Collaborative Proposal for Research Applications
of Existing Western US GPS Networks


Submitted by:
William Prescott, President, UNAVCO, Inc.

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Project Summary

The large-scale, instantaneous velocity field of the Earth's surface is one of the main predictions of physical models of plate boundary tectonic processes. Continuously operating Global Positioning System (CGPS) networks offer unparalleled resolution for investigating these processes. NSF has invested in GPS stations throughout the western United States as parts of regional networks in Alaska, the Pacific Northwest, northern California, southern California, the Basin and Range, and in the eastern Basin and Range/Yellowstone areas. The investment to date of some $25M in equipment, monuments, and scientific discovery by the Earth science community, foundations, and federal and state funding agencies has created both the technical and intellectual basis for the proposed Plate Boundary Observatory (PBO), a major component of NSF’s EarthScope MREFC Project. Building on the experience and scientific success of these prototype networks, the geodetic community has proposed building a much more ambitious network in the western United States, including GPS and borehole and laser strainmeters.

This proposal seeks bridge funding for existing CGPS networks and one laser strainmeter in the western U.S. until EarthScope construction is complete and the networks can be assimilated into the maintenance and operations phase of the Plate Boundary Observatory. The existing networks were built in the late 1990s by individual consortia of investigators to accomplish targeted regional scientific goals. The current operation of the networks continues to realize exciting scientific returns in the pre-EarthScope era. On the grounds of their geographic distribution and the quality of both signal and data, the community has selected a subset of 255 stations from the 470 stations in the regional arrays as the core upon which to build PBO.

We propose to continue observations at these 255 stations during construction of PBO, preparing them for complete integration into the PBO network. The existing stations will contribute uniquely to PBO by adding an additional decade of observations, doubling the length of time series of core PBO stations over the anticipated life of EarthScope. The temporal dimension of this resource will lead the way in meeting technical objectives of PBO instrumentation that are critical to realizing PBO science goals by optimizing characterization of time transient events, vertical deformation histories and sources of error. This temporal control is an irreplaceable component of EarthScope instrumentation.

The NSF merit review criteria include 1) intellectual merit of the proposed activity; and 2) its broader impacts. Integration of these networks responds to clear scientific needs by contributing to a deeper understanding of the plate boundary in western North America, including earthquake and volcanic processes, and by providing an essential nucleus of stations on which to leverage PBO. There are manifold broader impacts. This core network will be a major contributor to earthquake hazards research and mitigation. The geodetic community has made great progress in sharing data, tools and results. The RINEX GPS data format, the open data policy for continuous stations, the various editions of the International Terrestrial Reference Frame, and the widespread use of common processing software (e.g., GIPSY, GAMIT, and Bernese) are all results of this effective cooperation. Merging these once disparate networks into PBO will greatly improve tools for making this data available to the community in a more standardized format, thereby making it accessible to the large education and outreach community that is developing around EarthScope.
# Project Description

## Table of Contents

1.0 Overview .................................................................................................................. C-1

1.1 Relationship to EarthScope..................................................................................... C-2

1.2 Contribution of the Regional Networks to EarthScope Science Goals .......... C-2

1.3 Integrating These Regional Networks into EarthScope ........................................ C-4

1.4 Structure of the proposal ......................................................................................... C-4

2.0 Results of Prior NSF Support .................................................................................. C-5

2.1 Introduction .............................................................................................................. C-5

2.2 Southern California (SCIGN) ................................................................................ C-6

2.3 Northern California (BARD) .................................................................................. C-11

2.4 Basin and Range (BARGEN) .................................................................................. C-12

2.5 Eastern Basin and Range-Yellowstone (EBRY) ..................................................... C-14

2.6 Pacific Northwest (PANGA) .................................................................................. C-16

2.7 Alaska (AKDA) ....................................................................................................... C-17

3.0 Existing GPS Infrastructure as Nucleus of EarthScope ......................................... C-18

3.1 Regional Summary ................................................................................................. C-19

3.2 Southern California ............................................................................................... C-21

3.3 Northern California ............................................................................................... C-21

3.4 Basin and Range .................................................................................................... C-21

3.5 Eastern Basin and Range-Yellowstone Hotspot ................................................... C-21

3.6 Pacific Northwest ................................................................................................. C-22

3.7 Alaska ..................................................................................................................... C-22

4.0 Proposed Integration into EarthScope .................................................................... C-22

4.1 Data Flow, Maintenance and Operations ............................................................. C-23

4.2 Standardization of Quality Control, Archive Structure and Products formats ..... C-24

4.3 Integration of Existing Networks into EarthScope Operations and Maintenance C-25

5.0 Management Plan .................................................................................................. C-26

5.1 Management Responsibilities of UNAVCO, Inc..................................................... C-26

5.2 Role of UNAVCO Facility ..................................................................................... C-26

5.3 Role of Regional Investigators ............................................................................. C-27

5.4 Equipment Replacement ....................................................................................... C-27

5.5 Education and Outreach......................................................................................... C-28
Project Description

1.0 Overview

Through UNAVCO, Inc., the geodetic research community seeks support to integrate existing regional continuously operating GPS networks in the western U.S. into the Plate Boundary Observatory (PBO) component of EarthScope. Continued operation of 255 proven GPS stations and a long-baseline laser strainmeter that form parts of six existing networks provide the core on which PBO will be built, yet funding for these networks is not available through EarthScope until the maintenance and operations phase some five years from now.

The EarthScope/PBO science goals are described in substantial depth in the PBO white paper, resulting from two national workshops in 1999 (Snowbird, Utah) and 2000 (Palm Springs, California). These goals present significant challenges for EarthScope instrumentation. Uninterrupted operation of the existing networks is urgent, because their history of observation represents the foundation upon which these challenges will be met. Continuity of geodetic time series up to and through EarthScope implementation will provide the strongest possible basis for predicting its ultimate capability, and for optimizing proposed strategies for site locations. The integration of these sites into EarthScope will occur when most sites in these networks will have a decade or more of continuous data. These data in particular will bear strongly on three fundamental — and still controversial — questions regarding the performance of instrumentation critical to EarthScope science goals, best addressed through the longest possible time series of continuous GPS data:

(1) **Transient detection.** Can we discern whether the crust deforms uniformly in space and time, or are there significant transient behaviors 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 would best discriminate among geophysical models of earth deformation?

(3) **Error sources.** 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?

As we describe below, exciting new research results relevant to these issues are already emerging from the existing networks. Interruption of the data stream, even for a period of a few months, would compromise the time series analysis of these sites, and their ultimate linkage with the results of EarthScope. Maintaining these sites will build scientific momentum during PBO implementation, allowing significant progress before it is fully deployed, at a small fraction (~10%) of the total cost of EarthScope.

We therefore seek to continue uninterrupted observations of a subset (about half) of existing sites within these networks. We will formally integrate these stations into EarthScope, creating a federation that builds on the current status of individual networks, working toward the ultimate goal of EarthScope standards for data coordination and integration. Planning for EarthScope has been predicated on the existence of these stations. Combining these networks to form the nucleus of EarthScope would thus leverage the investment to date of some $25 M by NSF and other agencies, foundations, and the university community.
1.1 Relationship to EarthScope

PBO is a planned geodetic observatory consisting of a carefully designed and integrated network of strainmeters, GPS stations and geologic observations, optimized to sample plate boundary deformation across a broad spectrum of frequencies. Taken together these instrument types span the broad temporal spectrum of plate boundary deformation and will image the deforming plate boundary region in the temporal three spatial and dimensions. PBO is part of a larger EarthScope proposal for a solid Earth geophysical observatory that will characterize continental structure, the plate boundary and the San Andreas fault at depth. Results from the networks included in this proposal have driven articulation of the scientific questions that PBO will address and have verified the extraordinary power of the continuous networks in revealing plate boundary deformation processes over a spectrum of frequencies. Observations are locally dense enough to investigate earthquake occurrence and nucleation questions within some of the networks, as well as magma transport and deformation preceding volcanic eruptions.

