2013-2018 UNAVCO Community Proposal

Geodesy Advancing Geosciences and EarthScope: The GAGE Facility

UNAVCO

Volume 1

Project Description, Scientific Justification and Budget Plan

2013 - 2018

UNAVCO COMMUNITY PROPOSAL

GEODESY ADVANCING GEOSCIENCES AND EARTHSCOPE:

THE GAGE FACILITY

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Project Summary

UNAVCO provides support for geodesy, related research, and education and workforce training with broad societal benefits. This proposal seeks ongoing support for UNAVCO's advancement of cutting-edge community-based geodetic research around the world. NSF-funded geodesy investigators are active on every continent, across a broad spectrum of the geosciences, and facilitated by data and engineering services that, in this project, will be unified under a single Geodesy Advancing Geosciences and EarthScope (GAGE) Facility. The UNAVCO Consortium of universities has operated UNAVCO, Inc., home of two major facilities under Cooperative Agreements with the National Science Foundation. The Plate Boundary Observatory (PBO), an integrated set of geodetic networks, forms the world-class geodesy component of EarthScope. The UNAVCO Facility provides engineering and data services primarily to NSF-funded investigators who use terrestrial and satellite geodetic technologies in their research, and network operations to support community GPS networks and NASA's Global GNSS Network (GGN). NSF's Office of Polar Programs (OPP) funds facility support for PI geodesy research and GPS networks in Greenland and Antarctica, while NASA funds support the GGN underlying the internationally coordinated reference frame products that make high-precision geodesy possible. UNAVCO maintains critical stations within the GGN and supports the activities of the IGS Central Bureau.

The GAGE Facility will integrate and extend these capabilities under a single award, towards one goal: to create efficiencies in operation, reporting, and sponsor oversight, allowing UNAVCO to meet the needs of a vigorously growing and rapidly diversifying science community despite expected federal resource constraints from 2013 to 2018. The proposed GAGE Facility leverages the recent UNAVCO reorganization to better serve the UNAVCO community and all of its stakeholders. This proposal describes a diverse set of science and broad impact grand challenges that face geodesy, identifies UNAVCO's critical role in supporting advancement of each, and defines the facility's operational, management, and budget plan for the next five years. The total request to support the GAGE Facility from all sponsors is $92 million over five years. The plan includes a diverse set of new initiatives and directions that cut across all levels of the organization. Some of the larger efforts include: (1) the renewal and augmentation of PBO for real-time data flow and as a nucleus for a Network of Geodetic Networks spanning the western Americas; (2) the development of cyberinfrastructure to enable enhanced data discovery, access, and interaction; and (3) enGAGE, an online portal that extends UNAVCO's web presence and technical resources in a flexible and sustainable framework.

INTELLECTUAL MERIT

For more than two decades, space-based geodetic observations have enabled measurement of the motions of the Earth's surface and crust at many different scales, with unprecedented spatial and temporal detail and increased precision, leading to fundamental discoveries in continental deformation, plate boundary processes, the earthquake cycle, the geometry and dynamics of magmatic systems, continental groundwater storage, and hydrologic loading. Space geodesy furthers research on earthquake and tsunami hazards, volcanic eruptions, hurricanes, coastal subsidence, wetlands health, soil moisture, groundwater distribution, and space weather. Of particular importance are contributions to the understanding of processes related to global warming and climate change, including sea level rise and dynamic changes in glaciers and large polar ice sheets. Collectively, these studies integrate discovery, relevance, and education.

BROADER IMPACTS

The GAGE Facility will build on UNAVCO's strong record of facilitating research and education in the geosciences and geodesy-related engineering fields. An international community of geodesists uses 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). The discoveries of virtually every global geodesy study will be supported by some aspect of this project. A larger international community of surveyors and civil engineers access UNAVCO data streams, software, and on-line resources daily. In a global society that is increasingly technology-dependent, consistently risk-averse, and often natural resource-limited, communities need geodetic research, education, and infrastructure to make informed decisions about living on a dynamic planet. Using GAGE Facility services, 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 warning applications. Further, this award will directly support high-school teacher training. Under ancillary projects and partnerships, UNAVCO is advancing and modernizing undergraduate curriculum with relevant science applications; its summer undergraduate internship RESESS Program is recognized as a national model for increasing the diversity of students entering graduate school in the geosciences. Lastly, UNAVCO will establish expanded efforts to inform policy with relevant science, and engage more widely in international partnerships that build mutual capacity for authentic collaboration.

2013 - 2018 UNAVCO Community Proposal:

Geodesy Advancing Geosciences and EarthScope: The GAGE Proposal

1. Introduction

Since 1984, the UNAVCO university consortium has operated facilities to support geodesy research with core sponsorship from NSF and NASA, and additional support from NOAA, USGS, and others under various organizational structures. In 2001, the consortium established UNAVCO, Inc., an independent non-profit organization that undertook the construction and operation of Plate Boundary Observatory (PBO - the geodetic component of EarthScope) and transitioned support of investigator science by the UNAVCO Facility to the new management structure in 2003. Under this structure, UNAVCO has supported the scientific community for nearly a decade with the development, installation, and maintenance of geodetic networks, hardware, software, a free and open data archive, data products, cyberinfrastructure, and the necessary technical expertise to further cutting edge scientific research in this transformational field. At the same time, UNAVCO has established itself as a resource to the NSF Large Facilities Office for responsive facility management.

The geodesy community increasingly demands the integration of high-precision three-dimensional geodetic data sets at all spatial and temporal scales, to further our understanding of the Earth. Over the next decade, we anticipate that geodesy will be a major driver – perhaps *the* major driver – of advances in Earth System Science, by illuminating the interactions among the lithosphere, cryosphere, hydrosphere, biosphere, and atmosphere at local, regional and global scales.

Today, in collaboration with its Member institutions, UNAVCO maintains and operates a globally distributed geodetic observing system consisting of a combination of nearly 3,000 continuously operating GPS, strainmeter, tiltmeter, and seismic sensors. In addition, UNAVCO is the primary provider of TLS and GPS instrumentation and training to support NSF-funded PI field projects.

Throughout this proposal, we refer to the UNAVCO community, consortium, and facilities (both the core Facility and PBO) as “UNAVCO.” The proposal presented here for the 2013 to 2018 period differentiates plans for the GAGE Facility and its activities from those of the UNAVCO consortium, which is a community of scientists with associated university membership, governance, and oversight of the non-profit corporation, UNAVCO, Inc. and its management.

This proposal builds on a variety of community-wide and UNAVCO governance-vetted planning efforts including the *2011 – 2015 UNAVCO Strategic Plan [UNAVCO, 2011], A Foundation for Innovation: Grand Challenges in Geodesy [Davis et al.,* 2012], reports from the National Academies and numerous community workshops, which are publicly available and appropriately referenced in the text.

The UNAVCO consortium operates and oversees facilities under the organizational structure of UNAVCO, Inc. in order to advance its collective Strategic Vision:

We challenge ourselves to transform human understanding of the changing Earth and its hazards by enabling the integration of innovative technologies, open geodetic observations, and research, from pole to pole.

In order to advance understanding of Earth processes, two major scientific challenges face UNAVCO’s research and education community:

- To understand the ***dynamic evolution*** of the lithosphere, cryosphere, hydrosphere, and atmosphere on temporal scales spanning seconds to millennia.
- To investigate the ***processes*** that control natural hazards, including earthquakes, tsunamis, volcanic eruptions, and long term changes in climate, ice mass, global sea level, and coastal subsidence.

1.1 THE UNAVCO COMMUNITY

UNAVCO, a non-profit, university-governed consortium, facilitates geoscience research and education using geodesy. The consortium includes 104 US academic Members, nearly all of which are degree-granting institutions, that participate in its governance and science community (Figure 1-1). Another 78 Associate Members include organizations that share UNAVCO's purpose at home and abroad, giving UNAVCO global reach in advancing geodesy (Figure 1-2).

More than 600 individuals from around the world formally interact with UNAVCO on an ongoing basis through its scientific collaborations, governance, Facility science planning and engineering services, information services, and its Education and Community Engagement program and contributing to professional development of UNAVCO's employees.

1.2 GOVERNANCE AND MANAGEMENT OF UNAVCO

Governance and management of UNAVCO provides the interface between the scientific community, funding agencies, and UNAVCO programs (Figure 1-3).

A research community actively engaged in governance ensures that research requirements drive the development of UNAVCO facilities, focuses appropriate talent on common objectives, and allows scientists to do science instead of operating geodetic networks and infrastructure. Community involvement supports broad participation and effective oversight of UNAVCO programs. Each year, more than 50 scientists, primarily drawn from the 104 Member institutions, participate in the governance and oversight of UNAVCO. These scientists work with a professional staff led by the President and Senior Management Team: the Directors of Business Affairs, Geodetic Infrastructure, Geodetic Data Services, and Education & Community Engagement.

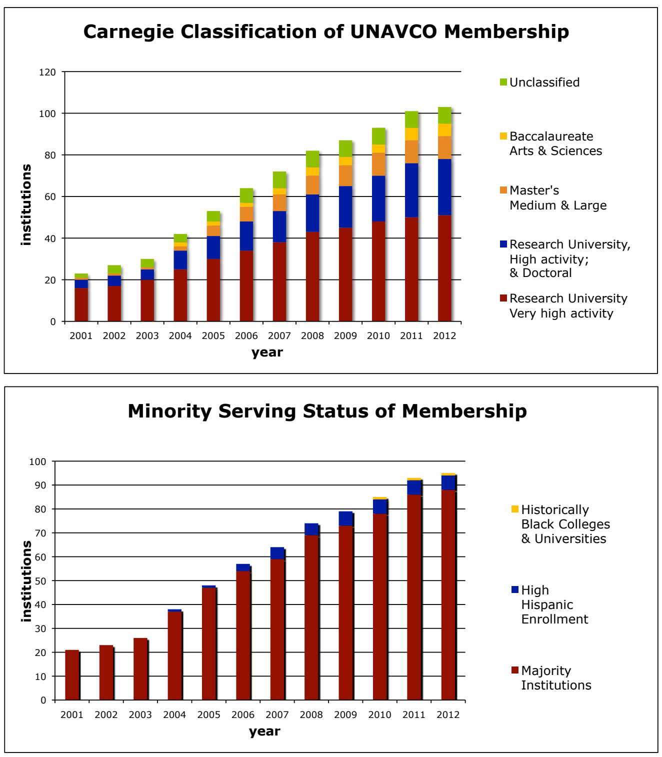


Figure 1-1. UNAVCO Membership profile. Universities and affiliated research organizations make up UNAVCO's governing membership. Carnegie classifications demonstrate UNAVCO Membership's institutional diversity and reach, including major research universities, comprehensive Master's granting universities, as well as a growing base of selective liberal arts colleges with research-active faculty and students. Participation by Minority Serving Institutions has steadily increased. Expanded activities in hydrogeodesy and terrestrial laser scanning have broad application and are expected to lead to continued growth and diversification.

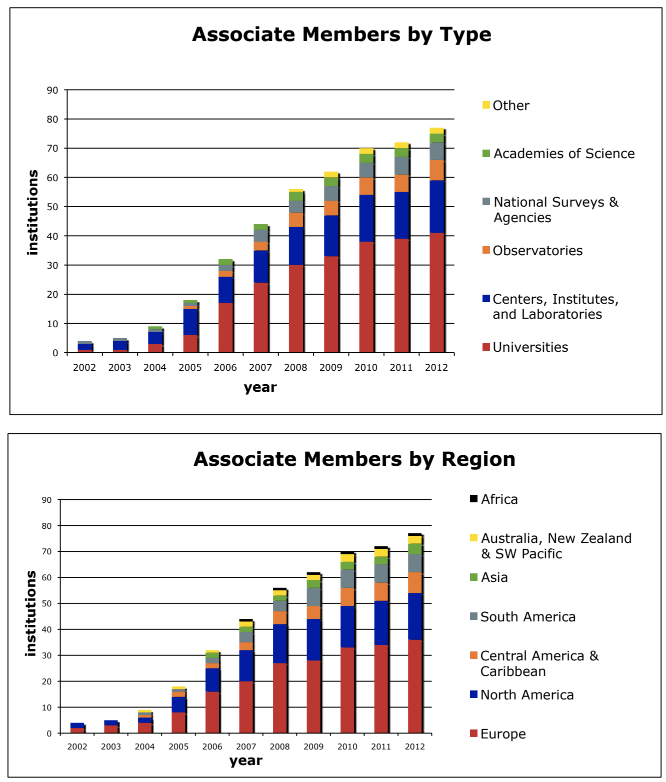


Figure 1-2. UNAVCO Associate Member profile since incorporation. Institutions are found on every continent except Antarctica, although UNAVCO investigators and staff are very active there. The Associate Members share UNAVCO's purpose and form a global community for scientists who may otherwise be geographically or professionally isolated. This community engages in international partnerships essential to the advancement of global geodesy.

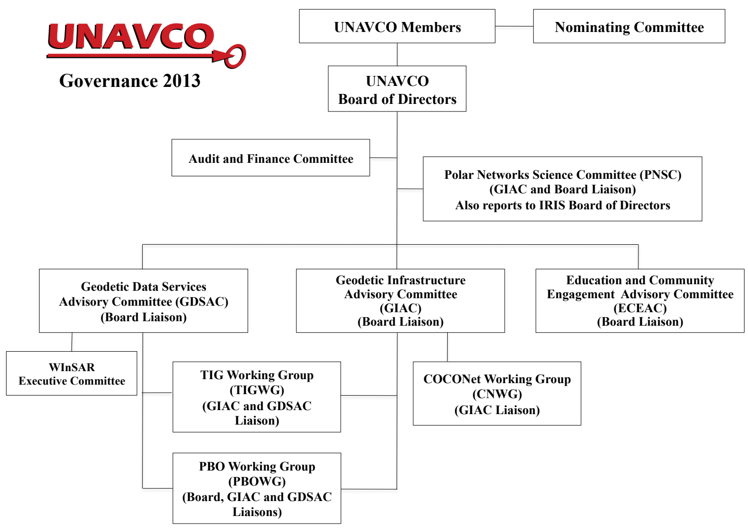


Figure 1-3. Governance by Design: Inclusive, engaged, reponsive, effective. The governance structure, bylaws, policies and committee charters are tailored to ensure meaningful community representation, roles and responsibilities in UNAVCO governance. The new committee structure will align community expertise with UNAVCO's reconfigured programs to ensure responsive and proactive management. Working groups will ensure integrated advisory oversight for major projects that cut across UNAVCO's program structure. TIG = Terrestrial Imaging Geodesy.

The UNAVCO community, using the expertise, strengths and passions of its members, sets the direction for its support of transformative geoscience research using geodesy and serves as the conduit for setting the community science agenda.

Finally, UNAVCO's Business Affairs staff provides NSF the fiscal, compliance, and legal structures for stable operation of facilities and programs, and a mechanism for developing financial support for the science vision of the science community.

1.3 STRATEGIC INVESTMENT IN NSF PRIORITIES

UNAVCO programs and facilities are managed in accordance with NSF strategies, as outlined in Empowering the Nation through Discovery and Innovation [2011-2016 NSF Strategic Plan, NSF 2011]. These priorities draw 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.

At the outset of the current NSF Cooperative Agreements in 2008, the UNAVCO Board of Directors, other key members of UNAVCO governance, community, and senior management developed a plan to guide strategic direction and ongoing resource allocation for managing UNAVCO. This strategic plan entitled *Positioning UNAVCO, Advancing Science through Geodesy [UNAVCO, 2011]* was revised during 2011 in preparation for the development of the GAGE Facility; UNAVCO's strategies (inset) closely align with NSF's own strategic goals to **Transform the Frontiers, Innovate for Society, and Perform as a Model Organization.** The UNAVCO Strategic Plan aids governance and staff in their efforts to set both short-term priorities and long-term directions for securing and allocating resources.

The plan also guides the GAGE Facility proposal in its goal of using resources freed by recently realized and planned efficiencies to respond to new initiatives. UNAVCO's six Strategy and Actions, outlined in the Strategic Plan, are woven throughout sections 2, 3 of the Project Description and the Budget Plan of this document.

As the operator of NSF's National Earth Science Geodetic Facility, UNAVCO coordinates with the NSF Division of Earth Sciences to maintain a program focused on the support of NSF-funded geodetic research, with specific focus on: NSF Earth Sciences, NSF Polar Programs, NASA Earth Surface and Interior, and shared support among other agencies such as the USGS and NASA for acquisition of InSAR data sets and similar efforts. From time to time, when the reach of a particular

UNAVCO Strategies

1. **Community & Science:** Continue to build the UNAVCO scientific community that uses geodesy by further developing core strengths in solid Earth science, while responding to emerging community needs and enhancing UNAVCO's visibility at home and abroad.
2. **Scientific Diversity:** Support expanded use of geodesy and integration of new communities across science disciplines.
3. **Support Services:** Provide effective and efficient support to the scientific community – through community planning, equipment acquisition and sharing, engineering and data services, and education and outreach activities.
4. **Technology:** Support innovative application of existing and novel technologies for the investigator community in funded science projects, education, and outreach.
5. **Resources:** Diversify the resource base in support of the science community.
6. **Leadership:** Continuously improve the leadership role and effectiveness of UNAVCO management and governance to support future growth.

program or resource can be expanded through a well-defined enhancement, NSF, NASA, USGS, and NOAA collaborations may augment core-funded program activities. Under its Cooperative Agreements, UNAVCO programs are first and foremost accountable to NSF's Earth Sciences Division. Additional activities are sometimes funded through independent awards that are carefully coordinated with the cognizant NSF program officer to best serve the needs of the UNAVCO community and to optimize resources on behalf of the sponsor. For example, the PBO O&M Cooperative Agreement was augmented in 2009 to upgrade an additional 250 GPS sites in Cascadia to high-rate, low-latency capability with NSF-ARRA funding, thus leveraging the initial NSF investment in PBO.The plan also guides the GAGE Facility proposal in its goal of using resources freed by recently realized and planned efficiencies to respond to new initiatives. UNAVCO's six Strategy and Actions, outlined in the Strategic Plan, are woven throughout sections 2, 3 of the Project Description and the Budget Plan of this document.

1.4 THE GAGE FACILITY

Until early 2012, guided by its two principal Cooperative Agreements, UNAVCO community research was supported by two UNAVCO programs that reflected our primary sponsors within NSF–EAR: the Plate Boundary Observatory and the UNAVCO Facility, funded by the EarthScope and Instrumentation & Facilities programs respectively. Under the PBO Cooperative Agreement, UNAVCO also accepted management responsibilities to sustain the San Andreas Fault Observatory at Depth (SAFOD) until NSF identifies a new organizational home. NSF-OPP Antarctic and Arctic Programs, and NASA also support the UNAVCO Facility Cooperative Agreement.

In anticipation of a single award for 2013 – 2018, UNAVCO undertook an internal reorganization to integrate activities that had been previously done in parallel, and to strategically and efficiently refine its community support and advisory committees (Figures 1-3, 1-4). The three new UNAVCO programs focus on: (1) the integration of observing systems and networks across techniques (Geodetic Infrastructure);

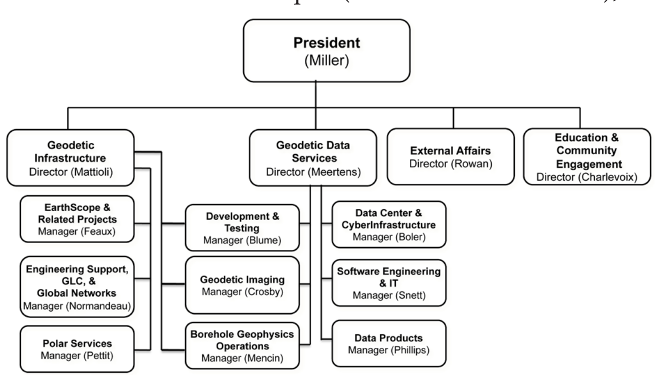


Figure 1-4. GAGE Facilty Organizational Chart.

(2) network data operations, enhanced community data products and cyberinfrastructure for data security, discovery and accessibility (Geodetic Data Services); and (3) education and outreach strategies, both within Education and Community Engagement, and integrated across the organization. Since 2008, UNAVCO's mission statement has articulated its commitment to the full integration of research support and education, which will be fully realized in the synergies among related activities under a single GAGE Facility plan. As of mid-2012, the staffing and organizational stage of program reorganization is now complete, with minor ongoing refinements to ensure efficacy, and new plans to achieve realignment of community governance (i.e. our advisory committees) by 2013.

Through its management strategies and practices, UNAVCO has built a reputation for responsive and innovative stewardship of public resources in support of community and sponsor priorities.

The GAGE Facility advances a broad geodesy community agenda, which includes:

- *supporting* EarthScope science as data sets mature with ongoing O&M and upgrades to the PBO Facility;
- *improving* data access and analysis with web services and cyberinfrastructure;
- *meeting demand* of burgeoning scientific applications for TLS technology and *advancing community interests* in LiDAR and InSAR data acquisition;
- *expanding* the use of autonomous integrated geodetic networks to new scientific targets, new geographic settings, and new science disciplines;
- *influencing* geodetic monument design and construction as well as open data protocols as GPS[1] networks continue to proliferate around the world;
- *broadening* access to real-time GPS and ancillary data streams from core geodetic networks;
- *bringing* emerging data sets and technologies to the attention of investigators in research areas such as atmospheric science and hydrology; and
- *focusing* attention and resources on education and community engagement to link these initiatives to the broader public, to educators who are teaching the next generation of scientists and citizenry, and to groups that are historically underrepresented in the Earth sciences.

UNAVCO management and governance aspire to operate GAGE as a model for next-generation science facility support: enabling the science community to advance research and its broad impact, strategically, effectively, and efficiently, while exploiting the full range of innovation and

1. The "Global Positioning System" (GPS), used throughout, relies on the US NAVSTAR satellite constellation for precision positioning applications. We restrict use of the more general term for all such constellations "Global Navigational Satellite System" (GNSS) to specific activities (GGN, Development and Testing) that are making early use of signals from other satellite constellations.

Table 1. Participation in UNAVCO Science Worskhop by discipline.

UNAVCO Science Workshop	2010	2012
	140 Participants	208 Participants
	11 Countries	11 Countries
Geodesy	87	91
Earthquake Deformation Cycle	63	62
Tectonic Plate Motion	55	45
Natural Hazards	51	58
Magma-Induced Deformation	29	22
Paleoseismology and Neotectonics	24	13
Glacial Isostatic Adjustment	21	14
Cyrosphere	17	15
Geodesy Education	17	24
Global Environmental Change	14	15
Hydrology	14	21
Geo-Technical	12	18
Geoid Determination	11	1
Atmosphere / Ionosphere	10	16
Oceans	6	5

cyberinfrastructure solutions for investigator and community science.

This proposal identifies the infrastructure support needed to sustain the scientific inquiry of a diverse, vibrant, and growing community of investigators who use GPS, geodetic imaging, strain, and other geodesy technologies to study the solid Earth and its fluid envelopes (Table 1).

1.5 THE GEODESY TOOLBOX

For more than twenty years, the observation and understanding of Earth's time-varying shape, gravity field, and rotation has benefitted from rapid technological advances that provide scientists with an unprecedented suite of tools to investigate these changes. The results include a wealth of applications for cutting-edge research in related scientific fields as well as many transformational applications in geophysics. These applications have far reaching impact on advancing fields of knowledge such as earthquake physics, volcanology, geodynamics, oceanography, atmospheric and climate science, hydrology, glaciology, geomorphology, ecosystem science, physics, and astronomy. In addition to these research applications, geodesy is used to study natural hazards and is systematically building a foundation for rapid detection of earthquakes, tsunamis, landslides, volcanic eruptions, and severe storms. The UNAVCO Community Toolbox in the accompanying textbox highlights the technology used to advance out understanding of Earth processes with benefits for research, education, and society.

1.6 STRATEGIC PARTNERSHIPS

UNAVCO's mission and capabilities are unique, yet highly collaborative; all activities, sponsors, and many international partnerships. Given this breadth, there are many lenses that one could use to categorize UNAVCO partnerships. Fundamentally, as NSF's Earth Science National Geodetic Facility, GAGE will sustain the coordinated presence for the geodesy community in its interactions both at home and abroad with shared and overlapping geoscience research and education goals (Figure 1-5).

At one end of the spectrum are some very practical and transactional relationships and peer to peer interactions that advance projects that are mission-critical and of mutual interest, either nearby or halfway around the world (*e.g.* executing international memoranda to sustain long-running geodetic instruments at specific sites, rebooting a telecommunications device at a GPS field station, or ensuring correct metadata for GPS and other observations). Activities such as these are critical to all aspects of geodesy, because the collection and stewardship of long-term geodetic observations is essential to nearly all studies of global change. At the other end of the spectrum and equally critical, lie intricate multi-national activities, which include geodesists at universities, agencies, and projects around the world, who collaborate under the umbrella of the International GNSS Service (IGS) to develop

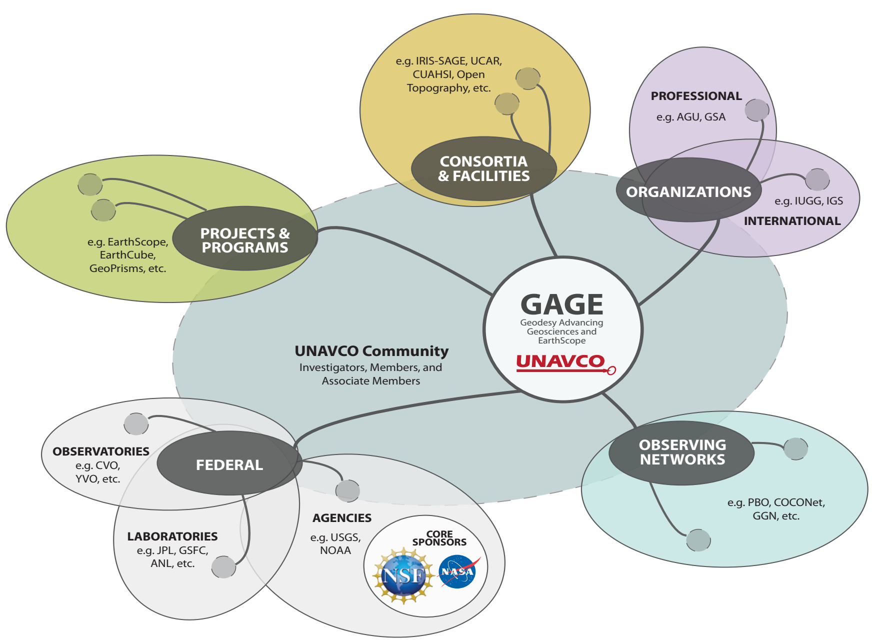


Figure 1-5. UNAVCO Partnerships. Through its membership and GAGE Facility activities, UNAVCO partners with dozens of organizations around the world in support of community science. A few examples in various categories are shown here.

The Geodesy Toolbox

Positioning geodesy observing systems:

GPS **Global Positioning System** – a geodetic technique that relies on the U.S. Navstar constellation of satellites for positioning, and yields precise measurement of Earth and ice deformation, as well as imaging precipitable water vapor in the atmosphere.

GNSS **Global Navigation Satellite Systems** – the general term for satellite navigation systems that provide geospatial positioning with global coverage, such as GPS, the European Galileo, and the Russian GLONASS systems.

GGN **Global GNSS Network** – the 67 GPS/GNSS stations maintained by UNAVCO in collaboration with the IGS Central Bureau at JPL with NASA support; data from these stations support IGS data products required for millimeter-precision global geodesy

GGOS **Global Geodetic Observing System** – the array of global networks of ground based geodetic stations for various techniques (including the GGN, IGS, and similar networks for VLBI, SLR, DORIS, etc.) that provide key infrastructure for all high precision studies by observing the Earth's shape, gravity field, and rotation, and their variation with time.

Borehole Geophysics, Strainmeters

BSM **Borehole Strainmeter** – measures the change in shape of a borehole at approximately 250 m depth, sensitive at the scale of one ten-millionth of a human hair.

LSM **Long Baseline Laser Strainmeter** - optically detects very small changes in length across a 500 m baseline above the ground and close to a fault.

Seismometer - measures ground deformation at very high frequencies with great sensitivity and is collocated with a borehole strainmeter in the Plate Boundary Observatory.

Tiltmeter - measures the changing inclination of the Earth's surface over time, at a scale of one ten-thousandths of a degree.

Geodetic imaging: Radar and LiDAR

InSAR **Interferometric Synthetic Aperture Radar** – a technique that differences pairs of radar images to map deforming zones such as faults, volcanoes, glaciers, and aquifers or oil fields.

GBIR **Ground-based Interferometric Radar** – a technique that differences pairs of radar images to map deformation of land or ice over tens of seconds to minutes, also known as terrestrial radar.

LiDAR **Light Detection and Ranging** - a technique that uses ultraviolet, visible, or near infrared wave length light pulses to image structures and surfaces.

TLS **Terrestrial Laser Scanner** – ground-based LiDAR, typically mounted on a tripod, providing very high-resolution imaging of small areas.

ALSM **Airborne LiDAR Swath Mapping** – airborne LiDAR imaging that provides exquisitely-detailed bare-Earth topography.

Essential Data Services: Data Center

IGS **International GNSS Service**, a voluntary federation of more than 200 worldwide agencies that pool resources and permanent GPS & GLONASS station data to generate precise GPS & GLONASS products that support an International Terrestrial Reference Frame. IGS activities are coordinated through its Central Bureau at the Jet Propulsion Laboratory, with technical support from UNAVCO.

TRF **Terrestrial Reference Frame** – a consistent set of calculated three-dimensional time-dependent coordinates for a network of globally distributed reference points that are used to define the locations of all other points, and their motion with time.

CI **Cyberinfrastructure** – integrated hardware for computing, data and networks, digitally-enabled sensors, observatories and experimental facilities; an interoperable suite of software and middleware services and tools.

sophisticated and technically complex data products that enable modern global geodesy to thrive in an environment of change. The UNAVCO community has long been well represented in IGS. Over the last five years, the role of UNAVCO staff in IGS has grown substantially, with major technical and governance contributions to several of the 14 IGS working groups, who continue to drive geodesy to millimeter-level global resolution. The Earth's diameter is nearly 13 billion millimeters; therefore the international geodesy community seeks to realize global observations with a sensitivity of one-tenth of a part per billion. At the recent 2012 IGS Workshop in Poland, attended by 200 participants from around the world UNAVCO staff had unprecedented impact, with posters and presentations, governing board service Development and Testing expertise and IGS Working Group service on display.

UNAVCO investigators, community members, and staff interact with dozens of organizations involved in global geodesy, geoscience research, and education. Our closest collaborators are those who advance geodesy data access, research, and education (*e.g.* NCALM, OpenTopography, IGS, JPL, SOPAC, MIT, Nevada Geodetic Laboratory, and CDDIS). Other collaborations, on projects of all sizes, where geodesy is coupled with other disciplines to advance a broad and integrative geoscience and education agenda, are also important (*e.g.* ESNO, IRIS, UCAR, NSIDC, and COOPEUS).

