Final Report to the National Science Foundation

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July 1, 2014 to June 30, 2015

Community Workshop:

The future of PBO in the GAGE Facility (2013-2018) and after EarthScope

September 22-24, 2014

DoubleTree Hotel, Breckenridge, CO

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EXECUTIVE SUMMARY

The National Science Foundation (NSF) sponsored a Community Workshop entitled "The future of PBO in the GAGE Facility (2013-2018) and after EarthScope," which was held at the DoubleTree Hotel in Breckenridge, CO from September 22nd through 24th, 2014. NSF provided $60.4K which, along with additional funds provided by the GAGE Facility Cooperative Agreement, allowed 69 individuals to participant in the three-day workshop. The assembled group included 42 scientists at academic institutions, including all four members of the organizing committee and the PIs of the workshop proposal, five USGS staff, including the Program Officer for Volcano Hazards, the NSF EarthScope and SAGE Facility Program Officer, four representatives from state departments of transportation or the state spatial reference networks, 15 UNAVCO technical and 2 UNAVCO support staff.

The objectives for the workshop were to initiate community discussion into how best to position PBO to support priority science topics and education and outreach within the context of current and likely future budgetary scenarios.

Invited speakers made two keynote presentations. The first, by Prof. Paul Segall of Stanford University was entitled "Looking back: Scientific discoveries, novel applications, and lessons learned." The second, by Prof. Michael Bevis of Ohio State University was entitled "Looking forward: Challenges and questions for the future." Both presentations are available on the UNAVCO website developed for the workshop (http://www.unavco.org/community/meetings-events/2014/pbo-future-14/pbo-future-14.html). In addition to these keynote presentations, participants were asked to submit a 500 word abstract to define goals and priorities related to the future of PBO. UNAVCO staff provided extensive backup materials for the workshop participants and gave several brief presentations related to current status of the EarthScope PBO.

The bulk of the workshop was organized around scientific and technical breakout sessions. The first breakout session was entitled "*Identify key values and scientific priorities for immediate and longer term future,"* with three working groups: 1) Interseismic deformation and long-term-tectonics; 2) Earthquake processes and aseismic deformation; and 3) Other observations and data products from PBO. The second breakout session built upon the results of the first, and was entitled *"Plan and scenario development: Optimizing infrastructure and data products for scientific priorities; alternative revenue streams; implementation."* This breakout session also featured three working groups: 1) Sensors and instrument clusters; 2) Coordination with key stakeholders; and 3) Data products: tools, users, and uses. All working group reports are available on the workshop website (see above).

The participants' recommendations are divided into immediate and longer-term strategies, with the former intended to guide UNAVCO actions and policies during the current funding period, and the latter intended to position UNAVCO and the PBO facility for research innovation in subsequent funding periods.

The immediate action recommendations optimize the current PBO operations to balance efficiency, data return, and the sensor network's ability to capture signals of greatest scientific interest. The longer-term action recommendations build a foundation for future groundbreaking scientific techniques and applications. Both are specifically designed to address the very broad range of purposes for which present-day data streams are used,

from more traditional tectonics studies to hazard monitoring to atmospheric and surface processes detection.

Recommendations for immediate action include:

1. Regularize maintenance and service schedules in regions where deformation transients are “less likely” (resulting in fewer field visits and reduced uptime).
2. Identify key regions (*e.g.* Cascadia) for immediate maintenance response where deformation transients are “more likely.”
3. Identify PBO GPS and BSM sites with the worst data quality and move to these to another location or decommission (or do not renew permits).
4. Otherwise, do not decommission GPS sites prior to 2018.
5. Defer all maintenance of low-value borehole installations, or divest the sites only producing seismic data to regional seismic networks; prioritization would need to occur based on additional community input.
6. Encourage NSF staff to aggressively pursue federal agency cooperation at the highest possible level.
7. Explore all avenues for “upreach,” or interaction with a range of stakeholders with broad interests or authority related to geodetic data streams.
8. Seek partnerships with other state and federal agencies to meet additional costs for earthquake early warning and other GNSS-enabled, high-rate, RT applications.
9. Explore adoption of O&M costs or collaborative sponsorship of some sensors or sets of sensors by other entities.
10. Leverage education and outreach (ECE) efforts to better engage the public and stakeholders in UNAVCO activities.
11. Upgrade stations to real-time where cost-effective communications and adequate power are already available.
12. Upgrade a limited number of GPS stations to full GNSS in strategic target areas of high scientific value, those that support large user communities, and for collection of data for UNAVCO and community-driven development and testing efforts.
13. Make immediate investments in the data management work flow to allow more data integration and sharing.
14. Expand UNAVCO’s ability to ingest and fully integrate or serve as a portal for data from non-PBO sources.

Recommendations to position PBO for the future include:

1. Develop a strong GNSS (*i.e*. GLONASS) + real-time streaming pilot project.
2. Develop a strong multi-timescale data products pilot (*e.g.* Mt. St. Helens).
3. Explore and test alternative methods of GPS (GNSS) data transmission.
4. Develop a pilot project to stream multiple sensor outputs and develop a flexible, generic data stream hardware + software system (leverage existing systems developed by Ocean Observing Initiative).
5. Develop new pilot data products for nontraditional users.
6. Build a management framework for institutionalizing adoption and sponsorship of sensors.
7. Collaborate with NASA for optimization and validation of NISAR and calibration and validation for SMAP.
8. Adopt a community-developed prioritization for BSM and LSM stations.
9. Explore alternative models for funding the BSM and LSM networks.

INTRODUCTION

The critical role of US national and global high precision geodetic infrastructure has been delineated by a number of recent studies completed under the aegis of the National Research Council and commissioned by National Science Foundation (NSF) and other federal stakeholders, including DoD, NASA, NOAA, and USGS. These documents: *Precise Geodetic Infrastructure*, NRC, [2010]; *Tsunami Warning and Preparedness*, NRC, [2011]; *New Research Opportunities in the Earth Sciences (NROES)*, NRC, [2012]; make a compelling case that additional resources and renewed commitment to geodetic science, instrumentation, and integrated systems of precision geodesy is in the US national interest. Reinvestment in global geodetic infrastructure will allow the US, in cooperation with its international partners, to address a wide array of emerging basic and applied science initiatives. Many of these endeavors have direct implications for evaluation of long-term global change, mitigation of natural hazards, and the development of a strong and diverse technologically literate workforce for the next century.

This report is based on the NSF-funded Community Workshop (EAR-1441122) entitled "The future of PBO in the GAGE Facility (2013-2018) and after EarthScope," which was held at the DoubleTree Hotel in Breckenridge, CO on September 22nd to 24th 2014.

