anchored strain series (black line). For periods of months or more, the strainmeter has stability comparable to GPS, while for shorter periods it has much lower noise: low enough to easily resolve the strain tides (which dominate the record), and indeed, for periods of a few days, strain changes as small as 0.1% of the GPS resolution. Being able to directly compare independent measurements of strain will yield important information about the limits of GPS measurements within the rest of the Nucleus network, and of PBO; we therefore consider the strainmeter an integral part of Nucleus. The EarthScope PBO project will install a network of new borehole strainmeters in the vicinity of GVS (Figure 11b). This strain array will be designed to complement the GVS.



<u>Figure 11a.</u> (Left) Location of the GVS strainmeter, as well as the SCIGN GPS sites within (and on) a polygon around it. <u>Figure 11b.</u> (Right) Time series of strain along the azimuth of the strainmeter, measured by fitting to the daily GPS displacements (red) and from the fully-anchored strain series (black line).

1.7 Three-dimensional Velocity Fields

Long time series are of irreplaceable value, not just for detecting and analyzing transients and discerning them from their errors, but also for a host of applications that constrain the continental-scale dynamics of plate boundary processes, both in the crust and mantle. The Southern California Earthquake Center (SCEC) version III crustal motion map, (http://www.scec.org/research/) is the result of more than 20 years of terrestrial and GPS observations in southern California. Continuous GPS data collected since 1991, some of which are PBO Nucleus stations, provide the backbone of this data set. Using a similar methodology outlined in Wdowinski et al. (2001), the normalized version III velocities, once transformed into the North America pole of rotation, show the details of transform motion across the NA - Pacific plate boundary (Figure 12). The horizontal axis (in degrees) denotes small circles about the NA pole of rotation, while the vertical axis (in degrees) is arbitrarily centered at the mid-point of the velocity field. Clearly delineated by the 0.5 normalized velocity contour is the trace of the San Andreas fault, with a clear step over to the San Jacinto and Cierro Prieto faults in the south. Also clearly delineated is the narrowing, from north to south, of the North America - Pacific plate boundary, and the wider zone of distributed deformation in the Eastern California Shear Zone. The resolution of this strain map is attributable in large part to the existence of a long uninterrupted time series from PBO Nucleus sites. As the density of stations along this boundary improves, so too will the resolution of the role that splinter faults, such as the San Jacinto, play in accommodating the Pacific-North American convergence.

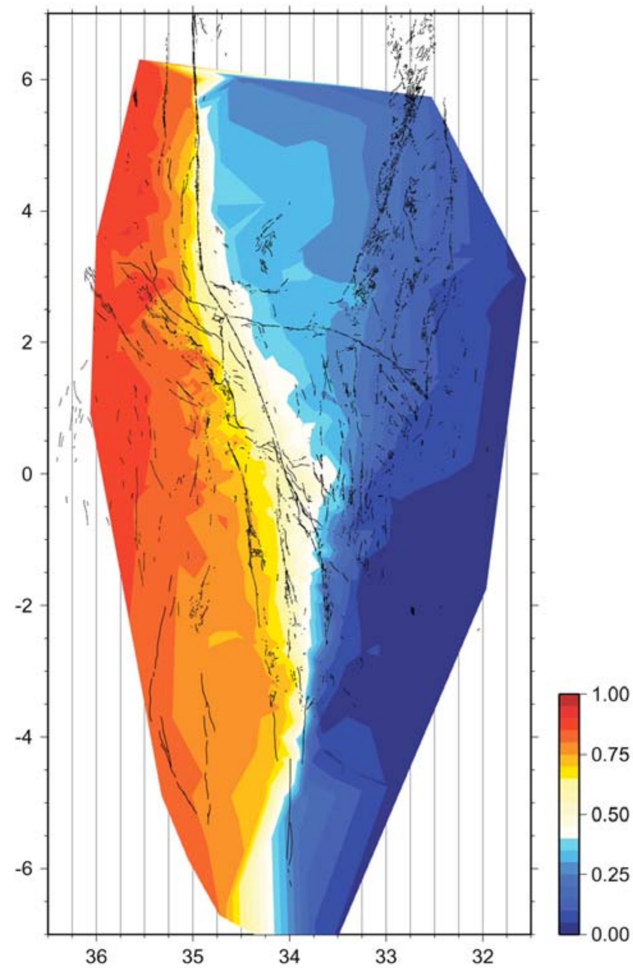
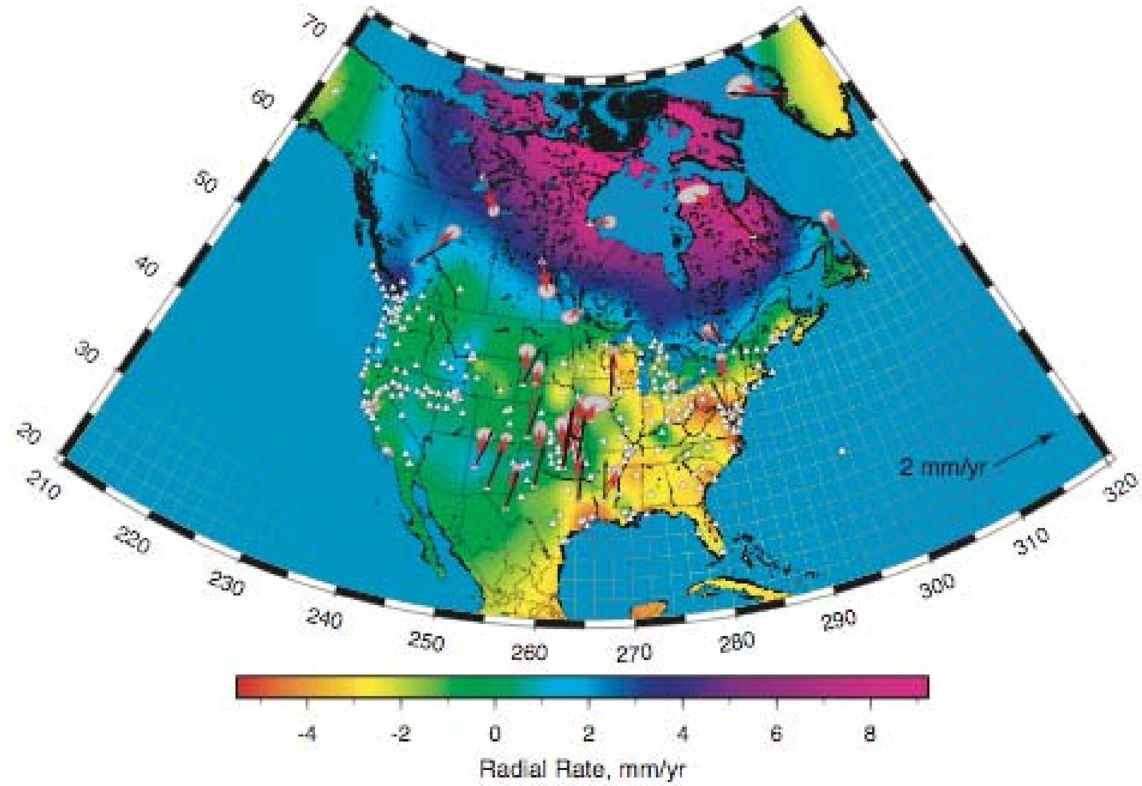


Figure 12. ***Contoured longitudinal component of the normalized velocities from SCIGN, S. California.***

The long time series of position estimates from GPS sites distributed across North America are now allowing reliable estimates of vertical motions in North America, which in turn reflect mantle dynamics. Figure 13 shows an example of GPS determined vertical motions. These results are generated as part of the UNAVCO-sponsored Stable North America Reference Frame (SNARF) working group activities. Although the general characteristics of this figure match the predictions from glacial isostatic adjustment (GIA) models, there is notable misfit. Uplift around Hudson's Bay, subsidence in most of the United



<u>Figure 13.</u> Horizontal and vertical velocities in North America determined from GPS measurements. The red vectors show GPS estimated horizontal velocities with 95% confidence ellipses; black vectors are predictions from a glacial isostatic adjustment (GIA) model with 70km thick elastic lithosphere and the ICE3G ice model. The colors are interpolated GPS vertical velocities from 364 sites distributed across the continent (white triangles), which have a median height velocity sigma of 1 mm/yr.