Within the US, UNAVCO also sustains partnerships to enhance its contributions to higher education in geosciences. These include facilities, agencies, projects, and universities (*e.g.* UCAR, USGS, University of Colorado and many others for RESESS & SOARS; IRIS, ESNO for EarthScope; SERC, key colleges and universities, and nationally ranked field schools for advancing geodesy curriculum; TOTLE, for teacher workshops). These collaborations enable impact far beyond the reach of any single geoscience discipline and provide integrated teaching and learning resources to non-specialist communities.

In summary, geodesy and the global high-precision geodetic infrastructure on which it depends underpin a wide range of Earth-observation systems, many of which are directly impacted by ongoing UNAVCO support and expertise. Geodesy is an important component of the Global Earth Observation System of Systems (GEOSS) that is being built by the Group on Earth Observations (GEO), a voluntary partnership of governments (85 countries plus the E.U.) and international organizations, including the International Association of Geodesy (IAG). The GAGE Facility and the UNAVCO community working together will continue US leadership in these and other international efforts that rely on geodesy.

2. Geodesy: Innovation for Research and Impact

Geodesy – the study of the shape, gravity field, and rotation of the Earth, and their change with time – is among the most rapidly advancing fields of science and among the most important for society. As technological innovation and investments in global infrastructure drive towards millimeter-level global geodesy, our ability to observe the restless Earth on human timescales dramatically advances. As a result, geoscientists now use modern geodetic techniques to investigate a diverse array of Earth processes both within and beyond solid Earth geophysics. Modern geodetic techniques allow scientists to make fundamental observations, including:

- *measuring* position, displacement, and strain at high precision and sampling rate locally, regionally, and globally;
- *imaging* Earth's changing surface using high-resolution LiDAR and radar;
- *observing* atmospheric water vapor, ionospheric electron content, and Earth-bound soil moisture with GPS radio wave delays and reflections; and
- *tracking* mass changes within the Earth System by combining observations of gravity with surface displacement changes.

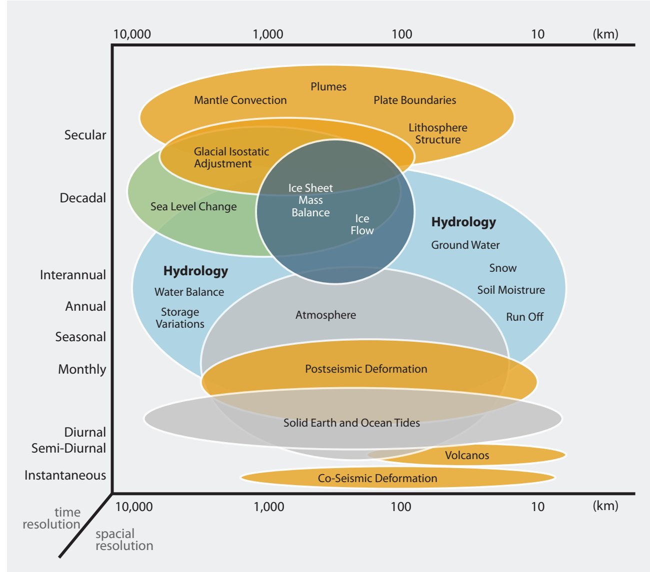


Figure 2-2. Spatial and temporal scales of geophysical processes. Geodetic observations carry signals from a wide range of processes in the solid Earth and its fluid envelope. The geodetic fingerprints of these processes have temporal scales from instantaneous to decadal and beyond, and spatial scales from point positions and their motions to global imaging. This figure emphasizes satellite gravity observations, GPS, radar, and LiDAR observations, which sample across the spectrum. Modified from Plag and Miller [2010].

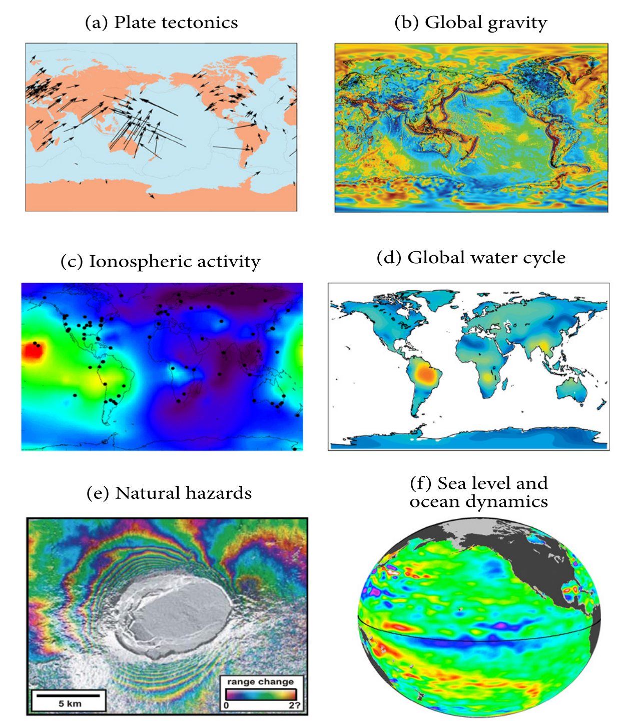


Figure 2-1. Applications of geodesy to geosciences. Geodetic observing systems include point observations (e.g. GPS, SLR, VLBI) and imaging capabilities (e.g. laser altimetry, InSAR, gravimetry). Integration of these data sets advances a broad range of geoscience applications. Modified from Davis et al. [2012]; based on Wdowinski and Eriksson [2009].

Geodesy is an increasingly powerful suite of techniques that are used to illuminate complex geophysical processes, and to define and discriminate the interactions of the lithosphere, cryosphere, hydrosphere, biosphere and atmosphere. Collectively, this integration allows geodesists to reveal Earth systems interactions and address critical science questions and their broad impact (Figure 2-1).

Over the past two decades, space-based geodetic observations have enabled measurement of the motions of the Earth's surface and crust at many different scales, with unprecedented spatial and temporal detail and increased precision, leading to fundamental discoveries in continental deformation, plate boundary processes, the earthquake cycle, the geometry and dynamics of magmatic systems, continental groundwater storage and hydrologic loading. Space geodesy furthers research on earthquake and tsunami hazards, volcanic eruptions, coastal subsidence and susceptibility to flooding, the health of wetlands, soil moisture and groundwater. Of particular importance are its contributions to the understanding of processes related to global warming and climate change, including hurricane tracking and intensity, sea level rise, and dynamic changes in alpine glaciers and large polar ice sheets in Greenland and Antarctica (Figure 2-2).

As global population disproportionately increases in hazards-prone coastal and tectonically active regions of the Pacific Rim, Indian Ocean, and the Caribbean and Mediterranean Seas, the societal relevance of quantifying, understanding, and poentially mitigating these natural hazards grows. Geoscientists using global geodetic infrastructure coupled with leading edge techniques are well poised to advance basic research that is in the public interest as the challenges of living on a dynamic planet escalate.

This proposal uses the term *geodetic science* to refer to research related to advancing geodetic data, infrastructure, and instrumentation, and *geodetic applications* to refer to science discoveries that advance through the use of geodetic tools. The distinction enables us to discuss a large number of such applications and their great value to Earth science without neglecting the underlying geodetic science that is the central activity of many researchers in the field, and that makes possible the continued development of new geodetic observing systems and new applications for the resulting data.

2.1 WHERE IS THE WATER?

UNAVCO community science studies are accelerating our understanding of the hydrosphere, with implications for the study of climate change, lithospheric dynamics, natural hazards, sustainable development, and the improvement of living standards around the world. The hydrosphere is arguably the most fundamental component of the dynamic Earth ecosystem. It supports life, it essential for agriculture, many industries and energy resources, and shapes the surface of the Earth. Water is exchanged on a variety of timescales among the oceans, atmosphere, cryosphere, biosphere, and lithosphere with geodetically observable consequences (Figure 2-2). UNAVCO provides access to GPS, InSAR, and LiDAR technologies that are uniquely suited to quantify these exchanges. In this section, we present three Grand Challenges focused on issues relating to water and climate.

2.1.1 Where does the Earth store fresh water?

Fresh water is the fundamental building block of terrestrial ecosystems and, ultimately, civilization. With the world's population expected to reach 9 billion by 2050, the demand for potable water will continue to grow, as will the need for water for the production of energy. Over-pumping of groundwater leads to irreversible compaction of aquifers, with implications for reduced storage capacity as well as hazards to roads, buildings and other infrastructure caused by land subsidence and fissuring. In summarizing the results of a 2010 IGCP hydrogeodesy workshop, Plag and Miller [2010b] propose: "A much improved observation system providing information on all reservoirs of the water cycle on regional to local scales is needed, if we want to avoid severe human and ecological disasters caused by inappropriate water management."

Global climate change and human activity continue to influence the redistribution and storage of the Earth's water. Water locked up in ice sheets and glaciers melt to join the oceans or become stored on the continents. GPS and gravity data provide a record of changes in the shape of the solid Earth under the weight of moving water (Figure 2.1-1). Geodesy is used to monitor snow depth [*Larson* et al., 2009], changes in the height of the ice sheets, the flow of glaciers [*e.g., Magnusson et al.,* 2011], and vertical land motion, and thus is critical to our ability to assess sea level rise [*Woppelmann et al.,* 2007]. Such measurements are influenced directly by glacier dynamics, deglaciation, sea level rise, and ultimately global climate change. The GAGE Facility will form a foundation of support for the UNAVCO community science investigations that seek to quantify and model the ongoing effects of water distribution and dynamics on Earth.

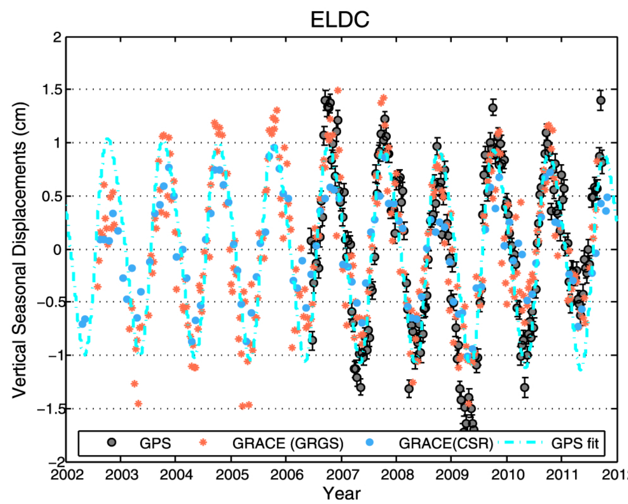


Figure 2.1-1. Annual vertical deformation from GRACE and GPS, Glacier Bay, Alaska. The station ELDC example of GPS vertical seasonal (detrended) time series is overlain on GRACE-modeled seasonal vertical displacements. GRACE solutions are from the Groupe de Recherche de Géódésie Spatiale (GRGS) and the Center for Space Research (CSR). Figure from Fu and Freymueller [2012].

Water vapor carries a significant amount of atmospheric energy. Quantification of the amount of water vapor is therefore important for climate models as well as accurate weather forecasts, especially in warm, humid systems such as tropical storms and hurricanes (Figure 2.1-2). The amount of water contained in the atmosphere may be determined from the delays to and refraction of GPS signals as they traverse the atmosphere [*Bevis, 1996; Bevis et al.*, 1992; *Herring*, 1992], with implications for meteorology [Braun et al., 2001; *Businger et al.*, 1996; *Kursinski et al.*, 2008] and climate dynamics [*e.g., Adams et al.*, 2011].

Products of water vapor sensing include estimates of locally-averaged (~15-20 km scale) precipitable water vapor using all GPS phase delays averaged over periods of approximately half an hour, and tomographic applications using intersecting slant-paths of closely-spaced stations [*e.g., Xie et al.*, 2005]. Strong interdisciplinary collaborations between Earth and atmospheric scientists have led to integrated networks for meteorological observations and continuous GPS, including SUOMINet, PBO, COCONet, and AfricaArray.

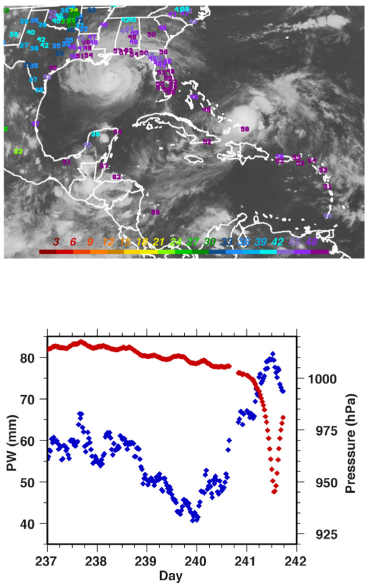


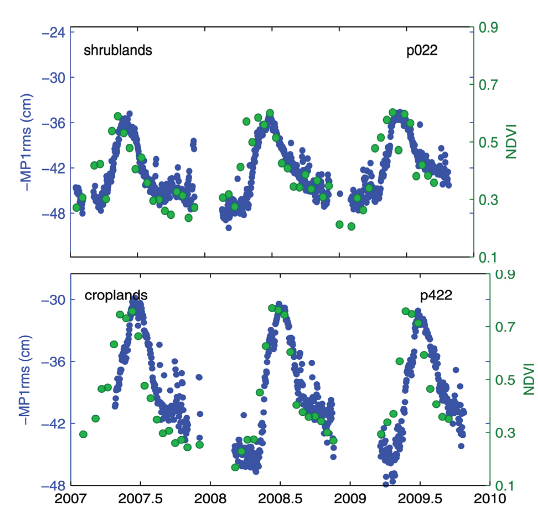
Figure 2.1-2. Precipitable water vapor (PW) in the atmosphere. Water vapor in the troposphere delays the travel of radio waves from GPS satellites, making it possible to calculate zenith integrated PW at individual GPS stations. The PW, color-coded and shown in mm, and overlain on an infrared GOES (Geostationary Operational Environmental Satellite) image is shown as Hurricane Gustav made landfall in 2008. The time series on the right show PW (red) and surface pressure (blue) at English Turn, LA, as Hurricane Katrina (2005) passed over the station. The time series ends when power and communications failed at the site. Improved determination of the moisture fields within the model yields a better description of the water budget, and therefore improved hurricane intensity and track predictions. Courtesy of J. Braun [2012].

The proliferation of real-time data streams in some of these networks further expands their applicability. These tools and the new techniques being developed to exploit them become even more valuable as more data are available at high-rate with low latency. UNAVCO is currently leading efforts to enhance US infrastructure, data protocols, and products to address these critical scientific and societal issues. These efforts will be expanded under GAGE.

Energy and mass fluxes into and out of the troposphere are also crucial to the forcing of weather and climate systems. In addition to constraints on tropospheric water vapor from GPS, observations relating to flux of water to and from the land surface can also be gleaned from GPS multipath measurements of soil moisture (Figure 2.1-3) [*Larson et al.*, 2008] and snow depth (Figure 2.1-4). Snow is an important component of both regional and global climate systems, as well as a critical storage component in the hydrologic cycle. Snow water equivalence (SWE), the product of snow density and depth, is the most important parameter for hydrological study because it represents the amount of water potentially available for runoff. Measurement of the amount of water stored in the snowpack and forecasting the rate of melt are thus essential for management of water supply and flood control systems [*Shi and Dozier, 2000*].

The GPS-derived changes in properties of the site environment are inferred from the changes in the amplitude and frequency of multipath interference (relating, respectively, to attenuation properties and position of reflective surfaces); these reflected signal observations, however, do not directly measure fluxes. For example, reduction of soil moisture partitions between downward percolation and upward evapotranspiration, and converting snow depth to mass change requires independent constraint of snow density. However multipath measurements could be combined with GPS water vapor sensing and meteorological modeling [*e.g., Valeo et al.*, 2005] to help quantify fluxes due to sublimation, ablation and evapotranspiration. GPS multipath measurements benefit greatly from high-rate sampling, which in turn require increased data storage and transmission bandwidth capabilities; these requirements are addressed with the planned upgrades to 250 additional PBO sites as part of the GAGE Facility.

Accurate estimates of large-scale continental water mass changes are useful for a wide variety of reasons. A relatively recent addition to the repertoire of geodetic techniques used to investigate this type of problem is the global measurement of long-wavelength time-variable gravity via the Gravity Recovery and Atmospheric Change Experiment (GRACE) mission that measures the mass changes over the ocean [*Leuliette and Willis*, 2011], as well as the complementary mass changes over the continents and ice. The GRACE mission has been a flagship for geodetic measurements of water mass changes [*e.g., Swenson et al.*, 2003]. GRACE measurements of Earth's gravity field have limited utility on spatial scales less than 500 km and timescales less than a month. GPS-measured deformation, however, could be



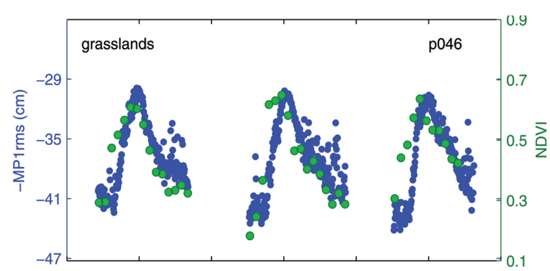


Figure 2.1-3. GPS Multipath and near-surface soil moisture. Signals routinely recorded by GPS receivers installed to measure crustal deformation for geophysical studies can be used to sense soil moisture proximal to the antenna. As with other environmental observations, soil moisture is capable of reflecting GPS signals, and can be quantified by using the GPS signal-to-noise ratio. Larson et al. [2010] present data from fall 2008 that show the effects of soil moisture on reflectivity. Precipitation units are 0.1 mm over 5 minute intervals; GPS measurements from three satellites (PRNs) are arbitrarily offset to agree with in situ measurements at 2.5 cm, with model results for 1 and 5 cm.

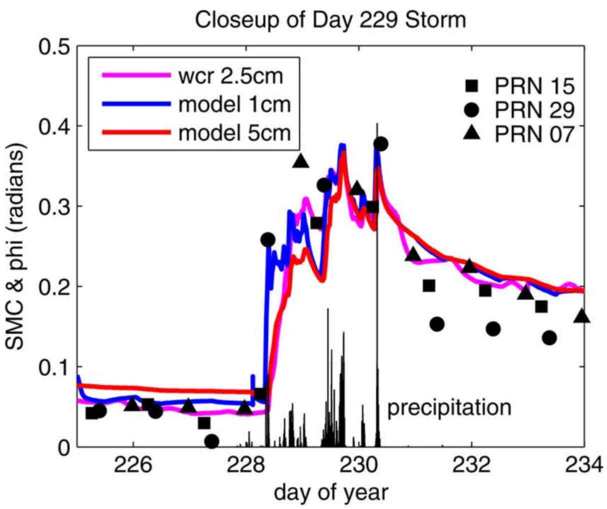


Figure 2.1-4. GPS snow depth retrievals. Snow depth can be estimated at GPS sites when the modulation frequency of multipath signals can be resolved. GPS snow depth retrievals are shown for PBO sites P360 (in eastern Idaho) and P101 (in northern Utah). The standard deviations represent the standard deviation of the individual satellite tracks and a formal error of 2.5 cm, added in quadrature. Comparison with nearby a SNOTEL network sensors (which collects snow and convert the weight to equivalent snow depth) time series shows a strong correlation.

used to estimate water mass variations on much shorter temporal and spatial scales than GRACE provides [*Tregoning et al.*, 2009].

Water is stored in a number of 'reservoirs' whose sizes vary on timescales from weeks to months, impacting both human and natural systems [*Bales et al.*, 2006; *Entin et al.*, 2000]. Spatial and temporal variations in soil moisture are needed for climate and weather modeling [GCOS, 2010; NRC, 2007; *Viterbo and Betts*, 1999], as it affects turbulent and radiative fluxes between the land surface and atmosphere [*Entekhabi and Rodriguez-Iturbe*, 1994; *Seneviratne et al.*, 2010].

Biomass is an active reservoir in the global carbon cycle. Changes in the amount of carbon stored in terrestrial biomass affect atmospheric CO_2 on timescales of seasons to decades and longer [*Houghton et al.*, 2009]. Biomass and soil moisture are tightly coupled via ecohydrological interactions, yielding a strong link between the terrestrial water and carbon cycles [*Rodriguez-Iturbe*, 2000]. Small et al. [2010] demonstrated that GPS reflection multipath signals could be used to sense biomass following the Normalized Difference Vegetative Index (NDVI) used for different land cover classifications (Figure 2.1-5).

As discussed below in 2.2 Earth the Machine, there are intriguing crossovers among hydrogeodesy, tectonics, and surface changes. Flow of liquid water and ice over the solid Earth surface also sculpts it, which enhances topographic relief [*e.g., England and Molnar*, 1990] and modifies orogenic deformation within the lithosphere [*e.g., Pysklywec*, 2006]. The presence or absence of water within the lithosphere

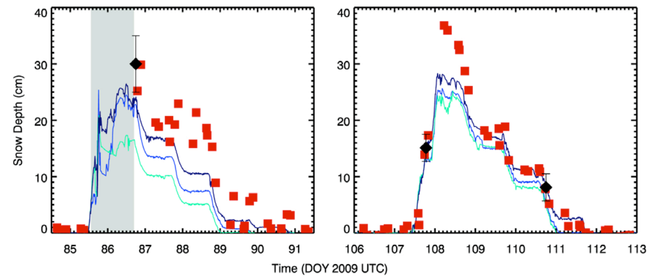


Figure 2.1-5. Sensing vegetation with GPS multipath. GPS/GNSS antennas are designed to receive signals from the entire sky with minimal signal attenuation in any particular direction, a design that makes them very effective at receiving both signal and problematic noise, including signals that have been reflected off the surface below the antenna (i.e. multipath). This difficult to model noise source for positioning applications is now used to characterize the surfaces that are reflecting the signal. The reflection multipath from GNSS (MP1 rms, blue) follows closely the Normalized Difference Vegetative Index (NDVI, green) for three different land cover classifications. Thousands of GPS antennas that are currently deployed for science, surveying, and navigation, could constitute a network of environmental sensors. From Small et al. [2010].

exerts a fundamental control on the response of lithospheric materials and fault surfaces to applied stress [*Carlson et al.,* 2005; *Dixon et al*., 2004; *Hirth and Kohlstedt*, 1996; *Kay and Kay*, 1993]. These influences play a decisive role in determining the breadth and geographic distribution of continental deformation, high topography, earthquake frequency and magnitude, magmatic activity, and the composition of the continental crust. Flow of water through the crust following large crustal earthquakes redistributes crustal stress over timescales of days to months, with implications for earthquake hazards risk [*Fialko*, 2004]. Thus processes through which the hydrosphere interacts with the solid Earth have vital implications for society.

UNAVCO Role: While hydrogeodesy is not yet well established, community interest is growing quickly and a set of UNAVCO community data products and techniques that address key questions is now emerging. Thus, geodetic measurement systems and data support by UNAVCO provide unique constraints on the motion of water through the hydrological cycle and its interaction with the solid Earth. New insights into these processes are stimulating collaboration between solid Earth scientists, hydrologists, glaciologists, oceanographers, and atmospheric scientists, collaboration that continues to lead to significant advances in understanding of the Earth system. The history of support for hydrogeodesy, and projections for GAGE 2013 – 2018 are discussed in subsections of 3.1.1 and 3.1.2.

Key questions for hydrogeodesy[1] :

- How do the cryosphere, oceans, atmosphere, and solid Earth exchange water on a wide range of temporal and spatial scales?
- What is the impact of climate change on continental water storage and sea level?
- What are the responses of the solid Earth to water redistribution?
- How does atmospheric moisture change in space and time and how can geodetic tools be used to add new constraints?

Long-term goals for addressing key questions:

- Integrate multiple ground-based and space-based observing systems to measure vertical and horizontal land deformation, snow depth, and gravity.
- Develop methods for integration of observations with different spatial and temporal resolutions.
- Maintain a stable global terrestrial reference frame with sub-1 mm/yr vertical accuracy.
- Carry out campaigns to calibrate and validate geodetic and local hydrological measurements.

2.1.2 How will the Earth System respond as mean sea level arise?

One of the greatest threats of climate change is the anticipated rise of sea level associated with thermal expansion from rising water temperatures, and the redistribution of ocean and continental water linked to melting of glaciers and ice sheets [*IPCC*, 2007]. Over the past several decades, geodesy has revolutionized our ability to measure sea level variations

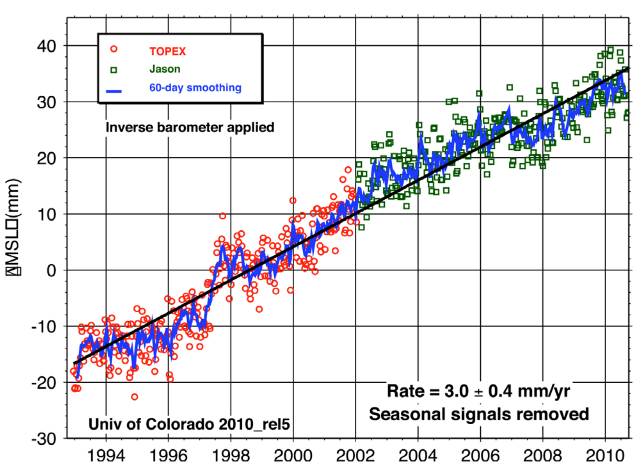


Figure 2.1-6. Global mean sea level is rising. Satellite laser altimetry is used to determine sea level rise over the last two decades, yielding a rate of 3.0±0.4 mm/yr, after solving for biases among TOPEX, Jason 1, and Jason 2 satellites. The two primary causes of sea level change are contributions from ice loss and thermal expansion of the oceans themselves. The latter is a little less than half of the observed change. Nerem et al. [2010].

1 The Key questions and Long-term goals for addressing key questions presented in this proposal are drawn from Davis, J. L., Y. Fialko, W. E. Holt, M. M. Miller, S. E. Owen, and M. E. Pritchard (2012), A Foundation for Innovation: Grand Challenges in GeodesyRep., UNAVCO, Boulder, CO.. Included here are those most relevant to UNAVCO capabilities and community accomplishments, and foundational to planning for the GAGE Facility.

globally. Satellite altimetry detects change in sea surface height with excellent spatial resolution and coverage as well as the required temporal resolution. The last two decades of satellite altimetry measurements indicate that sea level has risen at an average rate of 3.1 mm/yr (Figure 2.1-6) [*Nerem et al.*, 2010], nearly double the rate observed over the entire 20th century [*Woodworth et al.*, 2011]. There is considerable evidence that the loss of ice in Greenland and western Antarctica is accelerating [*Velicogna*, 2009] and this will further impact sea level rise. Prior to the advent of satellite altimetry, sea level change was determined mainly by sparsely distributed tide gauges [*Woodworth et al.*, 2011]. Their long history and measurement of relative sea level (*i.e.* sea surface elevation relative to land) at specific coastal locations, however, make tide gauges complementary to altimetry. Combined with geodetic measurements of vertical land motion, tide-gauge observations will continue to play a critical role in the determination of sea level change, because sea level rise will not be uniform around the world [*Riva et al.*, 2010; ., 2011].

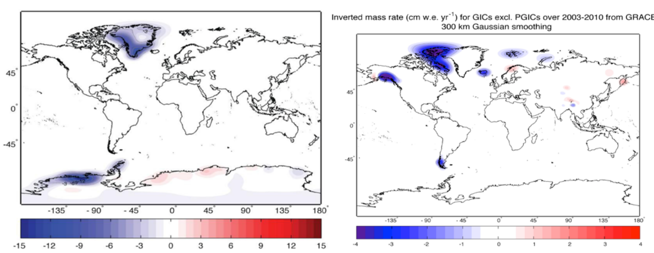


Figure 2.1-7. Global ice mass change. Changes in ice thickness during 2003-2010 measured by NASA's Gravity Recovery and Climate Experiment (GRACE) tandem satellites. GRACE observations must be combined with data from GPS bedrock stations that determine glacial isostatic adjustment (GIA) in order to resolve ice loss. Blue represents ice mass loss, while red represents ice mass gain in centimeters per year. Changes for Greenland, Antarctica and Peripheral Glaciers and Ice Caps (top) and Non-polar Glaciers and Ice Caps (right), averaged over each of the world's ice caps and glacier systems outside of Greenland and Antarctica. The total contribution to sea level rise from all ice-covered regions is 1.48 ± 0.26 mm – 1, which agrees well with independent estimates of sea level rise originating from land ice loss and other terrestrial sources. Figures from NASA [2012], study by Jacob et al. [2012].

Thermal expansion is expected to contribute tens of centimeters to sea level change by 2100. The exchange of water between the continents and the oceans may contribute up to 1-2 meters during the same period [*Pfeffer et al.*, 2008; *Rahmstorf*, 2007; *Vermeer and Rahmstorf*, 2009], mainly due to the melting of polar ice sheets. Greenland and Antarctica contain enough ice to raise global mean sea level by 7 m and 55 m respectively, and thus melting only a fraction of those large ice sheets can cause significant sea level rise. Alpine glaciers and ice fields, many of which are rapidly melting, contain another meter of potential sea level rise (Figure 2.1-7).

Because human population is concentrated in coastal regions, the impact of sea level rise will be significant; mitigation strategies will require accurate predictive capabilities. Geodesy provides the critical global reference frame for measuring sea level change, understanding the mass balance of ice sheets, and thereby enabling accurate forecasts. Geodesy also fosters development of critical technologies for predicting regional inundation due to sea level rise.

The prediction of future sea level rise, including its causes and regional variation, requires separating different contributions to sea level change and understanding them individually [*Leuliette and Willis*, 2011]. Both mean sea level change and its geographic and temporal variations are expected to continue to be on the order of millimeters per year. Thus, constraining sea level change and its variation requires a coherent suite of geodetic systems working together to provide a reference frame for accurate long-term measurements. Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) and GNSS positioning techniques together provide the accurate and stable terrestrial reference frames and geocenter variation determinations required to track vertical motions at the sub-mm/yr level. In addition, IGS data products are essential to the precise positioning of spacecraft, which make other critical Earth System observations.