1.2 Contribution of the Regional Networks to PBO Science Goals

Table 1.1 lists the science goals described in detail in the PBO White Paper, and summarizes how each of the regional nets relates to these goals. The southern California Integrated GPS Network (SCIGN) has the largest number of stations of the regional networks in the western U.S. with over 250 stations concentrated in an area about 400 km by 400 km; this network has both broad regional coverage and densely spaced profiles across active faults. The SCIGN network spans the entire plate boundary from the borderlands offshore to the Eastern California shear zone on the east. Along the plate boundary, the network extends from the creeping section of the San Andreas fault, through the locked segment in the Transverse Ranges to the spreading center in the northern Gulf of California. Velocity determinations for this network provide strong constraints on the distribution of plate boundary deformation, and thus on models that investigate the forces driving the deformation. SCIGN data played a major role in understanding the 1999 Hector Mine event (Mw 7.1), the only significant earthquake occurring since installation of the network began. Geodetic data contributed to several generations of southern California hazard
maps and SCIGN data now dominate the crustal deformation map for southern California. The SCIGN project also includes a high-quality laser strainmeter in the densest part of the array where a single strain measurement would best compliment the many GPS instruments. The instrument provides much higher sensitivity by factors of 100 to 1000 at short periods (minutes to weeks) and provides the project with two independent technologies with periods from months to years.

In northern California, the Bay Area Regional Deformation (BARD) network contains a few broadly distributed GPS stations and three more densely covered areas: San Francisco Bay area faults, Parkfield, and Long Valley. These stations have been critical in investigating the motion of the Sierra Nevada–Great Valley plate relative to the Pacific plate. The stations are a primary constraint on the total San Andreas slip budget in this area, and velocities derived from them are being used in the next generation hazard estimates and a better understanding of earthquake processes. The San Francisco Bay area and Parkfield stations contribute to this goal. At the Long Valley caldera, Mammoth Lakes California, deformation measurements have played a key role in monitoring volcanic activity.

The Basin and Range Geodetic Network (BARGEN) is a relatively sparse, 50-site network spanning the diffusely deforming northern Basin and Range province of western North America, but includes a dense cluster of sites around Yucca Mountain, Nevada. Strain rates across the Basin and Range province are slow relative to those along the San Andreas fault system. The continuous data make the BARGEN sites critical for testing models of fault system behavior in diffusely deforming crust where fault slip rates are generally less than a millimeter per year, as is typical of most continental plate boundary zones.

The eastern Basin-Range and Yellowstone network (EBRY) is also a sparse network covering a large area of EarthScope/PBO. The network covers a 700 km-long transition zone extending along the boundary of the Basin-Range and the stable North American plate. Deformation rates range from mm/yr values in tectonic regimes to cm/yr scales in Yellowstone. A combination of continuous and campaign GPS measurements reveal the overall pattern of west to northwest intraplate extension accompanied by ongoing transient deformation following the 1959, M7.5 Hebgen Lake, Montana, earthquake, the largest historic earthquake in the Basin and Range. GPS and other geodetic measurements in Yellowstone have revealed pronounced time-dependent variations of the Yellowstone caldera.

The Pacific Northwest Geodetic Array (PANGA) is another sparse network of CGPS stations in Washington, Oregon, and northern California that partners with the Western Canada Deformation Array in southern British Columbia. The network was established to measure millimeter-scale crustal deformation along the Cascadia subduction zone with an emphasis on using GPS velocity determinations to measure the effects of interseismic strain accumulation above the Cascadia megathrust, characterize deformation within the North America plate as the result of the three-plate interaction, and observe deforming volcanic centers in the context of other elements of the convergent boundary system.

Finally, the Alaska Deformation Array (AKDA) represents a critical inroad in the task of observing the expansive, tectonically active remote landscape of the nation’s largest state. The nascent network was established to study crustal deformation in Alaska, for orbit tracking, marine navigation, and for general GPS base station use. GPS data obtained for the Central Alaska earthquake sequence (Mw6.7 and Mw7.9) of late 2002 will provide further insight into continental deformation and fault interaction, and the processing of these survey-mode data will be greatly facilitated by the continuing operations of AKDA continuously operating stations. The
newly installed continuously operating stations near these earthquakes should record any post-seismic transient deformations that will be directly relevant to EarthScope science goals.

1.3 Integrating the Regional Networks into EarthScope

This proposal seeks bridge funding to operate a subset of the existing networks in the western U.S. until PBO construction is complete and these stations are assimilated into a maintenance and operations phase of PBO/EarthScope. The existing networks were initiated by individual consortia of investigators to accomplish targeted regional scientific goals; the current operation of the networks continues to realize these goals in the pre-EarthScope era. The great investment in equipment, monuments, and scientific discovery by the community via these networks represents both the technical and intellectual basis for the proposed EarthScope. On the grounds of their geographic distribution and the quality of both signal and data, some 255 stations have been selected from the regional arrays that will form a nucleus of EarthScope. These stations further contribute to EarthScope through mature observation histories up to a decade in length, as well as characterization of time transient events and error spectra. This added temporal dimension can never be replaced by new instruments and stations in a decade-long project. Continued data flow from the regional networks will nearly double the length of time series of the core PBO stations over the anticipated life of EarthScope. This will allow the widest possible examination of the spectral character of earth deformation using geodesy. Furthermore, the PBO planning process has assumed that these stations will be a part of EarthScope. As one example, in Southern California, PBO plans to install 170 new stations compared to 261 in Northern California. The difference is in recognition of the large number of SCIGN stations already existing in Southern California that directly address the EarthScope science goals.

The regional networks have met and exceeded the initial expectations for scientific discovery, in particular the sub-millimeter accuracy in geodetic velocities and the apparent detection of a surprising array of transient behaviors that are a major step forward in unraveling tectonic and volcanic processes, as described in the next section. Both the operators of the networks and the geodetic community recognize the potential for even greater scientific gain through the federation of these networks. This proposal represents the first tangible step towards that federation which will ultimately lead to their full integration under EarthScope. Because of NSF rules governing the Major Research Equipment (MRE) account, during the first five years of EarthScope when the PBO will be deployed, no provision is possible within NSF for funding continuing operations from that account. As PBO moves into a maintenance and operations phase in year six, the integration of the regional arrays will occur, through EarthScope designation and full transition into EarthScope maintenance operations, data flow, and data analysis.

1.4 Structure of the proposal

In Section 2 of this proposal, scientific results from each of the six networks are summarized. Section 3 describes the existing infrastructure in each region, including the number of stations, method of operations, data handling and related issues. The remaining sections describe the proposed strategy and management structure necessary for integrating these networks into EarthScope.
2.0 Results of Prior NSF Support

2.1 Introduction

Continuously operating Global Positioning System (CGPS) stations have proven to be a powerful tool for investigating crustal deformation processes. We have built six networks that collectively comprise over 400 stations: in Alaska, the Pacific Northwest, northern California, southern California, the Basin and Range, and in the eastern Basin and Range/Yellowstone areas (Figure 2.0). Much of the success of this work accrues community-wide, including: (1) perhaps most obvious, the articulation of the PBO/EarthScope concept and the scientific discovery that supports it; (2) widespread adoption of a common, easily shared RINEX GPS data format, (3) freely distributed data available upon collection by each network, thereby delivering on UNAVCO’s open data policy; (4) continuous improvements to the International Terrestrial Reference Frame that are strengthened by stations among these networks; (5) the rigor gained from the redundancy achieved through widespread use of independent processing software packages (e.g., GIPSY, GAMIT, and Bernese); (6) development of robust and internally consistent realizations of the North America reference frame for geophysically meaningful results; (7) major advances in understanding the factors that contribute to formal uncertainties in GPS velocities; and (8) improvements to data analysis that dramatically reduce those uncertainties and resolve rich and statistically significant variations in the spatial and temporal patterns of deformation.

In addition to these benefits to both local and global tectonic geodesy efforts, our data are
widely used by researchers in other scientific and engineering disciplines. These include basic research of the troposphere and ionosphere, engineering applications (e.g. differential GPS and real-time monitoring of structures such as buildings, bridges and dams), and fundamental support to a broad range of land surveying activities in the respective regions of the networks. These results have required effective coordination between these once-disparate networks.