States, and horizontal motions towards Hudson's Bay for sites outside of the peripheral bulge match none of the existing GIA models with spherical viscosity structure. However, at this large scale, where the effects of GIA extend over all of the land area of the North American plate, the GPS realization of the stable plate is not independent of the GIA model. The effects of GIA are dependent, among other things, on the viscosity structure of the mantle and this structure also effects the deformation in the boundary zone associated with stress transients. The expectation from GIA models is that most of the coterminous United States should be subsiding at about 1 mm/yr whereas the GPS results show the east coast subsiding faster than this and west coast uplifting relative to the east coast. These deviations are quite small, just a few mm/yr, and long time series of the measurements are required to determine vertical motions with uncertainties small compared to this deviation; it cannot be done with short (< 5 year) time series. Many of the PBO Nucleus sites contribute to Figure 13, although the uplift rate along the west coast, where PBO Nucleus sites are most numerous, is still too small to resolve. However, by 2008 a significant number of PBO Nucleus sites will provide estimates of far-field GIA uplift rates.

2. Project Plan

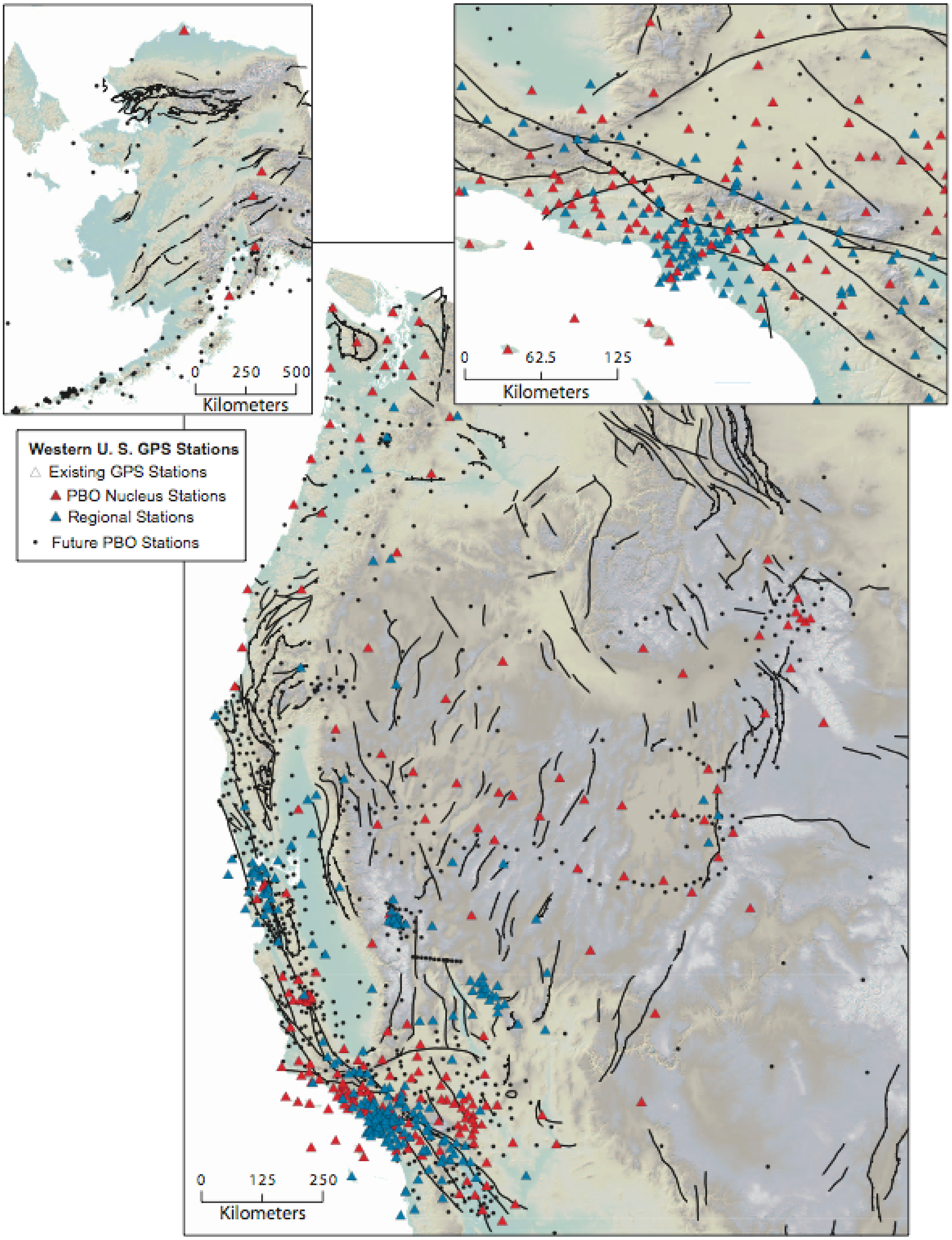


Figure 14. ***Station location map showing the PBO Nucleus stations, other existing sites, and planned PBO construction. Upper right inset shows the Los Angeles Basin. Quaternary faults are shown in black.***

2.1 Outline of Proposed Work

We plan to create a centralized, standardized, and economically viable geodetic network that will be fully integrated into EarthScope at the end of the funding period. Existing stations that have been constructed and operated by six independent regional network operators to varying specifications will be integrated and upgraded to uniform PBO standards under the management of the UNAVCO facility in Boulder, CO. This is a continuation of an effort funded under an existing NSF grant (EAR-0318549). As planned, we have restructured the operation of these networks, eliminating duplication of efforts at regional institutions; we have shifted the budgetary and operational responsibility to UNAVCO and reduced the size of subawards. The PBO Nucleus Steering Committee (see below) has developed detailed strategies for integration of the network into PBO in 2008. Data from this proposed network (Figure 14) will be fully integrated into the PBO data flow in the first six months of the funding period, initially doubling the data volume that PBO will have available for its early data products, and lengthening its time series by many years. We have included an Education and Outreach component to disseminate the knowledge derived from this network.

2.2 PBO Nucleus Steering Committee

This proposal has been developed by a group that includes all of the key scientists and technical staff of the existing geodetic networks in the Western United States under the direction of the PBO Nucleus Steering Committee. The Steering Committee has developed this plan for a transition from the original networks to EarthScope and will provide guidance in the implementation of the plan. The PBO Nucleus Steering Committee consists of:

Frederick Blume, Western U.S. Networks Project Manager, UNAVCO
Greg Anderson, PBO Data Products Manager, UNAVCO
Jeffrey Freymueller, AKDA P.I., University of Alaska
Tom Herring, SCIGN Chairman, MIT
Tim Melbourne, PANGA P.I., Central Washington University
Mark Murray, BARD P.I., University of California, Berkeley
Bob Smith, EBRY P.I., University of Utah
Brian Wernicke, BARGEN P.I., Caltech

Other community members who have contributed to the development of this plan include Nathan Niemi, Caltech, Andrew Miner, Central Washington Univ., Meghan Miller, Central Washington Univ., Barbara Romanowicz, UC Berkeley, Dave Drobeck, Univ. of Utah, Jim Davis, Harvard CfA, Yehuda Bock, UC San Diego, Ken Hudnut, USGS, Keith Stark, USGS, Duncan Agnew, UCSD, and Frank Wyatt, UCSD.