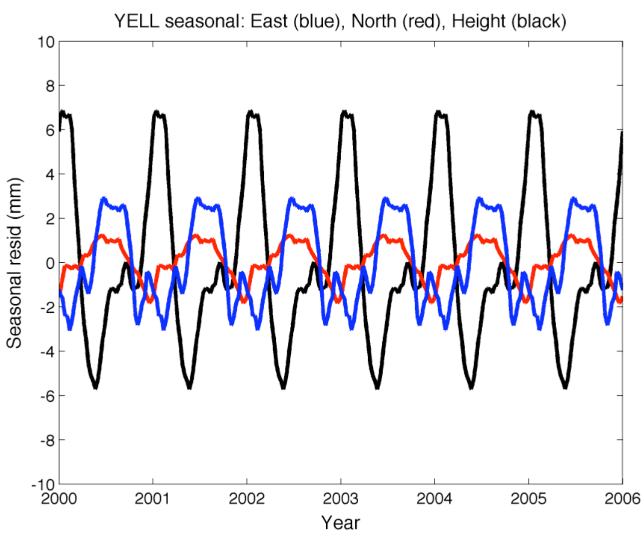


Figure 2.1-8. Estimated seasonal variations in GPS-determined position. Seasonal estimates for component site residuals at Yellowknife (YELL), Northwest Territories, Canada, are shown for north (red), east (blue), and height (black). Using an iterative technique, Freymueller [2009] demonstrates that time series are significantly affected when seasonal variations are included in the reference frame definition and such variations are not always sinusoidal in form. Seasonal changes in global water storage and atmospheric loading contribute to systematic seasonal deformation at individual GPS stations, which in turn contribute to oscillations in the geocenter. Thus, these processes that can only be understood with a well-constrained reference frame, also alter it.

Continuity of geodetic observations is of great importance when attempting to disentangle spatial and temporal variability. The largest error in interpretation of GRACE data for ice mass change is the contribution of glacial isostatic adjustment (GIA), thus its measurement will play a key role in tracking sea level change over the next decade. The seasonal variation in global water distribution is perceptible in the reference frame [*Blewitt et al.*, 2001], as are other changes of mass distribution, such as great earthquakes or ice loss [*Argus*, 2007]. Because the center of mass of the whole planet, including its fluid envelope, controls satellite orbits, the location of the barycenter is the fundamental parameter of the global reference frame, yet it is vulnerable to seasonal, secular, and irregular redistributions of mass in the atmosphere, hydrosphere, and cryosphere (Figure 2.1-8).

In summary, satellite altimetry, time-variable gravity, point measurements of relative sea level (from tide gauges), oceanographic data, and geodetic measurements of ice volume (see 2.1.3), are all required to unravel the mass and steric contributions to sea level change, as well as to determine the sources of mass change.

The GAGE Facility will be essential to the maintenance and enhancement of polar geodetic networks that are critical to assessing global ice flux. In addition, through the COCONet project, UNAVCO will contribute new geodetic resources to assess sea level rise in the Caribbean with the installation of collocated GPS instruments, meteorological instrumentation, and precise tide gauges. These ground-based instruments, while spatially sparse, are temporally dense with high precision and therefore an important complement to GRACE observations; thus they help to constrain mass changes over the ocean, continents, and ice polar sheets [*Leuliette and Willis*, 2011]. Measurement of relative sea level change at tide gauges tied into the global reference frame reveals regional variability, and coupled with measurements of coastal change due to subsidence, fluid extraction and tectonic forces, will support more accurate regional forecasts of local and widespread impact.

UNAVCO Role: Techniques needed to study the distribution and dynamics of ice, liquid water, and atmospheric water vapor lie at the heart of UNAVCO capabilities and contributions. These include the collection and archiving of long-term, high precision, GPS time series that constrain coastal vertical deformation patterns and thus also have implications for local relative sea level rise. Other satellite techniques are supported indirectly by UNAVCO's operation and maintenance of NASA's GGN stations is critical to establishing and maintaining the global reference frame.

Key questions for sea level studies:

- Is sea level rise accelerating and, if so, at what rate?
- How do we separate the contributions of glacier melting vs. ocean dynamics, circulation, and thermal expansion to sea level change?
- What processes control local variations in relative land and sea levels?
- How will patterns of flooding, drought, and storm surge change?

Long-term goals for addressing key questions:

- Sustain observing systems that have a long history and contribute to sea level measurements, particularly tide gauges and GNSS.
- Maintain a stable terrestrial reference frame with sub-1 mm/yr vertical accuracy.
- Integrate sea level observations by tide gauges into the terrestrial reference frame at the sub-1 mm/yr level.
- Improve the accuracy of precise orbit determination over shorter timescales.

2.1.3 How do Earth's glaciers and ice sheets change over time?

Ice now covers approximately 10% of Earth's land surface, with most of the ice mass being contained in the Greenland and Antarctica continental ice sheets. Changes in these as well as other ice sheets and glaciers result in uneven redistribution of water across the planet [*Cazenave and Remy*, 2011; *Mitrovica et al.,* 2001] but estimates of the net gain or loss of ice differ significantly [*Chen et al*., 2009; *Zwally and Giovinetto*, 2011; *Zwally et al*., 2005]. On a regional scale, decreases in the volume of alpine glaciers in places such as the Himalayas [*Barnett et al*., 2005; *Scherler et al*., 2011] and Peru are changing the timing of seasonal melt discharge that provides water to large population centers and serves as the primary water source for many fragile ecosystems. Predicting cryospheric change is thus of critical importance, and geodesy plays a key role.

An important challenge for geodesists is to design and execute geodetic experiments that enable researchers to improve our understanding of ice dynamics so that we can better predict (through numerical models) the response of the glaciers to climate change, and the feedback of this response to the climate. The scope of measuring changes to Earth's glaciers requires multiple geodetic observing systems to resolve the complexity at relevant temporal and spatial scales, which range from seconds or hours over tens of km (a calving event on a large outlet glacier) [*Joughin et al*., 2005; *Nettles et al*., 2008; *Wiens et al*., 2008] to annual, interannual, or decadal times on regional scales [*Bevis et al*., 2012; *Rignot and Kanagaratnam*, 2006] to thousand of years on a global scale (elastic and viscoelastic deformation associated with glacial cycles) [*James and Ivins*, 1995; *Lidberg et al*., 2010; *Sella et al*., 2007]. Adding to the technical challenge of collecting geodetic measurements, glaciers are often in the harshest environments on Earth, are highly inaccessible, and require considerable financial resources in order to operate safely and effectively [*Augustine et al*., 2012].

The Earth's surface deforms in response to present and past ice-mass changes. Research on GIA associated with now melted ice sheets such as Fennoscandia and Laurentia constrains both past climate change and Earth structure (Figure 2.1-9). Regional GNSS networks (e.g., BIFROST, EUREF, and CBN) provided the first accurate 3D crustal-velocity fields associated with GIA. Measurement of secular changes in surface deformation proximal to alpine glaciers and ice sheets (e.g., Greenland, Antarctica, Alaska, Patagonia, Iceland) is also provided by other regional GNSS networks [e.g., POLENET, GNET, PBO, and Parca, *Bevis et al*., 2012] (Figures 2.1-10; 2.1-11); [*Jiang et al*., 2010; *Khan et al*., 2007; *Pritchard et al*., 2009]. Together, surface deformation and gravity measurements are revealing the pattern, magnitude, and timing of accelerated mass loss in Greenland and Antarctica.

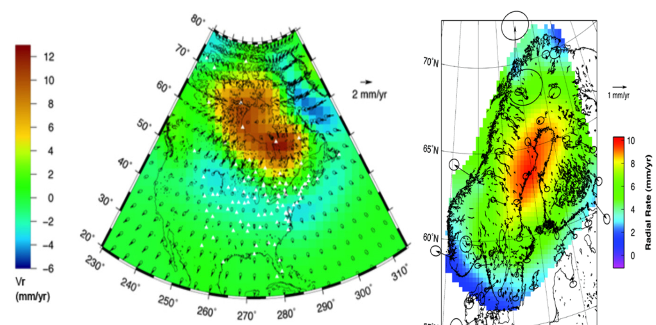


Figure 2.1-9. Rebound from vanished ice sheets. GIA is the ongoing viscoelastic deformation of the solid Earth in response to past changes in volume or extent of ice sheets. Rapid and significant changes followed the last glacial maximum (~18kyr before present), when ice began rapidly to melt. The Fennoscandia and Laurentia ice sheets have now disappeared, yet rebound continues, influencing GPS velocities and detectable in gravity observations. Interpolated vertical (background color scale) and horizontal velocities (arrows) show the GIA model used for the Stable North American Reference Frame used for PBO analysis. From Sella [2007]. White triangles are GPS stations. Fennoscandia figure uses data from Lidberg et al. [2010]. The geodetic observations constrain the extent of glaciation, mantle rheology, the structure of the continents, and past and present-day sea level change.

Interferometric Synthetic Aperture Radar (InSAR) data from European Space Agency's (ESA) ERS-1 and 2 tandem mission, radar data from Canada's RADARSAT mission, and optical imagery from USGS's Landsat and other missions have been combined to detect sudden and dramatic accelerations of deep outlet glaciers, frequently at rates of tens of percent per year up to 500% in just two years [*e.g., Moon et al*., 2012] (Figure 2.1-12). More extensive and frequent InSAR coverage of ice sheets, ice caps, and other glaciers would provide substantial contribution to our understanding of these complex systems.

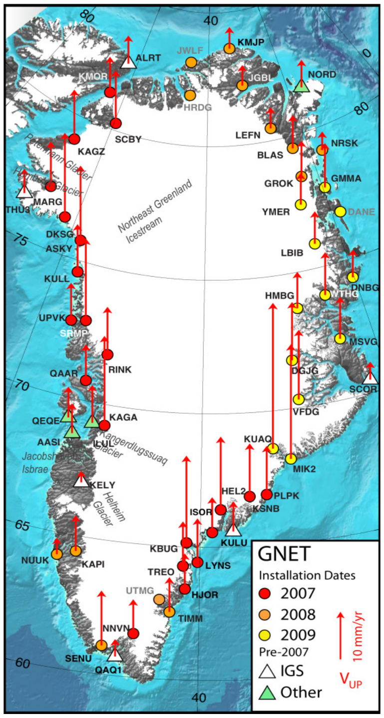


Figure 2.1-10. Vertical uplift of Greenland's rim. Observed average vertical velocities of GNET GPS stations in Greenland (in mm/yr) as reported by Bevis et al. [2012]. Some stations were strongly affected by the 2010 ice loss anomaly showing high rates of uplift. Longer time series show temporal variations in response to changing ice load.

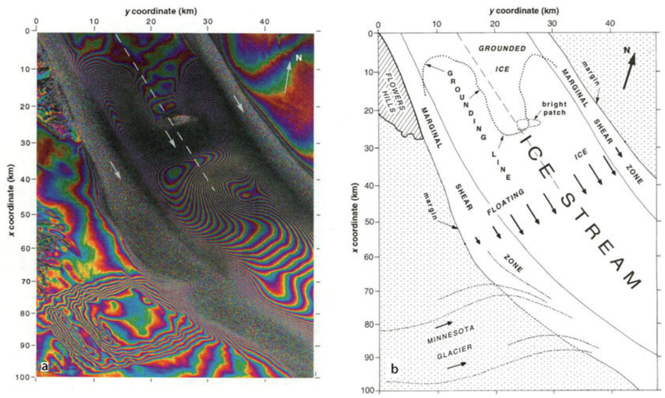


Figure 2.1-12. Part of the Rutford Ice Stream, Antarctica. (A) One fringe in this satellite radar interferogram represents a 2.8 cm movement toward the spacecraft. Superimposed on the interferogram is a radar amplitude image (conventional SAR image) of the same area, in shades of gray. (B) Location map for features in (A). The ice stream is unpatterned, flowing as indicated by arrows. Upstream from the dotted line, the ice is grounded; downstream, it is afloat. Dash-dot lines show flow traces, faintly visible in (A). From Goldstein et al. [1993].

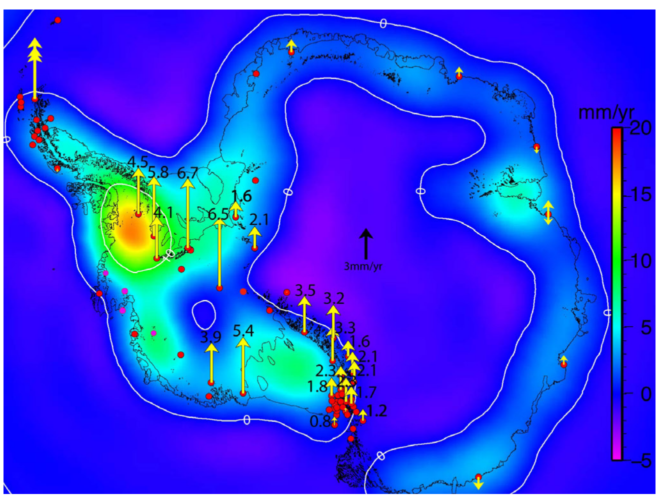


Figure 2.1-11. ANET preliminary results. In Antarctica, cGPS ANET reveals spatial variation in vertical uplift rates. Typical rates of 2-5 mm/year are much lower than some GIA model predictions (color contours, IJ05), which reach 15 mm/year (synthesis figure from Wilson, pers. comm.). Low Sv seismic velocities (unpublished data of M. Willis, 2011) suggest variable but relatively thin elastic lithosphere, with warm and relatively low viscosity upper mantle that may account for the lower rebound rates. ANET is also designed to characterize active tectonic deformation within West Antarctica.

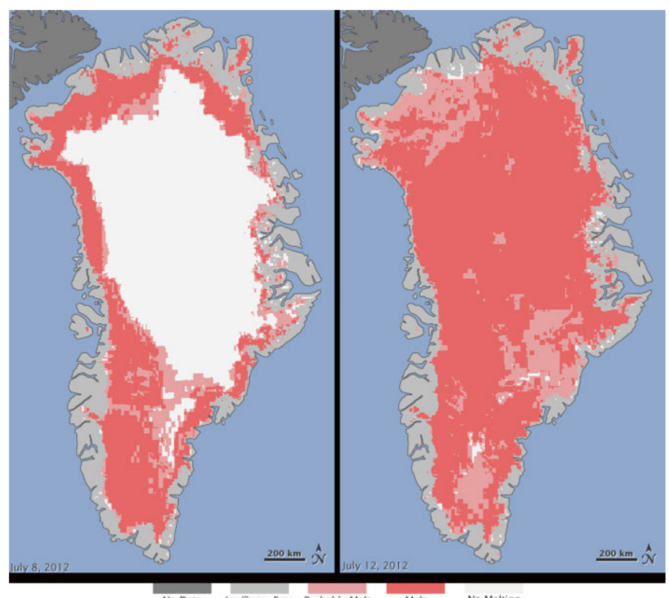


Figure 2.1-13. 2012 melting across Greenland. Nearly the entire ice sheet covering Greenland—from its thin coastal edges to its two-mile-thick center—experienced some degree of melting for several days in July 2012; an estimated 97% of the top layer of the ice sheet had thawed at some point in mid-July, the largest extent of surface melting observed in three decades of satellite observations. Figure (left) shows the extent of surface melting on 8 July 2012 grew to cover most of Greenland by 12 July 2012 (right). The extreme melting coincided with an unusually strong ridge of warm air—a "heat dome"—over Greenland. The ridge was one in a series that dominated Greenland's weather between May and July 2012. Even the area around Summit Station in central Greenland where UNAVCO supports GPS observations, which at two miles above sea level is near the highest point of the ice sheet, showed signs of melting. Photo credit: Nicolo E. DiGirolamo, SSAI/NASA GSFC, and Jesse Allen, NASA Earth Observatory.

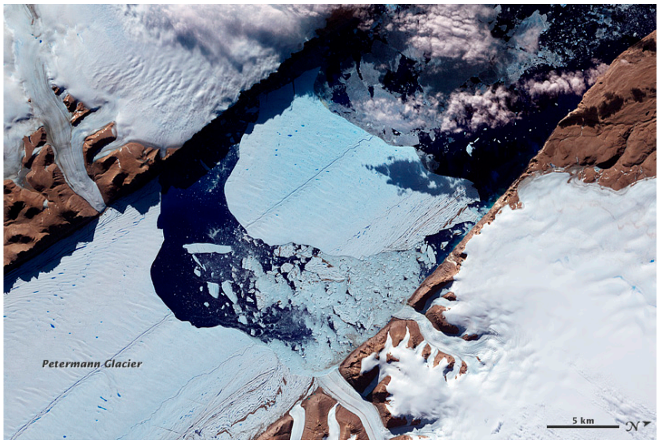


Figure 2.1-14. Ice loss summer 2012. In July 2012, a massive, floating ice island broke free of the Petermann Glacier in northwestern Greenland. On July 16, the giant iceberg could be seen drifting down the fjord, away from the floating ice tongue from which it calved. On July 21, 2012, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on NASA's Terra satellite captured this image of the iceberg's continuing journey. North is toward the right. This detailed image reveals that the iceberg covers an area of about 32.3 square kilometers. Ted Scambos of the National Snow and Ice Data Center observed melt ponds on the iceberg surface, but stated that the Petermann calving was likely associated with ocean currents rather than surface melt [NASA, 2010; Vinas, 2012].

In Greenland, outlet glaciers appear to be associated with the greatest mass loss from the system. The present day changes in the Greenland ice sheet are clear. Figure 2.1-13 from NASA shows that during a heat wave in July 2012 the top layer of nearly the entire ice sheet thawed. Also in July 2012, a massive, floating ice island broke free of the Petermann Glacier in northwestern Greenland (Figure 2.1-14).

Ground-based GPS studies indicate that the mechanics of these systems may be quite complex [*Joughin et al.*, 2008; *Rignot et al.*, 2011]. Seismologists have discovered ice instability can trigger small "glacial earthquakes" that appear to be caused by ocean-tidal displacement for some glaciers in Antarctica, or correlated with calving events and glacier flow-rate variations in Greenland [*Ekstrom et al.*, 2006; *M E West et al.*, 2010]. The glacial earthquakes occur in areas of greatest mass loss, and changes in their frequency may be associated with climate change. Ground-based GNSS study of these important glacier systems is currently the only way to achieve the high temporal resolution needed to make the connections between glacial earthquakes, glacier flow speed, calving, and ocean tides. GPS studies have also been useful for making connections between ice-sheet speed in Greenland and surface melting that leads to changes in the underlying hydrology of the ice sheets.

High-rate GPS observations of the cryosphere have transformed our understanding of dynamic glaciology. Since the advent of such, it has become apparent that glaciers can change flow speed and direction on timescales that were once thought impossible: seasonal, monthly, daily, and even minute by minute [*Anandakrishnan et al.*, 2003; *Nettles et al.*, 2008; *Wiens et al.*, 2008; *Winberry et al.*, 2009].

Understanding of the processes associated with these changes is in its infancy (*e.g.*, Figure 2.1-15), and thus such processes are not included in current models of ice-sheet flow. As a result, estimates of glacial contribution to sea level rise are imprecise [*IPCC*, 2007]. The role that the ocean and the atmosphere play in forcing these high-frequency changes in glacier flow [*e.g.*, see *Zwally and Jun*, 2002; *Zwally et al.*, 2002] are drawing the attention of UNAVCO community research. High-rate GPS instruments deployed on the ice surface can contribute to a better understanding of the dynamics of glaciers by allowing researchers to collect and analyze glacier flow data along with the ocean and atmospheric data. The GAGE Facility will acquire additional GPS/GNSS infrastructure that is designed for long-term deployment to support PI projects to study ice dynamics (see 3.1.1 and 3.1.2).

The best climate models do reasonably well at simulating changes in ice sheet accumulation (caused by snowfall) and melting—two major factors that contribute to ice sheet growth and shrinkage.

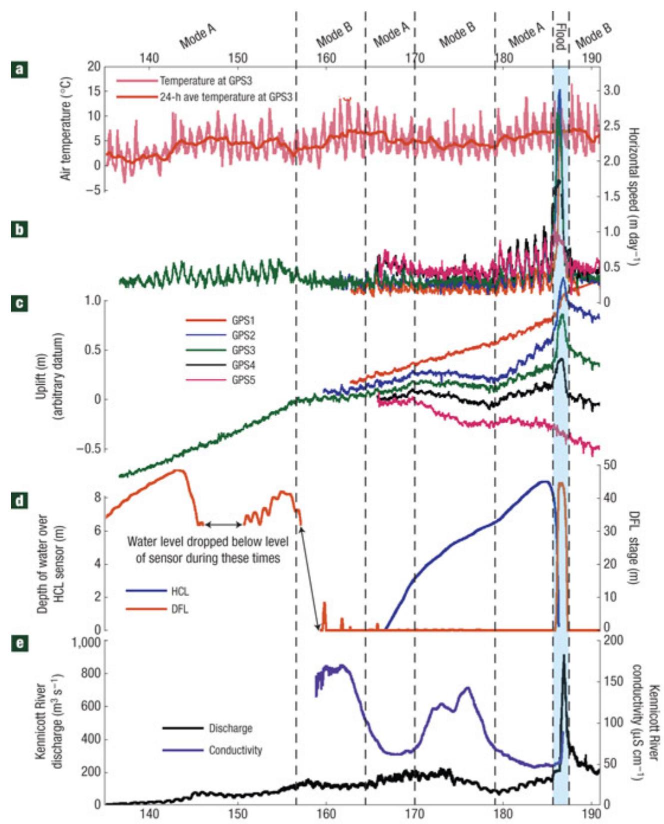


Figure 2.1-15. The record of surface motion of the Bench Glacier, Alaska. Vertical dashed lines identify two distinct glacier modes, A and B. The period of the Hidden Creek Lake outburst flood is shaded light blue. (a) Half-hour and 24-hour averaged air temperatures at GPS3. (b) Four-hour averaged horizontal ice speeds at each GPS receiver. (c) Uplift (vertical motion minus the surface-parallel trajectory) at each GPS receiver. (d) Lake level record at Hidden Creek Lake and Donoko Falls Lake. The Donoko Falls Lake stage is relative to the lake basin floor, whereas the Hidden Creek Lake record captures the uppermost 9 m (of 100 m) of lake filling and draining. (e) Kennicott River discharge and electrical conductivity. From Bartholomaus et al. [2007].

Whether they are good at predicting future changes to the ice mass is less certain, and limited by our lack of understanding of certain key processes. Sustained high-resolution monitoring of the global cryosphere is therefore extremely important, both to provide data to improve our predictive capability, and to provide up-to-date information on the current state of the system. Satellite, airborne, and ground-based geodetic measurements will continue to play a crucial role in observing the cryosphere. The NRC Decadal Survey [NRC, 2007] has recommended three geodetic missions (DESDynI, GRACE-II, ICESat-II), which together have the capability for measuring ice sheet mass, depth, and deformation as well as the distribution and dynamics of sea ice. In the temporal gap between ongoing and future satellite missions, airborne observations and expanding networks of ground-based GPS systems will play a vital role.

UNAVCO Role: UNAVCO supports a vibrant cryospheric and polar science community through Polar Services and through support of the ITRF. The POLENET GPS networks in Antarctica (ANET) and Greenland (GNET) rim the ice-laden continents. POLENET construction was led by UNAVCO community scientists in collaboration with UNAVCO staff who developed and built critical components in addition to training PIs and their students; UNAVCO supports these 100 high-latitude stations that provide the time-varying temporal history of rebound required to constrain changes in ice mass (vs. GIA), and strong regional reference networks for shorter-term GPS and TLS observations of changing glaciers and other polar landscapes. The history of support for polar projects, and projections for GAGE 2013 - 2018 are discussed in sections 3.1.1 and 3.1.2.

Key questions for ice mass change and dynamics:

- Where, and how fast, are the polar ice sheets and other glaciers changing in response to climate fluctuations?
- How do rheology, basal conditions and topography, and glacier thickness effect glacier flow?
- How do ocean tides moderate glacier flow for outlet glaciers?
- How can past changes in ice distribution and dynamics help us understand present-day changes?

Long-term goals for addressing key questions:

- Improve spatial and temporal resolution for regional and global observations and extend the coverage of long-term observations.
- Improve ties to the terrestrial reference frame in polar regions.

2.2 EARTH THE MACHINE

Earth and the tools we use to study it are constantly changing. The tectonic plates are continuously in motion, although generally at slower rates such that even with the highest precision instruments we need months or years of observations to measure them. Over the last several decades, the advent of space-based geodetic techniques have improved our ability to measure tectonic plate motion by several orders of magnitude in spatial and temporal resolution as well as accuracy, and to establish stable terrestrial and celestial reference frames required to achieve these improvements. Research using space geodetic tools has led to revolutionary progress in our understanding of plate boundaries and interiors. Parts of faults we once thought of as locked between major earthquakes are now known to experience episodic creep events that are sometimes accompanied by seismic tremor [*Rogers and Dragert*, 2003].

GNSS surveying will be significantly improved with the launch of the GPS III generation of satellites and with the continued development of international GNSS systems such as GLONASS and Galileo. Improvements in telecommunications infrastructure will also allow researchers easy and rapid access to data acquired from ground-based GNSS systems. The use of high-rate and real-time GNSS measurements is still in its infancy, and there is great potential for new discoveries from high rate 3D positioning and in its integration with strain and gravity measurements, as well as with seismic and other data. InSAR techniques are revolutionizing studies of the earthquake cycle and volcanic activity, and is moving towards the capability of providing synoptic line of site (LOS) velocity fields with ~1 mm/yr accuracy.

In this section, we discuss four topics identified by community planning [*Davis et al.*, 2012] and focus on the understanding underlying structure of the Earth and the forces that shape and transform its surface.

2.2.1 How do tectonic plates deform?

The spatial density and temporal resolution of GPS observations have allowed us to resolve how strain varies across the plates and at plate boundaries in both in space and in time [*E J Davis et al.*, 2008; *Elliott et al.*, 2010; *Freed and Burgmann*, 2004; *Kreemer et al.*, 2003; *Kreemer et al.*, 2010; *Kreemer et al.*, 2006; *Kreemer et al.*, 2012; and also see *Pollitz et al.*, 2012; *Thatcher*, 2009; *Thatcher and Pollitz*, 2008] (Figure 2.2-1). These plate-scale measurements have been critical in constraining how the lithosphere responds to glacial loading and unloading [*Sella et al.*, 2007], defining where strain occurs within the plate boundary zone interiors [*Berglund et al.*, 2012; *Hammond and Thatcher*, 2007; *Kreemer and Hammond*, 2007; *Payne et al.*, 2008], the recognizing strain transients within several subduction zones [*Brudzinski and Allen*, 2007; *Larson et al.*, 2004; *Obara*, 2002; *Ozawa et al.*, 2002; *Rogers and Dragert*, 2003], and understanding how

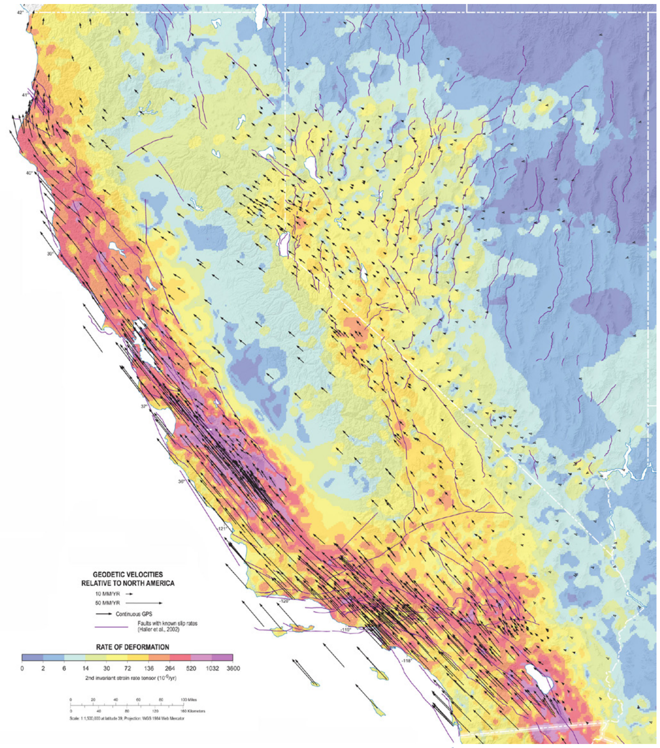


Figure 2.2-1. Geodetic strain rate model. A model of crustal strain rates derived from GPS measurements of horizontal station velocities indicates the spatial distribution of deformation rates within the Pacific–North America plate boundary from the San Andreas fault system in the west to the Basin and Range province in the east. Because rapid transient effects associated with earthquakes have been removed from the GPS data, these strain rates are a proxy for the long-term, steady-state, deformation associated with the accumulation of strain along faults. From Kreemer et al. [2012].

plate boundary forces are accommodated within zones of diffuse deformation such as western North America and the Alpine-Himalaya mountain belt [*Flesch et al.*, 2001; *Flesch et al.*, 2007; *Flesch et al.*, 2005; *Ozeren and Holt*, 2010; *Reilinger et al.*, 2006]. Furthermore, tidal loading response recorded by the PBO GPS network has now been used to constrain rheological models for the asthenosphere [*Ito and Simons*, 2011]. These examples show how innovative applications of GPS can yield unexpected discoveries about the interactions between the solid earth and ocean.

Although tremendous progress has been made in the measurement of kinematics of plate boundary zones, our quantification of crustal strain rates suffers from both spatial and temporal aliasing [*Sandwell*, 2010]. The continued augmentation of existing PBO sites with high-rate (1 Hz or faster) low-latency (<1 s) GPS promises to dramatically improve both the spatial and temporal coverage of steady-state and transient crustal strain. Additional PBO sites would be required, however, to diminish spatial aliasing for tectonic studies. Combining GPS with InSAR further improves the spatial coverage to resolve the 4-D deformation field [*Fialko et al.*, 2001; *Hammond et al.*, 2012; *Wei et al.*, 2010; *Wright et al.*, 2004]. One long-term UNAVCO community goal is to develop advanced data products which resolve estimates of crustal strain and displacement in near real-time.

Major challenges also remain in linking plate kinematics with dynamics. Factors influencing large-scale deformation within diffuse plate boundary zones (*e.g.* western North America and central Asia) remain enigmatic, but include the effects of accommodation of plate motions, body forces and coupling with mantle flow [*Choi and Gurnis*, 2003; *Flesch et al.*, 2001; *Flesch et al.*, 2000; *Flesch et al.*, 2007; *Humphreys and Coblentz*, 2007; *Z Liu and Bird*, 2002; *Sonder and Jones*, 1999; *Yang and Liu*, 2010].