The NSF Plate Boundary Observatory, the geodetic facility of EarthScope, includes ~1100 cGPS, 78 BSM, 6 LSM, 26 tiltmeter, and 126 surface met stations. The Geodesy Advancing Geosciences and EarthScope (GAGE) Facility (2013-2018) Cooperative Agreement (EAR-1261833) between the National Science Foundation (NSF) and UNAVCO, Inc. (hereafter referred to as UNAVCO) includes core funding to support the PBO as designed and implemented in the original EarthScope proposal (*e.g.* NSF-MREFC proposal, 2003 (Section 3.3 in the original proposal)) and those that were subsequently revised for continued operations and maintenance through the post-construction phase (*e.g.* NSF-PBO/SAFOD O&M proposal, 2007; Williams et al., 2010). The EarthScope Project, and its associated facilities (USArray, PBO, and SAFOD) were defined assuming a 15-year project term, which ends in September 2018.

Funds were requested in the GAGE Facility proposal to operate the full PBO network in a way designed to allow investigators to address any of the scientific problems detailed in the EarthScope Science Plan (Williams et al., 2010). The proposed budget for the PBO network included ongoing operations and maintenance costs based on actual expenditures for the previous five years, and additional funds to enhance and upgrade the PBO in anticipation of future needs and expectations from a wide-range of stakeholders; however, the proposal was funded at a reduced level. Cuts in the GAGE Facility first year budget and not restored in the second year of the GAGE Facility (October 1, 2013 through September 30, 2015) budget, which in turn affect the PBO base operating budget, require near-term decisions by UNAVCO management; these have medium- and long-term implications for the future of PBO after EarthScope.

GAGE Facility Goals and Vision for the Future

Management of the GAGE Facility builds on UNAVCO's legacy of leveraging investments in geodetic infrastructure in new and innovative ways that respond to community needs and sponsor priorities. This is particularly important given the large NSF investment in PBO ($100M in construction, $53M in O&M Phase I, and ~$47M in

O&M Phase II (as currently planned)), the ongoing costs associated with its maintenance, the challenging federal fiscal environment, and the rapid pace of change in geodetic and ancillary technologies (*e.g.* communications and data systems). The engagement of UNAVCO Membership in governance ensures close involvement of the research community in the development of GAGE facilities, focusing science talent on common objectives that in turn are supported by funding agencies such as the NSF; UNAVCO's programs and facilities are managed to align with NSF strategies for *Empowering the Nation through Discovery and Innovation* [2011-2016 NSF Strategic Plan, 2011], drawing directly from the NSF vision statement: *NSF envisions a nation that capitalizes on new concepts in science and engineering and provides global leadership in advancing research and education.*

GAGE leadership works closely with our core sponsors to maintain a robust program focused on the support of geodetic research and education. When the reach of a particular program or resource can be expanded through a well-defined enhancement, the NSF, NASA, or other funding agencies such as USGS and NOAA may augment certain core-funded program activities. *As outlined below, one of the key objectives of the PBO workshop is to explore what elements of the PBO are essential to each user community and sponsor to facilitate augmentation to the core GAGE Facility Cooperative Agreement.*

Broader Impacts of the GAGE Facility and EarthScope PBO

The GAGE Facility includes operational support for the NASA Global Geodynamics Network (GGN). An international community of geodesists uses the GGN and other data streams to establish Earth's reference frame, enabling mapping of the planet's shape and mass; to determine changes in the distribution of ice, water resources, and sea level; to characterize processes that contribute to natural and man-made hazards; and to recognize land-use changes (*e.g.* subsidence, soil moisture, and health of wetlands). Precise positions and velocities for the PBO ~1100 continuous GPS stations also depend critically on orbit products generated largely from the GGN, and in turn PBO data products are used to address a wide range of scientific and technical issues across North America. In a global society that is increasingly technology-dependent, consistently risk-averse, and often natural resource-limited, communities require geodetic research, education, and infrastructure to make informed decisions about living on a dynamic planet.

The western US and Alaska, where over 95% of the PBO sensor assets are located, have experienced and will continue to experience significant and potentially damaging geophysical events like earthquakes, volcanic eruptions, and tsunami. Using GAGE Facility services in concert with PBO data streams and data products, UNAVCO community science provides first-order constraints on earthquake, tsunami, and volcanic processes that are necessary for hazards mapping and zoning, and for early detection, characterization and warning applications.

A large US and international community of surveyors and civil engineers also access UNAVCO data streams, in particular those that comprise the PBO, software, and on-line resources daily. This emphasizes that the PBO has become a critical component of the national infrastructure in addition to being a world-class scientific research facility.

Lastly, UNAVCO is continuing to expand its efforts to inform policy with relevant science, and engage more widely in international partnerships that build mutual capacity for

authentic collaboration among a wide variety of stakeholders, sponsors, and civilian decision makers.

CURRENT STATUS OF THE EARTHSCOPE PLATE BOUNDARY OBSERVATORY

Overview of GPS and other colocated instrument operations

The PBO Facility operates and maintains 1,112 cGPS stations across an area of over 10,000,000 km^2 (Figure 1), spanning Shemya Island at the western end of the Aleutian Islands, the Brooks Range in northern Alaska, central Baja California, New Hampshire, and Puerto Rico. Of these, 1,084 are located in the contiguous western United States and Alaska, including the 209 that were upgraded and assimilated from PBO Nucleus networks, 19 in the eastern United States, seven in response to the 2010 El Mayor-Cucapah earthquake in northern Baja California, and two sites in Mineral, Virginia built after the 2011 M5.8 earthquake.