2.3 Merit Review Criteria

2.3.1 Intellectual Merit

Importance of the Proposed Work

The last several years have witnessed a broad reappraisal of the extent to which slow faulting accommodates long-term slip rates throughout active tectonic environments, nearly all of which has been driven by the Nucleus time series discussed here. The increasing precision and density of continuous geodetic instrumentation have allowed us to recognize that slow slip is a ubiquitous process that constitutes a fundamental mode of strain release globally. Deep (i.e., not near-surface) transient fault creep has now been identified in many locations where we have continuous long period instrumentation that can detect slow ground motion, in both interplate and intraplate environments, in oceanic and continental transform settings. Indeed, only in the last three to four years have we have come to realize that the dearth of historically reported transients is a consequence of our inability to observe them rather than their scarcity. The research community is only beginning to appreciate the pervasive effect that slow faulting bears on other tectonic processes; its modulation of seismogenic nucleation, for instance, remains an open question, as does its spatial/depth distribution and its net moment contribution to total fault zone energetics. The newness of the observations and, more fundamentally, the spectral and amplitude limitations to fully resolve deformation transients have precluded further understanding of these issues. EarthScope is poised to remedy this situation, and within PBO, the Nucleus stations play a key role in these efforts by vastly increasing the length of the available time series to conduct these studies. These stations are also strategically located to study specific geophysical targets of interest to the EarthScope project, and therefore are of great value to PBO. This project will integrate the Nucleus stations into PBO, with the result that all stations will have been upgraded to PBO specifications for instrumentation and communication with no disruptions in their time series**.** The station siting, network design, and operations and maintenance plans of PBO have been formulated under the assumption that the stations of the PBO Nucleus will continue to operate, and under the assumption that their data continue to be available. There is no alternative funding mechanism within the EarthScope project for the continued support of these essential stations. As discussed more fully in the budget justification, the PBO budget does not include funding for their operation during the PBO construction phase. After September 2008, when EarthScope moves into an operational mode, EarthScope will take responsibility for the operation of these stations.

Qualifications of the PBO Nucleus Steering Committee

This proposal has been developed by the scientists who founded and developed these networks. The effort is directed by a Steering Committee composed of these scientists, their technical staff, and UNAVCO management. With 20 years of experience in geodetic studies of tectonic phenomena, UNAVCO is uniquely qualified to assume management of the PBO Nucleus project. UNAVCO has responsibility for the PBO component of the EarthScope project, and close coordination of the Nucleus with PBO management and operations is essential to its success. William Prescott, President of UNAVCO, has a distinguished history in studying the tectonics of the Western U.S. and strong ties to the scientific community. Frederick Blume is currently managing the Western U.S. Existing Networks project and is therefore intimately familiar with the operational details and with the operators of the networks that will become the PBO Nucleus. The members of the PBO Nucleus Steering Committee have long experience in building and operating geodetic networks.

New aspects of this proposal

The design of the PBO Nucleus project proposed here is a radical departure from the previous mode of operation of the Existing Networks of which it is comprised. In contrast with past reliance on the efforts of regional Principal Investigators to coordinate station construction, operations and maintenance, data management and troubleshooting, we propose to centralize these responsibilities at UNAVCO, whose unique qualifications in geodetic network operation are described above. This proposal will eliminate duplicated efforts at these regional institutions and thereby reduce costs.

However, as the stations that are to be integrated were constructed using varied techniques and a variety of equipment types, we will continue to rely upon and support the expertise of the regional network operators during the proposed funding period at levels proportional to the number of stations that remain to be upgraded. The declining subaward levels in the third and fourth year of the project reflect the centralization and reduction in maintenance needs as new equipment is installed and UNAVCO assumes complete responsibility for the portion of the network that has been standardized.

Planning involved in developing the PBO Nucleus project

The PBO Nucleus project proposed here reflects the thorough analysis of the existing infrastructure, station permits, operations, maintenance, and data management procedures, and the corresponding requirements of PBO and its scientific objectives. The plan we present provides for the total and seamless integration of a carefully selected subset of the 432 Existing Network stations into PBO while operating these 209 stations at a substantially lower funding level than in the past. Care was taken to identify funding opportunities for the 224 existing sites not supported by this proposal so that data from these sites will continue to flow with the potential for their use in the PBO data analysis stream, and opportunities for use of surplus equipment created by upgrade purchases of this project have been identified.

Resources

The PBO Nucleus Steering Committee and UNAVCO are uniquely equipped to carry out this effort. Co-location of the Nucleus effort with PBO operations in Boulder provides easy communication between and integration of the two activities. The UNAVCO facility will make field engineer support available to this project under NSF core support at no cost to this project, and will help coordinate equipment purchases, which will significantly reduce its budgetary requirements. UNAVCO has the data and engineering facilities and staff required for this effort. The PBO Nucleus Steering Committee has years of experience in running these sites and is guiding the transition.

2.3.2 Broader Impacts

The PBO Nucleus stations have had a broad impact on the understanding of the Pacific North America plate boundary in the western United States. One measure of this impact is the number of investigators that have used data from these stations and the number of papers that they have published. A significant fraction of these investigators are not directly involved in running the stations. Nearly half of the 146 publications that have used data from these stations were published by a lead author who was not directly associated with the operation. The data from these stations serve a much larger audience than just the few people who work to keep them operating.

These statistics are summarized in Table 1, and a complete list of papers can be found on the PBO Nucleus web site (http://www.unavco.org/exnet/exnet.html).

***Table 1.* Numbers of Publications and Investigators relying on data from PBO Nucleus stations.**

	Number of publications	Number of Investigators
Network Operators	92	~20
Others (people with no direct role in operating these networks)	74	~244

Impact of this proposal on education

Several modules for secondary and undergraduate education will be developed and implemented here, including one for general students and one for geoscience majors. We will also incorporate research results from this network into existing educational resources such as the Electronic Encyclopedia of Earthquakes and the Digital Library of Earth Science Teacher Pilot products.

Impact of this proposal on underrepresented groups

We will involve teachers and faculty at institutions that serve underrepresented populations in curriculum development and dissemination, as detailed in the Education and Outreach plan.

Impact of this proposal on infrastructure

The primary aim of the PBO Nucleus project is to insure that existing critical infrastructure is maintained, upgraded to the current state of the art standards, and continues to be available to the broad research community as part of the EarthScope effort.

Dissemination of data and information from this effort

Data and data products from PBO Nucleus sites will be distributed under the completely open PBO Data Management Plan with no delays. The data and products from these stations, previously available only from the individual network operators, will be available from EarthScope data centers and completely integrated with other EarthScope data.

Impact of this proposal on Society as a whole

Through the EarthScope Portal currently under development as part of the EarthScope Facility, these data will used to produce products for a wide variety of audiences including non-scientists and scientists from other fields.

2.4 Leveraged Funding

In addition to funding requested by this proposal, the PBO Nucleus project will take advantage of many other sources of resources and funding. Existing relationships between the current network operators and various funding agencies, universities, K-12 schools, etc., will result in NSF funding being significantly augmented. Additionally, the stations of the Existing Networks not included in the PBO Nucleus network will, in most cases, continue to operate through other funding sources with data made available to the EarthScope community through informal agreements.

Through its National Earthquake Hazard Reduction Program (NEHRP), the USGS supports the operations and maintenance of the communications networks and other resources at 8 of the PBO Nucleus sites in Wyoming, Montana, Idaho, and California, that are collocated with seismographic stations. The USGS also supports network operations at Parkfield, and maintenance support will continue to be available to the Nucleus project.

The U.S. Department of Energy has increased funding to its Yucca Mountain geodetic network in the Southern Basin and Range. Operations and maintenance of 5 of the PBO Nucleus stations will be covered by this funding, and 10 additional stations of the current BARGEN network not included in the Nucleus will be operated in parallel, as will the Yucca Mountain sites.

An informal agreement with the Idaho National Engineering and Environmental Laboratory (INEEL) has resulted in collaborative development of their seismic monitoring network in southern Idaho with UNAVCO. INEEL operates an IP radio network for its seismographs, and has provided its access to 3 PBO Nucleus stations at no cost. As a result of our activities there, INEEL has applied for membership in UNAVCO and is designing a small regional GPS network in Idaho whose data will be freely available to the research community.

Other existing arrangements that will allow no-cost communications strategies to the PBO Nucleus project exist with many other entities, such as BYU-Idaho, the Teton Science School, Pierce County Washington, Alaska Tsunami Warning Center, and Utah County. As the network upgrades proceed, identification of new opportunities for collaboration and synergy will be a top priority for all involved.

There is a long (20-year) history of active, mutually-beneficial collaboration between geophysicists/geodesists and the surveying community in southern California (SC), including field GPS surveys beginning in the mid 1980's and continuous GPS installations starting in the early 1990's. The establishment of the California Spatial Reference Center (CSRC) in 1999 has enhanced and formalized this relationship. The goal of the CSRC is to use the GPS science infrastructure as a backbone for the establishment and long-term maintenance of a spatial reference system for California, as the legal basis for positioning (horizontal and vertical and their temporal changes). Currently, CSRC and its partners (e.g., Caltrans, MWD, SC Counties) are assisting PBO in locating and permitting new stations.