With EarthScope in place, the opportunity to resolve large-scale dynamics has never been brighter. Dynamic models now rely on seismic tomography to resolve crustal structure coupled with kinematic constraints from GPS measurements (Figures 2.2-2, 2.2-3). New results from crustal geodesy [*Berglund et al.*, 2012; *Kreemer et al.*, 2010; *Puskas and Smith*, 2009; *Shen et al., 2011*], together with crustal structure and mantle tomography models [*Buehler and Shearer*, 2010; *Burdick et al.*, 2008; *D E James et al.*, 2011; *Levander et al.*, 2011; *Lowry and Perez-Gussinye*, 2011; *Obrebski et al.*, 2010;

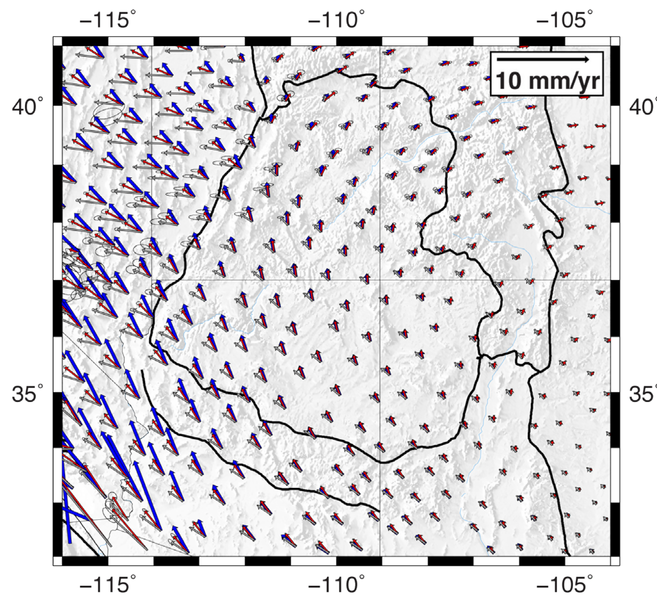


Figure 2.2-2. The Colorado Plateau: Integration of geophysical observations through dynamic modeling. The Colorado Plateau has long been interpreted as a strong lithospheric block passively rotating within the highly deforming western United States. Flesch and her colleagues have used integrated surface observations (receiver function analysis and GPS observations) to explore the surface response to two cases: 1) delamination, and 2) crustal under-plating of high density material. For each case, the dynamics, driven by lithospheric buoyancy forces, produces different deviatoric stress fields. The density structure from the above modeling was then combined with estimates of vertically averaged effective viscosity distributions, determined by dividing the magnitudes of deviatoric stress by the magnitudes of the GPS strain rate field, to produce dynamic velocities that can be directly compared to GPS observations. The dynamic velocities from the under-plated case (Blue arrows) provide the best fit to the surface velocity fields (Grey arrows), with velocities of the same magnitude but retain a counter clockwise rigid body rotation, which may indicate a residual reference frame issue. Red arrows show rotated surface velocities. From Flesch et al. [2012 written communication].

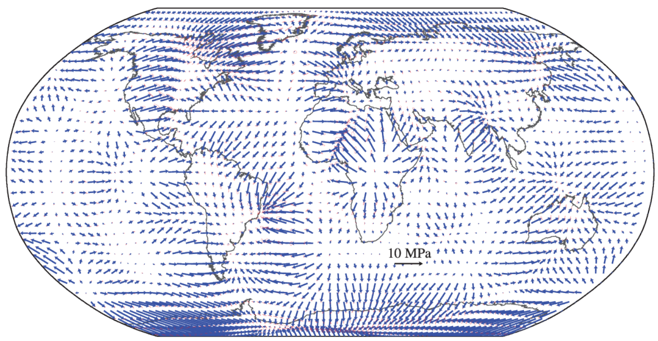


Figure 2.2-3. Mantle traction and global dynamics. Global dynamic model of geodetic observations of plate motions and boundary-zone deformation, lithosphere rigidity, and stresses. The model accounts for lateral viscosity variations in the top 200 kilometers of the Earth, as well as forces associated with topography and lithospheric structure, and coupling with mantle flow (shown here). Horizontal traction vectors at 100 km depth below sea level (blue), are shown with 95% confidence (red). This integration of structure, kinematics, and geodynamics into a self-consistent description of the Earth deformation expands one of EarthScope's central science goals for North America to global scale. Modified from Ghosh and Holt [2012].

Schmandt and Humphreys, 2010; *Sigloch*, 2011; *Sigloch et al.*, 2008; *Wagner et al.*, 2010; *West et al.*, 2009; *Xue and Allen*, 2010], provide new constraints for dynamic models that can test a variety of hypotheses, including the nature of coupling between the deforming lithosphere and mantle flow below western North America.

In the recent EarthScope science plan, of the stated goals for the USArray Transportable Array (TA) deployment in the east region of the US was "*to illuminate the causes and consequences of large magnitude earthquakes in continental interiors*" [page 22, *Williams et al.*, 2010]. Thus, another challenging frontier to be addressed by the UNAVCO community and the GAGE Facility in the next five years, and beyond, is the need to improve estimates of intraplate deformation. Intraplate earthquakes, while generally smaller than those concentrated along plate boundaries, have the potential to be equally or even more destructive, as recent earthquakes in inland China demonstrated. The August 2011 Mw 5.8 Mineral, Virginia, earthquake shook large areas of the East Coast and damaged structures in Washington, DC including the Washington Monument (Figure 2.2-4). At present, no comprehensive model exists to explain such earthquakes. We know little about their causes and the possible hazards they pose.

Intraplate earthquakes can also be large. For example, the 1929 M 7.2 earthquake on the Grand Banks of Newfoundland, caused a large (~1011 m^3) landslide of thick continental slope sediments, which cut trans-Atlantic telegraph cables and generated a tsunami. Other notable events include the 1933 M 7.3 Baffin Bay, 1755 M ~6 Cape Ann, Massachusetts, and 1886 M ~7 Charleston earthquakes. The 2011 Mineral, VA earthquake thus may be regarded as part of a diffuse seismic zone extending along the eastern continental margin of North America (Figure 2.2-5).

How this diffuse eastern seismic zone relates to more spatially limited central US seismic zones, such as those in eastern Tennessee, the Wabash Valley, and New Madrid is still poorly understood.

It is not known whether (1) these zones have sustained activity over time, but somehow do not express the repeated release of seismic energy in local topography, or (2) are simply the present loci of activity that migrates in space and time [*Stein et al.*, 2009], with individual faults active for short intervals and dormant for long ones [*Crone et al.*, 2003; *A Newman et al.*, 1999].

For example, in northern China, no large (M>7) earthquakes ruptured the same fault segment twice in the past 2000 years [*M A Liu et al.*, 2011]. On one hand, the locations of past small earthquakes are good predictors of the locations of future ones [Kafka, 2007]. On the other hand, rock mechanics predicts that aftershock sequences for large continental earthquakes should continue for hundreds of years [*Stein and Liu, 2009*] and thus current seismicity may be simply the "echoes" of large prehistoric earthquakes.

The forces driving intraplate seismicity also are unclear. On average, stress indicators for the eastern US show that compression is oriented ENE [*Zoback*, 1992]. This direction is similar to that predicted by models of intraplate stress due to plate-wide forces including "ridge push" caused by cooling oceanic lithosphere [*Richardson et al.*, 1979], mantle flow beneath the continent [*Forte et al.*, 2007], and combinations of these and other topographic forces [*Ghosh and Holt*, 2012] (Figure 2.2-3). These include "spreading" of lower density

Figure 2.2-4. Inspection of earthquake damage to the Washington Monument after the August 23, 2011, MW 5.8, Mineral, VA earthquake. Two PBO pool receivers were deployed to the epicentral region as part of a UNAVCO event response coordinated with community PIs working in the region as part of an NSF RAPID award. Photo credit: National Park Service.

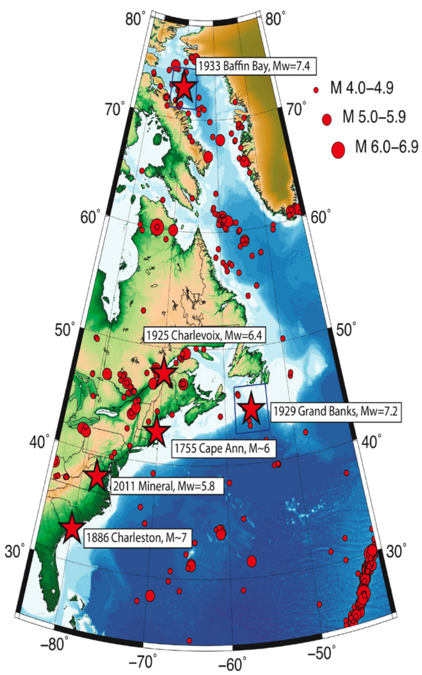


Figure 2.2-5. Notable earthquakes of eastern North America. Intraplate seismicity along the continental margin since 1980, taken from ANSS and Earthquakes Canada catalogs. Major historical events are also shown. Figure from Wolin et al. [2012].

continental crust over oceanic lithosphere [*Bott*, 1971], the load of offshore sediment [*Cloetingh et al.*, 1983; *Turcotte et al.*, 1977; *Walcott*, 1972], and stresses due to the removal of glacial loads [*Quinlan*, 1984; *Stein et al.*, 1989; *Stein et al.*, 1979].

Data from USArray and new stations being incorporated into PBO GPS processing streams will provide new constraints on crust and lithosphere structure, and mantle tomography and form the framework to develop rigorous dynamic models [*Forte et al.*, 2010; *Ghosh and Holt*, 2012; *L J Liu et al.*, 2008; *Moucha et al.*, 2008; *Spasojevic et al.*, 2009], but improvements are still needed in the difficult area of resolving horizontal motions associated with slow intraplate deformation[*Wolin et al.*, 2012]. Success resolving motions associated with GIA in eastern North America [*Mazzotti et al.*, 2005; *Sella et al.*, 2007] suggests that measurement of such small deformation may now be within reach. In addition, InSAR has provided uniquely detailed observations of intraplate earthquakes in recent years (Figure 2.2-6), with surface displacements from earthquakes as small as M4.4 reported.

UNAVCO Role: Support for GPS investigations of intraplate and plate boundary deformation is part of UNAVCO's legacy core competency, with contributions that extend over three decades. Through lead and collaborating roles, UNAVCO has been instrumental in establishing, supporting, and enhancing continuous networks in North America, South and Central America, Antarctica, Africa, and Greenland. By supporting continuous and campaign observations by the investigator community with equipment, engineering, and data services, UNAVCO has contributed to characterizing solid Earth deformation on every continent, and to data preservation and stewardship through the activities of the archive. The history of UNAVCO support for such projects, and projections for GAGE 2013 - 2018 are discussed throughout Sections 3.1 and 3.2 of this proposal.

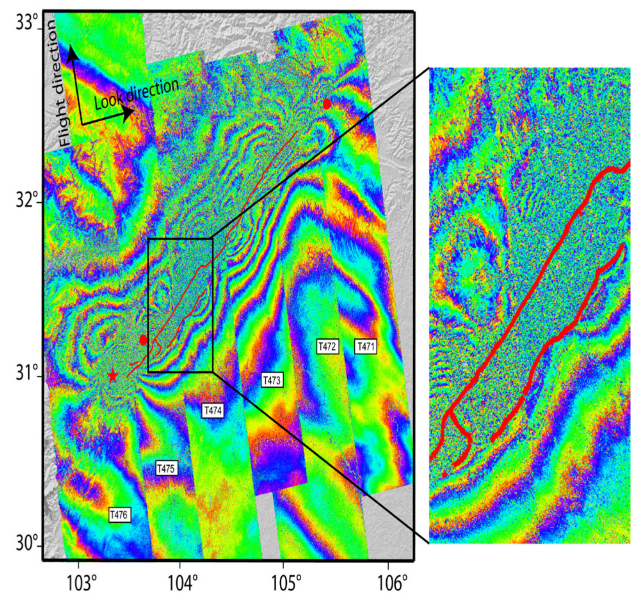


Figure 2.2-6. 2008 MW7.9 Wenchuan earthquake. A SAR interferogram of the 2008 MW7.9 Wenchuan China earthquake clearly imaged the earthquake rupture (red line) with fringes that quantify the magnitude of the coseismic displacement in the satellite line of sight direction. The earthquake epicenter is shown by a red star; red dots denote epicenters of two large aftershocks. Using InSAR, GPS, and field data together provides three-dimensional constraints on coseismic deformation. Figure courtesy of Y. Fialko and modified after Tong et al. [2010].

Key questions for intraplate and plate boundary deformation:

- What is the rheology and structure of the upper mantle and lithosphere?
- How does deformation of oceanic plates differ from that of continental plates?
- Why are broad plate boundary zones so common in the continents, and what controls the extent and distribution of deformation within them?
- What are the mechanics of plate boundaries?
- On timescales of 1 second and longer, what is the rheological response of the crust and mantle to loading and unloading by ice, water, sediments, and tectonic events?
- What are the driving mechanisms of intraplate earthquakes?
- What are the relative contributions of recoverable (elastic) and permanent (inelastic) deformation of the upper crust to the total strain budget of major fault systems, and how do these contributions vary with time?

Long-term goals for addressing key questions:

- Improve and extend (especially to the ocean floor) the spatial and temporal resolution and accuracy of deformation measurements.
- Integrate deformation measurements with data from seismic networks on a range of temporal and spatial scales.
- Integrate gravity and deformation measurements to separate mass motions and tectonic signals.

2.2.2 What physical processes govern earthquakes?

Since earthquake science began following the 1906 San Francisco earthquake, geodetic observations have led to fundamental advances in understanding earthquake behavior, from the formulation of viscoelastic rebound theory to the discoveries of postseismic transients, interseismic strain accumulation, and, more recently, slow slip events. As global population continues to increase and more people live near seismically active faults, understanding the nature of earthquakes remains a critical challenge of great societal importance.

Studying and forecasting rupture

UNAVCO supports studies in the US and worldwide using geodetic data to help describe the rupture during large earthquakes and better assess the location and extent of possible future ruptures. Dense networks of ground-based geodetic instruments (*e.g.*, GPS and strainmeters) and remote sensing (in particular InSAR and optical imagery) are now routinely used in combination with seismic observations to measure coseismic, postseismic, and interseismic deformation. Strain rate maps and block models of crustal deformation are increasingly being used as integral parts of probabilistic seismic hazard analysis that supports the US national seismic hazard maps [*M D Peterson et al.*, 2008].

The utility of these approaches is illustrated by the January 12, 2010 Mw 7.0 Haiti earthquake that killed over 240,000 people. Based on GPS measurements initiated in 2003, it was recognized that the major east-west sinistral fault, the Enriquillo Fault (EF), was capable of and accumulating elastic strain equivalent to a magnitude 7.2 earthquake, if released in a single earthquake [*Manaker et al.*, 2008]. Surprisingly, however, the earthquake did not rupture the vertical EF near the surface [*Calais et al.*, 2010; *Hayes et al.*, 2010; *Hornbach et al.*, 2010; *Hough et al.*, 2010; *Prentice et al.*, 2010]. Instead the fault ruptured in a complex fashion on the newly identified dipping Léogâne Fault, whose sense of coseismic motion was consistent with the transpressional environment that defined the pre-earthquake interseismic surface deformation measurements (Figure 2.2-7). Similar methods are being applied in many places worldwide, including within the Caribbean-wide COCONet network that UNAVCO is building in collaboration with its 31 international COCONet partners (Figure 2.2-8).

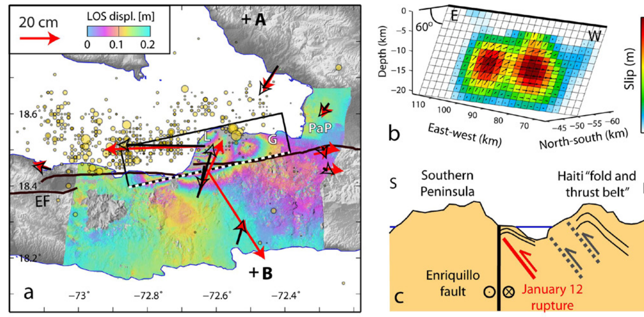


Figure 2.2-7. The January 12, 2010 MW7.0 Haiti earthquake. The Haiti earthquake killed more than 240,000 people in an area known to be capable of producing an earthquake of that magnitude [Manaker et al., 2008]. When the earthquake occurred, it did not actually rupture the known vertical Enriquillo fault; rather it occurred on a previously unidentified north-dipping fault and slip occurred in the expected direction. The InSAR image (a) shows of line-of-sight (LOS) surface displacement with GPS-observed (black) and model (red) coseismic displacement field; yellow circles show aftershock locations. A model for slip on the fault plane was estimated from the InSAR and GPS observations (b). The modeled slip surface corresponds to a blind reverse fault shown in red (c). From Calais et al., 2010.

Investigating earthquake mechanics

The role of geodesy in understanding earthquake mechanics is drawing great interest following three of the largest subduction zone events in over 40 years: the 2004 Sumatra-Andaman (Mw9.2) [*Banerjee et al.*, 2005], 2010 Maule (Mw8.8), and 2011 Tohoku-Oki (Mw9.0) earthquakes. Both the 2004 and 2011 events generated great tsunamis with a devastating number of fatalities and significant damage to infrastructure. Geodesy brings unique capabilities to study these large events [*Ali and Freed*, 2010; *Ide et al.*, 2011; *Sato et al.*, 2011; *Simons et al.*, 2011; *Vigny et al.*, 2011]. UNAVCO supports a wide range of geodetic studies of global subduction zones,

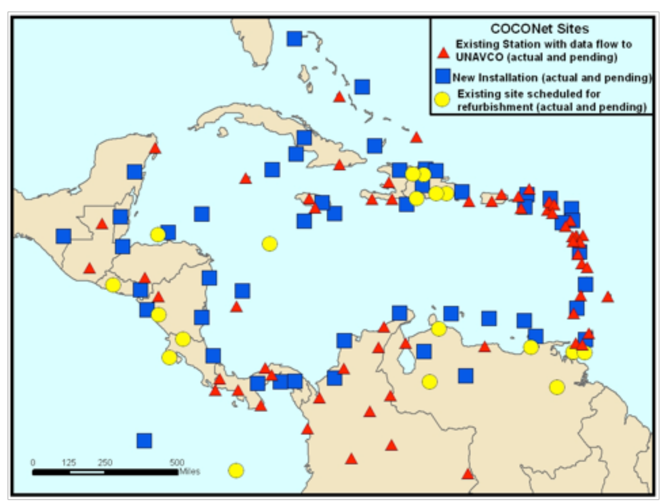


Figure 2.2-8. Continuously Operating Caribbean GPS Observational Network (COCONet). COCONet is a network of GPS and meteorological stations throughout the Caribbean that is currently under construction by UNAVCO. When complete, it will include 50 newly-constructed GPS and met stations (red) integrated with 65 existing GPS stations (blue) operated by international partners. Additional funding has recently been obtained to add several collocated tide gauges and high-precision GPS sites. The COCONet backbone of stations will facilitate additional experiments of higher spatial density that address specific science problems.

which are known to be capable of great earthquakes, including Cascadia, the Aleutians, Central America, the West Indies, and South America.

Dense on-land GPS observations at 1,200 stations during the Tohoku-Oki earthquake were complemented by combined acoustic and GPS (GPS-A) observations at 27 stations on the seafloor, providing the most complete constraints on a megathrust earthquake [*Grapenthin and Freymueller,* 2011; Sato et al., 2011]. Modeling of these observations indicates very large slip – up to 40 m, over a relatively small rupture area [*Ozawa et al*., 2011; *Simons et al*., 2011] (Figure 2.2-9).

An intriguing and potentially important aspect of subduction zone mechanics is the recent discovery of slow earthquakes on nearly regular intervals, which are associated with seismic tremor. UNAVCO continues to play a major role in the study of these recurring events, which were first recognized as short (several weeks) periods of deformation in GPS time series from the Pacific Northwest [*Dragert et al*., 2001; *Miller et al*., 2002; *Rogers and Dragert*, 2003]. The collection of GPS time series from the UNAVCO-supported PANGA network (Figure 2.2-10) illustrates the coherence and periodicity of the crustal deformation events [*Szeliga et al*., 2008].

Geodetic data have been used to explore a number of properties of episodic tremor and slip (ETS) events, including triggering mechanisms or modulation such as tidal stress (Figure 2.2-11) and passing seismic waves [*Gomberg and Felzer*, 2008; *Hawthorne and Rubin*, 2010; *Ide*, 2010; *Miyazawa and Mori*, 2005; *Peng et al*., 2009; *J. L. Rubinstein et al*., 2008; *Shelly et al*., 2007; *Thomas et al*., 2009]. Slip distribution derived from GPS observations during an ETS event in 2003 in Cascadia [*Melbourne et al*., 2005] indicate that the location of slip migrates significantly during the ETS event. With the addition of PBO borehole strainmeters to Cascadia and the upgrade of additional PBO sites to broadcast real-time GPS, even finer resolution of the space-time progression of ETS events is possible (Figure 2.2-12) [*Dragert and Wang*, 2011]. ETS has since been observed in other areas around the world [*Brown et al*., 2009; *Delahaye et al*., 2009; *Douglas et al*., 2005; *Jiang et al*., 2012; *Larsen et al*., 2004; *Obara*, 2002; *Ozawa et al*., 2002; *Peng and Gomberg*, 2010; *C L Peterson and Christensen*, 2009; *J.L. Rubinstein et al*., 2010; *Schwartz and Rokosky*, 2007; *Segall et al*., 2006; *Shelly*, 2010]

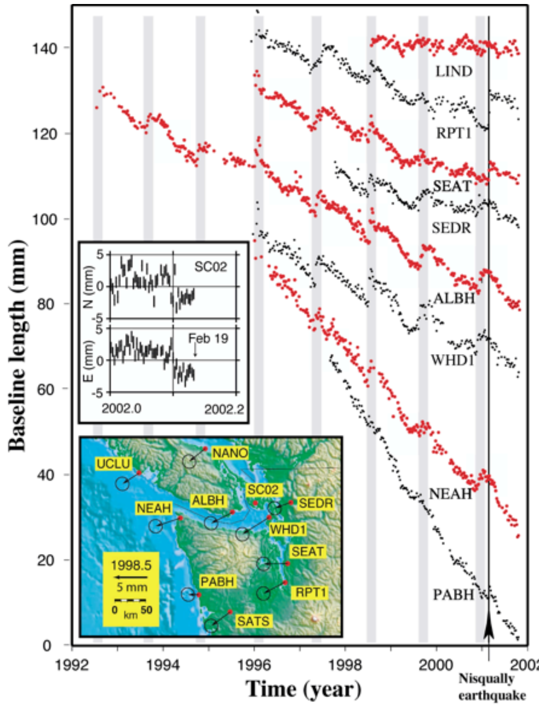


Figure 2.2-10 Time series for GPS stations along the Cascadia margin. Based on weekly station positions with respect to Penticton, B.C., secular baseline length changes increase with station proximity to the coast. Miller et al. [2002] first noted the apparent 14-month periodicity of events now known as Episodic Tremor and Slip (ETS), events that episodically reverse this accumulation of elastic strain across the forearc (inset), with a protracted creep event accompanied by seismic tremor. Friday Harbor (SC02) showed the onset of such an event that was ongoing when the 2002 paper appeared.

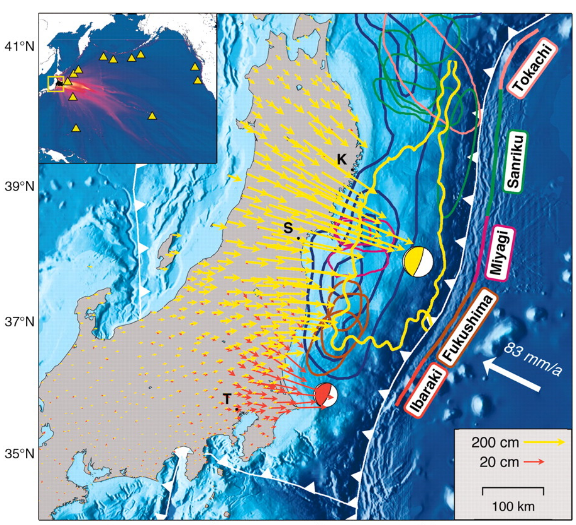


Figure 2.2-9. March 2011 Tohoku earthquake. Vectors indicate the horizontal component of the land GPS displacement fields for the Mw 9.0 main shock (yellow) and the Mw 7.9 aftershock (orange). Approximate locations of historical megathrust earthquakes are indicated by closed curves colored by region. Figure from Simons et al. [2011].

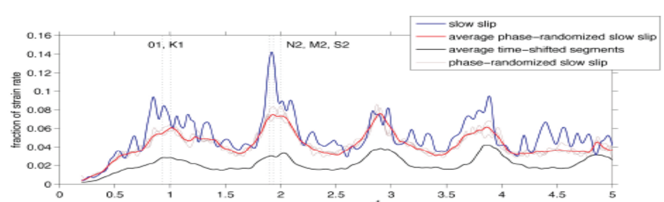


Figure 2.2-11. Tidal modulation of slow slip in Cascadia. PBO borehole strain meters uniquely reveal tidal modulation of evolving slow slip on during ETS events on the Cascadia subduction zone, a result below the threshold of sensitivity for GPS or even for a single strain meter taken in isolation. Amplitude of coherent strain rate modulation is shown as a function of frequency. By simultaneously fitting stacked data from multiple stations and slow slip events, Hawthorne and Rubin were able to demonstrate with 99% confidence the modulation of the strain rate with a 12.4-hour periodicity, for the tide with the largest amplitude. The amplitude of this modulation suggests that the slip rate during slow slip events oscillates, on average, 25% above and below its mean value during a tidal cycle. From Hawthorne and Rubin [2010].

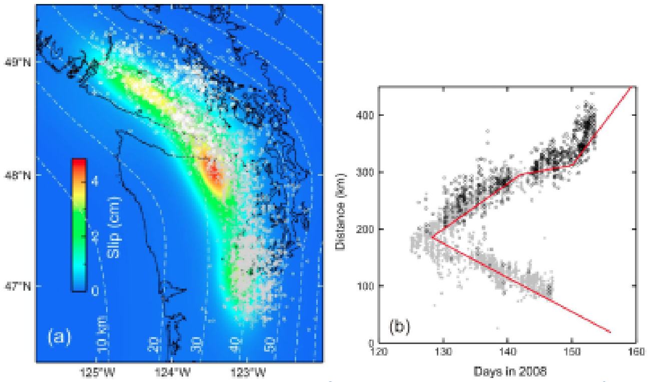


Figure 2.2-12. Recurring transient deformation in Cascadia. The densification of the regional GPS network and the installation of sensitive deep borehole strainmeters (BSM) in the Cascadia region as part of PBO have significantly advanced the ability to resolve spatial and temporal variations in ETS events. Dragert and Wang, [2011], made a comparison of slip and tremor of the 2008 ETS event. GPS data were inverted for source parameters on the subducting slab and BSMs were used to provide high precision time constraints. (a) Shows tremor sources on the background of the slip model. Depth contours of the plate interface are shown in white. Squares (white) and circles (red) are GPS and BSM sites where observed and modeled time series are compared. (b) Along-strike time migration of tremor sources and modeled onset of GPS motion and BSM deformation. The tremor locations are projected onto the 40 km depth contour of the plate interface. Tremor sources are shown as shaded and open circles. Linear piece-wise function was used to model bidirectional propagation shown with red line. The results show an initial progression at 8 km/day to the north followed by a pause and subsequent acceleration. To the south there was a steady progression at 6 km/day. Both figures modified from Dragert and Wang [2011].

The causes and mechanics of ETS events are topics of active investigation by geodesists and the broader geoscience community. Geodetic and seismic observations are consistent with periodic slip events, where several centimeters of displacement migrate along the subducting plate boundary over several weeks, within the transition between the creeping (velocity-strengthening) and up-dip seismogenic (velocity-weakening) parts of the fault [*Shibazaki and Shimamoto*, 2007]. A number of controlling processes have been hypothesized: rate and state friction laws [*Liu and Rice, 2005; 2007*], dilatant strengthening [*Segall et al*., 2010], and critical near-zero weakening [*Ben-Zion*, 2012]. Recent theoretical work suggests that this behavior implies high pore fluid pressure and low effective normal stress [*Peng and Gomberg*, 2010; *Rubinstein et al*., 2010]; spatial and temporal correlations of tremor and aseismic slip may corroborate the presence of highly pressurized pore fluids.

It is now recognized that ETS events increase stress on the up-dip locked megathrust, and a stable observatory is needed to support a vigorous research program to assess the hazard implications of this process. In some areas slow slip events are associated with swarms of small to moderate seismicity, but this behavior does not appear to be universal [*Peng and Gomberg*, 2010]. Cascadia is one of the few subduction zones in the world where instrumentation is sufficient to obtain full spatial detail of slip initiation, propagation and termination. In addition, megathrust earthquakes disrupt the seafloor, generating devastating tsunamis that may be detected within minutes using GPS early warning systems [*Crowell et al*., 2012; *Grapenthin and Freymueller*, 2011], thus mitigating damage and loss of life for heavily populated coastal communities.

The GAGE Facility will continue to play a unique and important role in the study and definition of ETS in the Pacific Northwest with its ongoing and planned RT-GPS enhancements to PBO; during the 2013-2018 period at least 4 more ETS events will likely occur, adding to the short catalog of these events.

High-resolution fault imaging

Historically, the best knowledge of how slip varies along a fault surface came from seismological data. This approach is limited by the fact that the earthquake must have occurred recently enough to be seismologically recorded, and also by the wavelengths detectable by seismic instruments. UNAVCO plays a key role in developing new technologies, notably light detection and ranging (LiDAR) surveying, that image the topography of faults in much greater detail than previously possible. The GAGE Facility will continue to expand UNAVCO efforts to develop the tools and provide the required support to image active and ancient faults with LiDAR.

Differenced airborne LiDAR images from before and after the 2010 Mw 7.2 El Mayor–Cucapah earthquake have demonstrated the power of this technique by illuminating a 120-kilometer-long complex rupture through northernmost Baja California, Mexico with effects extending into southern California [*Oskin et al*., 2012]. The second survey revealed numerous surface ruptures, including previously blind faults within thick sediments of the Colorado River delta. The resulting data can be used to constrain detailed rupture models (Figure 2.2-13).

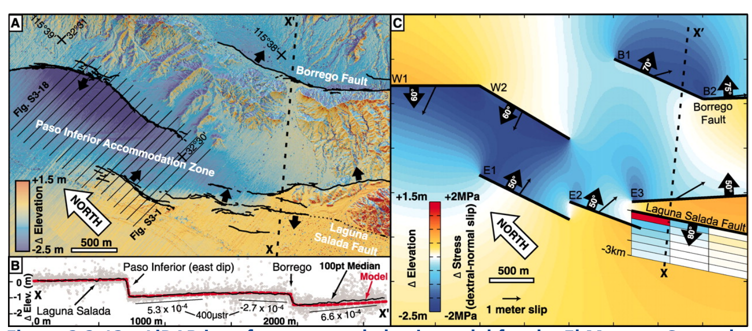


Figure 2.2-13. LiDAR interferogram and elastic model for the El Mayor – Cucapah earthquake. (a) Distributed coseismic deformation occurred along the right-stepping dextral Borrego fault system, at the California – Baja California border (striping reflects noise; black arrows show fault dip direction). (b) The profiled elevation difference (along dashed line X-X) steps at fault strand crossings. (c) A forward elastic model for coseismic deformation provides a good fit to the line-of-sight lidar observations, except in the southwest, where modeled normal slip exceeds observations by 30%. From Oskin et al. [2012].