Some of the most interesting scientific discoveries from these networks have been the unexpected observation of transient phenomena with no straightforward connection to earthquakes, or to extant continuum theories of earth deformation. As one example, periodic slip events occur on the Cascadia megathrust that are too slow to radiate seismic energy [Dragert et al., 2001; Miller et al., 2002]. As another, some baselines across Holocene normal faults in the Basin and Range province have been shown to be actively shortening, rather than extending, indicating transient pulses of strain of opposite sign to the regional average [Wernicke et al., 2000]. As a third, transient phenomena have been clearly related to man-made effects such as ground-water pumping and recharge [Bawden et al., 2001]. The existence of these phenomena would not have been detected without the continuity and accuracy of CGPS time series. The summaries of results from each network, detailed below, are only a sampling of the literature of discovery that the nascent CGPS technology has already yielded from western U.S. networks.

2.2 Southern California

The Southern California Integrated GPS Network (SCIGN) is the largest of the existing CGPS networks in the western U.S. and includes over 255 stations. The overall tectonic environment is one of rapid northwest right-lateral shear on the San Andreas fault system, with less rapid, yet seismically very active, northeast-southwest shortening accommodated by conjugate sets of strike-slip faults and thrust faults (Figure 2.1).

![Figure 2.1. Crustal velocity field from SCIGN and precursor geodetic networks relative to a fixed North America reference frame (SCEC Crustal Motion Map, Preliminary Version 3). Southwesternmost sites are moving at about 5.0 cm/yr.](image-url)
Simultaneous operation of dip-slip and strike-slip faults affecting the same volume of crust is an enigmatic and fundamental aspect of plate boundary deformation, and has been a focus of early research involving the SCIGN network. Our approach has been to combine SCIGN geodetic with geological and other data in an attempt to develop a rigorous kinematic model of this fault system [Walls et al., 1998; Argus et al., 1999]. Early kinematic models for the Los Angeles metropolitan region have emphasized that most of the geodetically determined north-south shortening is accommodated on the principal thrust systems, such as the Sierra Madre, Elysian Park and Santa Monica faults, and had largely overlooked the role of strike-slip and oblique-slip faults (Figure 2.2). For example, high rates of slip (3.8–5.5 mm/yr, Dolan et al., 1995, Morton and Matti, 1987) have traditionally been inferred for the Sierra Madre-Cucamonga fault zone flanking the San Gabriel Mountains, in part because of the substantial relief in its hanging wall and magnitude of deformation in Quaternary sediments on the footwall. However, geological observations along the central portion of the fault do not support late Quaternary rates of slip of more than about 1 mm/yr [Rubin et al., 1998], suggesting a greater role for conjugate strike-slip faults in the region [Walls et al., 1998]. Analysis of some of the longest SCIGN time series across the Los Angeles region, which also take into account the anthropogenic effects of groundwater loading, indicate ~6 mm/yr shortening across the region, providing for the first time a strong basis for comparing the total slip budget across late Quaternary faults with the geodetic data (Figure 2.2) [Bawden et al., 2001; Argus et al., 2002].

**Fig. 2.2** Crustal velocities for the Los Angeles area with respect to the San Gabriel Mountains (Argus et al., 2002), accounting for strain associated with the San Andreas fault and anthropogenic effects [e.g., Bawden et al., 2001]. Faults are in blue, arrows showing strike-slip faults, teeth showing thrusts. Palos Verdes Peninsula (pvep) is moving northward towards the San Gabriel Mountains (SGM) at a rate of ~6 mm/yr.
Although debate continues over the relative importance of strike-slip and thrust deformation and their partitioning though time, continued improvements in both geodetic and geological information can be expected to lend a better understanding of the behavior of this complex system.

In addition to interseismic slip rate comparisons across different time spans, SCIGN data (and data from precursor networks) have played a key role in a large number of studies of major earthquakes in southern California (Figure 2.3), especially the 1999 $M_W$ 7.1 Hector Mine earthquake.

Combined with survey-mode GPS, InSAR images, and surface trace mapping, the high temporal resolution of SCIGN continuous time series for several sites were crucial for establishing the existence and magnitude of subtle post-seismic motion following the Hector Mine event (Figure 2.4).

These data have been the basis of numerous investigations into the basic physical processes
governing the earthquake cycle. For example, modeling the post-seismic response with a laterally homogeneous structure, Pollitz et al. [2001] challenged the traditional view of continental lithosphere having a weak lower crust between strong upper crust and upper mantle. Recently acquired vertical velocities from SCIGN data for the post-seismic interval (Figure 2.5) provide further constraints on the rheological properties of the deep crust and upper mantle. A pronounced change in vertical velocities was detected in the region southwest of the source, defining a strongly asymmetrical pattern in the post-seismic response, implying that the rheological structure is laterally heterogeneous.

Figure 2.5. Vertical velocities following the October 16, 1999 Hector Mine earthquake, estimated from SCIGN data (Nikolaidis, 2002). Pattern shows strong uplift in the quadrant southwest of the rupture, with very little vertical motion in the other three quadrants. Box indicates study area of Pollitz et al. (2001).

Agniew et al. [2002] used SCIGN data in several ways to constrain estimates of coseismic displacements for the Hector Mine event based primarily on survey mode data. They were able to include pre-event data because similar studies following the 1992 Landers earthquake provided dense station coverage close to the 1999 rupture zone. Austin and Miller [2002] used SCIGN data in recalculating the coseismic displacement fields of both the Landers and Hector Mine earthquakes. Their calculations took advantage of well-established 1993 to 1999 velocities. They suggested evidence of kinematic loading of the Hector Mine rupture plane that substantiates predictions from new viscoelastic models. Simons et al. [2002] used InSAR, survey mode and SCIGN GPS observations to model the slip distribution of the Hector Mine earthquake. They used interferometric decorrelation, phase, and azimuth offset measurements to indicate regions of surface and near-surface slip. The interferograms indicated significant along-strike variations in strain, consistent with ground-based observations. They also inverted the InSAR and GPS data to derive subsurface fault geometry and distribution of slip. A layered model predicted more slip at depth than did a half-space model. Maximum slip at depth was greater than 5 m at a depth of 3 to 6 km.

Hudnut et al. [2002a] reported statistically significant time variation in the postseismic velocities at sites near the Hector Mine event (Figure 2.4). The postseismic velocity field was similar to that of the pre-Landers velocity field but was laterally shifted eastward and locally
twice the rate. They speculated that a portion of the crust east of the Landers rupture has now been entrained in flow along with the Pacific Plate as a result of the Landers and Hector Mine earthquake sequences. Owen et al. [2002] observed a total of 55 survey-mode sites after the earthquake, using SCIGN stations to maintain a reference frame. Stations were at distances of a few meters to 100 km from the Hector Mine rupture. They calculated a simple afterslip model that showed observed velocities were consistent with deep afterslip located beneath the coseismic rupture area. Pollitz and Sacks [2002] used a viscoelastic model calibrated by geodetic data to calculate the postseismic relaxation following the Landers event. The postseismic relaxation produced a transient increase in Coulomb failure stress of 0.7 bars on the Hector Mine rupture surface. The increase was largest over the broad surface that includes the nucleation point and site of peak slip. They argued that viscoelastic relaxation likely contributed to triggering of the Hector Mine earthquake.

Because SCIGN's initial priority was to install the GPS stations, installation of the laser strainmeter only began at the start of 2001. Though SCIGN is continuing to tune the performance of the instrument, it is fully functional. Figure 2.6 shows the time series so far, excluding only the most recent and the earliest 'shakedown' period. It is too early to say much about the long-term strains from these data. Fitting a line to the corrected residual gives a rate of -0.35 microstrain per year, which has the anticipated sign (shortening) but is substantially larger than is expected from the local tectonics. However, the uncertainties to this point are considerable; given the local topography, there may be a large (and genuine) annual cycle in the strain. We can say that the instrument, and earth, are behaving in a manner similar to what has been observed at other sites and what strain variations there are, are subtle.