Entity	**Development & Implementation Funds**	**In-Kind Support (implementation)**	**Annual Spend: Maintenance and Upgrades**	**Project**
CSRC (NOAA funds)	$350,000			Orange Cnty. Real Time Net. (RTN)
NASA SENH	$407,000			Orange and Riverside RTN's
Orange Cnty. PFRD	$88,500	$95,000 $25,000	*$25,000/yr (4 years total)*	Orange Cnty. RTN
Riverside Cnty DOT	$10,000			Riverside Cnty. RTN
Riverside Cnty. Flood and Water Conservation District	$25,000	*$10,000*	*$25,000/yr (4 years total)*	Riverside Cnty. RTN
San Diego Dept. of Public Works and Sheriff	$450,000	*$20,000*	*$25,000/yr (4 years total)*	San Diego County RTN
S. California Metropolitan Water District	*$70,000*	*$10,000*	*$25,000/yr (4 years total)*	Riverside County RTN
Imperial County Irrigation District		*$10,000*		Imperial County RTN
Imperial County Dept. Public Works		*$10,000*		Imperial County RTN
Totals	**$1,400,500**	**$180,000**	**$500,000**	**$2,080,500**

***Table 2.* Resources from Federal grants (NASA/NOAA) and SCIGN partners in support of real-time high-rate upgrades in southern California. Except for totals, bold numbers refer to funds already spent, plain numbers are secured fund, and italicized numbers are projections. Other efforts are in progress in Los Angeles County.**

Since 2001, the collaboration between geophysicists/geodesists and the surveying community, represented by counties, local governments, agencies, and private entities, has focused on upgrading SCIGN sites from routine periodic downloads of 15-30 s sampled data, to streaming high-rate (1 Hz or higher) data in real-time (<1 s latency). To date about 70 sites have been or shortly will be upgraded (Appendix A). These efforts were initiated after the 1999 Hector Mine earthquake when (30 s) SCIGN data were analyzed using the method of instantaneous positioning (Bock et al., 2000) to directly measure seismic motions and (Los Angeles) basin resonance effects (Nikolaidis et al., 2001). On the other hand, surveyors are interested in continuous access to high-rate data to support real time kinematic surveys (Andrew, 2003), for economical reasons, in support of photogrammetric and LIDAR airborne surveys, and to be able to better take advantage of the SCIGN and CSRC infrastructure.
The first effort was the Orange County Real Time Network (OCRTN), a collaboration of Orange County, CSRC, and SCIGN. Next, USGS Menlo Park, SCIGN, and UC Berkeley collaborated to upgrade 14 BARD and SCIGN sites in the Parkfield area (*Langbein and Bock*, 2004) – these sites are part of the PBO Nucleus. Countywide efforts are currently underway by SCIGN in San Diego, Riverside, Imperial Counties, and Los Angeles Counties. UCSD, San Diego County's Department of Public Works and Sheriff's Department are working with PBO engineers on real-time high-rate prototypes for the PBO project at several new sites in San Diego County. The UCSD effort is partially funded by a NASA SENH grant to develop an Integrated Real-Time GPS/Seismic System and deploy it in Orange and Western Riverside Counties, spanning three major strike-slip faults in southern California (San Andreas, San Jacinto, and Elsinore) and significant populations and civilian infrastructure.

SCIGN's goal is to upgrade the entire network to high-rate (1 Hz or less) tracking and real-time (< 1 sec latency) streaming, as feasible, in collaboration with its partners at CSRC, counties, local and state government, and other agencies, and to facilitate and support the same approach for PBO stations in the region. Not only do these efforts enhance our science objectives and provide significant education and outreach opportunities, but also they directly contribute to the longevity of the scientific networks (including PBO) by generating significant financial resources from "non-scientific" users. The resources and commitments leveraged by SCIGN to date through various awards and partnerships (~$2M) are shown in Table 2.

3. Results of Prior NSF Support

The 209 GPS stations of the proposed PBO Nucleus network are currently supported by the "Support for Existing Western U.S. GPS Networks" NSF EAR grant through February, 2005. Operations, maintenance, and data handling are primarily the responsibility of six independent network operators, funded via subawards; equipment purchases, oversight, and planning of the future of the network were coordinated by the UNAVCO facility. In addition to data acquisition, archiving, and analysis during this period, a great deal of additional progress has been made in laying the foundation for the transition of these independently operated networks into a single, coherent entity suitable for integration into PBO in the not-to-distant future.

The six networks included in the PBO Nucleus: the Alaska Deformation Array (AKDA), the Bay Area Region Deformation array (BARD), the Basin and Range Geodetic Network (BARGEN), the Eastern Basin and Range and Yellowstone network (EBRY), the Pacific

Northwest Geodetic Array (PANGA), and the Southern California Integrated Geodetic Network (SCIGN), included a total of 432 GPS stations. The PBO O&M budget plans for the operation phase of PBO beginning in 2008 contains support for approximately half of these. Consequently, the identification of the 209 stations to be funded by this support was a top priority. The selection process, coordinated by the UNAVCO Existing Networks Engineer, PBO management, and network operators, involved a detailed review of the characteristics of each station, including monument stability, maintenance history, geographic relationship to PBO new construction and scientific objectives. An effort was made to minimize the budgetary impact of adding modern IP-based communication to the many existing stations that were not designed with this consideration in mind. Opportunities for other funding (e.g. USGS, DoE, local surveying agencies) of the stations not included in the Nucleus were identified so that these sites will continue to operate in parallel for the foreseeable future, and efforts will be made to integrate as much of their data as possible into PBO by separate agreement. The resulting 209 sites (please see http://www.unavco.org/exnet/exnet.html for station details) form a network that can be economically operated, maintained, and upgraded in order to be integrated into EarthScope in 2008, allowing the inclusion of their long time series into PBO's data analysis, and thus, optimizing the scientific potential of the EarthScope project.

The process of upgrading the existing networks is also well underway. By the end of the current funding period 40 of the 209 stations will have been upgraded with Trimble NetRS receivers, IP-based communications, and improved power systems as necessary, funded by the current Western Networks NSF grant and coordinated by the UNAVCO facility. Although funding was requested to upgrade only 17 stations during this past period, reductions in equipment and communications costs have allowed a much better return on the current budget.

Data flow from the Nucleus stations has also been addressed, and intermediate steps to transition data management from the previously independent, network-specific procedure to EarthScope have been taken. Data wholesaling for all stations in the Nucleus network has been established at one of the two designated PBO archives: the SOPAC archive for the 111 stations that are currently part of the SCIGN network, and the UNAVCO facility for the remainder. This will permit a smooth transition to complete integration of the data into the PBO data products stream early in the proposed funding period, optimizing the early performance of PBO. It also allows centralized monitoring of overall network performance and coordination and planning of maintenance and upgrades, increasing the overall efficiency of the project (for example see http://archive.unavco.org/~dmagu/Reports/today_existing.rpt for current network status). Metadata for all stations have been verified and updated in the archive databases, further easing the proposed integration of the data stream into PBO early in the upcoming funding period.

Finally, many scientific publications have resulted from the data produced by the six Existing Networks. These have been produced by analyses done both by the network operators and by outside investigators. A comprehensive list of these publications is available on UNAVCO's PBO Nucleus web site (http://www.unavco.org/exnet/exnet.html). This bibliography clearly demonstrates the importance of the Nucleus network to the scientific community and its continued operation for the indefinite future.

4. Proposed Work

We propose to expand and enhance the EarthScope PBO network by integrating existing GPS stations and strainmeters in the western US into PBO operations starting in 2005. We call this network the PBO Nucleus. In 2005 we will integrate the data flow from these stations into the PBO data management system. During the period of this proposal we will upgrade to PBO standards, those 169 Nucleus stations, which were not addressed during the current funding period.