Investigating fault rheology

Earthquake coseismic slip results in stress changes that can be used as energy sources for experiments that probe the rheology of the lower crust and upper mantle. In the months and years following an earthquake, nearby regions relax by viscous flow, transferring stress back to the seismogenic crust and the surface, causing postseismic surface displacements [*Deng et al.*, 1998; *Freed and Burgmann*, 2004; *Freed et al.*, 2007; *Freed et al.*, 2012; *Hetland and Hager*, 2004; *Pollitz et al.*, 2012]. Earthquakes can be followed by afterslip, where certain areas of the fault, both within the rupture surface and down-dip, slip aseismically in the months and years after the earthquake, causing observable surface deformation [*Miyazaki et al.*, 2011; *Vigny et al.*, 2011]. In both cases, GPS measurements of the postseismic deformation can constrain numerical models that simulate these processes (Figure 2.2-14).

The study of post-seismic relaxation addresses questions about fault strength as well as the rheology of the lower crust and upper mantle. Such questions include: does a weak fault penetrate into the lower crust [*Hearn et al.*, 2009; *Shelly*, 2010]? What rheologic model best describes the lithosphere [*Burgmann and Dresen*, 2008]? What long-term conditions [e.g., mineralogy, creep mechanism, temperature, water content, strain rate, stress] control the response of the lower crust and mantle to loading [*Freed et al.*, 2012]? These are not just of academic interest, as the answers have direct bearing on the earthquake cycle and seismic hazards, as postseismic mechanisms play an important role in the evolution of stresses in the crust [*Freed*, 2005].

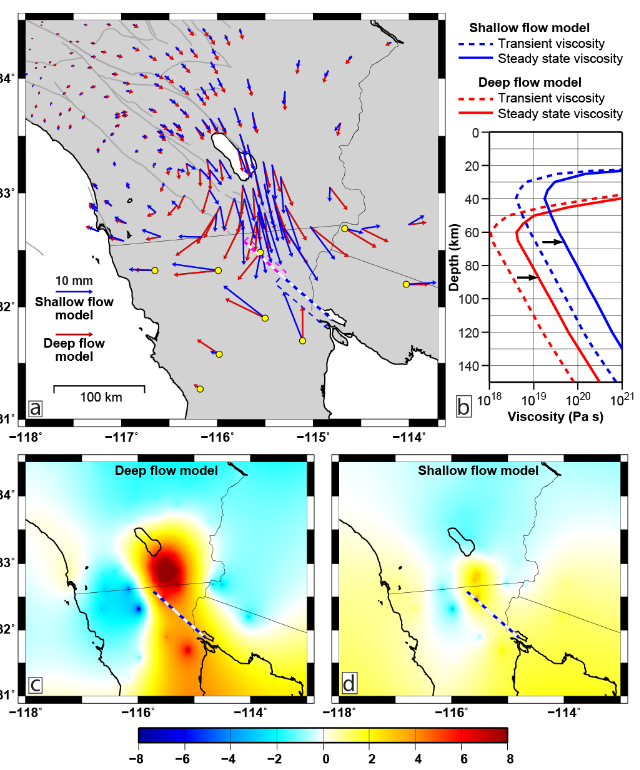


Figure 2.2-14. Post-seismic deformation constrains mantle rheology. (a) Predicted three year displacements at GPS sites, based on two possible models for mantle rheology, for the 2010 M7.2 El Mayor-Cucapah (Baja California) Earthquake. GPS stations added immediately after the earthquake, primarily by PBO, are shown with yellow circles. From Pollitz et al. [2012].

UNAVCO Role: The UNAVCO community using facility support has advanced understanding of the earthquake cycle and its human impacts over the past two and a half decades through the construction, operation and maintenance of investigator and community (UNAVCO-managed) GPS, strain, and tiltmeter networks. With support for acquisition of campaign GPS and InSAR data sets that characterize coseismic displacements, LiDAR imagery for paleoseismic studies, earthquake event response, including development of protocols for targeted post-seismic data acquisition, and community coordination for efficient use of scarce geodetic resources. The recent emergence of high-rate), low-latency GPS data streams, along with their recent integration with strong motion accelerometer records, has given birth to a new capability for GPS seismology. The history of UNAVCO support for study of the earthquake cycle investigations along with plans for the GAGE Facility during 2013 - 2018 are included in the activities, performance metrics, and projections throughout section 3.1 and 3.2 of this proposal.

Key questions for earthquake physics:

- What are the mechanisms of interseismic loading, co-seismic strain release, and transient deformation events?
- Are there detectable precursory deformation signals associated with large earthquakes?
- Do attributes of ETS events (e.g. period, updip extent, and amplitude) vary with time as the next large earthquake approaches?
- What controls the occurrence of slow-slip events and why do these differ from typical dynamic earthquakes?
- What is the role of ETS in the occurrence of large earthquakes in subduction zones? Can improved understanding of ETS and loading processes lead to improved forecasts of damaging megathrust events?
- What is the average magnitude of stress supported by active faults?

Long-term goals for addressing key questions:

- Integrate geodetic measurements of interseismic deformation, geologic fault slip rates, and paleoseismic determinations of earthquake recurrence intervals.
- Improve the accuracy of continuous, stable celestial and terrestrial reference frames, as well as other products required for positioning, such as high-accuracy orbits for GNSS satellites.
- Integrate high-rate and low latency continuous geodetic and seismic networks with developing early warning systems for earthquakes, tsunamis, and other natural hazards.
- Improve the spatial and temporal resolution of crustal deformation measurements in earthquake zones.
- Improve the capability for rapid deployment of high-resolution measurements in response to seismic events, through some combination of terrestrial (*e.g.*, GNSS surveys) and satellite observations (*e.g.*, InSAR).

2.2.3 How does Earth's surface evolve?

Earth's surface is being continuously reshaped, with profound implications for the terrestrial water supply (*e.g.*, floods, water quality, turbidity, etc.), ecosystems, landscape, and the built environment. Advances in geodetic imaging [Roering et al., 2009; Sigmundsson et al., 2010] in the last decade, when integrated with other geodetic methods, now allow precise characterization of the full set of parameters that govern land surface evolution: kinematics, the tectonic driving forces that move the landscape; mass balance (volume of material that is redistributed across the landscape); sediment transfer (what is moving, where it is going, and source-path-sink-storage); regional factors (local geologic, hydrologic, biomorphic, geochemical, ecosystem, and climate); and catastrophic events (infrequent large scale events that redefine the inter-period rates). High-resolution images and 3D/4D topography allow us to measure changes of the Earth's surface at the appropriate spatial scales (ranging from mm to 100's of km) and facilitate field-based tests of a new generation of quantitative models of mass transport mechanisms (Figures 2.2-15, 2.2-16 and 2.2-17).

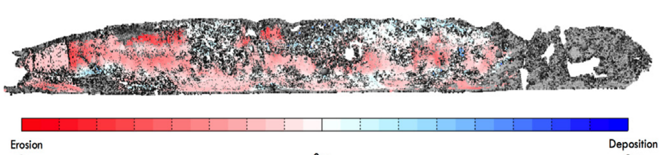


Figure 2.2-15. Bluff slough in Minnesota. Geodetic imaging is opening new subdisciplines for geodesy applications, as in this study of river bluff contributions to infilling of downstream lakes. Image from S. Day [2012]. Multiple terrestrial laser scans of a bluff on the Le Sueur River in Minnesota show the details of erosion and deposition over a two-year period. The scanned bluff is 18 m tall, 390 m long, and the average bluff retreat is 0.11 m/yr.

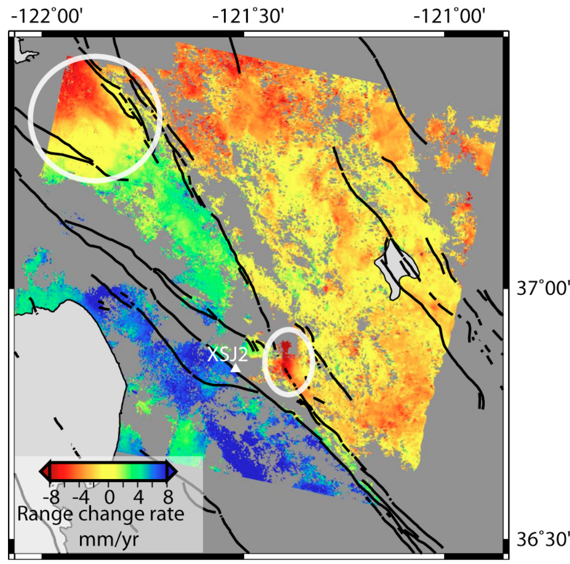


Figure 2.2-16. InSAR imaging the San Juan Bautista segment of the San Andreas fault. Moderate seismicity separates a locked and creeping section of the plate boundary. The InSAR stack from data spanning 5.75 years is scaled to an annual rate. White ovals outline basins where groundwater-recharge causes uplift; such areas were removed before the model inversion, which distributes creep on the San Juan Bautista segment. Below 3 km depth, the creep rate falls off considerably, causing a low slip zone at mid-seismogenic depths in the northern part of the San Juan Bautista segment that may represent the source region for some of the 19th century earthquakes. Image from Johanson and Bürgmann, [2005].

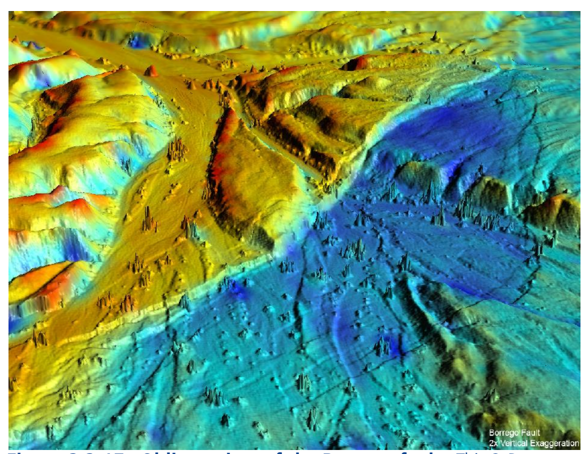


Figure 2.2-17. Oblique view of the Borrego fault. This 3-D airborne laser image of the surface rupture from the 2010 MW7.2 earthquake, northern Baja California, Mexico, shows a wide zone of small faults that slice the desert floor. Colors represent elevation change during the earthquake. From Oskin et al. [2012].

UNAVCO Role: UNAVCO support for geodetic imaging that facilitates the study of landscape evolution and dynamics has rapidly evolved since the major data acquisitions of airborne LiDAR and satellite radar undertaken by GeoEarthScope before 2008. Over the last five years, UNAVCO has acquired a pool of terrestrial laser scanning (TLS) instruments through MRI funding to support both NSF-EAR and NSF-OPP investigators, including instruments that are time-shared with partner universities and other consortia. TLS resources and field engineering support for data acquisition are important components of the Geodetic Infrastructure program under GAGE. UNAVCO staff partners with scientists and commercial companies to develop software tools and workflows for processing, analysis, visualization, and educating new users via short courses. The UNAVCO Board of Directors has recently developed a policy to provide open access to TLS data immediately upon acquisition and access to InSAR data within the constraints provided by international space agency data providers [*Pritchard et al.,* 2012]. Impelmentation of these new initiatives in geodetic imaging will be a major activity for Geodetic Data Services program under GAGE. Also, UNAVCO is working with other scientists to develop rapid deployment protocols and accessibility to equipment to rapidly initiate studies in response to earthquakes, landslides, and other events. Much of our current and planned activities under GAGE are driven by recommendations from the recent TLS community workshop report [*Phillips TLS et al*., 2012].

Key questions for Earth surface change:

- How does the surface morphology express and record the interaction between tectonic, hydrological, and gravitational processes and their modulation by climatic variation?
- What is the budget for strain loading and release during the earthquake cycle and to what extent does inelastic deformation lead to observed surface structures and morphology?
- How does the topographic form of the landscape relate to mass transport processes?

Long-term goals for addressing key questions:

- Develop new imaging techniques for 4D bathymetry at high spatial resolution and decimeter vertical precision and provide access to these techniques to the community.
- Provide open access to data, tools, and facilities for data processing, analysis, and visualization, and development of new algorithms and workflows.
- Expand tools for error analysis and LiDAR 3D point-cloud comparison over a wide-range of length scales for 4D surface change detection.

2.2.4 What are the mechanics of magmatic and eruptive systems?

Volcanic eruptions have a profound impact on society, including the destruction of life and property, in some cases altering or shutting down aviation for weeks, effecting weather, or changing global climate patterns [*McCormick et al*., 1995; *Sigurdsson*, 1982; *Swindles et al*., 2011]. Magmatic activity is an illustration of the heat engine that powers Earth's tectonics, produces new crust, and provides geothermal energy. Among the most spectacular manifestations of ongoing magmatic processes are mid-ocean ridges and volcanic chains associated with hotspot tracks and subduction zones.

While much has already been learned about volcanoes and magmatic systems, many unanswered questions remain, some of which may be uniquely addressed using an array of geodetic techniques and geophysical instruments coupled with geological knowledge of specific systems and improved models. When magma moves through the crust it displaces the surrounding rock, causing earthquakes and land surface deformation that can often be geodetically measured prior to many, although not all, eruptions. Advances in ground- and satellite-based measurement techniques, analytical and computational tools, and basic knowledge of volcanic systems have allowed for vast improvements in understanding the sources of volcanic deformation [see for example, *Dzurisin*, 2006; *Segall et al*., 2010].

Geodesy is essential for identifying pre-eruptive activity, sub-surface magma movement, magmatic and eruptive processes in concert with other geologic and geophysical techniques. Because continuous GPS observations can provide information on how the surface is deforming with high temporal resolution, geodesy is highly valuable for tracking magma movement [*Rubin*, 1995; *Rymer et al*., 1995] as well as placing strong constraints on the complex architecture of the magmatic plumbing system [*Hautmann et al*., 2010; *Mattioli et al*., 2010; *Owen et al*., 1995]. When surface deformation data are combined with other measurements such as lava efflux, additional constraints may be obtained on physical properties of the crust and the flux of magma into and through crustal reservoirs [*Elsworth et al*., 2008], which may allow us to place bounds on how some long-lived eruptions are modulated [*Foroozan et al*., 2011]. InSAR provides a synoptic view of the ground displacement field and can be used to survey global subaerial volcanoes to identify new activity [*Fournier et al*., 2010; *Pritchard and Simons*, 2002; 2004]. Volcanic unrest may be also accompanied by changes in the gravity field [*Battaglia et al*., 1999; *Rymer*, 1996], and while volcano gravimetry remains a promising geodetic technique, there have been few successful applications to erupting or restless volcanoes.

While instrumentation and computational capabilities have aided in illuminating the behavior of magmas, we do not yet have a full understanding of the processes that control magma production and ascent; hence our ability to predict eruptive events remains rudimentary. Several studies have recently demonstrated that seismic activity and deformation are linked in some volcanic systems and may remain the two most important indicators of an impending eruption [*Amelung et al*., 2007; *Walter and Amelung*, 2006]. Identifying the scales over which deformation and seismic activity reflect magma transport [*Yun et al*., 2006], and developing consistent models to explain both behaviors may lead to improved eruption forecasts, and therefore must be key focus areas of GAGE. In order to address many of the remaining questions, UNAVCO staff, in close collaboration with the scientific community, continues to develop approaches for measurement of deformation and gravity in real-time before, during, and after volcanic eruptions.

Prior to the 1980 eruption, Mt. St. Helens bulged at more than one meter per day [*Lipman et al*., 1981], while the 2004 eruption showed essentially no detectable precursory deformation [*Dzurisin et al*., 2005]. Clearly, not all eruptions are preceded by measurable deformation [*Poland*, 2010; *Taisne and Tait*, 2009]. In addition, it is well known that volatile content is likely to influence how magmatic systems develop [*Sparks,* 1978], and recent observations indicate that volatile evolution may play a significant role in geodetically detectable signals [*Linde et al*., 1994; *Voight et al*., 2006]. Therefore it is not only important, but absolutely critical, to observe many more volcanoes of different types and in a range of tectonic environments to learn how they behave. A complete census of deformation at all of the world's subaerial volcanoes is currently lacking, but the widespread application of satellite InSAR has increased the number of known deforming volcanoes from 44 in 1997 to 131 in 2011 [*Jonsson et al*., 2005; *Lu et al*., 2002; *M E Pritchard and Simons*, 2002; 2004; *Wadge et al*., 2006]. A major limitation to the global census is the lack of persistent observations over all of the world's volcanic regions (including remote ocean islands) that are frequent enough to avoid aliasing of deformation events.

We highlight efforts at the Yellowstone Volcano Observatory in the adjacent textbox and illustrate their multi-disciplinary and integrated studies, which are required to fully characterize complex magmatic systems.

UNAVCO Role: Support for advancing understanding of magmatic systems exploits a similar suite of geodetic imaging and precise point observations as those discussed above. The EarthScope PBO supports integrated networks for characterizing of several key volcanoes such as Mt. St. Helens and Augustine in the western US and Alaska, respectively, providing investigators with GPS, tilt, and strain observations. In some cases, geodetic imagery such as InSAR or TLS also is available. Many volcanoes around the world are the focus of study for the UNAVCO community collaborators and UNAVCO plays a key role in maintaining critical geodetic infrastructure at USGS volcano observatories.

Key questions for magmatic systems:

- What are the temporal and spatial scales, signature pattern, and magnitude of deformation preceding volcanic eruptions?
- How do they vary with eruption size and style at individual volcanoes and in different volcanic regions?
- What mechanisms (e.g., rheology, structure, magma/volatile input, pressure) control deformation and gravity changes in volcanoes?
- Where is magma stored before eruptions? Under what circumstances is magma transported through the crust, and what defines its transport pathways?
- How do changes in dynamic and static stress due to earthquakes affect magmatic systems?
- How do pressure changes in subsurface magma bodies affect regional stresses and seismicity?

How do nearby volcanoes interact with each other?

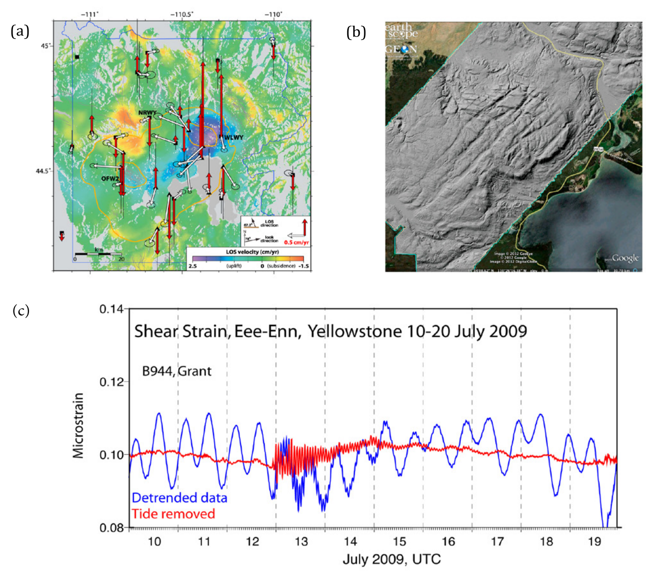
Long-term goals for addressing key questions:

- Develop approaches for measurement of deformation and gravity in real-time before, during, and after volcanic eruptions.
- Perform high-resolution characterization of deformation on all of Earth's major volcanoes.
- Develop instrumentation for seafloor geodesy and deploy on targeted submarine volcanic centers.
- Support open source modeling software capable of integrating diverse data types and physically realistic models for rapid assessment of restless volcanoes.

2.3 THE GLOBAL VIEW

The scientific challenges outlined above can be addressed only if Earth observations are organized and analyzed within a global framework, and the results shared with others in a timely, succinct, and useful manner. Geodesists are committed to this principle because modern geodesy itself is inherently a global science, and modern geodetic research focuses on analysis of global geodetic data, as well as on modeling and understanding of observed changes within the Earth system.

The UNAVCO community has adopted open data practices that exceed NSF requirements and challenge the international geodesy community to adapt professional standards for data attribution in our modern environment of data mining [*Pritchard et al*., 2012]. The international community has



EarthScope: Volcanic and Magmatic Systems

Volcanic and magmatic processes are a perennial source of fascination for scientists and the public alike. The hazards posed by eruptions, including disruptions to air traffic, property loss, and human health hazards, provide ample motivation for sustained, integrated research efforts. USArray and PBO data sets are foundational to advances in seismic imaging and GPS data analysis, leading to new insights into dynamics of mantle-to-surface melt transfer, separation and flux of volatile phases during magmatic intrusion events, and the interaction of magmatic intrusion with local tectonics. EarthScope augments instrument arrays at the Alaska Volcano Observatory (AVO), Cascade Volcano Observatory (CVO), and Yellowstone Volcano Observatory (YVO) in support of the USGS Volcano Hazards Program.

Yellowstone, a natural laboratory for interdisciplinary and integrative geophysics and natural hazards research, is a primary focus of EarthScope with campaign and continuous GPS, borehole strainmeters and seismometers, airborne and terrestrial laser scanning, and InSAR and broadband seismometers and magnetometers.

2008-2009 Yellowstone ground motion determined by InSAR (LOS velocity in background) and GPS velocities (vertical in red, horizontal in white). Integrated GPS and InSAR provide fully 3-dimensional velocities with the fine spatial resolution of geodetic imaging [From Chang et al., 2010].

Detailed topography from GeoEarthScope ALS reveals the bare earth surface with its complex structure of the Elephant Back fault zone in Yellowstone. Image courtesy of OpenTopography.

Microstrain data from PBO strain meter B944 in Grant Village near Yellowstone Lake. The blue curve is detrended, red has tides removed, revealing a seiche in this PBO data set. Subsequent observations show that seiches also occur when the lake is ice-bound, ruling out wind as a sole source.

demonstrated its commitment to organizing, analyzing, and sharing observations from multiple global observing systems, which has enabled an order of magnitude increase in precision over the three decades through the activities of the IGS and development of the ITRF, now in its 8th version and publicly accessible on the web [IGN, 2008]. Realization of the International Terrestrial Reference Frame (ITRF) (Figure 2.3-1) requires that large data sets from global observing systems and data analyses in concert to specified standards [NRC, 2010]. Responsibilities for the maintenance of global geodetic services fall under the International Association of Geodesy (IAG), an association of the International Union of Geodesy and Geophysics (IUGG). IAG services include the International DORIS Service (IDS), the International GNSS Service (IGS - the IGS Central Bureau is supported in part by UNAVCO's NASA-funded activities), International Laser Ranging Service (ILRS), International VLBI Service (IVS), the International Earth Rotation and Reference Systems Service (IERS) and other geodetic services, as well as the Global Geodetic Observing System (GGOS) initiative and other international organizations.

Geodesists from around the world secure support within their home countries in order to make global data products and mm-level global geodesy possible. Many research groups participate in this overall effort by performing software development and data analysis to the standards set by the global community. For example, the GAGE Facility will continue to support, through a subaward to MIT, development, free dissemination, and user support and training for GAMIT, a widely used high-precision GPS data analysis software package. Local, regional, and international capacity building often results from these collaborations; significant UNAVCO-supported contributions include GPS and meteorology networks in Africa (AfricaArray), the Caribbean (COCONet), and those in Earth's polar regions (POLENET).

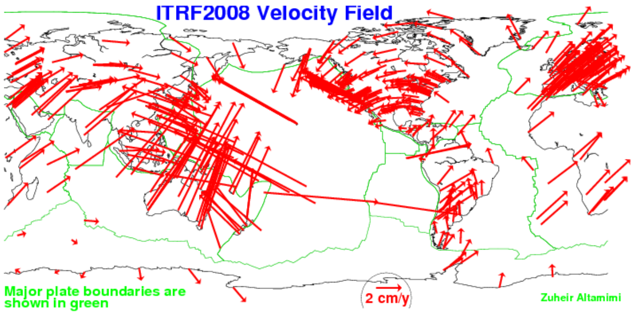


Figure 2.3-1. International Terrestrial Reference Frame. Accurate position time series and Earth Orientation Parameters from global GNSS, DORIS, SLR and VLBI sites are used to realize the International Terrestrial Reference Frame (ITRF) positions and velocity field. Depicted annual velocities belie a rich spectrum of signals within the underlying time series, including seasonality in the geocenter and the individual stations that define reference frame itself. Image from Z. Altamini.

This global framework has greatly altered our understanding of Earth deformation and expanded the benefits of geodesy to a large cross section of geoscience disciplines. Accurate analyses of regional geodetic networks, such as the PBO, depend on precise satellite ephemerides, clock corrections, and Earth orientation parameters, which are derived from analysis of a global network of GNSS receivers coordinated by the IGS, and maintained by UNAVCO through its NASA funding to support the GGN. The seasonal and decadal "noise" that has especially plagued the vertical component of PBO GPS stations is now recognized as a useful signal of hydrologic loading and multipath may be used to track soil moisture and show depth. These and other new applications are stimulating collaborations among new investigators in the emerging hydrogeodesy community as discussed above.

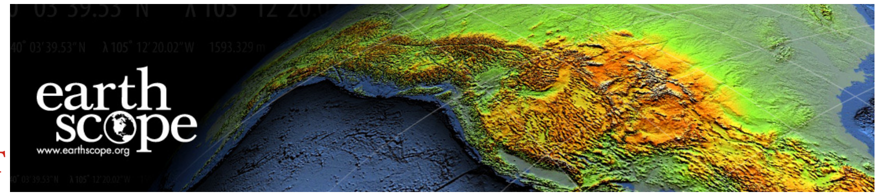
UNAVCO's 78 international Associate Members are located on every continent except Antarctica (although the UNAVCO science community and staff are very active there as well). Associate Membership in part develops a visible global geodesy research community, especially important for geographically isolated geodesists. Access to technical information and resources through collaboration with US investigators or UNAVCO projects is reciprocated by Associate Member support of GPS networks around the world.

All of these international activities and partnerships advance understanding Earth at the systems level, and reinforce the theme developed throughout this proposal: that in this decade, integrative geodesy will continue to reveal new signals in what was previously thought to be noise and thereby illuminate the interactions among the lithosphere, hydrosphere, cryosphere and atmosphere.

UNAVCO Role: Several UNAVCO activities planned to continue under GAGE advance this global integration: NASA's contribution to GAGE is focused on UNAVCO maintenance for the GGN, where 61 GPS/GNSS stations contributed to global GNSS data products. UNAVCO is working with JPL and GSFC on NASA's Space Geodesy Project that will collocate GNSS, VLBI, SLR, and DORIS (Figure 2.3-2). UNAVCO also supports the IGS Central Bureau at JPL, which coordinates many of the international activities in support of GNSS contributions to the global reference frame. In addition, UNAVCO community members and staff actively participate in IGS governance. As new satellite navigation constellations (e.g. GLONASS and Galileo) and the radio frequency spectrum evolve, technical evaluations conducted by the GAGE Development and Testing group are essential to the definition, refinement, and precision of the global reference frame and associated orbit, clock, and Earth orientation products.

Figure 2.3-2. Strengthening the reference frame to improve precision for global geodesy. (right) During 2012, UNAVCO coordinated the drilling of two deep drilled-braced GPS monuments at the NASA Goddard Geophysical and Astronomical Observatory shown collocated with the new 12-m VLBI antenna (left). These new GNSS installations are part of NASA's Space Geodesy Project which has the long-range plan of building, deploying and operating the next generation NASA Space Geodetic Network of integrated, multi-technique (collocated SLR, VLBI, GNSS, DORIS fundamental stations) next observing systems. This project ties into the broader GGOS goal to improve the International Terrestrial Reference Frame to sub-millimeter accuracy and stability of better than 0.1 mm/yr. UNAVCO will continue to work with JPL and GSFC to develop this system during GAGE.

2.4 EARTHSCOPE EXPLORING THE STRUCTURE AND EVOLUTION OF THE NORTH AMERICAN CONTINENT



EarthScope is an ambitious, multifaceted initiative to explore the structure, history and dynamics of the North American continent, and is the world's first interdisciplinary continent-scale geophysical observatory. A broad and growing population of scientists utilize data collected by the EarthScope Facility to investigate processes that shape the Earth's geological architecture and landscape, affect natural resources or relate to natural hazards. EarthScope science bears on processes that operate from the sub-second to billion-year timescales, from individual earthquakes to stresses driving lithospheric plate deformation. EarthScope's target, the North American continent, provides a diverse range of geologic processes, yielding fundamental new insights into this dynamic planet.

Three interlinking components compose EarthScope: (1) the EarthScope Observatories (PBO, SAFOD, and USArray) jointly operated by the UNAVCO and IRIS consortia, (2) a scientific research program that supports PI-led investigations, and (3) an investigator community, coordinated by an academic EarthScope National Office (ESNO), which actively participates in science planning, research, and facility governance. The EarthScope stakeholder community, broadly defined, also includes formal educators (e.g., K-12 teachers and university faculty) and informal educators (e.g., interpretive Park Rangers, museum educators) who make use of the education and outreach resources and programs provided by IRIS, UNAVCO, and ESNO, including online science content, published brochures, teacher professional-development workshops, and interpretive workshops for park and museum educators. These education and outreach activities are intended to maximize the broader impact of EarthScope science.

The EarthScope Facility acquires, delivers, and archives data, develops data analysis protocols and products, provides engineering services for field instrument deployment, and organizes community forums. The EarthScope Science program at the NSF sponsors a broad range of PI-driven research and workshops, with a particular focus on multidisciplinary efforts that make use of EarthScope data sets. The EarthScope research community is a growing, broad, and diverse body, conducting innovative research, informal and formal education, and governance of EarthScope facilities.

The continued vibrancy and success of EarthScope depends on the GAGE Facility for stability of geodetic operations and standards, on the research program for financial support, and on the science community as the energy source of innovation, discovery and communication.

2.4.1 EarthScope Observatories

The EarthScope Facility's three components include USArray, the Plate Boundary Observatory (PBO), and the San Andreas Fault Observatory at Depth (SAFOD). These components began construction and operation in 2003, and have evolved into an integrated system of mature and robust observing systems, providing fundamentally important datasets that have thrust researchers into new realms of data analysis and discovery as documented in the published literature and highlighted elsewhere in this proposal.

USArray has multiple observatory components: a Transportable Array (TA), a gridded network of 400 seismometers, barometers and infrasound sensors rolling across the lower 48 states and parts of southern Canada deployed for ~2 years per site, a Flexible Array (FA), which includes more than 2,000 seismic systems available for PI-driven field experiments, and 20 magnetotelluric systems used for campaign deployments on discrete targets.

PBO includes more than 1,100 continuous Global Positioning System (GPS) stations distributed across the United States, and concentrated on the active plate boundaries in the western contiguous US and southern Alaska (Figure 2.4-1). PBO also includes 75 borehole strainmeters and 78 borehole seismometers deployed along the San Andreas Fault and above the Cascadia subduction zone and volcanic arc. Tiltmeters (26) and pore pressure sensors (22) are also collocated with the other borehole instruments. The integrated nature of EarthScope observations has been especially important in Cascadia, where broadband seismic observations from over 70 stations (27 of them established through EarthScope) and high-rate, low-latency real-time GPS geodetic observations at 372 PBO stations are being supplemented with offshore observations at over 60 ocean bottom seismic stations and a number of temporary USArray FA deployments. Geodetic imagery and geochronology services supported under GeoEarthScope extend fault histories to millennial timescales.