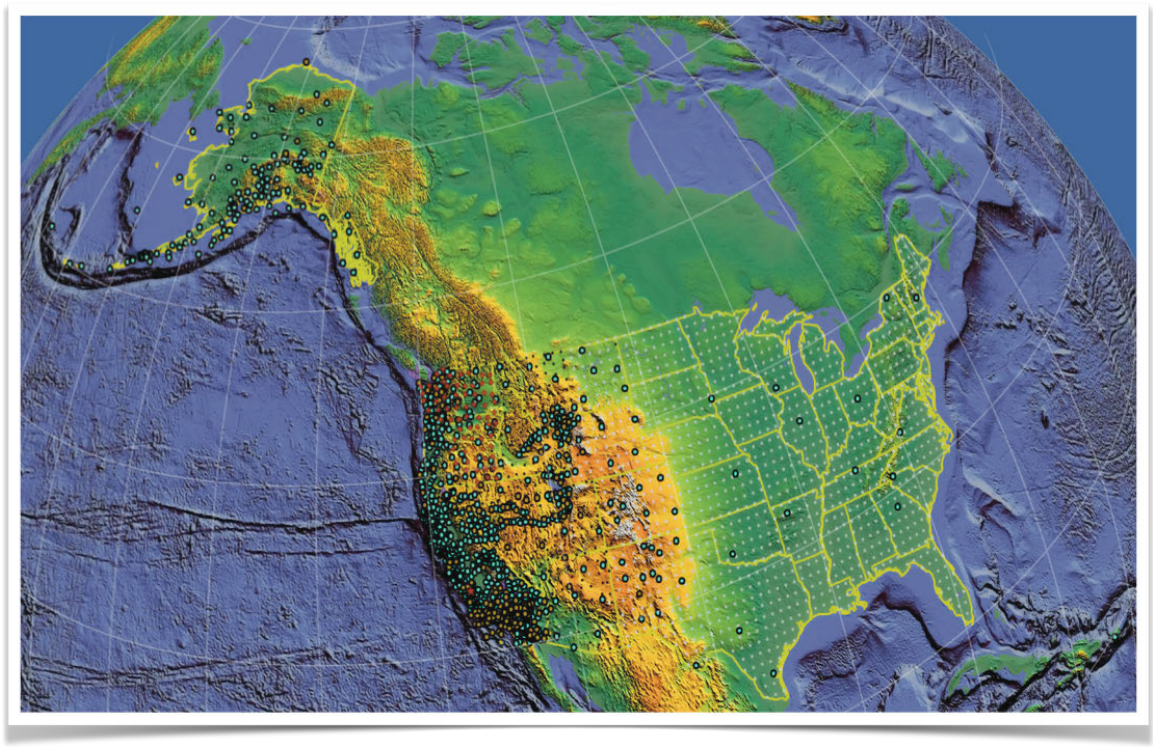

Figure 1. Map of the NSF Plate Boundary Observatory, the geodetic facility of EarthScope, which includes ~1100 cGPS, 78 BSM, 6 LSM, 26 tiltmeter, and 126 surface met stations.

To support the goal of meeting NSF-mandated performance standards for PBO outlined in the PBO/SAFOD O&M Phase I Cooperative Agreement (NSF-0732947), 10 full-time field engineers based out of four regional offices located across the Western US and Alaska were budgeted in the GAGE proposal submitted 2012. A primary metric is to ensure data return at or above the 85% requirement as set for PBO by NSF. Engineers visit each station every five years for scheduled battery and hardware maintenance and unscheduled maintenance is performed on a best-effort basis. Through staff attrition and

internal reorganization, the field engineering staff has been reduced 8 engineers and management structure has been streamlined from four to three regions, with the Alaska and Pacific Northwest regions combined under one regional manager effective October 1, 2014.

Regional offices in San Clemente, CA, Portland, OR, Anchorage, AK, and Boulder, CO continue to provide a base of operations for field engineering staff to optimize maintenance and new construction activities and to minimize travel costs and time. The remote offices also provide secure shipping/receiving and storage capabilities for regional operations. The GAGE GPS Operations Manager provides higher-level management for the GPS network, and four regional Project Managers coordinate day-to-day field operations in each region. Staffing levels for GAGE (number of stations per engineer) are consistent with other permanent networks such as BARGEN and SCIGN, and with known requirements established over the past five years.

The PBO network is an expandable platform on which additional colocated scientific instrumentation may be added to further scientific goals of the UNAVCO community. Currently, 126 meteorological instruments are colocated with PBO GPS stations; 100 of these were part of the original PBO network and 26 were recently added with NOAA funding. When combined with GPS, these metpacks provide constraints on column-integrated precipitable water vapor, a critical parameter in the regulation of energy transfer in the atmosphere and used for numerical modeling and weather forecasting.

PBO also includes 26 stations with electronic tiltmeters, an ancillary geodetic instrument installed to study selected volcanoes of interest, such as Yellowstone, those on Unimak Island, Mt. St Helens, and Akutan. Two PBO sites in the intermontane west have also recently been upgraded to include web cameras with height rods to calibrate snow depth calculations from GPS multipath, observations that support the emerging hydrogeodesy community. Future enhancements to PBO stations will include the integration of GPS and seismic systems, enabling a test bed for new research in the field of hazard monitoring and earthquake early warning. In particular, when coupled with RT-GPS-capable sites, low-cost micro-electro-mechanical systems (MEMS) accelerometers, may prove critical in real-time risk mitigation during large earthquakes (>M7) and eruptions (>VEI6). Community investigators are leading these pilot proof-of-application projects at PBO sites. We anticipate some addition of metpacks, tiltmeters, accelerometers, soil moisture sensors, and web cameras in response to investigator demand and as resources allow.

UNAVCO engineers provide network installation support for a number of PI projects related to PBO and the EarthScope program. This support includes budget preparation, project planning and execution, reconnaissance, permitting, installation, and operations and maintenance. During the construction phase of PBO, UNAVCO developed significant expertise in station permitting, especially on Federal lands, expertise that is being shared with IRIS in their planning for USArray deployments in Alaska. Permitting is a critical yet sometimes overlooked component of permanent station installation and operation; this requires long-term financial and logistical planning because many permits either expire in 2016-2017 and others extend beyond the nominal sunset date of PBO. UNAVCO staff also provides support to PIs by coordinating and assisting with site access for vegetation surveys and snow depth experiments.

Overview of Borehole Geophysics Operations

Borehole strainmeters are ideal for the high-precision observation of transient deformation with periods from seconds to weeks, and play a central role in observing phenomena that precede and accompany earthquakes, volcanic eruptions, and post-seismic transients. As part of PBO, UNAVCO operates and maintains 80 borehole geophysical monitoring sites that consist of some combination of tensor strainmeters (75); three-component borehole seismometers (79); environmental sensors that record information such as down-hole temperature, pore pressure, and barometric pressure; and above ground GPS receivers and power/telemetry systems. The boreholes are grouped into arrays that target scientific topics determined by the original PBO MREFC planning committees and include subduction zones (Cascadia), volcanic centers (Yellowstone, Mt. Saint Helens), triple junctions (Mendocino) and major strike-slip fault zones (San Andreas fault). UNAVCO maintains data return from these stations at or above the 85% EarthScope requirement, with critical unscheduled station maintenance activities prioritized by a governance-advised oversight committee. UNAVCO maintains 4.1 full-time-equivalent field and network engineers for borehole operations located in Boulder, CO and Portland, OR.

Biannual Biennial visits for maintenance and calibration are coordinated with two- and three-year scheduled maintenance trips during which expendable materials such as batteries (3 - 5 years) and VSAT feed-horn elements (every 2 years) are replaced; power-supply systems, such as propane-powered thermoelectric generators, are maintained every six months; and software and firmware upgrades are performed as needed (certain components of the strainmeter require on-site firmware upgrades). We also anticipate that stations will suffer some failures and require unscheduled repairs.

As part of the GAGE Facility, UNAVCO maintains the ability install and operate borehole strainmeters and associated instrumentation, and to process, synthesize, and distribute these data. UNAVCO staff develop data products, conduct short courses, and support community workshops focused on the unique constraints provided by strainmeters to study aseismic creep, slow-slip, generation and rupture of small (<M5) earthquakes, and volcano deformation.

PURPOSE OF THE FUTURE OF PBO WORKSHOP

UNAVCO senior management in close consultation with the UNAVCO Board of Directors, other governance groups, including the Geodetic Infrastructure Advisory Committee and the PBO Working Group, and the GAGE Facility Program Officer developed a proposal to support a PBO community workshop. NSF provided $60.4K on July 1, 2014 to support approximately 40 participants (EAR-1441122); additional funds from the GAGE Facility Cooperative Agreement were also used to support a small number of UNAVCO staff as well as the participation of selected members of UNAVCO advisory and governance groups. We anticipated that this would be the first of a series of workshops to better define the future of the PBO as well as the GAGE Facility after the close of the current NSF Cooperative Agreement (CA) in 2018 (EAR-1261833). The next NSF-funded community workshop, “Future Seismic and Geodetic Facility Needs in the Geosciences,” will be held in Leesburg, VA on May 4th to 6th 2015.