![Figure 2.6. Laser strainmeter record from SCIGN. Blue: the uncorrected strain between the two ends; Red - residual strain with tidal signal removed; Green: corrections from the optical anchors at the south and north ends; Pink: correction for changes in the vacuum; Bottom Blue and Red: fully-corrected strain and residual strain.](image-url)
Clearly, the SCIGN data, in particular the temporal resolution afforded by continuous measurement, provides an indispensable component of multidisciplinary studies of plate boundary deformation in southern California. In turn, these studies have inspired a new generation of physical models of the relationship between the accumulation and release of strain energy in the crust.

2.3 Northern California

The Bay Area Regional Deformation (BARD) CGPS network consists of ~ 25 continuously operating permanent GPS stations in northern California. The primary goal of the network is to monitor crustal deformation across the Pacific-North America plate boundary and in the San Francisco Bay Area for earthquake hazard reduction studies and rapid earthquake emergency response assessment.

Several groups have used the BARD infrastructure to study broad scale deformation patterns associated with the Pacific-North America plate boundary. The stations in the Sierra Nevada-Great Valley region provide boundary constraints on the deformation across the Basin and Range province [Bennett et al., 1998; 1999; Thatcher et al., 1999; Dixon et al., 2000; Murray and Segall, 2001] (Figure 2.7). These studies show that the Sierra Nevada and Great Valley move as a rigid block at 10-12 mm/yr northwest relative to stable North America with little internal deformation. The motion of the rigid Sierran-Great Valley block is oblique to the trend of the San Andreas fault system, causing 2-4 mm/yr fault-normal convergence over a narrow (25-km wide) zone in the Coast Ranges on the western edge of the Great Valley [Prescott et al., 2001; Murray and Segall, 2001]. This convergence may be responsible for the long-term uplift of the Coast Ranges [Argus and Gordon, 2001].

The San Andreas fault (SAF) system accommodates 37-40 mm/yr right-lateral shear of the Pacific-North America relative plate motion in the San Francisco Bay Area [Prescott et al., 2001; Murray and Segall, 2001]. Motion of the BARD sites in a profile from the central Bay Area to eastern Nevada can be described using a simple model combining only long-term rigid plate motions and interseismic elastic strain accumulation on three faults approximating the SAF system [Murray and Segall, 2001]. A combination of GPS, InSAR, surface creep measurements, and microseismicity showed that the Hayward fault is not significantly locked at shallow depths [Bürgmann et al., 2000]. In the Parkfield region, a variable slip-rate model inverted from GPS

Figure 2.7. Predicted (open) and observed (solid) site velocities, with 95% confidence regions, relative to NA. A) northern California and Nevada B) San Francisco Bay area. Faults: SA = San Andreas, H = Hayward, CC = Concord/Calaveras, NWLB = northern Walker Lane Belt, CNSZ = Central Nevada Seismic Zone. (From Murray and P. Segall, 2001.)
data, in general agreement with earlier trilateration results, showed a slip-rate deficit at the southeastern end of the segment near the high-slip region of the 1966 M6 earthquake [Murray et al., 2001].

Transient deformation has been observed at several of the BARD stations, most notably in the Long Valley caldera [Webb et al., 1995; Dixon et al., 1997], which experienced a non-eruptive, but significant episode of unrest in late 1997 and early 1998 that provides constraints on possible viscoelastic rheology models of the caldera [Newman et al., 2001]. The only non-volcanic transient detected by the BARD network was a 4-mm displacement at one station in the vicinity of the 1998 Mw 5.1 San Juan Bautista earthquake [Uhrhammer et al., 1999].

2.4 Basin and Range

To investigate the active tectonics of the province, a 50-station network of continuously operating GPS stations was established across the northern and central Basin and Range province (Figure 2.1). The velocity field, relative to the North American plate show increasing west to northwest velocity from near 0 mm/yr on the east side of the province up to 12 mm/yr on the west, becoming more northerly from east to west (Figure 2.8). The west components of motion increase gradually westward, indicating broadly distributed extensional strain at a rate of ~10 nstr/yr. The north components of velocity are near zero across the eastern half of the province, but increase rapidly westward from central Nevada to the Sierra Nevada to values near 7 mm/yr.

Figure 2.8 A: Shaded relief map of a transect across northern Great Basin showing seismicity, traces of selected fault zones, and GPS velocity vectors (with 95% confidence ellipses) from continuous sites from 1996 to 1999 (from Wernicke et al., 2000). Historic seismicity from Council of the National Seismic System. Historic earthquakes in central Nevada seismic belt (CNSB); DVF—Dixie Valley (1954); FPF—Fairview Peak (1954); PVF—Pleasant Valley (1915). Faults (in pink): CVF—Crescent Valley fault; DVF—Dixie Valley fault; FPF—Fairview Peak fault; HLF—Honey Lake fault; PVF—Pleasant Valley fault; WFZ—Wasatch fault Zone. IGS—International GPS service. ISB—Intermountain seismic belt. B: North components of velocity as a function of longitude, with 1 s error bars. C: West components of velocity as a function of longitude, from BARGEN continuous GPS data (red, from Bennett et al., 1999; and campaign GPS data (green, from Thatcher et al., 1999).
These results, while preliminary, demonstrate the power of combining modern geodetic and geologic data, especially in areas where transient signals are easily distinguishable from interseismic strain accumulation. In areas where strain accumulation is rapid (100s of nst/yr), as along the San Andreas fault or in the Ventura or Los Angeles basin areas, postseismic transient strain rates are of the same order or smaller than strain accumulation rates, occupy a large fraction of the total interseismic period; and may be strongly overprinted by strain accumulation signatures of major plate boundary faults [e.g., Hager et al., 1999]. However, in areas such as the Basin and Range, transient strain rates may be much easier to characterize because they are of the same magnitude as in rapidly straining areas (i.e., earthquakes in the Basin and Range are about the same size as those in the Los Angeles basin), but are an order of magnitude larger than the average strain accumulation rate, persist for only a small fraction of the interseismic cycle, and are relatively uncontaminated by strain accumulation signals from neighboring faults. The clearest illustration of such transients are the velocity of the baseline LEWI-MINE (Figure 2.8), which shows contraction of about 2 mm/yr across the Crescent Valley fault, whose last major event had a total slip of 5 m about 2500 years ago. Clearly, the contemporary regime of shortening could not have resulted in a large normal fault earthquake, and is therefore transient, perhaps a result of viscoelastic relaxation from the last century of earthquakes in the intermountain seismic belt to the west [Wernicke et al., 2000]. The longest time series from the BARGEN network are beginning to show measurable accelerations. For example, the west component of site EGAN, which is several hundred kilometers away from any historic earthquake, has been decelerating relative to North America at a rate of 0.4 mm/yr² from 1997 to 2002 (Figure 2.9). Thus in addition to transient behavior indicated by long-term mismatch between of geodetic and geologic slip rates (at the level of a sign difference for LEWI-MINE), time series for sites far removed in both time and space from earthquakes, in relatively slowly deforming areas, are beginning to reveal phenomena we are only beginning to understand.

In addition to these results based on horizontal velocity measurements, the longest time series (~5-6 years) are beginning to show relatively coherent patterns in the vertical. GPS is geometrically less sensitive to vertical motions than to horizontal motions. Concomitant with the reduced geometrical sensitivity is an increased sensitivity to elevation-angle dependent errors, such as atmosphere modeling errors and multipath.
Vertical rates from our most recent solution in an approximate North America-fixed reference frame suggest that on average the region is subsiding at 3.2 mm/yr (Figure 2.10). According to one model for glacial isostatic adjustment (GIA), the NBAR sites lie in the peripheral bulge, and therefore should be subsiding due to GIA, except the average rate is much higher than predicted by the model (Figure 2.10). The large negative value for the average rate may indicate that an adjustment is required in the value for lower mantle viscosity, which controls the location of the peripheral bulge. The model used in Figure 2.10 predicts maximum subsidence at a rate of 3–5 mm/yr in Montana and Wyoming, but the maximum subsidence would be located farther southwest if the lower mantle viscosity were increased.