SAFOD is a 3.1-km deep borehole penetrating the San Andreas Fault system near Parkfield, CA. Rock core was recovered during deep drilling sampled across the seismogenic zone, and is the focus of a variety of rock mechanics and related studies. At present a high-frequency seismometer is deployed and is maintained downhole by the USGS at SAFOD, recording a unique seismic dataset at a depth of ~660m below the surface. Under the current

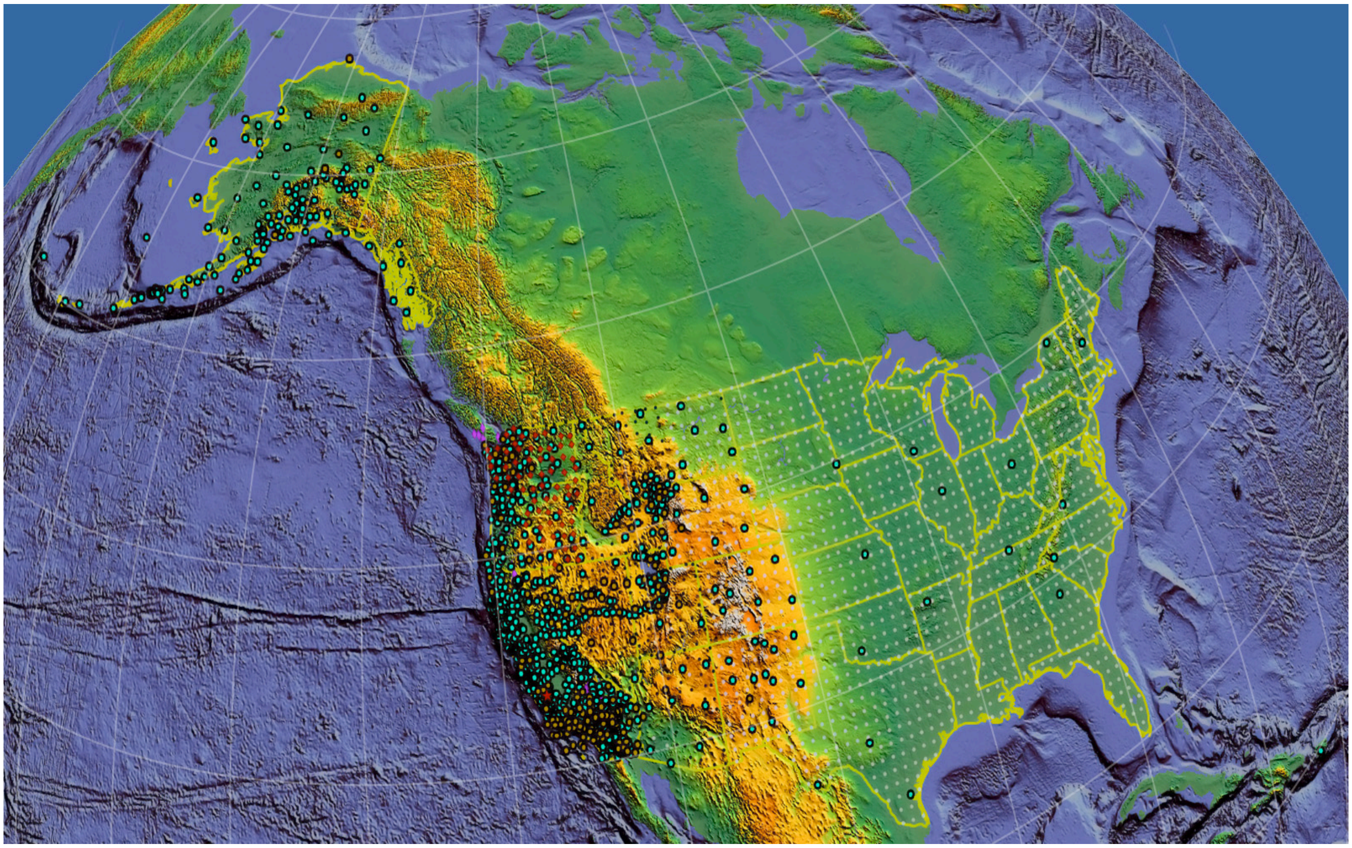


Figure 2.4-1. The Earthscope PBO Facility. PBO field facilities (GPS and borehole geophysics) span Alaska and the continental United States.

NSF-Cooperative Agreement for PBO, UNAVCO manages both PBO and SAFOD. SAFOD management will transition to a newly established SAFOD Management Office (SMO) in coordination with NSF in the near future.

Ongoing PBO O&M, the upgrade of GPS-only systems to those with full GNSS capability, and RT-GPS data stream enhancements will be significant activities under the GAGE Facility. The details are outlined below in Section 3 *The GAGE Facility.*

2.4.2 EarthScope Achievements

EarthScope has become an international community platform for Earth science investigations. Data collected by the EarthScope Facility have supported groundbreaking science, including new discoveries in Earth's atmosphere, surface, crust, mantle, and core. Hundreds of published papers have used EarthScope data, and new results enabled by EarthScope are published weekly. EarthScope has enabled new data processing techniques as well as innovative visualization tools. EarthScope has enabled new discoveries that already mandate rewriting key portions of Earth science textbooks.

While many of the fundamentally new results that rely on EarthScope data are discipline-based, some of the more exciting discoveries have emerged from EarthScope's goal of encouraging interdisciplinary studies that integrate geology, geodesy, seismology, geochemistry, geodynamics, and geophysics. EarthScope has encouraged a new generation of young scientists to start their careers in an interdisciplinary framework, and some of these scientists are now entering leadership positions within the scientific community. These efforts continue to challenge the community to maintain a broad scope of research activities. Ongoing EarthScope research support strengthens these research directions.

Some examples of the breadth of EarthScope discovery and transformative science include:

- Tracking, imaging and elucidating ETS along the Cascadia and the San Andreas fault systems, characterizing this recently recognized mechanism that operates within the earthquake cycle.
- More precise constraints on surface deformation driven by slip along the San Andreas fault.
- Clear evidence for extremely low friction coefficients on fault rocks sampled by SAFOD, confirming that the fault slips under very low shear stresses.
- Integration of accelerometer records with GPS data for characterizing earthquakes, advancing GPS-seismology and early warning systems.
- Direct three-dimensional mapping of crustal deformation patterns and mountain uplift in the western US.

- Unprecedented seismic imagery of the structure of the crust and mantle that underlies the western US, revealing the fate of more than 100 million years of Farallon plate subduction.
- New seismic images of the lithosphere-asthenosphere boundary, mantle transition zone and structures that provide a record of western US tectonomagmatic history.
- New constraints on the location and geometry of lithospheric instabilities that influence the dynamics of western US deformation.
- Insights into mechanisms of Great Basin deformation that accommodate gravitational collapse of the continental interior.
- New seismic constraints on deep mantle dynamics, core-mantle structure, and internal core structure.

2.4.3 Building on EarthScope Success: 2013 – 2018

In October 2009 the EarthScope community met in Snowbird, Utah to discuss science goals, to plan for the future of the program, and to clearly articulate its underlying scientific priorities. The report from that meeting, *Unlocking the Secrets of the North American Continent: An EarthScope Science Plan for 2010–2020* [*Williams et al*., 2010] charts the state and direction for EarthScope science.

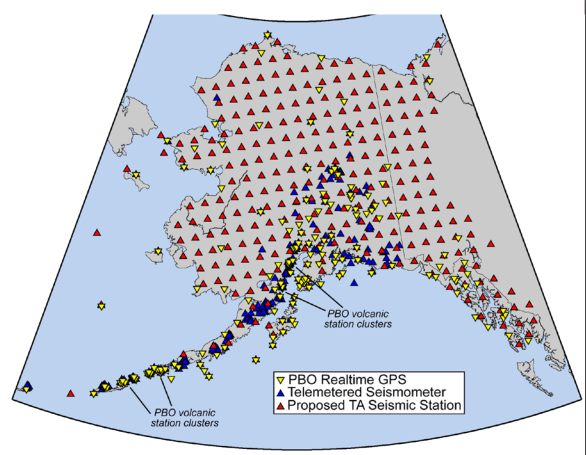
This GAGE Facility proposal describes the status and direction of EarthScope science, providing an update to topics in the Science Plan, and includes additional topics that have come to the fore since 2009. Because of the breadth of disciplines and development of technologies that compose EarthScope research, sustained efforts and unique opportunities continue to advance the sciences of Earth observation, modeling, integration, interpretation and dissemination of results.

Over the next 5 years, the EarthScope facilities, operated jointly by the GAGE and SAGE (*Seismology Advancing Geosciences and EarthScope* – see companion NSF proposal) Facilities, will continue to support and advance this community science plan. Specific tasks outlined in this proposal include:

- *Growing* the EarthScope community. Support for workshops, institutes, community involvement, education and outreach efforts, and governance will be essential to maintain this element.
- *Expanding* EarthScope's geographic focus. Completion of observations by the TA to the Eastern margin of North America, the expansion of the TA to Alaska and the continuation and augmentation of Plate Boundary Observatory observations will focus regional activities

Alaska: A Geoscience Frontier

During 2013-2018, the collective observing power of EarthScope in Alaska will yield an extraordinary scientific impact. Some 132 PBO GPS stations in Alaska have been operating for over five years, yielding precise time series, and thus useful constraints on regional surface deformation. Beginning in 2013 the USArray Transportable Array (TA) will deploy a grid of ~290 stations across Alaska and into parts of Canada–each site equipped with broadband seismometers, infrasonic sensors, and (at some sites) strong motion accelerometers. Alaska promises to produce a rich dataset given that it has a seismicity rate five times higher than the lower 48 states combined; a complex crustal history; continental-scale fault systems; and significant surface motion everywhere relative to stable North America. Further, there is a high likelihood of recording a magnitude 7 or larger earthquake during any five-year time window and any major volcanic activity has a reasonable chance of being captured simultaneously by the PBO GPS network and the TA seismic and infrasound network.



Earthscope in Alaska, showing PBO GPS stations (yellow symbols), the proposed USArray Transportable Array deployment (red symbols) and existing realtime seismic stations (blue symbols).

The 2011 EarthScope workshop report 'Opportunities for EarthScope Science in Alaska In Anticipation of USArray' highlighted the EarthScope science opportunities in Alaska. As the report notes, "In many ways Alaska is a geoscience frontier with enormous area never having been studied beyond reconnaissance level." The report highlights a number of globally relevant science topics that will be addressed by EarthScope in Alaska, including subduction processes, mantle flow, terrane accretion, far-field deformation, and glacial unloading. That the Alaskan subduction zone is capable of producing great earthquakes and devastating tsunamis heightens the societal relevance of the research. Taken together, the scale and scientific opportunities in Alaska make it an ideal target for EarthScope and more than justify the great operational challenges associated with deploying and maintaining stations there.

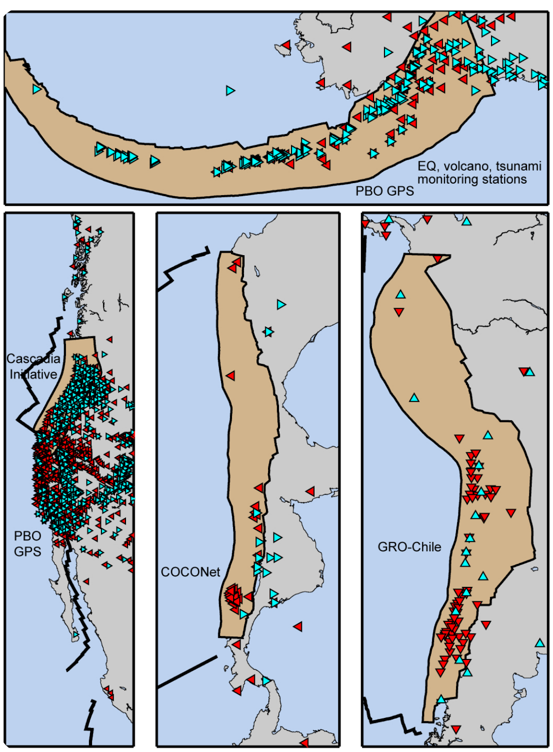
and opportunities for partnerships with other communities and programs such as GeoPRISMS.

- *Strengthening* data analysis, integration, and interpretation. Continued development of data products and cyberinfrastructure will be guided by the recent report "A Preliminary Strategic Plan for EarthScope Cyberinfrastructure" [*Gurnis et al.*, 2012]. Open access to higher-level data products that build on the expertise of community members will provide information that is easily accessible to an increased number of users.

2.4.4 EarthScope Beyond 2018

EarthScope has become the global standard for a broad-based, community-driven, integrative research facility that provides a nexus for interdisciplinary science. The Earth system processes of relevance to the EarthScope scientific community operate on timescales longer than the originally planned 15-year lifespan of the facility, and we expect that a legacy of EarthScope observing systems (for example, PBO as a nucleus for the Network of Geodetic Networks) will continue to sample time-varying phenomena beyond the 2018 horizon. Tectonic deformation is a slow process, and commonly does not occur in a steady state. Earthquake cycle deformations, which are both subject to and offer insight into the rheology of the Earth, can vary over decades to centuries. Just as new and unexpected mechanisms of plate boundary deformation such as ETS were discovered when precise geodetic observations became available at interannual periods, and were better understood in light of high resolution seismic mapping, additional new, interesting, and important modes of deformation related to hydrogeodesy are revealed as interdecadal records become available. In addition, managing, mining, visualizing, and integrating very large, disparate datasets are now coming of age with enhanced cyberinfrastructure, driven by such new initiatives as EarthCube at NSF and COOPEUS in Europe. These efforts are integral to the Geodetic Data Services program within GAGE and are discussed in more detail in Section 3.2.

Beyond 2018: A Subduction Zone Observatory?



The SZO, showing locations of present GPS (red) and seismic (blue) stations that report data in near-real-time. Top: Aleutians-Alaska Peninsula; Left US-Canada west coast; Center: Central America; Right: South America. The brown shading indicates the lateral extent of the seismogenic portions of subducting slabs, illustrating the tremendous variability in subduction processes and other plate boundaries along the length of the SZO. At present, the availability of observations along the SZO varies widely.

The success, knowledge, and experience gained during EarthScope provide an unprecedented launching point for IRIS and UNAVCO to collaborate on the creation of a planetary-scale Subduction Zone Observatory (SZO). This observatory, stretching 18,000 km along the eastern Pacific Ocean, from the Aleutians in the north, to the tip of Tierra del Fuego in the south, will provide an integrated, interdisciplinary approach to understanding the entire subduction zone as a system. SZO research will have enormous societal relevance, given the population centers all along the coast that are subject to earthquake-, tsunami-, and volcano-related hazards.

Existing geophysical networks and observatories will provide the SZO's starting backbone. The Plate Boundary Observatory (PBO) core—the set of GNSS sites that will form the post-EarthScope backbone in North America—will be one of an anticipated federation of geodetic networks that overlap with new SZO. Current NSF-funded IRIS and UNAVCO activities, such as the GRO-Chile seismic network, the COCONet GPS network, and the onshore and offshore stations of the Cascadia Initiative will provide key infrastructure. The SZO will grow through infill with strategic deployments of broadband seismometers and high-sample-rate GPS. Small, flexible PI-led projects can be designed and performed within this larger framework.

SZO will be a major international initiative, and IRIS and UNAVCO propose to to collaborate now on bringing together the necessary geographic, organizational, and disciplinary representation to develop the SZO concept and articulate the science benefits.

2.5 GEODESY FOR BROAD IMPACT

Modern geodesy relies on a set of technological innovations that have wide application, creating synergies for sectors far beyond the basic science contributions of the geodesy investigator community. Some innovations themselves (specifically GPS and TLS) have broad commercial applications, creating a mutual benefit for civic and commercial sectors, which use NSF and NASA sponsored-research infrastructure, while UNAVCO community researchers benefit from GPS and GNSS hardware pricing that reflects corporate competition for a much larger commercial user base. Hazards science and geodetic observing systems support early detection of geophysical events - such as earthquakes, tsunamis, volcanic eruptions, and extreme storms or space weather events - even as they are unfolding, creating the opportunity to mitigate their impact on life and property. Geodesy also has broad impact in engaging the public in both formal and informal learning environments, and contributing to national global competitiveness by preparation of a technically advanced science workforce.

2.5.1 In the Public Interest: Societal Benefits

Geodetic research supported by UNAVCO has clear benefits to humanity, as we seek to understand the fundamental nature of processes in the Earth system that impact humanity. In a number of key areas related to natural hazards, for example, geodesy research aims to produce direct benefits, including: 1) contributing to long-term hazard assessments; 2) mitigating hazards by reducing vulnerability; and 3) providing short-term or real-time warnings. Early detection and real-time warning are an important new area of focus under GAGE, largely the result of deliberate PBO GPS network upgrades at 332 sites for high-rate, low-latency data streams. Further enhancement of RT-GPS is a target area within EarthScope science goals [Williams et al., 2010], with numerous societal benefits.

Earthquake and Tsunami Hazard Assessment

In Honshu, billions of yen were spent building tsunami walls along one third of Japan's coastline, a distance longer than the Great Wall of China [*Onishi*, 2011]. Yet the coastal defenses underperformed during the 2011 Tohoku tsunami (Figure 2.5-1) largely because the seismic and associated tsunami hazards were underestimated [*Geller*, 2011]. The very great potential for geodesy to improve earthquake and tsunami hazard estimates is not yet fully realized.

Earthquake hazard assessment is typically based on a map showing expected magnitude, shaking and acceleration probability. In this case, the expected maximum earthquake magnitude offshore of Tohoku was estimated to be less than M8 [*Chang*, 2011], and in the March 2011 event, the Mw9 Tohoku earthquake produced a tsunami much larger than anticipated, thus overtopping 10-meter high seawalls. Many coastal residents assumed incorrectly that the seawalls would protect them, and unfortunately delayed evacuating, or evacuated only far enough above sea level to be safe in a small tsunami [*Ando et al.*, 2011]. Several incorrect assumptions contributed to the underestimation in magnitude [*Stein and Okal*, 2011]. A major factor was the implicit assumption that much of the subduction occurred aseismically, an assumption belied by the GPS data that show a much higher than expected rate of strain accumulation on the plate interface [*Loveless and Meade*, 2010]. Based on what we have learned from this devastating event in Japan, it is *critical* to incorporate the best available geodetic data into seismic and tsunami hazard assessments.

Figure 2.5-1. Tohoku tsunami. The tsunami generated by the March 2011 Tohoku earthquake overtopping a high seawall.

In light of this experience and emerging opportunities to study subduction zones both onshore and offshore, new efforts to improve geodetic characterization of active offshore fault systems, including deployment of seafloor geodetic sites at other trenches are now being articulated [*Newman*, 2011]. To date, UNAVCO's facilities have only played minor roles in the development of seafloor geodesy – for example, enhancing sampling rate along the coast to support positioning a ship – yet there is great interest in this topic from the UNAVCO science community.

UNAVCO Role: UNAVCO supports community geodetic networks and PI campaigns and longer term observations that provide critical boundary conditions for determining strain rates and assessing earthquake hazards. UNAVCO also maintains stations within the GGN, that are foundational to the reference frame essential to high precision..

Volcano Hazard Assessment

Volcanic activity, such as magma chamber inflation or deflation, dike intrusion, and effusive or explosive eruption, is often accompanied by measurable surface deformation that can vary rapidly in space and time [*Dzurisin*, 2006]. For example, GPS stations on either side of the Kilauea rift zone dike recently shown more than tens of centimeters in baseline length changes occurring over a few to tens of hours during dike emplacements [*Poland et al.*, 2008; *Segall et al.*, 2001]. Because these types of events often precede or accompany hazardous eruptions, telemetered GPS networks combined with low latency processing strategies are major components of many well-established volcano observatories worldwide, including in Hawaii, the Cascades, Yellowstone, and Italy.

UNAVCO plays a major role in the growing application of geodetic data that has potential for fundamental advances in volcanology, with a focus on cGPS, geodetic imaging such as InSAR, and borehole geophysical observations including strain, tilt, and seismicity. Evidence from many volcanoes shows that ground motion reflecting magma rising from depth can be detected months or weeks before the rising magma gives rise to earthquakes or other eruption precursors. Geodesy complements seismology by extending the study of volcanic activity from periods of seconds to decades, and also provides constraints on the geometry, volume, or pressure changes of magma bodies within the volcano. Because InSAR reveals volcano deformation from space without the need for significant ground-based resources, it is especially valuable in remote and hazardous areas and in conducting a global deformation inventory.

The Greek island of Santorini was the site the Minoan eruption circa 1650 B.C., one of the largest volcanic events in human history and one that buried the major port city of Akrotiri with more than 20 meters of ash. After decades of quiescence, in January of 2011, a series of earthquakes accompanied by surface deformation began. A UNAVCO-supported GPS network indicates rapid inflation by a crustal magma body [*Newman et al.*, 2012] (Figure 2.5-2); these observations and models are being used by authorities to help assess the volcanic and tsunami hazards. In addition, PBO GPS stations on Augustine volcano in 2006 imaged magma migration and constrained magma chamber deformation 60-90 days before eruption, the time-scale of which corroborated by petrologic data from erupted products [*Williams et al.*, 2010].

High-rate, low-latency data hold significant promise for volcano monitoring. It is not only the direct magma-related signal associated with a volcano that warrants low-latency GPS observations, however. It is well known that the steep slopes of island volcanoes can fail catastrophically and generate a tsunami with the potential to substantially impact coastal populations [*Day et al.*, 1999; *Mattia et al.*, 2004; *Ward*, 2002]. The extremely large displacements associated with a catastrophic volcanic sector collapse likely accumulate over time-scales from seconds to minutes. Similar to subaerial landslides, some ocean island volcano flanks exhibit slow-slip [*Cervelli et al.*, 2002] and very little is known about the presumed precursory transition from stable to catastrophic failure. Further complicating matters, volcanic edifice stability and magmatic processes may be closely related. For example, *Brooks et al.* [2008] showed that a flank-related slow-slip event at Kilauea was likely triggered ~15-20 hours after a dike intrusion in the east rift zone stressed the flank (Figure 2.5-3). Thus, high-rate GPS data are needed to avoid temporal aliasing of flank motion signal and low-latency data transmission is needed for detection of precursory motion.

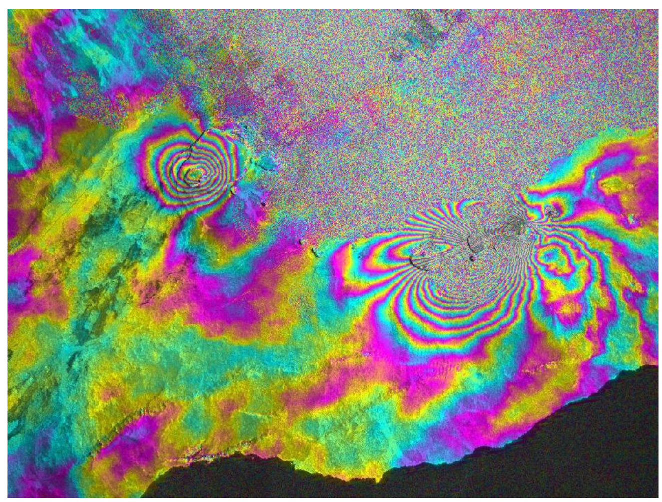


Figure 2.5-3. Kilauea fissure eruption. On March 5, 2011, a large fissure eruption began on the east rift zone of Hawaii's Kilauea volcano. InSAR image shows deformation for two days following the onset of the eruption (the time interval also spans several preceding weeks). The concentric fringes (upper left) show deflation. The butterfly pattern (right) shows rift dike intrusion and subsequent fissure eruption taking place. Image courtesy of P. Lundgren of JPL [2011].

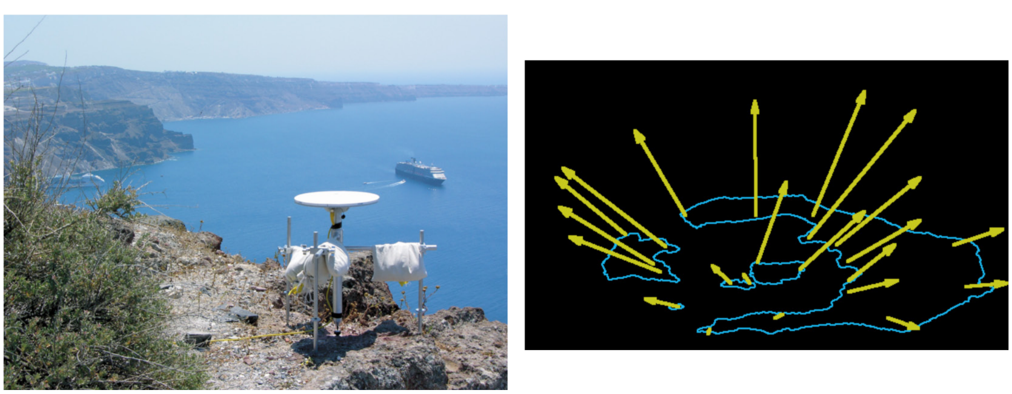


Figure 2.5-2. Inflation at Santorini, Greece. GPS observations show the three-dimensional deformation in response to inflation of the caldera (right). Meanwhile, behind a deforming GPS station, a cruise ship is visible moored above the inflating caldera. Approximately 50,000 people visit Santorini each day. Figure from A. Newman et al. [2012].

UNAVCO Role: UNAVCO community scientists rely on UNAVCO services to study volcano deformation, primarily with InSAR data acquisition and cyberinfrastructure for ordering and access, and with GPS deployments. Many consortium scientists have also contributed to planning for a US SAR mission.

Furthermore, because the stations are likely to be destroyed during a catastrophic event, streaming of data will be critical for their recovery for scientific or hazards purposes.

Rapid Deformation Detection for Hazard Warning

Hazard assessment focuses on establishing the vulnerability of a region through event frequency and magnitude characterization; it anticipates the effects of a possible event that cannot be predicted with great specificity. Technological advances in geodesy allow detection of the onset of a hazardous event creating the possibility for early warning that may mitigate the risks from earthquakes, tsunamis, volcanic eruptions, landslides, or extreme weather events.

Early hazard warning depends on three key capabilities: 1) the science must be sufficiently understood to allow rapid identification and characterization of the unfolding event; 2) data transmission and accurate analysis must be faster than the evolving hazard; and 3) preparedness by hazards management agencies and communication with scientists must be sufficiently well developed to exploit the short warning time. Studies within the UNAVCO community demonstrate that geodetic capabilities fulfill the first two requirements. The third relies on further strengthening relevant, nascent relationships, and on the civic will to commit resources to risk mitigation.

Figure 2.5-4 illustrates a geodetic approach to the problem that the hazard of a major tsunami may be underestimated using seismic data; initial magnitude estimates utilizing only seismic data for both the 2004 Sumatra and 2011 Tohoku earthquakes were quite low (Mw 7.0–8.5). An earthquake's tsunamigenic potential, however, can be more accurately and rapidly determined using real-time GPS observations [*Blewitt et al.*, 2006; *Blewitt et al.*, 2009].

A powerful new tool for such studies is GPS seismology that uses high-rate GPS data to produce broadband displacement waveforms for rapid centroid moment tensor estimation and finite fault slip modeling [*Bock et al.*, 2011; *Crowell et al.*, 2012]. Access to high-rate GPS data and estimated static offsets can help constrain automated finite source models, which in current operational systems are determined using seismic waveform data alone [*Crowell et al.*, 2012; *Melgar et al.*, 2012]. With the addition of GPS surface displacements during an earthquake, joint inversions of seismic waveforms and static deformation can improve kinematic models [e.g., *Rolandone et al.*, 2006]. Rapidly determined finite source models may be used to characterize near-fault strong ground shaking, which can be important in areas without strong motion instruments or where they fail during heavy shaking [*Dreger et al.*, 2005; *Rhie et al.*, 2009]. The advantage of GPS data is that it may be used to independently determine the location and orientation of the rupture plane, and therefore is not subject to inherent errors in a seismically determined event location, magnitude estimate, or moment tensor solution.

Tsunami warning has particular requirements with regard to calculating an accurate magnitude, propagation direction, and vertical and horizontal motion of the sea floor. The goal of tsunami warning systems is to reduce the amount of time required to recognize that a tsunami has been generated and improve the prediction of where the wave will rise on near and distant coasts [*Bar-Sever et al.*, 2009; *Titov et al.*, 2005]. The models require information about the motion of the sea floor to predict how an ocean wave will propagate. Displacements at on-land GPS sites are used to infer seafloor motion by constraining a fault slip model, which in turn predicts displacement of the seafloor and continental shelf [*Song et al.*, 2008].

Studies of the 2004 Sumatra event showed that GPS data, had it been available and interpreted in real-time, could have estimated the real magnitude of the event in less than 15

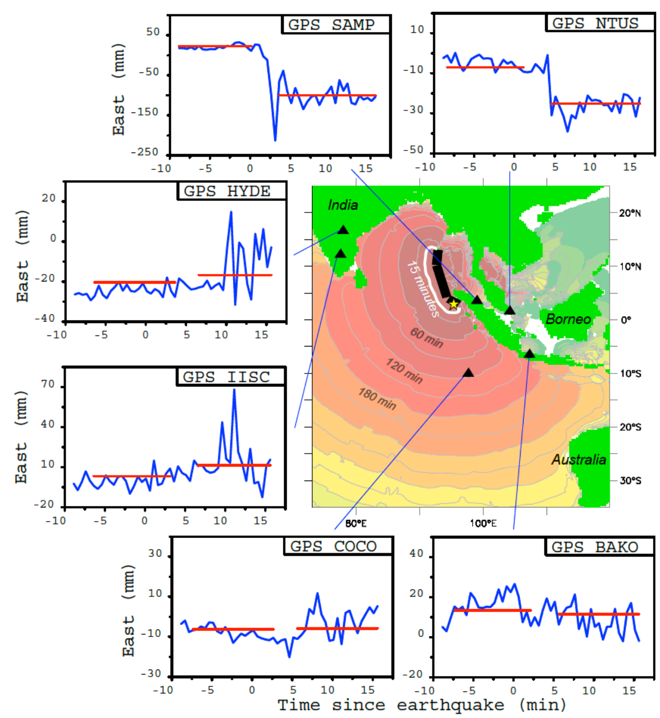


Figure 2.5-4. Foundation for tsunami early warning. The time interval between tsunami delay contours in map view, and the delay for GPS station displacements (east component offsets shown) give promise that the science behind plans for tsunami warning is tractable. The implementation of monitoring, data communication, informing responders, and mobilizing emergency response will present many challenges, however. From Blewitt et al. [2006].

minutes [*Blewitt et al*., 2006] an improvement over seismic methods that took over 45 minutes to estimate the magnitude as >M9 [*Kerr*, 2005]. Although new techniques to estimate true magnitude using very long period P-wave data have significantly improved the ability of the tsunami warning centers to respond more rapidly to tsunamigenic earthquakes [*Kanamori and Rivera*, 2008], near field real-time GPS provides a basis for robust tsunami prediction, perhaps within minutes of the initiation rupture [*Bock et al*., 2011; *Crowell et al*., 2012; *Grapenthin and Freymueller*, 2011; *Melgar et al*., 2012].