The goals of the *Future of PBO* workshop were both community and NSF motivated, and they were based on a charge to the workshop organizing committee from the UNAVCO

Board of Directors and guidance provided by NSF EAR staff. The emphasis for the workshop was on elucidating the current and future use and scientific value for the different PBO sensors (GPS, BSM, LSM, tilt, surface meteorological, and pore pressure sensors), the needed observation frequency (standard versus high-rate GPS, for example), data delivery mechanisms and latency (real-time versus polled), and the location and spatial density of various sensors, in particular the ~1100 cGPS stations.

Additional workshop goals, outlined below, were further driven by UNAVCO governance committees and the broader NSF EAR science community. Specifically, the workshop was designed to focus on these objectives:

- Review the science and technology achievements of PBO to date and explore anticipated new findings from PBO sensors and data products as data sets from PBO mature under GAGE.
- Define the technical requirements and network characteristics to support existing and emerging science goals.
- Review and refine various scenarios to modify or prune the existing PBO network design, which was formulated during the MREFC planning process and construction award (EAR-0323700) and maintained from 2008-2013 under the PBO/SAFOD O&M Cooperative Agreement (EAR-0732947).
- Identify and define co-dependencies among NSF basic research objectives and UNAVCO community PIs and other federal and state mission-oriented agencies (for example USGS and NOAA) and further to explore the costs, benefits, and leverage provided by the NSF investment in PBO through EarthScope.
- Define technology requirements that best serve the PBO user community through 2018 and possibly beyond, as PBO could form the nucleus of a hemispheric-scale geodetic observatory after the completion of the EarthScope project. These include technologies such as evaluation of communications methods and costs, GPS/GNSS receivers and antennae, observation type and frequency, communication methods and robustness, and ancillary sensors.
- Define data formats and data products that serve the broadest possible PBO user community. Currently many formats and delivery mechanisms exist to serve PBO user communities, including NMEA, RTCM, BINEX, SEED/MiniSEED, RYO and others. Should all of these be maintained and whom do they serve? Why and at what cost?
- Define community based data acquisition and data processing strategies in light of the emerging use of PBO assets in earthquake early warning and volcano eruption monitoring systems. Clarify the role that UNAVCO should play, given that its core funding is from NSF.

The workshop brought together a diverse range of user communities, sponsors, and non-academic stakeholders, such as representatives from the fields of tectonics, seismology, geodesy, hydrogeodesy, atmospheric sciences and numerical weather simulation, natural hazards, earthquake early warning, and cyber infrastructure. Plenary and Breakout Sessions were designed around the above goals.

PBO Workshop Deliverables

As outlined in the proposal to support this Community Workshop, three deliverables were expected from the NSF-funded community workshop.

Preliminary Report. A preliminary written summary was prepared and provided to program officers and senior management at NSF in February 2015. The report outlines the primary initial findings of the workshop and will serve as a stimulus for further discussion and recommendations by the community.

PI Mattioli reported on the preliminary findings and recommendations from the *PBO Workshop* through oral presentations to the UNAVCO Board of Directors (Boulder, CO, September 2014, with an update in Arlington, VA, February 2015), to the NSF Assistant Director for Geosciences, Dr. Roger Wakimoto (Boulder, CO, October 2014), to the EarthScope Steering Committee annual meeting (Boulder, CO, October 2014), and to the California Land Surveyors Association workshop (Ontario, CA, October 2014) and Land Surveyors Association of Washington annual meeting (Kennewick, WA, March 2015). Abstracts were also presented at the Annual Meeting of GSA in Vancouver, BC (October 2014; Mattioli, 2014) and Fall AGU Meeting in San Francisco, CA (December 2014; Mattioli et al., 2014). The relevant slides from these presentations were made available to NSF EAR staff in February 2015.

Prioritization for GAGE budget planning for FY2014 and beyond. This internally-oriented document includes various budget scenarios for PBO O&M and possible upgrades to communications infrastructure or observation type, changes to the current network configuration, and network renovation, all informed by input from the workshop participants, this report, and additional community and sponsor input.

PI Mattioli has worked with UNAVCO staff responsible for PBO operations and maintenance to implement the initial recommendations of the *Future of PBO Workshop* at the conclusion of the workshop. As discussed in more detail below, this included developing a budget to upgrade existing GPS sites to GNSS capability, revisions to the scheduled maintenance to achieve immediate cost savings through less frequent site visits and battery swaps, and by restructuring PBO regional management for additional cost savings and improved efficiency.

Final Workshop Report. The information and recommendations from the workshop are incorporated into a final report (this document) that will be presented to NSF and the participating communities by electronic means. The initial goal was to complete this report by no later than December 31, 2014; this was revised to a more realistic date of April 15, 2015. The report will also be posted on the UNAVCO website once it has been approved by NSF.

THE FUTURE OF PBO: WORKSHOP STRUCTURE

The PBO was designed as the geodetic facility within the 15-year EarthScope science project. The specific goals were developed through numerous community workshops, which in some cases required participants to produce "white papers" to better define specific scientific priorities and targets for the deployment of NSF-funded resources. While these goals were revisited and updated in 2009 (Williams et al., 2010), key elements, scientific themes, and priorities have remained throughout the EarthScope project.

The workshop agenda included two keynote presentations by invited speakers. The first, by Prof. Paul Segall of Stanford University was entitled "Looking back: Scientific discoveries, novel applications, and lessons learned." The second, by Prof. Michael Bevis of Ohio State University was entitled "Looking forward: Challenges and questions for the future." Both presentations are available on the UNAVCO website developed for the workshop (http://www.unavco.org/community/meetings-events/2014/pbo-future-14/pbo-future-14.html). In addition to these keynote presentations, community members who participated in the workshop were asked to submit a 500 word abstract to define goals and priorities related to the future of PBO. UNAVCO staff provided extensive backup materials for the workshop participants, including the *Workshop Charge and Objectives*, *EarthScope and NSF EAR Data Policies*, the revised *EarthScope Science Plan (2011)*, the NRC report on *Precise Geodetic Infrastructure*, the *NROES 2011 report*, the *Grand Challenges in Geodesy,* the Community Workshop proposal to NSF to fund this workshop, and *GAGE Facility Proposal* submitted by UNAVCO to NSF in 2012. Several UNAVCO staff members also gave presentations related to current state of funding for the EarthScope PBO since Operations and Maintenance Phase I commenced in October 2008 and technical details related to the current status of the GPS, BSM, and Geodetic Data Products from PBO. These presentations are also available on the workshop website.