209 GPS sites are included in the PBO Nucleus. These sites were selected from existing stations by the PBO Nucleus Steering Committee (Section 2.2) and reviewed and approved by PBO Siting Working Groups. The complete list of included stations can be found on the UNAVCO web site: http://www.unavco.org/exnet/exnet.html. By September 2008 all stations supported here will be fully integrated into PBO, with the station performance, hardware, communications, and data flow conforming to PBO standards. We note that the EarthScope MREFC (Major Research Equipment Facility Construction) budget cannot include funding for any existing stations, and the EarthScope O&M (Operation and Maintenance) budget does not include funding for the Nucleus stations until October, 2008, so this proposal requests support from March 2005 (when the current funding ends), through September 2008, after which operations will be done as part of EarthScope. During the period of this proposal, the project will be managed by the UNAVCO Facility in Boulder, Colorado under the supervision of the Western U. S. Network Project Manager, who is responsible for all aspects of it; we are requesting full support for this position. Additional field engineer support will be provided through the UNAVCO Facility's NSF Core funding at no cost to this project.

4.1 Operations & Maintenance

To run a permanent GPS station we need support for power, data communications, replacement of failed equipment, and the personnel who monitor performance and make repairs when needed. Our O&M budget also includes the costs of equipment upgrades, since these will be done by the UNAVCO facility, usually at times when equipment failures necessitate repairs. We are requesting support to operate and maintain all but 5 of the 209 GPS stations. These 5 will be operated and maintained by the BARGEN network operators with Department of Energy funds; we ask only for equipment upgrade costs.

The current Existing Networks grant supports operations and maintenance through subawards to individual network operators from UNAVCO, Inc., with oversight and coordination of the project by the UNAVCO Western U.S. Networks Project Manager. This is necessary because of the variations in types of equipment and communications currently in use; this inhomogeneity of the networks has meant that only the local network operator is familiar with the system, so that each network has had personnel to monitor the data and perform repairs. Initially, we will continue this style of O&M support for stations in the BARD, PANGA, and SCIGN networks not yet upgraded to PBO standards. As stations are upgraded, the UNAVCO facility will become responsible for all aspects of the station O&M. Subaward levels thus decline over funding period, according to the number of upgrades that have been done (Table 3). However, communications and power costs for all sites (upgraded or not) will be paid directly by UNAVCO (except for BARGEN as noted above). O&M for all stations now within the AKDA and EBRY, and BARGEN networks will be covered directly by the UNAVCO facility, using facility personnel, from the beginning of the funding period. A small sub-award will support ongoing communication and permitting costs associated with the BARGEN sites.

Institution	Existing Network	Number of Stations in Nucleus	Network P.I.
Univ. of California, Berkeley	BARD (N. Ca.)	12 (2 upgraded before 3/2005)	Barbara Romanowicz
California Inst. of Technology	BARGEN (Basin and Range, S. Ca.)	26 (6 upgraded before 3/2005), O&M for 5 paid by DoE.	Brian Wernicke
Univ. of Utah	EBRY (Rocky Mtn., Basin and Range)	16 (6 upgraded before 3/2005)	Robert Smith
Central Washington Univ.	PANGA (Pac. NW, N. Ca, Basin and Range)	26 (6 upgraded before 3/2005)	Tim Melbourne
Univ. of Southern California	SCIGN (S. Ca.), Parkfield (N. Ca.)	124 (15 upgraded before 3/2005)	Thomas Jordan
Univ. of California, San Diego	Glendale-Verdugo Laser Strainmeter	1	Duncan Agnew

Table 3. ***Institutions performing Operations and Maintenance of PBO Nucleus stations under sub-awards during the proposed funding period. Stations will be maintained by UNAVCO after upgrades have been performed. 5 Alaska stations will be upgraded prior to March, 2003.***

O&M will be performed by both UNAVCO and regional network personnel as outlined previously. If a problem appears, they will first attempt to remotely troubleshoot stations; after five days of data loss, a field visit will be scheduled if possible (seasonal weather may not allow this in Alaska and some mountain sites). When failures occur we intend to upgrade the station to PBO standards (NetRS receivers and IP based communications) rather than repair aging equipment; there are no longer spare parts available for the GPS receivers at many of the stations, and the radio telemetry and solar power systems have often exceeded their operating life. For efficiency we may defer repair visits until we can also upgrade nearby sites, though not if the delay would result in the loss of scientifically critical data.

The O&M budget includes one site visit per year for existing stations for preventive maintenance prior to upgrade, and then one visit every two years afterward, since the new equipment (next section) has features that allow fewer maintenance visits. Maintenance visits to stations may be conducted by PBO regional staff if they are available and nearby. New PBO stations are currently being installed in all of the regions containing Nucleus stations; a short visit by PBO personnel may require little or no extra resources from PBO. Similarly, UNAVCO facility staff and regional operators may also help with PBO maintenance or installation efforts when possible. Close coordination of Nucleus and PBO field activities is an integral part of the operations and maintenance plan.

As noted above in Section 1, the Nucleus network includes a long-base laser strainmeter at the northern edge of the Los Angeles basin, installed as part of the SCIGN network; see http://jacinto.ucsd.edu for more information. As with the other PBO Nucleus stations, the sole support of this instrument beyond Spring 2005 is this proposal. Operations and maintenance support for the Los Angeles strainmeter will be provided through a subaward to UC San Diego; there is no parallel to the upgrade of GPS equipment, so the amount of this subaward stays roughly constant. At the end of the proposed funding period, PBO will assume full responsibility for operation, maintenance, and data flow of this instrument.

4.2 Equipment Upgrades

We must standardize the network to meet our primary goal of integrating the Nucleus network into PBO. We can do this only by upgrading the current set of aging and obsolete receiver types and data communications systems to the PBO standard. We thus request support for the purchase and installation of NetRS receivers, choke ring antennas where necessary, and IP based communications equipment so that all GPS stations will conform to PBO standards by the end of the funding period. Note that the EarthScope O&M budget includes funds for these stations beginning in October, 2008, but does not include funds for hardware upgrades. 40 stations will have been upgraded using current funding prior to March, 2005. Funding for the remaining 182 upgrades is requested here. We will follow PBO in using CDMA modems or IP-based radio links to existing Internet connections, with satellite systems such as VSAT for remote areas. Where feasible we will take advantage of co-located NSN stations with USGS-sponsored satellite systems, and of similar arrangements with other agencies such as universities, or of communications infrastructure that will be installed by PBO during its construction. As detailed in the budget justification, roughly 45% of the Nucleus network will use cellular CDMA communications, 20% will use IP radios to existing Internet connections, and 30% will use existing IP connections, with no hardware upgrades needed. The remaining stations, which may require VSAT systems, will be upgraded as late as possible to take advantage of any improvements in the communications infrastructure in the next few years. All equipment purchased will be coordinated with PBO or UNAVCO community purchases to take advantage of quantity discounts. While all stations will require the purchase of a Trimble NetRS receiver, only 10% of the stations will require a choke-ring antenna, and only 5% will require a new monument. If antenna changes or remonumentation are needed, we will perform multi-antenna ties to solve for the phase center position shift imposed by these changes, and correct any effect on the time series of the station. We will prioritize upgrades in several ways. As noted above, any station that requires a site visit for some reason will be upgraded rather than repaired. Stations with existing communications that are expensive or inefficient will be given higher priority, as will stations that can be upgraded cheaply; those requiring re-monumentation or VSAT communications will be done last.

These upgrades will make available much aging but functional equipment: we estimate about 200 receivers, and 100 sets of communications gear, as well as many computers currently used for serial data downloads. Ownership of the upgraded equipment will remain with its current institution, but most of the equipment will be made available for loan to the research community by request to the UNAVCO Facility. This equipment could be used as permanent or temporary replacements for failed existing sites, particularly those not part of the PBO Nucleus network; as part of new GPS sites to be built using institutional funds of the current owners; or in campaigns by the geodetic community at large. If the replaced equipment is owned by UNAVCO, it will return to the UNAVCO pool for general use.

4.3 Data Management

We intend the PBO Nucleus to serve as the proving ground for PBO efforts to make the data stream and analysis scale-independent, and to provide automation of all stages of quality control, archiving, data analysis, and data products. Data from the PBO Nucleus stations will be some of the first data to be handled by the newly developed PBO data management system. As such, it will serve as a test case with the added advantage of receiving focused attention from scientists close to the data. As noted above, during the current funding period we are moving the data flow, archiving, and processing of the PBO Nucleus stations to the designated PBO archiving and processing centers, so that only a small additional effort will be required to completely integrate the data flow from these sites into the PBO archiving and data products plan. We will do this at the start of the funding period, so that by the end of

2005 there will be 209 GPS stations in addition to the new PBO sites constructed during this period from which to produce PBO data products, while the remaining PBO infrastructure is being built. All these sites have known high quality, past history, and connections to the PBO science goals.