The variations in velocity about the average do not appear to be entirely due to random scatter. The weighted root-mean-square (WRMS) residual velocity about the average is 1.3 mm/yr, which is reasonable in absolute terms, but is a factor of ~8 larger than expected from the formal uncertainties in individual site velocities. Further, the convex-up spatial pattern on the east side of the network is roughly centered on former Lake Bonneville, where we might expect some ongoing relative uplift. Estimates of the vertical coordinate of site position, however, are sensitive to processing techniques and systematic errors, especially for short time series. Another source of errors may lie in the realization of the vertical reference frame for North America. Our scatter of only 1.3 mm/yr is encouraging, but an increase in the timespan afforded continued monitoring will be crucial to evaluate these issues.

2.5 Eastern Basin and Range – Yellowstone (EBRY)

The eastern Basin Range-Yellowstone (EBRY) network was designed with two primary science objectives. The first is to measure and understand the spatial and temporal variations of the crustal deformation accompanying earthquakes on the 370-km long Wasatch fault and surrounding faults of central and northern Utah. This is achieved by using a combination of campaign and continuous GPS surveys which provide the precision and spatial scale necessary to understand the kinematics of fault-related deformation. These efforts focus on determining
earthquake hazards by combining the historical seismic record, the paleoearthquake history, and the GPS-determined contemporary strain field. The data suggest at least 3 mm/yr of slip must occur below 10-km depth to produce the observed surface deformation. This information is essential to estimate contemporary loading of the Wasatch fault and to serve as a constraint for intraplate dynamic models of the Basin-Range deformation as well as providing new information for probabilistic earthquake risk assessments [Chang and Smith, 2002].

The second science objective of the network relates to the Yellowstone hotspot. The Yellowstone component of EBRY consists of ~20 continuously operating, permanent GPS stations centered on the Yellowstone volcanic field and spanning a 600 km by 700 km area of northern Utah, Idaho, Wyoming, and Montana. The network focuses on the overall strain and deformation field of the northern Basin-Range province that includes Yellowstone and the track of the 800 km-long Yellowstone hotspot across the Snake River Plain, as well as the 370 km long Wasatch fault zone (Figure 2.1).

Initial results from the Yellowstone GPS measurements indicates a regional pattern of ~4 mm/yr NE-SW extension occurs across the volcanic system and surrounding fault zones, slowing to ~2 mm/yr NE extension down the eastern SRP [Puskas et al., 2001]. The transient nature of the deformation field was punctuated by caldera-wide deformation changes from a 50-year period of uplift recorded since 1923 to subsidence and contraction, from 1985 to 1996, followed by a return to caldera uplift and expansion in 2000 (Figure 2.12). This pattern was preceded by caldera uplift measured by precise leveling from 1923 to 1985 revealing a living, breathing caldera accompanied by remarkable correlations of increased seismicity with caldera deformation reversals [Chang and Smith, 2002; Waite and Smith, 2002, in press]. Inverse strain models of the Yellowstone data imply that caldera deformation is accommodated by volumetric strain change in the 0-9 km depth range, likely related to hydrothermal fluid migration in and out of the Yellowstone Plateau, driven by deeper magmatic sources. The bottom of the modeled crustal strain source notably coincides with partial melts inferred from seismic tomographic images.
The Pacific Northwest Geodetic Array (PANGA) is a network of ~50 continuously operating GPS stations that extend the length of the convergent margin. A great earthquake (Mw~9) ruptured the length of the subduction zone in 1700 A.D. [Satake et al., 1996; Yamaguchi et al., 1997]; the recurrence interval for such events is 500-600 years, yet has been as short as 180 years during the Holocene [Atwater and Hemphill-Haley, 1997]. The megathrust seismic cycle, the deformation in response to three plate interaction, and the locus and deformation rates of crustal faults are targeted by PANGA investigations.

A five-year investment in GPS resources in the Pacific Northwest has triggered a rapidly evolving understanding of subduction, the seismic cycle, and geodynamics along the Cascadia convergent margin. Continuous and campaign measurements have established a budget for crustal faulting within the North America plate and have constrained models of subduction zone locking [Dragert and Hyndman, 1995; Dragert et al., 1994; Khazaradze et al., 1999; McCaffrey et al., 2000; Miller et al., 2001; Murray and Lisowski, 2000; Savage et al., 2000]. The CGPS network recorded the February 28, 2001, Nisqually earthquake despite its great depth [Dreger et al., 2001; Miller et al., 2001a; Nabelek and McCaffrey, 2001]. The recognition of a creep event on the Cascadia megathrust during the summer of 1999, termed a silent earthquake [Dragert et al., 2001a] hinged on continuous GPS observations within PANGA. This event is now recognized to be one in a time series of such events that have regularly affected the plate interface observed since the beginning of continuous GPS observations in 1992 [Miller et al., 2002] (Figure 2.5). Oblique subduction results in seismic hazard and deformation within both

![Velocity model for campaign and EBRY continuous sites (red dots) and leveling around the Yellowstone volcanic system. Outline of caldera shown in yellow, Teton and Hebgen Lake faults shown in pink. Velocity field shows dramatic reversal in vertical motion, from subsidence (1987 to 1995) to uplift.](image)
plates. In Oregon and Washington, subduction is accompanied by northward migration of a fore-arc sliver [Wells et al., 1998; McCaffrey et al., 2000; Miller et al., 2001; Wells and Simpson, 2001]; this deformation abruptly dies out across Puget Sound where the northward penetration of the fore-arc is buttressed against Vancouver Island. This pattern results in ~5 mm/yr of shortening across northwestern Washington [Miller et al., 2001], on the order of that accommodated across the Los Angeles Basin [Argus et al., 1999]. The Puget Sound landscape is as young as the last glacial retreat and is bereft of older-than-Holocene markers that have been used elsewhere to offer tight paleoseismic and geomorphic constraints on the distribution of such crustal faults [Haugerud, 2000]. Thus geodesy proves critical in characterizing how continental lithosphere responds to fore-arc impingement.

2.7 Alaska

The Alaska Deformation Array (AKDA) consists of 14 continuously operating, permanent GPS stations, five of which are operated by the Geophysical Institute at the University of Alaska. The network was established to study crustal deformation in Alaska, although stations installed for other purposes have also proven useful.
In a region where there are few geodetic quality permanent stations, the continued operation of the CGPS stations in Alaska takes on an importance beyond the research results obtained from those stations alone. Excluding the University of Alaska stations, and the Alaska Volcano Observatory (AVO) volcano sites recently installed in the Aleutians, there is only one geodetic quality CGPS station located within 1500 km of Fairbanks, Alaska, in any direction (e.g., Whitehorse, Canada is 800 km away). A circle of radius 1500 km would encompass almost the entire western ‘Lower 48’ states. Without these stations, survey-mode GPS results from Alaska would be of reduced quality, and it would be harder to establish a strong reference frame for geodetic studies in the region.

The most important result from these stations was a completely unexpected finding. Beginning around the middle of 1998, a very strong transient deformation signal was observed at station ATWC and many survey mode sites covering an area roughly 100 by 150 km (Figure 2.6). This signal can be explained by a transient pulse of slip on the plate interface where the total transient slip is proportional to the logarithm of time since the start of the event (rate \( \sim 1/t \)). This is a similar result to that predicted for the decay of afterslip following a large shear stress change on a fault obeying a rate-and-state friction law [Marone et al., 1991]. This slip event occurred well downdip of the 1964 earthquake rupture zone, in a part of the interface that was apparently creeping before the event. This makes it different from slip events seen in Cascadia and Mexico, in which patches that were normally locked failed in slip events lasting ~weeks. Another puzzle posed by this event is that, even though the data can be explained by an afterslip-type model, there was no preceding seismic or aseismic event. A small, rapid aseismic event cannot be ruled out, but it would have to be small compared to the “afterslip” that followed. Thus, the triggering mechanism for this event remains a mystery.