Most of the workshop was organized around scientific and technical breakout sessions. Each breakout session involved three breakout groups and was divided into three periods. The participants were divided into three approximately equal-sized groups and asked to attend each working group in one of the three periods. Within each period, each group selected a scribe and presenter to report back to the assembled workshop participants. The first breakout session was entitled "*Identify key values and scientific priorities for immediate and longer term future,"* with three working groups: 1) Interseismic deformation and long-term-tectonics; 2) Earthquake processes and aseismic deformation; and 3) Other observations and data products from PBO. The second breakout session built upon the results of the first, and was entitled *"Plan and scenario development: Optimizing infrastructure and data products for scientific priorities; alternative revenue streams; implementation."* This breakout session also featured three working groups: 1) Sensors and instrument clusters; 2) Coordination with key stakeholders; and 3) Data products: tools, users, and uses. The workshop organizing committee met formally at the end of each day to review and assemble written documentation from each working group. All working group reports are available on the workshop website (see above).

Review of EarthScope Science goals related to PBO

In the first session of the Breckenridge workshop, participants reviewed and expanded on the 2011 EarthScope Science Plan. Three major thematic areas were identified: 1) Earthquakes and tectonics; 2) Earth System Science; and 3) Volcanic processes. Specific scientific problems and remaining questions, targeted processes, and recommendations are identified within each of these three major themes and these are shown as a bulleted list below. Participants identified which of the core scientific problems outlined in the EarthScope science plan have already been addressed well or can be given the data in hand now or that will be in hand by 2018, and which problems remain significantly unresolved and would benefit most from ongoing collection of new data. The lists are ordered according to the general consensus of priority for future investigations within each theme.

Earthquakes and Tectonics

- Observing multiscale (*i.e.* in both time and space) solid Earth transients
- Observing the effects of secular changes to fault and crustal properties (*e.g.* do fault coupling, locking depth, and frictional properties change through the earthquake cycle? Or in response to large events?)
- Integrating observations of SSEs, ETS, other transient stresses (*e.g.* from tides and hydrology) and related phenomena into fault loading and rupture nucleation models
- Using surface observations to constrain rheology
- Extending geodetic observations offshore; extending observations to multiple tectonic boundary zones to capture important phenomena

Earth System Science

- Observing solid Earth responses to hydrologic, oceanic, and atmospheric loading
- Observing glacier dynamics and mass change, postglacial rebound, as well as relative and absolute sea level change
- Providing GNSS data streams for weather *nowcasting*, forecasting, climatology, and modeling *over a range of time scales*
- Observing hydrological signals in the atmosphere and the critical zone
- Improving observations of space weather

Volcanic Processes

- Constraining physical models of magmatic systems
- Detecting surface response to unrest, impending and ongoing eruptions, and post-eruptive processes

Each of these key thematic areas has detailed recommendations and specific science questions that may be addressed using EarthScope PBO assets through the end of the current Cooperative Agreement between NSF and UNAVCO that supports the GAGE Facility and beyond 2018. Please see the materials provided on the workshop website.

Some scientific problems that motivated the original deployment of PBO did not receive high priority on these future-looking lists. For example, one major original goal of the PBO was to provide measurements of the secular velocity field across the deforming part of North America, which could be used to study large-scale tectonic deformation. There remain a number of interesting problems that still need to be answered about the active tectonics of North America, but the workshop consensus was that 10-15 years of continuous GPS data is adequate to provide the velocity field for most of the deforming part of the continent, at least in places where the motions observed thus far have been steady in time and significant transients or earthquakes are judged to be unlikely. ***Future studies could focus on regions that were relatively sparsely covered by PBO, or on the non-linear components of time series to study transient deformation, seasonal and interannual variations in the hydrologic cycle, or other problems that are not steady in time.***

Other scientific problems from the original motivation for the PBO have only grown in importance over time. This is particularly true of the range of scientific problems that are associated with transient time-dependent motions. The observed spectrum of fault transients, volcanic transients, and hydrological/cryospheric transients is now known to be far richer than was ever imagined 15 years ago. For many of these problems, existing data do not sample densely enough in space or long enough in time to allow us to fully address the scientific questions. The discovery of longer-duration transients (*i.e.* transients of up to roughly a decade in length have now been observed) also raises the question of what is the upper limit on transient timescales? Can fault behavior vary on a timescale of decades?

To date, the main tectonic transients observed within the PBO network have come from subduction zones (*e.g.* Cascadia and Alaska), and it is likely that volcanic deformation is never truly steady in time. Also, significant post-seismic transients have been observed within the San Andreas fault system and around the Denali fault in the form of post-seismic deformation from major earthquakes such as the 2002 Denali fault earthquake and the 2010 El Mayor-Cucapah earthquake. The latter occurred just outside the original PBO footprint, but is responsible for significant time-dependent deformation within part of the PBO. Significant transients can be expected from future large or great earthquakes that may occur within the network. A variety of hydrologic and cryospheric transients have been observed, including some that involve the majority of the PBO network.

Problems like developing and operating an Earthquake Early Warning (EEW) system combine scientific research and meeting broader societal needs. The ongoing west coast EEW research efforts, like many other such efforts, depend on the existence of dense PBO geodetic instrumentation for their future operation. The question of how to prioritize specific research questions relative to longer-term operational monitoring for EEW, volcanic monitoring, measurements of atmospheric water vapor, water resources, or other uses of the PBO data was discussed in both of the breakout sessions. The multi-disciplinary of the PBO network is a strength that should be used to develop a strategy for multi-agency long-term support of PBO or a part of PBO to meet stakeholders' needs.

Primary issues of concern for PBO identified by workshop participants

1. Longevity and continuity of GPS station time series with the fewest possible equipment changes or disruptions are essential to nearly every scientific question and broad theme outlined above.
2. Maintaining the capability of PBO to measure transient deformation on a variety of spatial and temporal scales is a very high priority.
3. Spatial density of current PBO stations is not optimal for all future needs: some regions are sparse and others are extremely dense. For example, southwestern Oregon needs additional resources to improve characterization of ETS initiation and propagation in Cascadia and more stations in the Cook Inlet region of Alaska are needed to measure the large slip transients that have been observed there. In addition, off-fault strain is not fully characterized, and this is critical for seismic hazard analysis, integrated deformation budgets, and better understanding of fault mechanics. Some sections of the San Andreas system, however, have very dense clusters of PBO sites that (so far) are measuring simply linear motion with time.
4. Non-tectonic observations required by other scientific communities require a more uniform distribution of stations than the present PBO distribution, in particular those related to numerical weather simulation, climatology, hydrology, ionospheric studies, and water resource management. These applications need only a portion of PBO where it is dense, but some require more uniform measurements over the entire continent, including the central and eastern US.
5. Stations are sparse along the Aleutian arc and this makes it difficult to fully characterize interseismic deformation, possible strain accumulation, and coupling along the plate interface. Expanded and upgraded stations in this region will allow better reconciliation of seismicity and deformation as well as possible along-strike variations in the physical properties of the subduction zone and how these may affect dynamics. Improved station distribution in Alaska would allow more quantitative comparison with Cascadia and other more densely instrumented subduction zones globally.
6. The distribution and variation in surface water, snow, and groundwater loading coupled with atmospheric water vapor must be fully characterized to better constrain solid Earth processes. To this end, additional and improved constraints on the vertical component of the deformation field are required. New and improved processing tools and methods to obtain the most precise vertical velocities are essential to support these key science targets.
7. Additional GNSS observations promise to reduce position estimate errors, but these improvements are likely to be for sub-daily (*i.e.* near-real-time) solutions. In order to support the broadest number of stakeholders, and to take advantage of enhanced GPS and other satellite constellations, however, PBO needs to modernize its existing GPS-only infrastructure.
8. PBO surface deformation observations are required in order to take full advantage of current, new, and soon to be launched InSAR missions, whose goals are to examine and document volcanic and magmatic interaction and activity. Therefore there is a need to maintain research capacity to examine these processes beyond 2018. GPS and InSAR observations are synergistic and allow robust atmospheric correction and also provide data to fill in gaps. Even with improved InSAR coverage, 3-D deformation measurements at high temporal resolution from GPS will be required.