EarthScope PBO management has agreed that the integration of Nucleus data into the PBO Data Management Plan should be achieved as soon as possible. We propose, during the first six months of the funding period, to change the data flow from one of the existing networks over to the PBO data flow model. We will proceed in order of network size, starting in March 2005 with the 5 sites now in AKDA, and then transferring the 16 sites now in EBRY, followed by those in BARGEN, PANGA, BARD, and finally SCIGN/Parkfield by September 2005. PBO will retrieve data from all stations with Trimble NetRS receivers and IP-based communications. For other stations, not yet upgraded, PBO will download raw and translated BINEX data from a central collection node located at the currently established archive for that network. All Nucleus data will flow to PBO Headquarters for quality checks before being distributed to the PBO GPS Analysis Centers for analysis and data product generation, and to the PBO GPS Archives for archiving and delivery to end users. Metadata will be stored and maintained from the PBO Operational Database (POD), the central storehouse for all PBO metadata. PBO staff will work with UNAVCO Facility and SOPAC to transfer metadata to the POD during the transitional period. The PBO Data Products Manager will have responsibility for all aspects of Nucleus data and data product management, including data flow, archiving, analysis, delivery to end users, and metadata storage and maintenance, and the PBO Data Management Plan will govern all Nucleus data and data products, including station metadata. Funding for data flow, archiving, analysis, and metadata storage and maintenance will flow through the most current PBO funding mechanisms, and the PBO Data Products Manager will have administrative authority and responsibility for these funds.

We are requesting funding for archiving and analysis of data from Nucleus sites at a rate of $250/site/year for archiving and $250/site/year for analysis. Archiving during the transition period for all but the SCIGN sites will be done by the UNAVCO facility archive under the facility's core support at no cost to this project; support for the archiving of SCIGN data for six months will be paid via sub-award under current levels to SOPAC. Additional processing of all of these stations will be required to carry out specific scientific investigations, to test or develop specialized processing techniques, to investigate transient phenomena, and to carry out other non-standard exploration of the data from these stations. This value-added processing will not be conducted as part of the proposed work, and support for it is not requested.

PBO plans to install five laser strainmeters and 143 borehole strainmeters, all of whose data will be archived at the PBO Strain/Seismic data archives, and will be processed by the PBO Laser Strain Analysis Center. Archiving and processing of the data from the Glendale-Verdugo Strainmeter (GVS) will be done through these PBO centers beginning in 2005, and will be supported by funds requested here at the same level and mechanism as for the GPS stations discussed above.

4.4 GPS Station Permitting

As with equipment, the permits for the PBO Nucleus stations are inhomogeneous in their terms, duration, and costs: something that needs to be corrected by the time PBO starts to administer the network in FY 2009. We propose to support the current network operators to review and (if needed) renegotiate all permits for Nucleus stations. Our aim is to have permits for as long as possible (ideally through 2017, the nominal life of EarthScope) with an absolute minimum of recurring costs. Realizing that elimination of recurring costs may require up-front outlays, we request $750 per site to support permitting fees. This effort will be coordinated by PBO permitting staff, with 10% FTE support requested.

4.5 Education and Outreach

EarthScope's scientific programs will generate a large amount of scientific data. Science education specialists have recognized that students need to be given the opportunity to collect, manipulate, analyze, interpret, and report data in order to understand what science is and how it is done. "Whether taking students in the field, running experiments in the lab or using the latest technological tools to examine data sets, engaging students with data is a powerful way to teach both the content and methods of science" (SERC, 2004; Manduca and Mogk 2003; Lukes. 2004).

Student involvement in real data collection can and will be part of EarthScope, and EarthScope is developing ways in which middle and high school students, undergraduates, and even the public can collect data which might become part of the EarthScope database (EarthScope, 2002). The PBO Nucleus Network will generate a large quantity of data that, when integrated with PBO, USArray and SAFOD, will have a large role in accomplishing the EarthScope Education and Outreach Goals. We request support here for a dedicated E and O program that will make use of the PBO Nucleus network and its scientists in achieving these ends.

4.5.1 Goals

In collaboration with EarthScope E and O, this project will increase awareness of geodetic research and its role in understanding Earth processes. A second goal is to create resources for education and outreach that provide access to cutting edge EarthScope research and that are based on sound educational theory, research, and practice including students' collecting and/or using authentic data. Evaluation of the processes and products according to professional standards will ensure a high quality program and will ensure that resources will be widely disseminated.

4.5.2 Program Plan

To achieve our goals, the program will produce a minimum of one module for Earth Science classrooms (8^{th}/ 9^{th} grades), one module for undergraduate general education, and one module for geophysics majors. These modules will integrate geodetic research results related to the PBO Nucleus Network. Aside from these new educational resources, we will collaborate with curriculum developers in other organizations to incorporate and integrate geodetic research into existing resources (e.g. Electronic Encyclopedia of Earthquakes, IRIS workshops, and DLESE Teacher Pilot products).

The original modules will be written and designed by a team of scientists, UNAVCO staff, and teachers of appropriate level with input from other potential users and then tested in a series of teacher workshops at secondary and undergraduate levels. We will develop an interactive website utilizing resources for collaborative work such as a wiki (a collaborative web site comprised of the perpetual collective work of many authors) and other web services and organize 6 regional and 3 national workshops for developers and users, to both build a network of scientists and educators dedicated to improving geoscience education and to help teachers use PBO Nucleus results in the classroom. Posters, brochures, and curricular materials demonstrating how PBO Nucleus data can be used in educational settings will be created for workshops and regional and national meetings of NSTA, GSA, AGU and other undetermined opportunities. All of the above activities will follow sound pedagogical practice based on research (Kastens, et al., in press; Manduca et al, 2004, 2003; NRC, 2000; Barstow et al, 2001). We will ensure that teachers and faculty from underserved populations and those who teach in institutions who serve underrepresented populations will participate in curriculum development.

The project will be managed by Dr. Susan C. Eriksson, UNAVCO Education and Outreach Coordinator who will dedicate 25% of her time to this project at no cost. We are requesting support for a full time assistant to work with Dr. Eriksson and travel support for an advisory committee (2 research scientists, 2 undergraduate faculty, 2-4 secondary teachers) to oversee the implementation of the E and O effort.

***Table 4.* Timeline for PBO Nucleus Education and Outreach**

Task	Year 1	Year 2	Year 3	Year 4
Establish Advisory Committee	x			
Advertise and Hire Project Personnel	x			
Establish detailed Evaluation Plan	x			
Design, build and maintain Project Website	x	x	x	x
Identify Module Developers	x	x	x	
Identify Summer Workshop Participants	x	x	x	
Plan and Implement Workshops	x	x	x	
Publications				
Poster		x		
Brochure		x		
Curricular Materials		x	x	x

4.5.3 Evaluation

We propose to evaluate the outcomes and impacts of this E and O component on teachers, faculty as teachers and researcher, and students using both qualitative and quantitative measure in the context of a logic model (NSF, 2002, 1997; Taylor-Powell et al, 1996; Weiss, 1994).

Inputs	**Processes**	**Outputs**	**Outcomes/Impacts**
Teachers Faculty Project Structure Project Personnel	Curriculum Development Network Infrastructure Workshop design and implementation	# Teachers and Faculty Education Modules Workshops delivered Degree of communication and collaboration	For teachers For faculty For students

***Table 5.* Education and Outreach evaluation process.**

The study will be conducted according to the Joint Committee Standards on Program Evaluation (1994). Dr. Eriksson has already worked with a consultant to design a detailed evaluation plan and will work with a graduate student at the University of Colorado to conduct external evaluation where needed. Teachers and faculty will help collect evaluation data on their students. Results will be used in both a formative and summative way.

4.5.4 Dissemination

Regional and National workshops are both the product and a short-term means of dissemination. The educational modules will be submitted to DLESE and to a smaller themed collection on geodesy within the Electronic Encyclopedia of Earthquakes (under development SCEC and others) as part of the National Science Digital Library and DLESE. UNAVCO will build and maintain an educational website in support of this work. We will publish the results of this project in the peer-reviewed Journal of Geoscience Education.