### 3.0 Existing GPS Infrastructure

The existing GPS infrastructure in the western United States consists of 470 stations (Table 3.1); nearly all of these stations will contribute to EarthScope scientific objectives. Fortunately, a large number of these stations (nearly half) are expected to enjoy continued support from non-
NSF sources. For example, on the basis of seismic hazards mitigation in the Los Angeles Metropolitan area, the USGS internal program is expected to continue to provide very strong support for SCIGN operations. Similarly, on the basis of site characterization activities for Yucca Mountain, the DOE is expected to support the cluster of BARGEN sites focused on the proposed high-level nuclear waste repository.

Table 3.1. Existing GPS networks and number of stations requesting support

<table>
<thead>
<tr>
<th>Network</th>
<th>Name</th>
<th># Stations</th>
<th># Requesting support</th>
</tr>
</thead>
<tbody>
<tr>
<td>AKDA</td>
<td>Alaska Deformation Array</td>
<td>14</td>
<td>5</td>
</tr>
<tr>
<td>BARD</td>
<td>Bay Area Regional Deformation Array</td>
<td>64</td>
<td>40</td>
</tr>
<tr>
<td>BARGEN</td>
<td>Basin and Range GPS Network</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>EBRY</td>
<td>Eastern Basin Range Yellowstone</td>
<td>19</td>
<td>15</td>
</tr>
<tr>
<td>PANGA</td>
<td>Pacific Northwest Geodetic Array</td>
<td>47</td>
<td>35</td>
</tr>
<tr>
<td>SCIGN</td>
<td>Southern California Integrated GPS Network</td>
<td>276</td>
<td>125</td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td>470</td>
<td>255</td>
</tr>
</tbody>
</table>

3.1 Regional Summary

The strength of the geodetic community and the success of each of the existing networks is evidenced by their ability to construct monuments and install stations (Figure 3.1), establish data communications, maintain and document sites, conduct meaningful data analysis efforts, share and publish data products, and publish significant scientific results. Many of the investigators and expert staff involved in the construction and maintenance of the existing networks will participate in applying lessons learned from these arrays to the new PBO/EarthScope sites.

Figure 3.1 Network growth, in terms of number of stations installed (y-axis) versus time (x-axis). Black is SCIGN, upper purple BARGEN, green BARD, lower purple PANGA, red EBRY, blue AKDA.
Table 3.2 summarizes minimum, maximum and median root-mean-square scatter of the daily position estimates about linear fits for the existing networks. In spite of differences in equipment, monuments and installation procedures, there is relative uniformity across the various networks. The networks have all relied heavily on local expertise, however most networks also contract tasks to the UNAVCO Facility. Some actively collaborate with each other through (1) coordinated planning and installation where networks interdigitate; (2) mirroring of archives, (3) performing redundant data analysis, and (4) sharing resources during earthquake-response efforts. More formal integration of the networks affords the opportunity to develop mature standards, and this work must be done in preparation for EarthScope. For instance, the International GPS Service (IGS) formal site logs are an invaluable but awkward standard for station metadata to which all our networks adhere. Recent advances in the UNAVCO-developed GPS Seamless Archive (GSAC) allow more useful alternatives to recording and public access to station metadata. Providing standard data, metadata and station documentation is the basis for network integration upon which EarthScope will be built.

<table>
<thead>
<tr>
<th>Network</th>
<th># Estimates(1)</th>
<th>Component</th>
<th>Min (mm)</th>
<th>Max (mm)</th>
<th>Median (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AKDA (2)</td>
<td>7</td>
<td>N</td>
<td>2.1</td>
<td>3.4</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E</td>
<td>2.4</td>
<td>4.5</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>U</td>
<td>5.2</td>
<td>12.3</td>
<td>7.7</td>
</tr>
<tr>
<td>BARD</td>
<td>50</td>
<td>N</td>
<td>0.7</td>
<td>5.6</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E</td>
<td>0.7</td>
<td>5.9</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>U</td>
<td>2.6</td>
<td>17.7</td>
<td>5.1</td>
</tr>
<tr>
<td>BARGEN</td>
<td>65</td>
<td>N</td>
<td>0.5</td>
<td>1.7</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E</td>
<td>0.6</td>
<td>2.1</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>U</td>
<td>2.1</td>
<td>19.0</td>
<td>3.7</td>
</tr>
<tr>
<td>EBRY</td>
<td>14</td>
<td>N</td>
<td>0.9</td>
<td>6.9</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E</td>
<td>1.3</td>
<td>7.3</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>U</td>
<td>3.3</td>
<td>11.8</td>
<td>6.2</td>
</tr>
<tr>
<td>PANGA</td>
<td>27</td>
<td>N</td>
<td>0.8</td>
<td>9.7</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E</td>
<td>0.8</td>
<td>9.9</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>U</td>
<td>3.1</td>
<td>19.0</td>
<td>4.3</td>
</tr>
<tr>
<td>SCIGN(3,4)</td>
<td>396</td>
<td>N</td>
<td>0.5</td>
<td>8.3</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E</td>
<td>0.5</td>
<td>7.3</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>U</td>
<td>1.6</td>
<td>15.6</td>
<td>3.5</td>
</tr>
</tbody>
</table>

(1) # estimates is number of rms values calculated (includes discontinuities in time series)
(2) RMS may be elevated due to the small number of stations and the network is at the edge of the defined processing boundary. Additional increase in RMS could be due to one station having a clear change in
(3) One outlier removed station COSO (Urms = 51.9)
(4) Some RMS values elevated due to post-seismic transients
The networks vary considerably in size, geographic setting, distance between stations, site access, existing communications, power infrastructure and monumentation type. For example, the SCIGN network is primarily located in urban southern California where multiple sites can often be visited in a single day. A majority of the sites in the SCIGN network are monumented with deep drilled braced monuments and about half of the sites utilize AC power. In contrast, some sites in the EBRY network require helicopter support and are inaccessible for winter and spring months, monuments consist of a combination of concrete, reinforced invar rod, and short drilled braced monuments, and stations run off DC (i.e., battery recharged by solar) power. Because of the differences in support requirements and support costs, the overall characteristics of each network are summarized below as a basis for the Budget Justification for the operation of each network presented in Section G. Despite these differences between the networks, the data and solution quality is high and consistent across the networks. The summary presented in Table 3.2 is based on 828,000 station-days between January 1992 to June 2002.

3.2 Southern California
The 276 station SCIGN network is operated by a collaboration between the Jet Propulsion Laboratory, the Scripps Institution of Oceanography and the U. S. Geological Survey (Figure 2.1). Slightly less than half of the network’s annual operations budget will be supported via this proposal. The network consists primarily of high quality deeply anchored monuments [Langbein et al, 1995] with Ashtech Z-XII dual-frequency GPS receivers, SCIGN radomes, and choke-ring antennas [Hudnut et al, 2002b]. Stations are powered using a mix of AC and DC sources and data telemetry is handled using direct dial-up and internet, radio modems, repeaters, and download hubs. About 150 of the 276 stations have horizontal position RMS scatters of less than 1 mm with a similar number of sites having less than 3.5 mm RMS scatter in the height estimates (Table 3.2).

3.3 Northern California
The BARD network is operated by the University of California, Berkeley and currently consists of over 64 sites (Figures 2.1 and 2.7), 40 of which will be supported by this proposal. The network consists of a mix of monument types ranging from roof mounted systems, concrete piers in bedrock, strainmeter borehole casings, invar rods cemented in bedrock, and deeply drilled braced monuments. Receiver types include Ashtech Z-XII, Trimble 4000 SSE/SSI, and Turborogue dual frequency receivers. A mixture of antennas are used in the network including choke ring (primary) and Ashtech and Trimble geodetic antennas. Antenna radomes include the SCIGN tall dome and a UNAVCO designed dome, with a few antennas left uncovered.

3.4 Basin and Range
The BARGEN network is operated by the California Institute of Technology and the Harvard Smithsonian Center for Astrophysics and currently consists of 50 stations (Figure 2.1), 35 of which will be maintained under this proposal. This is a very homogenous network with deep-drilled braced monuments, Trimble 4000 Ssi receivers, choke ring antennas and SCIGN radomes used at every station. Data download is accomplished by radio modem telemetry to download hubs where standard and cell phone dial-up connections are made to transfer data.