THE FUTURE OF PBO: RECOMMENDATIONS

Immediate recommendations for PBO operations

All of the detailed reports from three working groups that were convened during the breakout sessions are available on the workshop website (http://www.unavco.org/community/meetings-events/2014/pbo-future-14/presentations/presentations.html) under the Workshop Presentations link. Some of the key recommendations from the workshop for the short term *(i.e.* pre-2018) are summarized below:

1. Regularize maintenance and service schedules in regions where deformation transients are "less likely" (resulting in fewer trips to the field but reduced uptime).
2. Identify key regions (*e.g.* Cascadia) for immediate maintenance response where deformation transients are "more likely."
3. Identify PBO GPS and BSM sites with unacceptable data quality and move to these to another location or decommission (or do not renew permits).
4. Otherwise, do not decommission GPS sites prior to 2018.
5. Defer all maintenance of low-value borehole installations, or divest the sites only producing seismic data to regional seismic networks; prioritization would need to occur based on additional community input.
6. Encourage NSF leadership to aggressively pursue federal agency cooperation at the highest possible level.
7. Explore all avenues for "upreach," or interaction with a range of stakeholders with broad interests or authority related to geodetic data streams.
8. Seek partnerships with other state and federal agencies to meet additional costs for earthquake early warning and other GNSS-enabled, high-rate, RT applications.
9. Explore adoption of O&M costs or collaborative sponsorship of some sensors or sets of sensors by other entities.
10. Leverage education and outreach (ECE) efforts to further engage the public and stakeholders in UNAVCO activities.
11. Upgrade stations to real-time where cost-effective communications and adequate power are already available.
12. Upgrade a limited number of GPS stations to full GNSS in strategic target areas of high scientific value, those that support large user communities, and for collection of data for UNAVCO and community-driven development and testing efforts.
13. Make immediate investments in the data management work flow to allow more data integration and sharing.
14. Expand UNAVCO's ability to ingest and fully integrate or serve as a portal for data from non-PBO sources.

Long-term recommendations and scenarios for PBO

Funding for EarthScope PBO has remained flat during GAGE Year 1 (2013-2014) and Year 2 (2014-2015) after an initial cut of ~9% from the FY2012 base level. Current funding is $9.3M per year and supports ~37 FTE for field engineering to support routine scheduled and unscheduled maintenance and operations, data archiving, and data processing activities. The PBO Director and chair of the workshop organizing committee,

G. Mattioli, presented historical data on PBO funding from 2008, the start of O&M Phase I, along with three different scenarios for the future of PBO beyond 2018. The total funding to support PBO, including the ARRA funding to support the real-time upgrades to Cascadia, was $53.7M ($10.7M/yr average) from 2008-2013. The current (and anticipated) funding under GAGE is $46.4M ($9.3M/yr average) for 2013-2018.

The workshop participants considered recommendations for action in three potential scenarios for post-2018 funding: 1) 25% reduction in core support from NSF with no additional funds from other sponsors; 2) flat funding at $9.3M (in 2012 dollars) regardless of source; and 3) 25% increase in support from all possible sponsors. The impact on the total number of GPS stations in PBO is shown below in Figure 2 for these scenarios. In particular, a downward step function in funding at 2018 probably requires removing some stations prior to 2018, because the average cost of removing a station is close to the cost of operating the station for one year.