UNAVCO Role: UNAVCO community science and PBO data sets form a foundation for hazards assessment and early detection strategies that are now under development in California and the Pacific Northwest as well as along active plate boundaries abroad [*Hammond et al.,* 2011; *Hammond et al.,* 2010]. In particular, 232 PBO stations have been upgraded to real time in the tsunamigenic Cascadia subduction zone with NSF-ARRA funding; another 100 stations were already in place within PBO, and an additional 40 are scheduled for upgrade before initiation of GAGE. UNAVCO has and will continue to provide equipment, infrastructure, engineering, and data services to the community for studies of fault-related and volcano deformation around the world.

Three UNAVCO Consortium Members, University of California Berkeley, Caltech, and the University of Washington, have received a multi-million dollar grant from the Gordon and Betty Moore Foundation to develop earthquake early warning capabilities. Their approach will rely on a number of early detection strategies, including the integration of real-time GPS and strong-motion accelerometer records at PBO and community network GPS stations. The SOPAC and CWU geodesy laboratories are developing protocols to enhance streaming of positions from CRTN and PANGA; both networks also include a large number of PBO stations. Collectively the UNAVCO science community and supporting facilities are critical to this work.

We anticipate that better event information will become available for citizens and emergency responders after an earthquake. Early displacement maps can help emergency responders and planners identify locations where disruption to infrastructure is likely [*Crowell et al*., 2009]. Earthquake early warning systems are intended to provide information about an ongoing earthquake so quickly that many locations may receive a prediction of shaking before it occurs. The Japan Meteorological Agency and National Research Institute for Earthquake Science and Disaster Prevention have been operating a public early warning system for approximately two years. While this and other existing systems are based on real-time seismic data, it is clear that RT-GPS will play a vital role in early warning for large seismic events with long ruptures [*Bose and Heaton*, 2010]. In particular, having pairs of GPS stations on opposite sides of important faults (*e.g*., the San Andreas fault), or in the farther field in Cascadia, will provide the ability to track an ongoing large-scale rupture in real-time.

Space Weather and the Ionosphere

GPS is also useful for monitoring the interaction of solar radiation with the Earth's outermost atmosphere (*Jakowski et al*., 2002), solar storms that can disrupt modern telecommunications pathways including those foundational to GPS observations and data flow. Thus the GPS systems uniquely observe at the same time that they are vulnerable to these disturbances (*Fisher and Kunches*, 2011). The properties of ionospheric plasma depend on electron density, temperature of ions and electrons, and composition of ions. Modeling ionospheric processes emphasizes solar forcing of the outer atmosphere and plasma in addition to mass and energy transport. Analogous to studies of the troposphere, atmospheric scientists currently devote their efforts to space weather and after-the-fact research designed to better understand the physical conditions of past "significant events." Also analogous to troposphere studies, both types of efforts entail assimilation (via Kalman filtering) of observations into a physics-based dynamical model. Physical models are constrained by observations from ground-based radar "sounders", and satellite data (including GPS occultation data), but the primary data source consists of ground-based GPS slant measurements of total electron content (TEC) derived from differences in L1 and L2-frequency phase delays. GPS estimates of slant TEC are by far the most plentiful observations of the ionosphere and provide the best global spatial sampling, so global models necessarily rely on them. A society that is increasingly dependent on wireless telecommunica-

UNAVCO Role: While NSF-EAR geodesy investigators most commonly interact with the space weather community only indirectly, UNAVCO builds and supports networks and distributes data sets that form the basis for this research, through globally distributed data streams. These are sustained by the work of the Geodetic Infrastructure Program, and the UNAVCO Data Center and supporting cyberinfrastructure for data discovery and access. Equatorial stations are of particular interest, and are relatively sparse. The space weather research community actively participated in the 2010 AfricaArray workshop at Howard University to inform GPS site selection during the installation phase of that project. Practical limitations in moving data quickly from Africa pose obstacles to its full integration in space weather models.

tions also depends on advancing understanding of space weather events and their impact on critical telecommunications infrastructure.

Collateral Benefits for Science and Society

Geodesy is closely related to the fields of surveying and navigation, and each field benefits from advances in either of the other two. GPS was developed by the US Department of Defense in the 1970s as a real-time positioning and navigation system. Systematic investments in both geodetic science and applications expanded its benefit to science and civic sectors. Such broad use attests to the power of this technology and seeds natural collaborations among disparate communities of users. Science applications were an early impetus to improve position estimate precision, accuracy, and produce geophysically meaningful global reference frames. Civil navigation applications were early drivers of requirements for low latency and high sampling rates. Commercial users in great numbers have made rapidly evolving capabilities affordable for all; further, the purchasing requirements of PBO were leveraged by UNAVCO to allow GPS instruments with tailored specifications to be made available to the UNAVCO community at competitive prices.

Because of these synergies, GPS user communities will continue to enjoy rapidly evolving, sophisticated, and affordable instrumentation. Public data sets are widely shared among users, and science applications have been a vigorous driver of improved technologies. Geodesists are well poised to influence monument standards and open data protocols as civic and commercial real-time GNSS networks proliferate around the world. All three communities make extensive use of UNAVCO tools such as the online Knowledge Base, with nearly 400,000 pages viewed in 2011, and the UNAVCO-developed teqc software, used for GNSS pre-processing and quality control, with nearly 14,000 downloads in 2011. Support and new development of teqc will continue under GAGE.

Geodesy also has a role to play in planning for human infrastructure and mitigating risks posed by the natural and engineered environment. While the understanding of sea level rise and coastal subsidence is a prime science focus of geodesy, the built environment is similarly characterized by GPS and TLS observations.

UNAVCO Role: Many UNAVCO resources are used far beyond the international geosciences community. UNAVCO has strengthened geodesy, surveying, and navigation through development and testing of GNSS and communications technologies as constellations evolve; development and support of freely available utilities like Knowledge Base and teqc (metrics cited above); open access to PBO data streams for wide use in the surveying and civil engineering fields; and additional mutual benefits realized by the commercial and civic sectors, and the science community by driving GNSS instrument capabilities, specifications and pricing.

Society's ability to inventory the built environment, its changes with time, exposure to inundation, high winds, seismic shaking, or other natural hazards, and responsive planning could be significantly strengthened by exploiting modern geodesy data sets and capabilities including GNSS, LiDAR, InSAR, and other techniques.

2.5.2 Teaching our Children

Public education is the cornerstone of democracy, and the erosion of education standards, specifically in the sciences, is a matter of great national concern. While Thomas Jefferson spoke to the need first and foremost for an informed electorate, he also recognized that education further developed the next generation of scientists and policy makers. Both of these ideals underlie an important goal recently identified by the geodesy community:

Nurture a deeper public understanding of geodesy and its benefits, and engage the children who will become the next generation of talent for advancing science and informing policy and planning [Davis et al., 2012].

UNAVCO Role: UNAVCO strengthens public education is through secondary school teacher training in partnership with other organizations as part of its Education and Community Engagement program. Because of the synergies with other programs and institutions, UNAVCO has had significant reach with modest investment, and has disseminated teaching resources that put geodetic data and geodetic science applications in the hands of hundreds of secondary school teachers.

Many changes that geodesists observe on the dynamic planet and in the relationship of the solid Earth to its enveloping oceans, ice caps, surface waters, and atmosphere, relate directly to events and processes with great societal impact. The public hears prompt and frequent reports of loss of life or infrastructure damage from large earthquakes or volcanic eruptions, but they often misunderstand the causes, predictability, and implications of those events. The role of geodetic technologies and measurements in observing ice sheet mass loss, sea level rise, land subsidence, or aquifer depletion is not widely known. By engaging directly in the teaching of our children, in public forums, by educating and empowering teachers, by providing easy access to real-world examples and fresh data, and by helping to craft educational policies, science meets its urgent responsibility to create a science- and Earth-literate citizenry and government, and to attract and train the future scientific workforce. Geodesy offers both the excitement of basic science discovery and great relevance to an increasingly global society and to the nation that supports our work.

This is a fundamental challenge to geodesists: to bring the problems, possible solutions, and innovations of our time into the classrooms, so that we can appropriately inform and call the next generation to action to pursue science, policy, and civic duty. A major purpose of public education in a democratic society is to create an informed electorate; geodesy has great, but mostly unrealized potential to advance this goal.

2.5.3 The Next Generation: The Geodesy Workforce

The national interest commands a forward-looking and sophisticated professional workforce that can use the tools of geodesy to address a spectrum of hazards, planning, and science applications. Geoscientists pursue careers in basic and applied research, oil and gas exploration, mining, environmental sciences, geotechnical engineering, land-use planning, geospactial operations, resources managment, risk assessment and other fields. The grand challenges posed here in Section 1 and in other recently published documents [*Davis et al*., 2012], combined with their role in supporting the national interest in global competitiveness, require that we attract and prepare the next generation of investigators. The UNAVCO community maintains a strong commitment to advancing education in geophysics and geodesy and to continue US leadership in these critical scientific and associated technical fields.

Geodetic applications have flourished over the past decade, yet fundamental education and research in geodetic science and infrastructure has experienced an acute decline and the challenge of integration of geodesy into geophysics curricula at the undergraduate and graduate level remains unmet [*Davis et al*., 2012; NRC, 2010]. The low number of geodesists in training puts our extraordinary science and its broad applications at risk.

Aspiring geodesists must learn the fundamentals of positional geodesy, including geodetic astronomy, relative positioning, and point positioning. Positioning will necessarily include the theory and methods for defining reference frames and reference systems. Students of geodesy also explore geophysical geodesy, orbit determination, the modes of crustal deformation on a range of timescales, inverse theory, error analysis, electromagnetic wave propagation, and signal detection. Assembled from a variety of academic disciplines, this broad combination of topics constitutes the unique and challenging geodesy curriculum.

Geodesists recommend a vigorous and focused effort on geodetic science and education as an urgent and transformational priority. The geodetic community must work to sustain the science of geodesy as a critical element of undergraduate and graduate geosciences curricula. A creative and widespread effort to increase awareness of, experience with, and interest in geodetic science among undergraduates lies at the heart of this collective undertaking. With its broad and practical applicability, real-time data access, and attractive, challenging field settings, geodesy is well poised to lead a revitalization of the geophysics workforce.

UNAVCO Role: At UNAVCO, the Education and Community Engagement (ECE) program has taken some strategic steps in meeting this challenge. Its nationally recognized RESESS program provides mentored undergraduate research internships designed to bridge the transition to graduate school for a diverse population of high-achieving geoscience students. ECE has contributed to a number of secondary and undergraduate curriculum efforts in a variety of partnerships for curriculum development and teacher training (TOTLE, SERC, IRIS EarthScope, NSTA, etc.), and is advancing a UNAVCO-led initiative that will provide relevant curriculum modules with a focus on geodesy for university-level courses, leveraging the tools and resources of UNAVCO and its partners.

2.5.4 Summary

Technological innovation and technique integration have brought about a renaissance in geodesy with major science breakthroughs. Taken together these drive the groundbreaking and rapidly evolving grand science challenges for geodesy and its Earth systems science applications. Broader impacts of this geodetic renaissance are significant and growing. These impacts include hazards mitigation to reduce losses, improved management of water resources, enhanced communication, navigation and space-base operations, education for an informed electorate, and training for the next generation of geoscientists.

Collectively, these advances provide the foundation for planning GAGE Facility activities and science community support for 2013 – 2018.

2.6 EMERGING DIRECTIONS AND NEW INITIATIVES IN GAGE FOR 2013 – 2018

The science challenges discussed above and geodesy's broad impact stem from an agenda advanced by an interdisciplinary community of geoscience investigators through individual, collaborative, and community proposals and projects [*Davis et al*., 2012]. Many of the themes are further developed through topical and community workshops that articulate requirements for geodesy facility support. GAGE activities will align with this community planning.

Building on the accomplishments and capabilities of the UNAVCO Facility and PBO, the newly constituted GAGE Facility will support investigators through services tailored to project requirements. Here we discuss current and emerging directions identified and advanced by the community through workshops, proposals, and governance for focus during 2013 - 2018. These directions are discussed under four broad topics: "Targeted Natural Laboratories", "Support for Emerging Technologies", "Innovations in Cyberinfrastructure for Community Data Products", and "The Human Dimension to Ensure Broad Impact". In keeping with the themes developed throughout this proposal we emphasize geodesy's contributions to understanding the interactions of Earth systems and the frontiers of knowledge enabled by integration of geodetic techniques. In Section 3 we detail the GAGE Facility activities that will support this community science agenda and provide projections of relevant performance metrics for the upcoming award interval.

2.6.1 Targeted Natural Laboratories

The UNAVCO science community has targeted a number of geographic areas for the deployment of geodetic infrastructure for study over the next five years: an eastern US plate interior observatory, a fully deployed EarthScope (integrating USArray and PBO) in Alaska, extending the PBO model to the Caribbean and Central America, maturing data sets in Africa, enhanced polar studies, developing international relationships to support a "Network of Networks" along the western Americas, and expanding focus on subduction zones. We also anticipate that future earthquakes will direct community interest and resources to unanticipated regions and emerging science topics, supported by the GAGE Facility event response capabilities.

EarthScope: 2013 - 2018

As USArray has migrated into the eastern US and is now poised to deploy to Alaska in 2013, the interest of the EarthScope and GeoPRISMS communities is gravitating to the east and north. Cascadia is also a region of great interest, discussed below under emerging technologies in light of its unique concentration of dense RT-GPS observations and OOI interest in seafloor geodesy.

Eastern US-North American Plate Interior Observatory

GPS is now sufficiently precise to further the study of slow deformation rates in plate interiors, and map the effects of GIA in eastern North America [*Calais et al., 2006; Sella et al*., 2007], where it is the primary deformation signal (Figure 2.1-9). Interannual and interdecadal signals from environmental sources are likely present as well. GPS resolves even the smallest GIA signals south of the hinge-line separating post-glacial rebound to the north of the Great Lakes from subsidence to the south. Seismic moment release decreases southward along the margin, consistent with the variation in vertical motion rates observed by GPS, perhaps suggesting that north of the hinge line, GIA is an important contributor to intraplate seismicity. South of the hinge line, however, other stress sources should be more significant [*Forte et al*., 2010; *Ghosh and Holt*, 2012] for other larger, intraplate earthquakes, many of which occur well outside of recently glaciated areas.

A similar conclusion emerges from geological observations of vertical motions. In particular, in the mid-Atlantic region, deformed stratigraphic and geomorphic markers, localized high-relief topography, and rapid river incision show uplift of the Piedmont and Appalachians relative to the Coastal Plain for the past 10 Ma, suggesting that the current seismicity reflects active and long-term deformation [*Pazzaglia et al*., 2010; *Pazzaglia and Gardner*, 2000]. These surface motions may reflect dynamic topography in response to mantle flow [*Liu et al*., 2008; *Moucha et al*., 2008; *Spasojevic et al*., 2009].

New efficiencies realized under the current PBO subawards support PBO processing centers to assimilate an additional 500 GPS sites in North America into the current 1200-station PBO data processing stream on an exploratory basis during 2012 – 2013. And after this initial resource-intensive ingestion of data, metadata, and evaluation, undertaken with current funding, these efforts will continue as part of the GAGE Facility at no additional cost.

Alaska – A Geoscience Frontier

Increased community focus on Alaska will support study of the kinematics and dynamics of the subduction process, large-scale continental deformation, volcano deformation, transient strain phenomena, and GIA. Alaska boasts spectacular examples of these phenomena [*Biggs et al*., 2010; *Biggs et al*., 2009; *Elliott et al*., 2010; *Freed et al*., 2006; *Freymueller et al*., 2008; *Hreinsdottir et al*., 2006; *Johnson et al*., 2009; *Larsen et al*., 2004; *Lu and Dzurisin*, 2010; *Lu et al*., 2005; *Pollitz*, 2005]. Integration of GPS and InSAR techniques can constrain time-variable magma flux beneath Alaska's volcanoes [*Fournier et al*., 2009]. GPS also reveals a crustal velocity field with contributions from interseismic strain, associated primarily with the subduction of the Pacific Plate beneath North America, as well as large postseismic viscoelastic and afterslip effects [*Ali and Freed*, 2010; *Freymueller et al*., 2008]. GPS data further confirms the existence of the long-hypothesized Bering Plate, which is rotating clockwise relative to North America about an Euler pole in East Asia [*Cross and Freymueller*, 2008]. Deformation within and transport of the Wrangellia terrane and the Yukatat microplate produce rapid uplift rates on the Wrangell and St. Elias mountain ranges. The Queen Charlotte-Fairweather and Denali Fault systems, the longest continental strike-slip faults in the world, also bound tectonic terranes.

Alaska is home to widespread historical seismicity. Significant earthquakes have included the great 1964 Alaskan Earthquake (Mw 9.2) and the 2002 Denali Earthquake (Mw 7.9), the largest recorded strike-slip earthquake to occur on the North American continent. Such events produce substantial and far-reaching post-seismic deformation, now being measured with GPS and InSAR, which provide constraints on the rheology of the crust and upper mantle and present-day stress rates [*Biggs et al*., 2009; *Freed et al*., 2006; *Hreinsdottir et al*., 2006; *Johnson et al*., 2009; *Pollitz*, 2005; *Suito and Freymueller*, 2009]. In addition, southeast Alaska has lost large volumes of ice since the Little Ice Age; for example the largest sustained uplift rate observed within the PBO footprint (>30 mm/yr) occurs at Glacier Bay [*Elliott et al*., 2010]. The response to the unloading history provides constraints on the rheology of the crust and upper mantle, as well as the coupling of climate change with tectonics [*Larsen et al*., 2004].

As noted in the GeoPRISMS Alaska report, planned seismic and geodetic observations in Alaska over the next five years offer exciting scientific opportunities for improved understanding of Alaska kinematics and dynamics: advances in telecommunications technologies are expected to enable the affordable transmission of higher frequency observations; the portable GAGE GPS receiver pool is available for PI-led projects along this transient-rich margin; and lastly the maturation of time series from PBO stations at the volcanoes and fault zones of Alaska will support many UNAVCO community science goals through their analysis.

Multi-hazards Observatories: Mexico, the Circum-Caribbean and Africa

PBO is unique both in scale and in the variety of geodetic systems and networks that are integrated into a single observatory; it has inspired a new generation of multi-hazard research observatories where integration of GPS, other geodetic sensors, and meteorological observations characterize the processes that shape Earth and atmospheric hazards. Through workshops and awards supported outside of its core cooperative agreements, UNAVCO has contributed to expanding on PBO's success in a coordinating role and through network construction beyond the PBO footprint. For instance, six stations in the Mexican state of Baja California were added to PBO through an NSF RAPID award shortly after the Mw 7.2 El Mayor - Cucapah earthquake in 2010.

UNAVCO has advanced community multi-technique GPS-based networks in Africa (AfricaArray) and the Caribbean (COCONet) to provide an observational backbone to support a broad range of Earth and atmospheric science investigations.

An international workshop co-sponsored by NSF and CONACyt led to the formulation of a plan to build the Trans-boundary Land and Atmosphere Long-term Observational and Collaborative network – TLALOCNet (named for the Aztec god of water, feared for his ability to deliver hail, rain, and lightning upon the inhabitants). As part of TLALOCNet, 100 new GPS stations are planned at Servicio Meteorologico Nacional de Mexico (SMN) observatories. US scientists are proposing to integrate existing NSF-funded GPS infrastructure in the region and extend current capabilities to ~20 new PBO-quality sites with the goal of building on the established synergies with the international geodesy community that studies crustal deformation along the Mexican subduction zone and North American-Caribbean transform margin.

In both the Caribbean and Mexico there is strong interest in developing regional data archives and local GPS processing centers, which build capacity for international partners, based on UNAVCO's extensible capabilities for a seamless archive. While GAGE will continue to have primary responsibility for archiving any NSF-funded geodetic investigations, we are planning cyberinfrastructure solutions to expand international and open-data global geodesy capacity for archiving.

Network of Networks for the Western Americas

The international networks mentioned above build on the PBO model while extending the benefits of multi-hazards investigations beyond the Earth sciences. Enhancements like RT-GPS and meteorological observations ensure the broader impact of these research investments. Taken collectively with other projects such as the RAPID GPS station deployments in Chile and Argentina after the 2010 M8.8 Maule earthquake, and international investments in GPS observations along the backbone of South America, sufficient infrastructure has been realized to invite us to imagine a set of hemisphere-scale plate boundary geodetic and environmental observatories along active plate boundaries of the western Americas and the Caribbean. The elements for such a network of geodetic networks may be largely in place by 2018, similar to the situation for western US geodetic networks that were assimilated as the PBO Nucleus. Although there are some key regional gaps and key data sharing relationships to be addressed, the UNAVCO community, governance, and EarthScope advisory bodies have been clear in their intent to sustain PBO beyond 2018, in transient-rich, transient-prone, and required backbone areas; and to extend such observations to subduction zones worldwide.

PBO and sister networks like SUOMINet have also served as a model for multihazards observatories in adjacent regions - COCONet in the Caribbean and TLALOCNet in Mexico as discussed above. These networks and collaborations position the UNAVCO community to link subduction zone observations along the western boundary of the Americas by 2018.

Because the initial 15-year funding cycle for EarthScope ends in 2018, such an initiative requires a careful community-driven planning process during the early part of the GAGE award period. The first steps are to develop the scientific case, requirement specifications, and network evaluations to support planning for plate boundary geodesy across the Americas. This will be a major focus of governance, community activities, and ancillary workshops, under the initial GAGE award.

Ice Dynamics on a Changing Planet

POLENET, a great investment in polar geodesy made during the International Polar Year (2007-2008), has stimulated a wealth of new discoveries. Polar geodesy and seismology have both thrived as a result, and taken together have rapidly advanced our understanding of the structure and dynamics of the ice caps. Continuous GPS networks now rim Greenland and much of Antarctica, providing critical constraints on mass changes and the short- and long-term isostatic adjustments in the underlying lithosphere. These data sets will continue to mature, and the GAGE Facility anticipates continuing demand for polar deployments, especially for GPS and TLS geodesy.

Polar research, however, is commonly limited by cost and logistical constraints; the rapid growth of the polar science community and their observing systems was stimulated by recent increases in observational capacity like POLENET. We anticipate pressure on TLS resources, and vigorous ongoing demand for POLENET and other PI-driven data sets. This proposal makes restrained predictions for growth in the number of polar projects over the initial GAGE interval, based on current OPP capacity for logistical support and the limited supply of TLS instruments. These projections will prove to have been conservative if capacity is enhanced with additional resources during the GAGE period.

Collectively, these natural laboratories are rich with opportunity for the geodesy community to advance understanding of local processes and their global scale interactions. Support for continued geodetic observations in these natural laboratories, which are simply areas of UNAVCO community scientific interest, are an essential part of the GAGE Facility and its planned activities from 2013-2018.

2.6.2 Developing technologies

Building on a decades-long legacy of burgeoning technological innovations applied to critical science questions, several developing tools are advancing quickly. Through UNAVCO's community governance, critical capabilities have been identified for the next five years.

We expect the growth of TLS to continue to scientifically diversify the UNAVCO community, drawing in investigators who focus on surface processes and geomorphology. RT-GPS has made rapid advancements during the last three years, with key regional investments in PBO and investigator networks such as PANGA and CRTN. Recent advances in understanding water-cycle effects on GPS time series and the use of InSAR and LiDAR to characterize environmental change is opening up new fields of hydrogeodesy and environmental geodesy. NASA's focus on improvements to infrastructure in support of millimeter-level global geodesy will lead to new applications in these and other areas.

Looking even further ahead, two emerging geodetic techniques capture the imagination of the investigator community, both of which are likely to mature beyond 2018. The first, tripod radar interferometry, images centimeter- to millimeter-level changes to the landscape over timescales shorter than hours. The second is seafloor geodesy. Two-thirds of the Earth's surface and nearly every kilometer of subduction zone fault lie under the oceans. While seafloor geodesy has grown over the last two decades, its expense has prohibited the development and deployment of widespread observing networks. Recent innovations show promise and the recent occurrence of great megathrust earthquakes worldwide has renewed the interest of UNAVCO geodesists in seafloor geodesy.

With NSF's major investment in ocean observing systems, the UNAVCO community and GAGE Facility will watch for opportunities to contribute to the development of seafloor observing systems in light of UNAVCO's core competencies in technologies such as GNSS and remote telecommunications. The UNAVCO community and GAGE Facility will follow these developments closely as opportunities emerge.

RT-GPS: PBO and COCONet

Real-time data allow for real-time science and hazards applications and have a place in technically advanced society. GPS data and higher-level products provided in real-time will greatly enhance their use for scientific and other purposes.

The benefit that low-latency information provides to society for applications such as early hazards warning or navigation is discussed above. The importance of the ability to detect, characterize, and communicate events rapidly was clearly demonstrated following the 2004 Sumatra and 2011 Tohoku-Oki earthquakes and tsunamis.

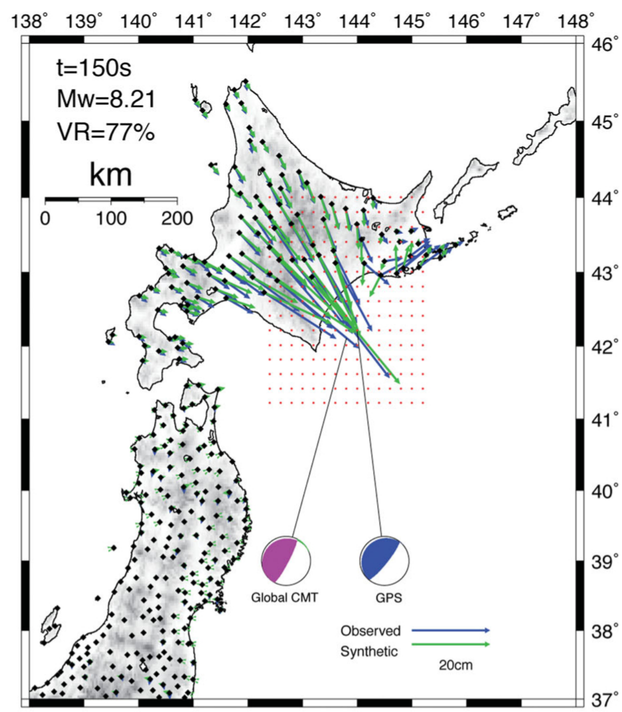
Integration of seismic and GPS data at the time series level promises to push forward the science of true broadband seismology. Only a very small part of the spectrum of short-term deformation events is visible to seismometers; geodesy is critical to understanding strain release over a range of periods and the full displacement field that accompanies seismic shaking. For example, recent earthquake clusters near Lake Tahoe [*Smith et al.*, 2004], and Reno, Nevada [*Anderson et al.*, 2008; *Blewitt et al.*, 2008] indicate that while hundreds to thousands of small to medium earthquakes occurred, most of the deformation occurred aseismically. Studies of what have been considered to be seismic energy sources will be increasingly viewed as studies of Earth deformation events, only

EarthScope and Real-Time GPS

Continental deformation operates on time scales that span seconds (earthquakes) to millennia (tectonic deformation), processes that can be best studied using seismic and geodetic observations that measure displacements over vastly different time scales. Merging seismic and geodetic data streams into rigorously integrated broadest-spectrum records will unify observation of Earth processes from fault rupture dynamics, and postseismic transients, to long-term plate motion.

A significant advancement in recent years has been development of high-rate GPS measurements delivered in real time (RT-GPS). While RT-GPS data are crucial for natural disaster research and warning, they also provide improved temporal resolution in observations of natural processes. Recent ARRA-funded upgrades of hundreds of GPS stations in the Pacific Northwest together with newly planned upgrades as part of GAGE have created new opportunities and incentives to develop RT-GPS for EarthScope science and applications.

RT-GPS measurements provide several unique capabilities. For example, sites in epicentral regions provide near instantaneous measure of deformation allowing for more rapid earthquake and magnitude detection and derivation of earthquake source parameters, than can be achieved with seismometers alone. The figure shows the excellent agreement between the displacements associated with the 2003 MW 8.3 Tokachi-oki, Japan earthquake and estimated moment tensor solutions [*Melgar et al*., 2012]. In addition, whereas seismometers record ground velocity or acceleration with very high sensitivity, they may saturate with large ground motions. RT-GPS, while less sensitive than seismometers, provides complementary data, which extends the observational bandwidth by directly recording large ground displacements, without need for integration, over periods of seconds to years [*Bock et al*., 2011].



As highlighted in the 2011 workshop on "***Real-time GPS position data products and formats***", the UNAVCO community is actively working towards the availability of solutions that are both high-rate and low-latency, which have the required precision and reliability, and can be operationally applied to data from hundreds to thousands of stations [Mencin et al 2012]. Continued development of RT-GPS will require the combined efforts and resources of the GAGE and SAGE Facilities and the UNAVCO and IRIS communities.

some of which are accompanied by energy propagated as elastic waves from the source. Many deformation processes associated with the earthquake cycle (including fault slip, viscous flow of rocks, fluid flow and postseismic deformation), volcanic activity and non-tectonic deformation processes do not produce seismic waves and can occur over a very wide range of timescales. Thus, the use of high-rate, high-precision geodesy is essential to the understanding of the nature of such events and the spectrum of strain release mechanisms.

High-rate GPS data can effectively serve as a strong motion displacement instrument that never saturates, and that avoids the difficulties in the double integration of strong motion acceleration records [*Larson*, 2009; *Bock et al.*, 2011]. Inertial accelerometers cannot distinguish between accelerations caused by rectilinear motions and those that arise when a seismometer is tilted in the Earth's gravity field. In addition, the correct double integration of seismic data also requires extreme linearity of the seismometer system as well as knowledge of the initial ground velocity at the start of integration. This means that most strong motion records must be high-pass filtered to remove spurious long-period signals. This filtering also removes critical information about the rupture process. GPS systems do not suffer from these shortcomings. *Larson et al*., [2003], *Bock et al.*, [2004; 2011], *Ji et al.* [2004] and *Miyazaki et al*. [2004] demonstrated that high-rate GPS data can be incorporated in finite-source inversions in the same manner as traditional seismic waveforms, and can provide direct measurements of arbitrarily large dynamic and static ground horizontal displacements. *Genrich and Bock* [2006] using methodology developed by *Bock et al.* [2000] and *Nikolaidis et al.* [2001] show that GPS position time series with sample rates as high as 50 Hz are useful for increasing the potential for integration of 3D positioning data with traditional seismology. UNAVCO is collaborating with community researchers to test the viability of these techniques within PBO. As part of the GAGE Facility, planned enhancements to geodetic infrastructure and data processing will support continued community efforts in this rapidly evolving area of geodesy.