3.5 Eastern Basin and Range - Yellowstone Hotspot
The EBRY network is maintained by the University of Utah and currently consists of 19
stations, 15 of which are slated for continued support under this proposal. The network consists of a mix of monument types including concrete reinforced invar rods, invar rods directly cemented into bedrock, and invar rods attached to seismic borehole casings. Receiver types include primarily Trimble 4000 SSE/SSI systems with a few Trimble 4700’s and Ashtech Z-XII’s. Antennas are all choke rings with a mix of UNAVCO and SCIGN-developed radomes. For most monuments in this network, leveling mounts were not used and antennas were mounted directly to invar rods. A number of stations in this network are collocated with seismic instruments and satellite communications (VSAT) bandwidth is shared for GPS data streaming/data downloading.

3.6 Pacific Northwest

PANGA, operated by Central Washington University and the Canadian Pacific Geoscience Centre in Canada, consists of 47 stations (Figure 2.1). Thirty-five U.S. sites will be supported under this proposal. The network monuments are a mix of deep drilled braced, short drilled braced, and concrete reinforced invar rod (the latter two in bedrock), as well as two rooftop test sites. Data from National Geodetic Service (NGS) stations on 10 m towers are also routinely analyzed but they were not installed or maintained by the PANGA consortium. Receiver types include Trimble 4000 SSI and 4700’s, Ashtech Z-XII and Z-Dual frequency receivers; Turborogue and Leica dual frequency receivers are used in British Columbia. Choke ring antennas are standard although one site has the Trimble microcenter antenna. Antenna radomes include the SCIGN tall and UNAVCO domes with a few antennas left uncovered.

Stations are powered using mostly AC; six have DC sources. Data transfer is primarily by land-line dialup but a subset of stations in the Puget Lowlands use radio modems, radio repeaters, and a download hub, and two have Internet connections.

3.7 Alaska

Support for five stations of 15 in the Alaska Deformation Array is requested in this proposal. The stations were primarily installed as a base network for campaign measurements but provide valuable information as a standalone network (Figure 2.1). These five sites are relatively inexpensive to operate because the sites chosen are relatively accessible, at least by Alaska standards. The network is a mix of monument types including invar rods in bedrock braced with concrete and tripod-like monuments cemented into ~3 m-deep concrete pads. Receiver types in this network include Trimble 4000 SSI and 4700 systems. Antennas include Trimble L1/L2 geodetic and L1/L2 compact geodetic antennas. One site has a conical radome to shed snow, and another site is located inside a structure, viewing the sky through a pyramidal skylight. At the other sites, wind blows the snow off of the antenna ground planes and no radomes are used.

4.0 Proposed Integration into EarthScope

Based largely on the success of the regional networks described above, planning for a greatly expanded network of GPS and strain instruments throughout the Western U.S. The PBO component of EarthScope is designed to characterize the four-dimensional strain field resulting from Pacific-North America plate boundary deformation. When fully implemented, PBO will consist of about 875 CGPS stations, 175 borehole strain meters, and several long baseline strain meters. These instruments will extend along the plate boundary from Alaska, south to the Gulf of
California. PBO includes both comprehensive coverage of the plate boundary zone necessary to capture the secular tectonic component of deformation while providing an increased station density for detecting localized and time transient deformation related to specific faults and volcanic centers. As described above, the core of regional networks, in turn, uniquely contribute to EarthScope: the existing decade-long deformation time history cannot be duplicated in any other way over the planned life of the experiment. Thus, the integration of existing networks forms a critical nucleus for EarthScope research and is crucial to its success.

Approximately 470 GPS stations comprise the western U.S. regional networks; of these, 255 have been selected for integration into EarthScope on the basis of their geographic distribution relative to the intended scientific focus of EarthScope as well as their quality and performance. Each of the federation networks is engaged in monitoring the quality of each station being analyzed and, wherever possible, corrective maintenance is routinely performed.

We propose a five year project that will sustain the regional arrays during construction of PBO/EarthScope and realize their integration into EarthScope. This consists of the following component tasks: 1) direct support of data flow through maintenance and operations of selected GPS stations, including continued evaluation and remediation of station health; 2) coordination of quality control, archive structure and products formats as the testing ground for EarthScope standards; and 3) integration of the supported stations into EarthScope during its maintenance and operations phase.

4.1 Data Flow, Maintenance and Operations

Maintaining the data flow from the network stations requires: selection of the stations, maintenance and replacement of equipment at each installation, support for data download infrastructure, and maintenance of the archives. Staff at the sub-award institutions will accomplish maintenance and operations for the existing networks through the life of this project; ultimately these will be integrated into the EarthScope maintenance and operations phase.

Regional network technicians routinely attempt to remotely troubleshoot stations that fail to produce data. Typically, after a five-day period of data loss, a field maintenance visit is scheduled unless special access conditions prevent such a response. Depending on season and location (e.g. Alaska, Rocky Mountains, Olympic Mountains), site visits can be deferred until logistics, weather, or overriding science goals permit; although in most cases expediency is paramount. Once the condition is corrected, a maintenance report is logged for all troubleshooting and repairs. In addition to routine maintenance, yearly station maintenance visits will be scheduled for all stations not visited in the previous year. These visits will include replacing gel cell batteries, cleaning solar panels, performing a site inventory, repairing broken equipment, updating documentation, visiting critical site contacts, and clearing vegetation from around the site.

A majority of the existing stations have been operating since the early or mid 1990’s, often in harsh environments, and represent equipment and infrastructure in critical need of replacement and repair. The GPS receivers at many of the stations are Trimble 4000 and Ashtech Z-12 series receivers, for which the spare parts are in short supply or no longer available. In some cases radio telemetry (antennas and radio modems) and DC-based solar power systems (batteries and panels) are in need of maintenance or have exceeded their operating life. In some networks, scientifically critical geodetic monuments are in need of maintenance or replacement. The amount of replacement equipment needed is estimated to be 5% of the number of stations supported per year. This equipment will be purchased by UNAVCO, Inc. and supplied to each
of the networks based on need, and will benefit from competitive pricing available for large acquisitions and will be compatible with installations for EarthScope.

Data flow into the GPS Seamless Archive Center (GSAC) is already well developed. The regional network data are routinely archived locally, with long-term archives at both of the two GSAC retailers as well, the UNAVCO Facility and Scripps Orbit and Permanent Array Center (SOPAC). Most of the regional networks have implemented the standards to become a GSAC wholesaler or are in the last stages of doing so; all are routinely providing data to the GSAC. The GSAC provides an organizational structure that allows better handling of metadata and to improve these standards in a centralized way that will support EarthScope.

4.2 Standardization of Quality Control, Archive Structure and Products formats

The integration of the existing networks provides an excellent opportunity for implementing detailed planning for the PBO component of EarthScope. A tremendous amount of work is in progress and planned in order to make the data stream and analysis scale-independent; existing networks are the proving ground for these advances while EarthScope is under construction. Automation of all stages of quality control, archiving structure, data analysis, and data products format is rapidly evolving with the GSAC construct. These tasks require the focused attention of the scientists close to the data and the technical staff that support them in order to stage for a fully implemented PBO.

In PBO/EarthScope, the station maintenance and data flow will be handled by Regional Engineers located within specified PBO/EarthScope regions (Figure 4.1). Adding existing regional stations under the EarthScope umbrella will result in an additional ~260 stations spread across the six regions of PBO/EarthScope. These stations will be folded into the EarthScope process in terms of station documentation, maintenance, data flow, and data processing and results, requiring only a moderate increase in personnel resources.

The transition from regional networks to a PBO/EarthScope network will be accomplished by coordination of standards among the existing networks, to a EarthScope standard. This task will include a thorough inventory of station equipment, migrating station documentation from an IGS-only standard to a standard that is also consistent with proposed EarthScope station documentation, routine station maintenance and site visits, development of consistent quality control standards and protocols, and data piping to the GSAC archive. All of these tasks are performed at some level by the regional networks; it is the coordination and development of EarthScope standards that will be implemented under this project.