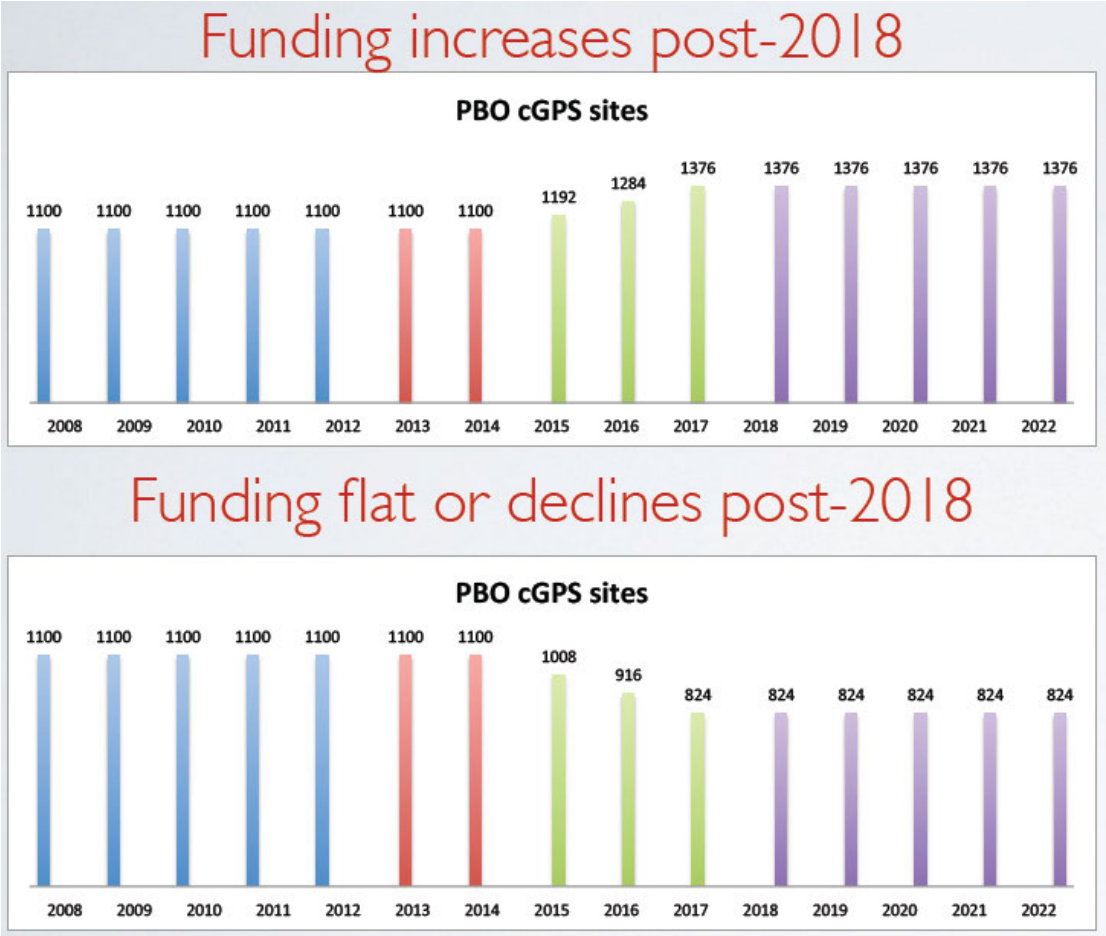

Figure 2. Impact on the total number of continuous GPS stations in the PBO given a 25% increase in funding from all possible sponsors (top panel) or flat-funding or a 25% decrease in funding from NSF (bottom panel). The reason the number of sites decreases under a flat-funding scenario is because of the need to replace aging Trimble NetRS instruments and to increase the number of real-time stations, both of which require resources.

PBO was recognized by workshop participants as a critical national geodetic resource in addition to being a world-class scientific research facility. Nevertheless, the aging PBO infrastructure – which was planned for partial replacement and upgrading (*i.e.* increased number of real-time and GNSS-capable stations) in GAGE, is not possible as planned under current budget scenarios. In order to meet current budget constraints, PBO management has mandated that O&M costs be reduced, which means possible loss of data and likely will decrease sensor uptime in the long run.

PBO is now viewed as a "utility" by many critical stakeholders, who do not directly support its ongoing O&M or any costs for new capital equipment; some stakeholders need upgrades to PBO sites to make fuller use of this utility.

Stakeholders who depend on the continued operation of parts of the PBO include the USGS (Earthquake Hazards Program and Volcano Hazards Program), NOAA (both the National Geodetic Survey and National Weather Service), NASA (ARIA project, earthquake early warning pilot projects, future mission calibration and validation), state Departments of Transportation and/or Natural Resources, and the land surveying community in most western states. Currently or in the longer term, some of these stakeholders require enhancement to the current PBO stations, because they require real-time or near-real-time data and/or observations from additional GNSS systems like Galileo or GLONASS. This highlights the need for high-rate and real-time data streams and archived products to position UNAVCO for future funding and relevance (*e.g.* for both NSF and non-NSF projects).

Once additional GNSS systems become mature, adding multi-GNSS capability will directly benefit all users of the data, including enhancing the precision and accuracy of the measurements to address the original goals of NSF. In fact, hardware upgrades are needed simply to maintain reliability and all hardware sold today is multi-GNSS capable, so the only question is whether or not to pay for other GNSS systems to be enabled. By 2018, we can expect that multi-GNSS observations will clearly be worthwhile and needed to keep PBO at the forefront of measurement capabilities, although today the impact of other satellite constellations remains relatively minor.

Upgrades to real-time capability will need to be prioritized carefully, as this can be expensive. For example, the estimated cost to renew and upgrade all PBO Alaska stations to real-time would be considerable ($2.1M one-time funds and $1.0M/yr ongoing costs using current technologies). Therefore, unless substantial new funds become available for real-time upgrades, it is likely that only selected stations should be upgraded, and the needs and degree of buy-in from other stakeholder agencies should be considered in these decisions.

There is no question that geodetic infrastructure and open data policies, like those of the PBO, are vital to multiple communities and agencies – but how will these be sustained? The workshop participants recognized that the NSF (and NASA/USGS to a lesser degree) has made the initial investment - but the need for sustaining partners remains paramount through the end of the EarthScope project in September 2018 and beyond.

Impact of material loss (*i.e.* de-scoping the NSF EarthScope project) or degradation of PBO assets (both physical and human) on stakeholders who are charged with Safety of Life warnings, Initial Crisis Response, and development and maintenance of state and national Spatial Reference Network systems needs additional evaluation and mitigation.

In order to position PBO for the future, some key long-term actions were proposed:

1. Develop a strong GNSS (*i.e*. GLONASS) + real-time streaming pilot project
2. Develop a strong multi-timescale data products pilot (*e.g.* Mt. St. Helens)
3. Develop a pilot project to stream multiple sensor outputs and develop a flexible, generic data stream hardware + software system (leverage existing systems developed by Ocean Observing Initiative)
4. Develop pilot data products for nontraditional users
5. Build a management framework for institutionalizing adoption and sponsorship of sensors
6. Collaborate with NASA for optimization and validation of NISAR and calibration and validation for SMAP
7. Adopt a community-developed prioritization for BSM and LSM stations
8. Explore alternative models for funding the BSM and LSM networks
9. Explore and test alternative methods of GPS (GNSS) data transmission

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LIST OF APPENDICES

2014 Community Workshop:
The Future of PBO in the GAGE Facility (2013-2018) and After EarthScope

DoubleTree Hotel • Breckenridge, Colorado • September 22-24, 2014

Sunday - September 21

Scheduled Activities: Evening Dinner on own

Monday - September 22

8:00 - 8:45	Stroll in Breakfast	Columbine B
8:45	Meeting Kick off	Columbine A
8:45 - 9:00	Welcome message from UNAVCO President and Charges for Workshop	M. Miller, UNAVCO
9:00 - 9:30	Current state of affairs for PBO, context, and expected outcomes	G. Mattioli, UNAVCO
9:30 - 10:30	**KEYNOTE 1: Looking back: Scientific discoveries, novel applications and lessons learned** Invited Speaker - Paul Segall, Stanford University	
10:30 - 10:45	Light AM Break	Columbine B
10:45 - 11:45	**KEYNOTE 2: Looking forward: Challenges and questions for the future** Invited Speaker - Mike Bevis, Ohio State University	
11:45 - 12:45	Lunch	Columbine B
12:45 - 1:30	**TECHNICAL SUMMARY: - Cost of stations, health and data quality of stations and sensors, costs of demobilization, technical upgrade needs, status of other sensors**	UNAVCO Staff

1:30 - 3:00	**SCIENTIFIC BREAKOUT 1:** **Identify key values and scientific priorities for immediate and longer term future**	
Please attend two different working groups during SB1 & SB2	WG1: Interseismic deformation and long-term tectonics	Columbine A
	WG2: The earthquake cycle and aseismic deformation	Paintbrush
	WG3: Other observations and data products from PBO	Mt. Elbert B
3:00 - 3:30	Light PM Break and group photo (3:20pm)	Columbine B
3:30 - 5:00	**SCIENTIFIC BREAKOUT 2:** **Identify key values and scientific priorities for immediate and longer term future**	
	WG1: Interseismic deformation and long-term tectonics	Columbine A
	WG2: The earthquake cycle and aseismic deformation	Paintbrush
	WG3: Other observations and data products from PBO	Mt. Elbert B
5:00 - 6:00	Initial reports from working groups	Columbine A