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F. BUDGET JUSTIFICATION

The project is designed to fully integrate 209 existing GPS stations into PBO by September 2008, meaning that the station performance, communication specs, and data flow will conform to the standards established for newly constructed PBO sites. These stations are currently supported by NSF-EAR grant 0318549: Support for Existing Western U.S. GPS Networks through February, 2005. Funding requested here will allow the continued flow of data from these tectonically strategic GPS stations and the Glendale Laser Strainmeter.

EarthScope funding comes from two sources. The construction of the EarthScope Facility (PBO, USArray and SAFOD) is funded from the Major Research and Equipment Facility Construction (MREFC) account at NSF. This funding is specifically for new facilities and cannot be used to maintain and operate stations, existing or new. Funding for operation and maintenance of EarthScope has been requested from NSF. The first year of this funding, largely for USArray has already been received. Funding for operation and maintenance of these existing stations is included in the budgeting for PBO beginning in 2008. By direction from NSF, the funding for operation and maintenance of these existing stations until 2008 is being requested through a separate proposal, this proposal. As the PBO budget does not include funding for operations, maintenance, or data handling for these stations until 2008, funding to cover these expenses is requested here. The proposal requests support for the 3 year, 7 month period beginning March 1, 2005, when the current funding will expire.

The proposal requests support for the purchase and installation of hardware necessary to upgrade all of the sites in the network to PBO standards. 40 of these will have been upgraded under the current grant; funding to upgrade the remaining 169 is requested here.

Station maintenance, including upgrades, preventive maintenance visits, and troubleshooting, will be handled by a combination of UNAVCO staff and local operators with the primary goal of minimizing travel costs. The primary responsibility for maintaining an existing site in the California and Pacific Northwest regions will generally lie with a local operator until it is upgraded, at which point the primary responsibility will shift to UNAVCO. As the number of sites upgraded to PBO standards increases during the funding period, the need for local operations staff to handle equipment failures and data downloading will decrease, and the sub-award levels will be reduced accordingly. Sites in the Basin and Range, Rocky Mountain, and Alaska regions will be maintained primarily by UNAVCO throughout the proposed funding period. Stations in need of maintenance will be handled in a time frame dictated by the availability of requested staff and resources; this time frame is discussed below. At the end of the funding period, all operations and maintenance will then be taken over by PBO. Funds have been budgeted for this task as of Year 6 of the EarthScope project.

Subcontracts are included here for the six institutions shown in the table above for continued operations and maintenance of existing stations that have yet to be upgraded. Salary support is generally limited to network coordinators who will perform field maintenance, upgrades, and assist in the process of permit analysis and renegotiation as necessary, and field expenses are also included. Detailed justification discussions accompany each subcontract budget.

UNAVCO, Inc.

The UNAVCO Consortium is a member-governed, non-profit, organization whose mission is to support and promote Earth science by advancing high-precision geodetic and strain techniques such as the Global Positioning System (GPS). In this capacity, UNAVCO is providing the coordination and business management for this project on behalf of the university-based GPS research community. The UNAVCO President, Dr. William Prescott, will serve as Principal Investigator and will generally oversee the subcontracts, although no salary support is requested here. The UNAVCO Headquarters in Boulder, CO will serve as the business center for the project grants administration, task coordination, subcontracting to participating institutions, equipment purchases, and providing salary and other support for participating UNAVCO Facility staff. UNAVCO is currently operating under a low (<10%) indirect cost structure, which allows the centralization of spending in this project to result in large savings over the current award structure, which supported independent network operations primarily through heavily burdened subcontracts.

Personnel and Salaries: The UNAVCO Western U.S. Network Project Manager, Dr. Frederick Blume, will have primary responsibility for all operational and budgetary aspects of the project, and will interface with regional network operators; 100% salary support is requested here for Dr. Blume. He will also be performing as much of the field maintenance and upgrades as possible, and design and coordinate communications upgrades in collaboration with PBO and subcontractor regional staff.

The Education and Outreach component of the project will be managed by the UNAVCO E&O Coordinator Dr. Susan Eriksson, 25% of whose time will be dedicated to this effort at no cost. Salary support is requested to hire a full-time Education and Outreach assistant who will carry out the detailed implementation as described in the project description.

Coordination of the standardization of station permits will be performed by PBO Permitting staff under the direction of PBO Permit Coordinator Kyle Bohnenstiehl; salary support at 10% FTE level is requested here to fund this effort.

Substantial additional UNAVCO personnel support and resources will be available to this project at no cost. Field engineer support for maintenance and upgrades will be provided by the UNAVCO Facility, through its NSF core funding. PBO regional field staff will perform maintenance and upgrades when their availability permits, when requested through the PBO Operations Manager. The UNAVCO Facility's Data Management and Archiving Group will perform wholesaling for most of the Nucleus sites during the early part of the project at no cost, and will continue to provide PBO with BINEX translations of data files as necessary throughout. Equipment development, testing, and configuration expertise will be available from the UNAVCO Facility and PBO engineering groups. Shipping and inventory support for equipment purchased here will be provided by the UNAVCO Equipment and Purchasing groups.

Upgrade Hardware: 40 of the 209 PBO Nucleus stations will have been upgraded to PBO specifications, using funds from the current grant, by March, 2005; hardware for 169 will be purchased by this project. 169 Trimble NetRS receivers is included in this proposal The receiver price of $3,600 is based on the community pricing of a NetRS/Zephyr purchased in quantities of 50 or more, so purchases will be coordinated in order to receive the lowest price. Only 15 of the Nucleus stations will require new choke ring antennas to replace other existing varieties, and 22 have already been purchased. Given the historically low failure rate of these antennas, we do not request funding here for further choke ring purchases. As Trimble will not sell NetRS receivers without antennas at a lower price, we will be purchasing them as a set, and surplus Zephyr antennas will be integrated into the UNAVCO Facility equipment pool. As the value of the receiver/antenna installations after upgrades will be greater than $5,000, they will be considered major equipment and exempted from overhead.

IP capable data communications hardware will be required as follows:

- 45% (76) of the stations will use CDMA modems @ $795

- 20% (34) of the stations will require ethernet radios @ $2,200/pair
- 20% (34) of the stations will require VSAT systems @ $1,700

The remainder of the network will use existing IP communications or make use of future PBO installations and will not require any hardware purchases. A primary goal of the project will be to make optimum use of no-cost opportunities, and to delay installation of satellite systems in the expectation that increased CDMA coverage, PBO constructions, or other developments can allow us to use cheaper means to upgrade the remote sites; the budget does not reflect this.

Ancillary equipment (batteries, solar panels, enclosures, etc.) for replacement or upgrade of existing equipment is budgeted at $1,000 per site, which should be adequate to ensure proper functioning of each site for the duration of the project.

Data Communications: Communications costs for 217 sites (5 of the sites will be paid for by BARGEN Dept. of Energy funding) are calculated by network wide averages of costs before and after an IP upgrade. The pre-upgrade cost (utilizing telephones for dial-up serial communications) is $325/site/year, and the post-upgrade cost (based on $900/year for CDMA service at 45% of the stations and $760/year for VSAT at 20%) is $550/site/year. For each year the number of existing sites will decrease as they are upgraded, and costs will increase correspondingly. The increased cost in upgrading from a variety of serial communications to the IP methods we will use will be offset by a savings in time and travel expenses necessary to maintain the cheaper but historically failure-prone dial-ups and serial radios.

Field Travel Expenses: As outlined in the operations plan, the UNAVCO facility will be responsible for field maintenance of sites that have been upgraded network wide, and all sites currently in the AKDA, BARGEN, and EBRY networks. The upgrades will be performed by the UNAVCO facility, and regional network technicians whose costs will be covered by subawards. Expenses are requested here to cover two annual maintenance trips per station prior to an upgrade, and one per year afterward, as we expect the new equipment to fail much less frequently than the aging existing equipment. The expense budget has been calculated assuming that multiple site visits and upgrades will be performed by UNAVCO Boulder personnel on a single trip, which may require a delay in response time when a single station fails.