The handling of data from the existing regional networks will be consistent with the plans for EarthScope data management and archiving. All campaign and continuous GPS data
will continue to be made immediately available to the community via the archives and the GSAC websites. This data management process will be streamlined by taking advantage of the GPS community’s long history of successful data transmission and archiving, by having a single point of collection and dissemination of station metadata, and by utilizing new data distribution tools and interfaces. The proposed model for data flow seen in Figure 4.2 shows data moving from regional networks through a data transport layer to archives, processing centers, and end users.

The last piece is the development of a common set of data products that will be made routinely available by the regional networks. This will be a proving ground for the developing EarthScope standards. Data and data products will include, in standard formats that exist or will be developed, daily and integrated solution files, the original data and meta data, time series in ascii and graphical form, and velocity fields in a selection of reference frames. These products and format standardization will be developed under this project.

4.3 Integration of Existing Networks into EarthScope Operations and Maintenance

The goal of this project is the ultimate integration of the existing networks into the Operations and Maintenance of EarthScope. This goal will be achieved by the ultimate transfer
of the existing regional networks into EarthScope, and the development of standard data archive and products. Each network brought into EarthScope will have standardized documentation including station reports and metadata information stored in a common database accessible to PI’s via a web interface. Existing stations will have been evaluated for critical equipment upgrades with an emphasis on streamlining the data path from the station to EarthScope processing and archive facilities. Data will follow the PBO/EarthScope model where individual stations are downloaded by the Regional Centers. The data will be picked up from Regional Centers using automated data pick-up software and deposited at PBO/EarthScope processing centers for analysis. EarthScope personnel will maintain stations on a regular basis with additional station visits in the event of critical outages.

5.0 Management Plan

5.1 Management Responsibilities of UNAVCO, Inc.

UNAVCO, Inc. is the coordinating entity and has overall management and budgetary responsibility for the conduct of work described within this proposal. Given the importance of continued support to the western US GPS networks, the UNAVCO, Inc. President will play an oversight role in coordination of the effort serving as PI. Regional PI's and Co-I's will conduct the on-scene operation of the regional networks on subcontract from UNAVCO, Inc.

The management responsibility for UNAVCO, Inc. has four major elements:

1. Oversight and coordination of network operations by the UNAVCO, Inc. President. The President will work with the Regional PI's and Co-I's to evolve common standards for operation and equipment. Every other year, the President will convene a workshop of Regional PI's and Co-I's to discuss these issues, identify operational issues of common interest, and develop and implement new procedures and standards.

2. Coordination with the larger EarthScope effort by the UNAVCO, Inc. President.

3. Centralized purchasing of major GPS equipment components that will allow upgrades of aging equipment at individual stations on an as-needed basis.

4. Implementation and monitoring of subcontracts, providing a means for common fiscal oversight and development of a unified inventory.

To accomplish these tasks will require, we estimate, 15% effort of the UNAVCO, Inc. President, Executive Director, Purchasing/Contracts Specialist, Finance Manager, and Administrative Assistant.

5.2 Role of UNAVCO Facility

The staff and technical capability of the UNAVCO Facility will support the effort described in this proposal consistent with their usual role in NSF-EAR funded projects. UNAVCO Field Engineers will conduct specific field activities, such as installing replacement receivers, upgrading monuments, or repairing faulty power or communications systems, on an as-requested basis. Tasking for these activities will come to the Facility via the project support request mechanisms already in place.

The UNAVCO Facility will provide ongoing support to the regional arrays, and support data flow and quality control at their current levels, and implement coordinated EarthScope standards. The costs of this element vary with the geographic, logistical, age, and technical history for each

C-26
network. To varying degrees, existing networks presently rely on the support of the UNAVCO Facility in these efforts.

There is a need within the proposed work for a dedicated Facility Engineer who will coordinate with the regional network operators, including conducting site visits as required, to complete and improve the quality of the site descriptions and meta-data for all the regional stations. Such data include a physical description of the site, detailed installation diagrams, and an inventory of hardware and software components by type and serial number. These data are critical for maintaining the long-term integrity of the data record and for effective configuration management and maintenance of the network. This information will be put into the UNAVCO Facility station database and/or other station databases developed for EarthScope for public access by the community. This Engineer will also serve as the Network Engineer for the combined regional network, the duties of which include reviewing data availability and quality for each station on a daily basis and then coordinating with the regional network operators for troubleshooting and repair of stations as required. In addition to this full-time Engineer, a part-time (25%) Equipment Technician will support this project.

5.3 Role of Regional Investigators

The regional investigators of each network will retain primary responsibility for continued operation of GPS stations within their networks over the life of this project. Funds will be provided to these groups via subcontracts from UNAVCO, Inc. These groups are best positioned to maintain these networks based on their history of success, proximity and availability of a trained technical staff, developed over many years. This approach supports the considerable variability in conditions under which these networks are operated. Many GPS stations in southern California, for example, are operated in an urban environment with excellent access via major highways. Stations in the Rocky and Olympic Mountains, on the other hand, are virtually inaccessible except by helicopter or, depending on environmental constraints, by foot or horseback. Because of such variability, each of the network operators has developed over many years specific capabilities and approaches to maintaining their networks. The goal of this proposal is to maintain that capability on behalf of the community while improving access to network data and meta-data through a more centralized data management and archiving activity as previously described. UNAVCO, Inc. will develop a standard Statement of Work for the regional network operators based on a requirement for common data standards and availability.

The operational requirements for each network depend on its unique properties, including number of stations, station accessibility and nearby infrastructure, and network size. The Regional Investigators, based on the properties of the networks for which they are responsible and on many years of operational experience, have developed operations plans and budgets that require differing numbers of personnel and other resources. Subaward budgets with detailed Budget Justifications are included later in this proposal.

5.4 Equipment replacement

Stations within the regional networks range in age from the mid-1990s to present. Aging of equipment, commonly in harsh environments that include exposure to snow, rain, salt air, lightening, and other hostile environments have taken their toll on existing equipment. Along with obsolescence of replacement components, this poses a first order challenge to maintaining the data flow from the stations that have been identified as critical to EarthScope. Prior to this
proposal, individual investigators were responsible for equipment replacement. We propose to centralize this effort, making decision for equipment repair and upgrade on the basis of overall EarthScope science goals and network status. Purchasing and price negotiation will be the responsibility of UNAVCO, which has a history of obtaining advantageous pricing based on volume. We request funds for complete station upgrade and replacement at the conservative rate of ~5% per year. Replacement/upgrade includes GPS receiver, GPS antenna, solar panels, batteries, communication equipment (including transmitter and antenna, for the large number of sites with no Internet access), and miscellaneous electronics and cables. The equipment budget for UNAVCO, Inc. is based on a current cost of $14K for the entire replacement system, with and environmentally enhanced system for Alaskan sites having a cost of $17.7K.

5.5 Education and Outreach

Education and Outreach (E&O) activities are a vital part of the proposed scientific research endeavor. They provide a mechanism for disseminating research results beyond the confines of the small research community; they provide an opportunity to enhance the visibility, and in turn, support for the scientific research among the public; they provide a resource for educating Americans, at all levels, about the value of scientific research in general, and geophysical research in particular; they provide a focal point for interest and involvement in scientific activities by the next generation of geophysics students, and thus are essential for maintaining the human infrastructure on which our science depends.

UNAVCO outreach activities make earth science accessible to a broader community through:

- Field-based education activities including student;
- Web-based education activities including mapping tools and educational tools;
- Community activities including preparation for EarthScope E&O.

The UNAVCO, Inc. E&O Manager will lead E&O activities for the proposed project. The E&O Manager will have three specific responsibilities:

(1) Developing integrated web access to products from the existing networks.

(2) Development of new data products from the existing networks in formats that are accessible to the broader community including students of all ages, government officials, and the general public.

(3) Coordination between these networks and the EarthScope E&O effort.

To accomplish these tasks will require, we estimate, 15% effort of the UNAVCO, Inc. Education and Outreach Manager. This E&O Manager will be hired during Year 1 of the proposed project, and we therefore request support for only 7.5% effort during Year 1.