6:00 - 6:45	Informal Reception and Cash Bar	Foyer Area
6:45 - 8:00	Dinner	Columbine B

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Tuesday - September 23

8:00 - 8:45	Stroll in Breakfast	Columbine B
8:45 - 9:00	Brief report/summary from Day 1	Organizing Committee
9:00 - 10:30	**SCIENTIFIC BREAKOUT 3:** **2018 and beyond GAGE: Identify key values and scientific priorities for the future of PBO after EarthScope**	
Choose which WG you would like to participate in and discuss the topics that came out of yesterday's breakouts	WG1: Interseismic deformation and long-term tectonics	Columbine A
	WG2: The earthquake cycle and aseismic deformation	Paintbrush
	WG3: Other observations and data products from PBO	Mt. Elbert B
10:30 - 11:00	Light AM Break	Columbine B
11:00 - 12:00	Plenary discussion of science breakout sessions *Panel with representatives from each working group*	Columbine A
12:00 - 1:00	Lunch	Columbine B
1:00 - 2:30	**PARALLEL BREAKOUT GROUPS** **Plan and scenario development: Optimizing infrastructure and data products for scientific priorities; alternative revenue streams; implementation**	
Randomly assigned participation, each group will discuss in parallel	WG1: Sensors and instrument clusters	Columbine A
	WG2: Coordination with other key stakeholders	Paintbrush
	WG3: Data products: tools, users, and uses	Mt. Elbert B
2:30 - 3:00	Reports from Parallel breakout goups	Columbine A
3:00 - 4:00	Light PM Break	Columbine B
3:00 - 4:00	Group leaders prepare summary recommendations and strawman plan	Columbine A
4:00 - 6:00	**Presentation, dicussion and modification of recommendations and strawman plans:** 4:00 - 5:00: Scientific Targets for present , 2018 and beyond 5:00 - 6:00: Implementation, desired instrumentation, and targets for alternative revenue steams	
6:00 - 6:45	Informal Reception and Cash Bar	Foyer Area

Wednesday - September 24

8:00 - 9:00	Stroll in Breakfast	Columbine B
9:00 - 10:00	**Group Discussion:** Updated recommendations and prioritization plan	Columbine A
10:00 - 10:30	Wrap-up, dicussion of future planning process and key milestones	
10:30 - 10:45	Light AM Break	Columbine B
10:45 - 12:00	Conclusion, departures and the Workshop Committee write draft report	

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Registrants by State

State	Count
CA	21
CO	13
WA	5
VA	3
TX	4
AK	2
OR	2
HI	2
IN	1
MA	1
MD	1
MT	1
NM	2
NV	1
NY	2
OH	1
PA	2
AZ	1
BC	1
UT	1
DF	1

Registrants by Country

Country	Count
USA	66
Canada	1
Mexico	1

Registrants by Position Type

Position Type	Count
Regular faculty (college or	23
Researcher or research faculty	17
UNAVCO Staff	14
Other	8
Student - Graduate	3
Post-doctoral researcher	2
Sponsor	1

Registrants by Other Position Type

Other Position Type	Count
Federal Government	1
Private Sector Consultant	1
Project Scientist	1
Public Utility	1
Research Assistant	1
Scientific Administration, Program	1
Senior Land Surveyor	1
Space Weather Physicist	1

Registrants by Highest Degree

Highest Degree	Count
Doctoral Degree	49
Masters Degree	7
Bachelors Degree	4
Associates Degree	2

Registrants by Highest Degree Year

Highest Degree Year	Count
1972	1
1973	1
1975	1
1979	1
1981	4
1982	3
1983	2
1987	1
1988	3
1989	3
1990	2
1992	1
1993	1
1994	1
1995	1
1996	2
1997	2
1998	1
1999	4
2000	2
2001	4
2002	2
2003	2
2004	1
2005	3
2006	3
2009	1
2010	1
2011	2
2012	4

Highest Degree Institution

Institution	Count
Caltech	3
CCAF	1
Chapman University	1
China University of Geosciences	1
College of the Redwoods, Eureka	1
Columbia University	1
Cornell University	2
CWU	1
Free University Berlin	1
University of Alaska Fairbanks	1
M.I.T	4
Northwestern University	1
Oregon State University	1
Princeton University	2
San Diego State University	1
Simon Fraser University, Canada	1
Stanford	5
The Ohio State University	1
UC Berkeley	1
UC San Diego	1
UCSD, Scripps Institution of	1
UNAVCO	1
Univ. of Rhode Island, Graduate	1
Univeristy of Colorado, Boulder	4
University of Alaska	1
University of Alaska Fairbanks	2
University of Arizona	1
University of B.C.	1
University of California San Diego	1
University of California, Berkeley	1
University of Durham, UK	1
University of Hawaii	2
University of Houston	2

University of Miami	2
University of Oregon	1
University of Oxford	1
University of Utah	3
University of Wisconsin-Madison	3

Principal Count

Count
40

NSF Funding Count

Count
45

NASA Funding Count

Count
32

USGS Funding Count

Count
21

NOAA Funding Count

Count
8

Other Funding Count

Other Funding	Count
DoD, State and local agencies	1
DOE, EPA	1
Federal Highway Administration	1
Geological Survey of Canada	1
Gordon and Betty Moore	1
Industry	1
NGA	1
ONR, USAID	1
Panama Canal Authority (ACP)	1
Private company	1
private foundations	1
Regional Public/Private Cooperative	1
SCEC	1
US Taxpayers	1
Utilities (Edison, PGE)	1

Registrants by Gender

Gender	Count
F	15
M	49
N	4

Registrants by Citizenship

Citizenship	Count
N/A	9

Non US Citizen	3
Permanent Resident	4
US Citizen	52

Registrants by Ethnicity

Ethnicity	Count
Hispanic Or Latino	1
N/A	20
Not Hispanic Or Latino	47

American Indian Alaska Native	Count
	0

Black or African American	Count
	0

Native Hawaiian/Pacific Islan	Count
	1

Asian	Count
	6

Caucasian	Count
	49

Registrants by Science Application

Application	Count
General/Atmosphere / Ionosphere	4
General/Cryosphere	2
Solid Earth/Earthquake Deformation Cycle	15
General/Geo-Technical	5
General/Geodesy	19
General/Geodesy Education	5
Solid Earth/Glacial Isostatic Adjustment	1
General/Global Environmental Change	3
General/Hydrology	5
Solid Earth/Magma-Induced Deformation	5
General/Natural Hazards	15
General/Oceans	1
Solid Earth/Paleoseismology and Neotectonics	3
Solid Earth/Tectonic Plate Motion	8

Registrants by Science Technique

Science Technique	Count
LiDAR/Airborne swath mapping	3
Borehole Geophysics/Borehole Strainmeters	7
General/Education	5
General/Equipment purchase	7
General/GeoEarthScope geochronology services	1
General/GPS data collection, data products, and	17
General/InSAR	9
Borehole Geophysics/Strainmeters	7
LiDAR/Terrestrial laser scanning	2
Borehole Geophysics/Tiltmeters	5