Data Management: The PBO budget includes charges of $250/site/year to handle the data flow from their newly constructed sites, and a similar charge will be applied to the 209 GPS sites of the PBO Nucleus network. As PBO's involvement in year 1 is transitional, the charge is reflected accordingly. The sites currently in the SCIGN network will be archived under subaward support for six months, while the others will be archived by the UNAVCO facility under its core funding.

Permitting Fees: We request funds for one time station permit fees to be paid as necessary during the funding period in the amount of $750/station when existing permits are renegotiated. PBO has no funding to cover recurring permit costs once these sites are integrated in 2008.

Education And Outreach: An important component of the education and outreach component of this project is the development of curricular materials that will be disseminated, in part, through workshops at regional and national meetings. We are requesting annual funding for a $1500 summer stipend and $500 academic year honorarium for one Master Teacher of Earth Science and one undergraduate faculty member to develop educational modules. These will then be tested by a group of teachers and faculty in their own classrooms. Travel support and a small stipend are included in the participant support request for two workshops in Years 2-4. We have included travel to two professional meetings each year for project personnel and $3000 each year for publication costs.

California Institute of Technology

The Caltech subaward portion of this budget is ear-marked to cover three specific aspects of the BARGEN network operations over the next four years. First, the Caltech network coordinator will interface with UNAVCO, Inc. on a regular basis, and will participate fully in the process of selecting the order and priority of BARGEN site upgrades to PBO specifications. Such selections will be based both on technical considerations, as provided by UNAVCO, as well as considerations regarding data continuity, ongoing scientific interests, and existing lease conditions, all of which will be provided by Caltech. We anticipate this coordination will take one month of time in year one of this award, decreasing to three weeks in year two and two weeks in year three. No time is expected to be allotted to this task in year four.

Second, upgrade of BARGEN sites to PBO specifications will generally result in significant alterations to site communication links, with radio telemetry systems replaced by either cellular modem systems or satellite Ethernet links. These alterations will require permit amendments to be requested for all sites on public land, and right-of-way relinquishments or lease terminations for all telemetry relay sites that become obsolete as part of this upgrade. Additionally, PBO specifications require that all sites have unencumbered leases or right-of-ways through the year 2017. We expect that amending, canceling, and renewing site permits will take one month of time in year one, three weeks in year two, and two weeks each in years three and four. Finally, the BARGEN network will have ongoing operational costs until it is completely folded into PBO in 2008. These costs included existing payments on negotiated private leases and public right-of-ways, as well as site communications fees for data retrieval. Lease fees are largely constant through 2008, since the majority of the BARGEN leases are negotiated through that time. Site communication fees are anticipated to decrease through time as PBO upgrades and incorporates BARGEN sites.

Central Washington University

Salaries: The PANGA PI, Timothy Melbourne, will participate at no cost to the project. Salary for the PANGA GPS Networks Engineer (A. Miner) is included at 100% FTE in year 1 and 50% FTE in years 2 and 3. He will continue to ensure data flow and maintain the sites prior to upgrade, and will assist in the installation of new equipment. He will track all meta-data changes until a site is upgraded.

Travel: Visits for site maintenance are conducted, on average, once per year per site, with travel distances averaging 300 miles. The number of stations maintained by this subaward will decrease from year to year as upgrades are performed, and travel costs decrease accordingly.

University of California, Berkeley

Salaries: Support for PI Barbara Romanowicz is contributed at no cost to this project. The Junior Development Engineer will perform field maintenance, and assist in the process of permit analysis and renegotiation as necessary and in the upgrades of the sites to integrate them into the PBO network. He is part of staff of several other engineers and technical staff whose support is contributed at no cost to this project. Salaries are based on current levels with projected annual increases of 3.5% effective Oct. 1 for technical staff (Jr. Devel. Eng.). Benefit rates are based on current levels.

Supplies and Expenses: Supplies are for shipping, site repairs, battery, radio and other telemetry replacement, and other miscellaneous expenses. These costs will decrease as sites are upgraded and become part of the PBO network maintained by UNAVCO. We request support for 10 sites in year 1, six sites in year 2, four sites in year 3, and zero sites during the final 6 months of the budget period. Permitting analysis and renegotiation assumes 4 sites per year at $300/site.

Travel: Visits for site maintenance are conducted, on average, once per year per site, with travel distances averaging 250 miles. All sites are easily accessible by automobile except for a few Sierran sites during the winter months.

University of California, San Diego

The operation and maintenance budget for the longbase strainmeter reflects our best estimates for the average costs associated with running a single instrument in one location, with that location in the unusual environment of a freeway margin. The bulk of the cost is salaries of the expert personnel who monitor the instrument, make decisions on dealing with apparent problems (Wyatt), and perform the repairs (Bralla). We have also included salaries for personnel to deal with the tasks (routine but nonstandard within PBO) of data handling and editing, to provide data for the PBO strain data archive and strain processing center, and to cover other tasks such as ordering supplies and tracking costs.

Power for the site is provided by the Glendale Department of Water and Power; the current load (1100 W, mostly for the air conditioners) currently runs about $200 per month. We have budgeted for replacement supplies used each year, and also the annualized cost (depreciation) for replacing the more expensive items that have multi-year lifetimes.

Travel includes four regular trips each year, with four more allocated for dealing with repairs and emergencies (for example, site floodingó which has occurred in the past).

ìOther costsî mostly covers site communications currently done using a dedicated PC and a point-to-point radio link to Glendale Community College. These costs are dominated by the network charges assessed locally for UCSD and IGPP computer support.

University of Southern California

SCIGN requests 50% support for network coordinator, Keith Stark, during the transition process to PBO maintenance. Keith monitors the status of the stations and the telemetry, keeps track of the download and determines the cause of any problems at stations or telemetry hubs. He monitors processing results to detect problems with receivers or antennas, schedules preventive maintenance and any necessary repairs, swaps, or upgrades, and supervises the field personnel who perform them. He also keeps track of the status of station permits, renewing them as necessary. He also handles any problems that arise with landowners, including power, communications, vandalism, and any site modifications.

Dain Delis (75% time during the transition) works under the day-to-day supervision of Keith Stark. He performs preventive maintenance and helps repair or upgrade stations as necessary.

We will also hire a part-time coordinator to assist with the transition of permits from SCIGN control to UNAVCO/PBO control.

Our only other costs are routine maintenance of the field stations, decreasing over time as PBO assumes future maintenance.

SOPAC Subcontract Budget Justification (PI: Yehuda Bock)

As outlined in the proposal, SOPAC will archive SCIGN data for the first 6 months of the project, after which the data will be archived by PBO.

SOPAC currently maintains for SCIGN, 73 stations in Imperial (7), Orange (11), Riverside (32), and San Diego (6) Counties, San Clemente Island (1), Santa Catalina Island (1), Northern Baja California (2) and Parkfield (13). Half of these stations (37) are part of this proposal, and will transition from SCIGN to PBO by year three. These stations have been or will be upgraded by SOPAC (for SCIGN) to high-rate (1 Hz) real-time (less than 1 s latency) operations. SOPAC will continue to maintain these stations during the transition period, and work with PBO to ensure that high-rate, real-time capabilities (including access to the communications backbone) are properly transferred.

The maintenance budget includes salary for John Unwin (3, 3, 1.5 months), travel to stations, and supplies.

University of Utah

Salaries: The University of Utah PI, Robert B. Smith, will participate at no cost to the project. Salary for the University of Utah GPS Engineer (D. Drobeck) and a student assistant is included at partial support that decreases with the period of the grant as budgeted. The engineer will continue to assist with advising PBO with GPS site permitting, advising on development of field recording and telemetry systems, site selection, assist with maintenance of PBO sites that are near or co-located with University of Utah seismograph station sites and telemetry links, ensure data flow, and maintain the sites prior to upgrade and change over to PBO. He will track changes until a sites are upgraded and/or installed. The student support is needed to assist the engineer on fieldwork for logistical assistance, assist with data support for insuring data quality, etc.

Travel: Travel for site and telemetry-relay permitting and related maintenance will be conducted as needed on average, once or twice year per site, with travel distances averaging 1000 miles or more per trip. Travel may involve backcountry sites with helicopter access as required. Travel for station support, permitting, etc. will decrease throughout the grant period as budgeted.