Geodetic Imaging

Recent NSF investments in UNAVCO's geodetic imaging capabilities include acquisition of a pool of TLS instruments, providing new capabilities for university investigators. As GPS instruments were 25 years ago, TLS scanners are currently very expensive, unfamiliar and challenging to use in the field, and technologically rapidly evolving. Recommendations from the 2011 community workshop *Charting the Future of Terrestrial Laser Scanning (TLS) in the Earth Sciences and Related Fields* [UNAVCO, 2012] identified focused areas for PI support under GAGE: instrument pool upgrade and expansion; PI resources for data acquisition; and support for data archiving, management, and processing.

The science community requires an updated pool of these rapidly evolving instruments with a spectrum of capabilities:

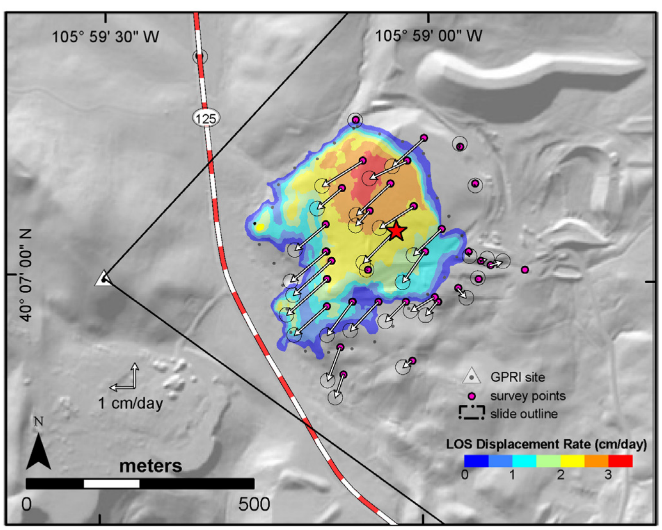


Figure 2.6-1. Ground-based interferometric radar. GBIR is another emerging geodetic tool that shows potential for imaging small displacements associated with mass movements [e.g., Casagli et al., 2010; Luzi et al., 2004], as well as glaciers and other surface processes. In contrast with satellite-based and airborne InSAR, GBIR acquisitions can be acquired rapidly (10s of seconds to minutes) for rapidly moving phenomena [e.g., Lowry et al., 2012]. This figure shows daily displacement rates of the Granby, CO, landslide determined by 280 GBIR interpolated interferograms (color contours) and GPS survey measurements from June 2012 (white arrows). In order to acquire experience with this new technology, UNAVCO engineers participated in this field survey. From Lowry et al. [2012].

longer ranges, wavelength suited to imaging snow and ice, full waveform and phase shift scanning, and water penetration. Given the high cost of scanner acquisition, instrument purchases themselves are not budgeted as part of the GAGE proposal; UNAVCO will pursue opportunities to sustain and upgrade its TLS pool for both polar and solid Earth/geomorphology applications through companion and community proposals.

UNAVCO capabilities for calibration, validation, documentation of best practices, and error analyses are already in high demand. Lastly, metadata standards and capture tools, remote PI access to centralized processing, and solutions for data archiving and management must be developed. These recommendations confirm those of the 2011 UNAVCO Management Review, where the panel urged UNAVCO to adapt its quarter-century legacy of GPS core competencies to TLS support on an aggressive schedule.

Under its current Cooperative Agreements and other funding, UNAVCO has already taken proactive steps to integrate TLS support into its core activities. As the number of GPS campaign requests has remained steady, field engineers are being cross-trained to support TLS data acquisition for both OPP- and EAR-funded PIs. Under GAGE, core engineering and data services capabilities will continue to be used to advance TLS and other emerging geodetic tools, in particular terrestrial radar. Figure 2.6-1 shows landslide motion in Colorado imaged with ground-based interferometric radar (GBIR) capable of detecting motions as small as 1 mm/hour.

Millimeter-level Global Hydrogeodesy

Hydrogeodesy relies on a precisely defined and stable terrestrial reference frame to yield mm-level accuracy on a global scale. The challenges to achieving and sustaining mm-level global geodesy are well substantiated [NRC, 2010], including activities to be undertaken by GAGE: sustain and enhance current geodetic infrastructure, complement existing fundamental geodetic stations, support the infrastructure for real-time GNSS, support international services like the IGS, and sustain a long-term commitment to the ITRF. The achievements of modern geodesy rely on these international activities.

The Third Annual IGCP 565 Workshop: Separating Hydrological and Tectonic Signals in Geodetic Observations developed a set of actionable recommendations aligned with three themes that were identified during the workshop [Plag and Miller, 2010a]. Its recommendations detailed the importance of support for the reference frame, modeling, infrastructure requirements, and outreach [Plag and Miller, 2010a]. The planned GAGE Facility plays a critical role in many of these activities, including supporting the GGN and IGS Central Bureau, developing and sustaining continuous GPS observations around the world (PBO, AfricaArray, COCONet,

EarthScope in Cascadia and Synergy with GeoPRISMS and the Consortium for Ocean Leadership

Twenty-five years ago, scientists debated whether the Cascadia subduction zone was capable of generating great earthquakes. Today, Cascadia has rocketed to scientific prominence because of the GPS-based discovery of aseismic slip transients, accompanied by tectonic tremor. Thus, Cascadia is indeed active despite its perplexing historic paucity of earthquakes. Now, EarthScope GPS stations, borehole strainmeters and seismometers, and ocean-bottom seismometers yield data streams that document Cascadia's interseismic activity. UNAVCO and IRIS play key roles in deploying and maintaining these instruments, archiving the data, and making data products available to the Earth science community worldwide.

During EarthScope construction, PBO installed 245 continuous GPS stations in the US Pacific Northwest, as well as 45 borehole strainmeters and collocated seismometers. With funding from the American Reinvestment and Recovery Act (ARRA), NSF launched the Cascadia Initiative, upgrading most PBO Cascadia GPS stations to real-time, providing denser onshore seismic observations, and deploying an array of ocean-bottom seismometers for offshore community experiments. In parallel, the Consortium for Ocean Leadership advanced a new Cascadia MREFC facility: Ocean Observatories Initiative. The OOI and UNAVCO communities met in Seattle this spring to articulate the science agenda and practical challenges for Cascadia seafloor geodesy [Wilcock et al., in preparation]. The central recommendation:

There is strong scientific and hazards monitoring justification for seafloor geodesy in the Pacific Northwest because it provides critical information about the subduction zone that cannot be obtained by other means.

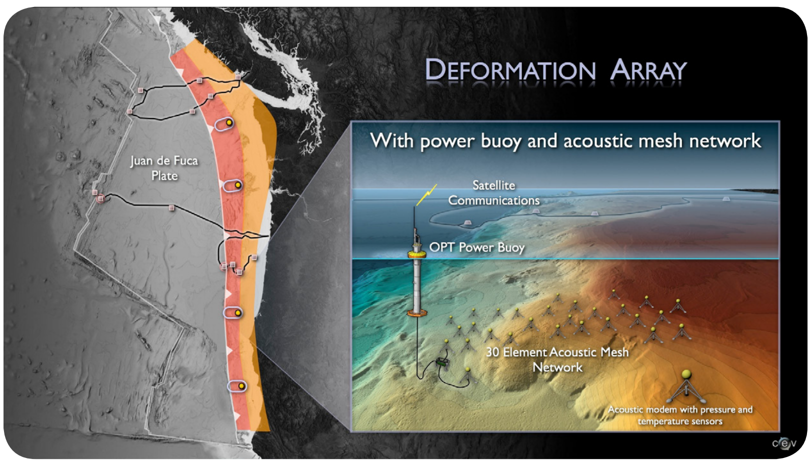


Image courtesy of John Delaney (2012)

The NSF-funded GeoPRISMS program has selected Cascadia as one of three primary sites for the Subduction Cycles and Deformation (SCD) Initiative. The Ocean Observatories Initiative and UNAVCO community scientists are exploring synergies that might one day advance Cascadia seafloor geodesy, building on the OOI's planned cabled networks and marine infrastructure. This natural laboratory promises rich interdisciplinary collaboration among the science communities of EarthScope, GeoPRISMS, and the Consortium for Ocean Leadership for transformative science.

TLALOCNet, POLENet, and numerous PI networks), distributing PBO position time series and PBO-H2O products, building capacity with international colleagues to strengthen national geodetic infrastructure abroad, and technical training and workforce development provided through GAGE ECE.

Seafloor Geodesy

Most of the Earth's surface is not observable using traditional geodetic techniques because it is under water. Nonetheless, subduction zone processes and oceanic plate motions have captured broad interest and are critical to any accounting of global plate motions and underlying geodynamics. In locations such as the Cascadia convergent margin fundamental parameters to be determined range from plate motion, rigidity, and Euler pole locations to the evolution of deformation both along strike and throughout the great earthquake cycle, seismo-tectonics of the accretionary wedge and its locking or creeping mechanisms, ridge transform interactions, the role of aseismic deformation, and, of course, long-term, seasonal, and abrupt, wave-related changes in local sea level height. The subducting Juan de Fuca plate has no land, and cannot be observed directly by GPS geodesy.

In regions of subduction beneath continental margins, elastic strain accumulation and release, postseismic deformation, and the thrust faults that define the plate boundary all continue offshore. The GPS-Acoustic (GPS-A) approach for seafloor geodesy (Figure 2.6-2) determines the position of a kinematic GPS system on a floating platform (ship or buoy) using acoustic ranging to an array of seafloor transponders [Spiess et al., 1998]. The technique can measure the horizontal position of the seafloor with centimeter resolution in the same global reference frame used by land-based GPS. The GPS-A method has to date permitted the accurate

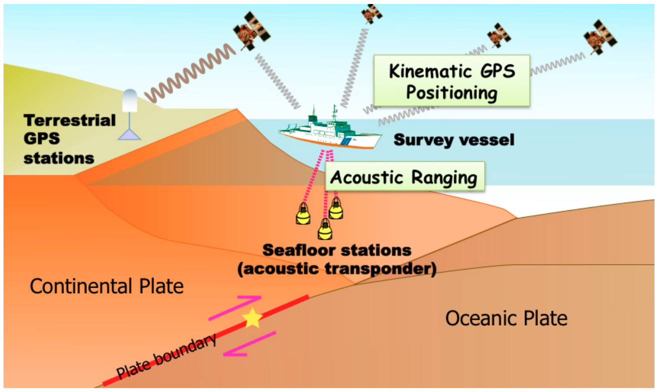


Figure 2.6-2. Components of precise GPS seafloor geodesy. The GPS-A (GPS Acoustic) technique relies on precisely positioning a platform on the sea surface with respect to the GPS constellation and transponders or beacons on the seafloor (Image contributed by Ishikawa, written comm., 2012).

determination of plate velocities at a dozen or so locations on the seafloor. For example, in offshore Peru GPS-A was used to measure displacement of two seafloor arrays on the submerged continental slope, and revealed its movement towards the South American plate. GPS-A measurements in offshore Japan measured interseismic strain and coseismic strain release during the 2005 Mw7.2 Off-Miyagi earthquake, followed by re-establishment of interseismic strain accumulation. Horizontal deformation near the offshore hypocenter of the March 11, 2011 (Mw9.0) Tohoku earthquake was estimated using GPS-A to be ~24 m, with vertical deformation of ~3 m (Figure 2.6-3). Seafloor deformation measurements are fundamental to addressing questions about the largest seismic hazards on Earth. Subduction zones generate the world's largest earthquakes and destructive tsunamis [*Sato*, 2011].

Recent technological innovations hold promise that more affordable seafloor geodesy may be available in the near future and mature over the next decade as the Ocean Observatory Initiative (OOI) is established. Current discussions focus on techniques ranging from acoustic GPS using transponders or beacons, pressure (for sea height), tilt (for transients), fluid flux, and precise bathymetry. Cabled networks, like those planned for OOI, provide infrastructure that could further leverage these emerging technologies. As these efforts by a sister facility move forward, key capabilities of the GAGE Facility, such as high rate positioning for sea surface observing platforms and remote telecommunications, are likely to play a role.

2.6.3 Data Products and Cyberinfrastructure

The rapid evolution of capabilities in data services and cyberinfrastructure, support enhancements to access, discovery, usability, quality, and understanding of increasing volumes of geodetic data. During 2011 and 2012, UNAVCO undertook an internal reorganization to take better advantage of emerging opportunities in geodetic data services, and capitalize on synergies within GAGE and in partnership with sister organizations.

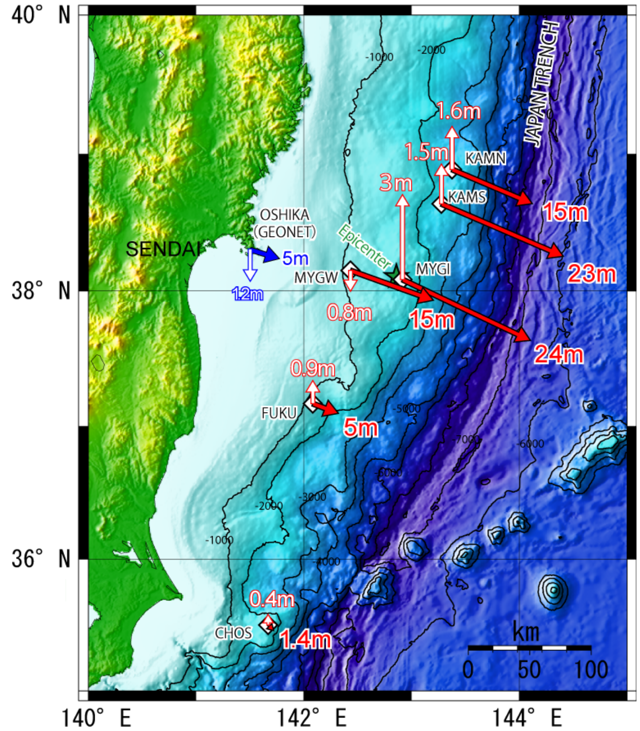


Figure 2.6-3. Coseismic seafloor displacements associated with the 2001 Tohoko earthquake. Seafloor geodetic measurements for the first time captured a major subduction zone earthquake. The observed motions (up to 24 meters in this study and 31 meters detected in another by Tohoku University) were 4-5 times larger than land based GPS measurements. The resulting slip model based on the combined seafloor acoustic and terrestrial GPS indicates a maximum slip of 56m along the plate interface, twice that of the terrestrial GPS only solution. From Sato et al. [2011].

The fundamental challenge for cyberinfrastructure is the natural tension between the specificity of subdiscipline user requirements and the interoperability required for broad integration. The EarthScope strategic plan for cyberinfrastructure [*Gurnis et al.*, 2012] refers to the first as vertical integration (i.e., within communities) and articulates salient opportunities for advancement under EarthCube in the US and COOPEUS in the international arena. Such integration provides a framework for GAGE Facility contributions, and builds on the intent of within-discipline facilities to meet unique and highly evolved user requirements. During the past five years, key investments by NSF and NASA have rapidly advanced the functionality and sophistication of the workflow for geodetic data management and archiving, including GPS, InSAR, LiDAR and data products. This work has taken place in partnership with collaborative geodesy organizations such as NCALM, OpenTopography, CDDIS, SOPAC, and the Nevada Geodetic Laboratory.

The EarthScope cyberinfrastructure plan also emphasizes horizontal integration and interoperability across Earth science subdisciplines. The partnership between UNAVCO and IGS, GeoPRISMS, CUAHSI, and IRIS to enhance accessibility and usability of all EarthScope data sets as a coordinated whole are examples. The fundamental challenge is to

enGAGE: A web portal for community engagement

enGAGE will be an online portal promoting community interaction and engagement focused on geodetic instrumentation, tools, data, and educational materials. UNAVCO has a well-established, contemporary web presence reflecting its new organizational structure and community focus. The recently refreshed website provides the foundation for a process to develop an integrated system that promotes knowledge transfer and sharing (both in and out), document management, community content management, social networks and interactions, and linkages to social media. enGAGE is envisioned as a flexible and sustainable framework to integrate core technologies, content management work flows and broader participation in web content and interactions. The goal is to have a participatory web environment and coherent community portal for connecting, communicating and promoting collaboration among the UNAVCO community and partners at home and abroad.

reimagine an EarthScope portal that takes advantage of the great strides in cyberinfrastructure, on a foundation of user requirements that crosses disciplines. Powerful tools such as web services, high performance computation, and virtualization may serve as a stepping-stone to the rapid evolution of cloud computing.

2.6.4 The Human Dimension

The science of geodesy is global and interdisciplinary in nature and involves scientists from geodetic sciences and beyond, as demonstrated above. Geodesy also has a strong connection to society through the illumination of the science of natural hazards, including tsunamis and rising sea level, and the supply of data and tools to help identify such hazards as well as provide society the information it needs to mitigate and adapt .

Key areas of UNAVCO's focus during the GAGE proposal are: (1) to ensure that a sustainable and sound geodetic infrastructure exists (for example, the enhancements to PBO and its future role in the Network of Networks); (2) to build viable cyberinfrastructure, such that (3) data are accessible to both the UNAVCO community, international geoscientists and the public [enGAGE]. Development of these key areas, in particular enGAGE, will provide the framework for stakeholders to access not only data and information, but the ability to visualize and interpret the information in a meaningful way. Access to information and data and the ability to share content through UNAVCO's enGAGE web portal will help multiple aspects of society: policymakers and emergency managers can make more informed decisions, students and teachers will have a consistent mechanism to learn about fundamentals of geodesy through real-world data and examples. enGAGE can also provide the international geodesy research community a mechanism to contribute and share information. UNAVCO will also sustain its current focus on engaging a rapidly growing and diverse community of NSF investigators, equipping PIs to harness the power of the rapidly evolving geodetic technologies discussed here.

enGAGE will build on the highly successful UNAVCO web resources such as the online Knowledge Base and Data Archive Interface (DAI). Expanding these two very popular and frequently accessed resources will provide needed services to the UNAVCO community, allowing for broader impact and easier access of data. Based on usage metrics, data from preceding years, and the online nature of how citizens access information, the enGAGE portal has the potential to become the most highly used resource in geodesy.

As a complement to GAGE, UNAVCO's ECE Program is addressing wide-reaching impacts that are a priority for the UNAVCO community as identified during various planning workshops. UNAVCO is responding to community requests for the development of a suite of complementary geodesy curriculum components focused on university students (introductory, undergraduate geosciences major, and graduate levels). UNAVCO also supports the development of the next generation of geoscientists through an NSF-funded undergraduate research program, RESESS. Since 2005, RESESS has sponsored 37 student interns, 21 of whom are still undergraduates, 16 have bachelors' degrees, two are working as geoscience professionals and 12 are in graduate school (10 in the geosciences).

In response to recommendations following its 2011 NSF Management Review, UNAVCO has also prioritized the need to enhance and coordinate its efforts in External Affairs with a focused position for outreach to policymakers and planning for coordination with the international geodesy community. In support of and in collaboration with its member institutions UNAVCO aspires to secure key international data sharing agreements that build on recent partnerships in the circum-Caribbean region as part of COCONet, and thus continue to advance hemisphere-wide integration.

In the next section, we describe the capabilities of NSF's national geodesy facilities as currently operated under the oversight of the UNAVCO consortium and plans to integrate these activities as the GAGE Facility during the years 2013 through 2018. GAGE will provide engineering and data services to the science community to advance understanding of the Earth system interactions outlined in the grand challenges above.

Teachers on the Leading Edge participants point in direction of motion for the Plate Boundary Observatory GPS station and North America at Elma, Washington.

3. GAGE Facility Plan: The Next Five Years

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 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.

In the first sections of this proposal, we have outlined the tools, techniques and ongoing and emerging scientific issues that invigorate the UNAVCO science community. This section describes how the GAGE Facility will play a critical role in development and testing of new and existing techniques, processes and technologies, installation of enhanced or upgraded instrumentation, maintenance of existing geodetic resources, in particular the PBO component of EarthScope, and, perhaps most importantly, training and field engineering support for members of the UNAVCO and the broader global geodetic communities in pursuit of their NSF- and NASA-funded scientific projects. UNAVCO's commitment to building extensible capabilities within its staff and international communities has supported a global proliferation of geodesy resources that address a broad range of geoscience applications (Figures 3-1 and 3-2).

During the past decade, the UNAVCO science community has been energized by the diversification of its subdiscipline communities and the increasing diversity of available geodetic technologies and applications. Part of this enhanced

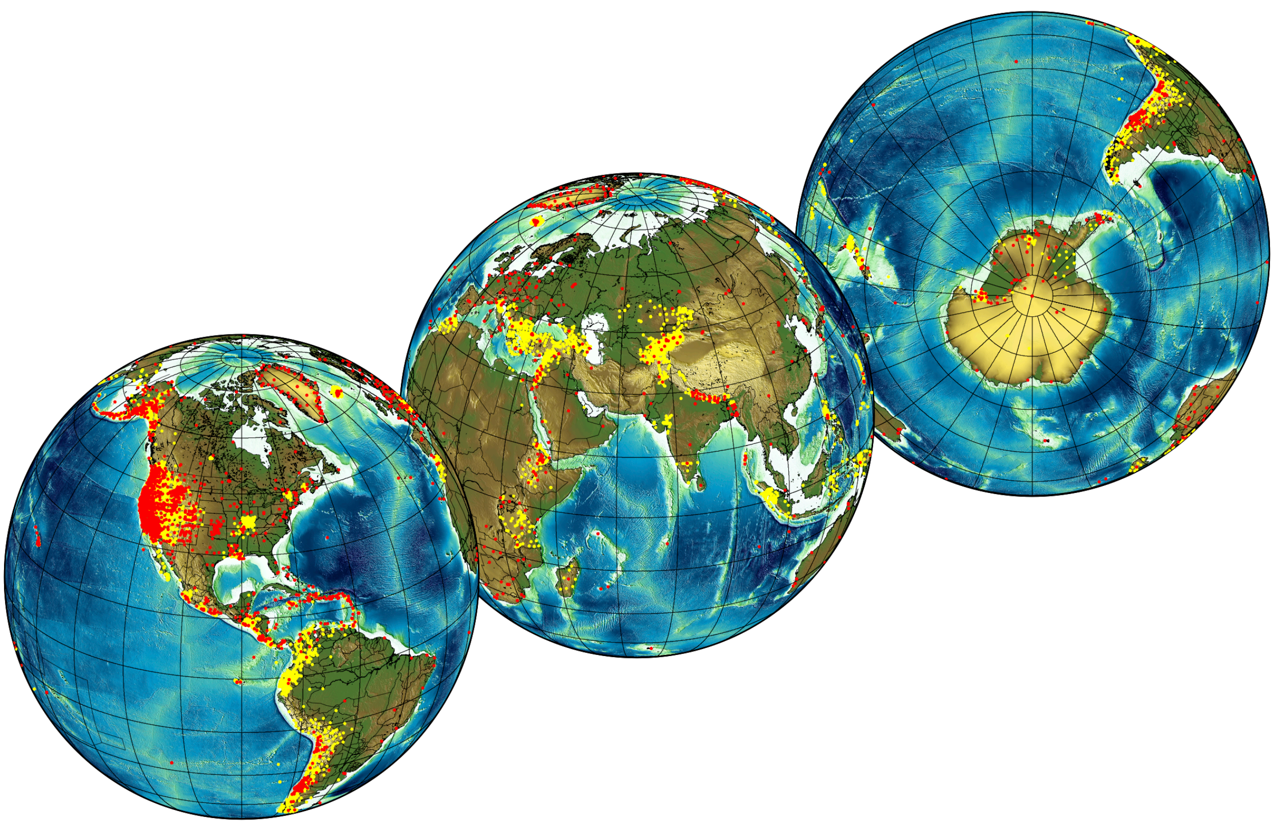


Figure 3-1. Growth in global geodesy resources. In the five years since the last core support proposal, the number of continuously operating GPS (cGPS) stations archived at the UNAVCO Data Center has grown considerably and now numbers 2,376 stations. A proliferation of community networks modeled on the Plate Boundary Observatory now provide denser cGPS observations (red) on every continent and rim both Greenland and Antarctica. Campaign observations (yellow) provide even greater spatial density in actively deforming zones. Topography from the Global Digital Elevation Model (GTOPO30), U.S. Geological Survey, EROS Data Center Distributed Active Archive Center (EDC DAAC). Figure made with GMT.

growth may be directly attributed to the return on the NSF's EarthScope investment, as UNAVCO has developed capabilities in the construction and operation of large autonomous networks of GPS stations, strainmeters and other borehole observational systems, in acquisition of geodetic imaging data (LiDAR and InSAR), and in project management and business systems responsive to the requirements and expectations of the NSF Large Facilities Office.

This diversification has also been supported by community, sponsor, and facility initiatives, which have expanded UNAVCO Facility and EarthScope capabilities, including:

1. Data Center *enhancements,* which improve seamless access to GPS data,
2. *integration* of Polar Project Services into core Facility operations,
3. *development* of autonomous observation infrastructure for use in extreme environments,
4. *selection* of UNAVCO by the WInSAR consortium to be its umbrella organization, and
5. *the establishment* of UNAVCO capability to host NSF facilities to support Terrestrial Laser Scanning (TLS), through acquisition of an equipment pool and provisioning of field engineering and data processing services by UNAVCO staff.

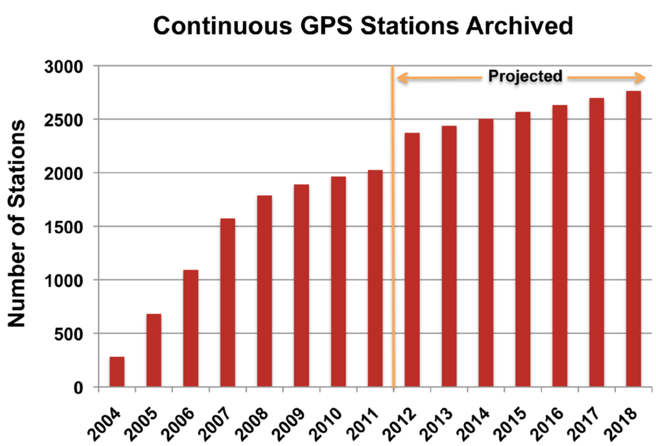


Figure 3-2. Continuous GPS stations archived. There are currently 2,376 continuously operating GPS stations actively returning data to the UNAVCO archive. Continued growth is expected with projections of 2,800 cGPS by the end of 2018. The largest collection in the archives is the 1,112-station PBO network operated by UNAVCO. To various degrees, UNAVCO supports the operations of nearly one thousand additional sites that span the globe from pole to pole, operated by PIs, NASA, and collaborators.

Emerging technologies such as TLS, Ground Based Interferometric Radar (GBIR), and real-time GPS are increasingly applied to scientific problems that had not traditionally been investigated by members of the UNAVCO community. These techniques require dissemination of new knowledge, skills, documentation of best practices and appropriate and efficient workflow processes, and new tools. The Education and Community Engagement (ECE) program supports these goals through workshops, short courses, and web-based applications for geoscientists. ECE also creates and distributes educational materials to increase public awareness, understanding, and appreciation of these science applicattions.

Management of the GAGE Facility will build 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 investment in PBO, 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 will work closely with 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; when such related awards are granted they are carefully coordinated with the cognizant NSF program officer. The proposed GAGE Facility combines the previously separate UNAVCO Facility and PBO Cooperative Agreement's into a single seamless organization and management entity, thus realizing the most efficient use of available resources for our sponsors and the UNAVCO community.

Finally, as a business entity UNAVCO, Inc. provides NSF the fiscal, compliance, and legal structures for stable operation and award management needed to support the science vision of its community. Through its professional staff and governance structure, UNAVCO provides continuity in institutional and personnel resources for operational activities and to incubate new capabilities on behalf of its membership.

We detail below the services that UNAVCO has provided under the cumulative 2003 – 2013 Cooperative Agreement's with performance metrics and critical success factors, together with projections for the GAGE Facility during the 2013 – 2018 proposal period. The work described here will support the core activities and emerging directions (Section 2.6). The discussion follows UNAVCO's organizational structure, with ties to the Work Breakdown Structure (WBS)

Dictionary (Part III). The WBS Dictionary identifies the activities to be undertaken by GAGE Facility staff. Specific WBS elements referenced here are defined in Part III, with the basis of budget estimates.

3.1 GEODETIC INFRASTRUCTURE (GI) PROGRAM - (WBS U1.1)

This new program integrates all geodetic infrastructure and data acquisition capabilities for continuously operating observational networks and shorter-term deployments. Supported activities include development and testing, advanced systems engineering, the construction, operation, and maintenance of permanent geodetic instrument networks around the globe, and engineering services tailored to PI project requirements. The GI program coordinates closely with Geodetic Data Services to assure the highest standards of data quality control, integrity of metadata, ease and transparency of data access for the UNAVCO user community, and to provide appropriate and timely metrics on data usage for sponsors. Major projects currently supported by the GI program include the 1,112 station Plate Boundary Observatory (PBO), Polar networks in Greenland and Antarctica (GNET and ANET, together known as POLENET), COCONet spanning the Caribbean plate boundary, the multi-disciplinary AfricaArray, and several other smaller continuously observing geodetic networks.

The GI program also provides engineering services to individual PIs for shorter-term GPS and TLS projects, and other investigator-led data acquisition that had been previously managed by the UNAVCO Facility.

While many GI resources are tied to ongoing Operations and Maintenance (O&M) of the PBO, GGN, and POLENET continuous GPS (cGPS) networks and ongoing support to PI projects, we have identified two key areas for enhancement in support of new initiatives (I-2.6):

1. The continued upgrade of PBO to high-rate (>1 Hz), low-latency (<1 s), well-hardened sites in order to support research activities related to dynamic fault rupture and volcanic eruption processes;
2. Continued evaluation and upgrade of all GPS receiver pools for implementation of full GNSS capability.

Both of these tasks build on the specific recommendations of the report on *Precision Geodetic Infrastructure National Requirements for a Shared Resource* [NRC, 2010].

The recent RT-GPS workshop addressed the topic of real-time upgrades to PBO [*UNAVCO*, 2012]. It is a necessary first step towards GPS seismology in which RT-GPS observations are combined with collocated accelerometers, as recommended by the NROES committee in its *Instruments and Facilities Needs for Faulting and Deformation Research* findings [NROES, NRC, 2012]. This task is an extension of the original scope of work funded by the American Recovery and Reinvestment Act of 2009 (ARRA) Cascadia project, which will have upgraded an additional 272 stations. The Cascadia award built on the 100 PBO pilot RT-GPS sites. Below we outline a plan to upgrade an additional 50 PBO sites per year to RT-GPS capability. Site selection criteria will be developed by the GI Advisory Committee (which will itself be newly constituted by 2013). The 2018 close of the proposed GAGE Facility Cooperative Agreement will coincide with the formal end of the EarthScope program as originally proposed to NSF; at that time, we envision that at least 622 of the original 1100 PBO sites (56%) will be RT-GPS operational.

The second of these tasks, upgrading existing PBO GPS infrastructure from GPS-only to new GNSS-capable instruments, is driven by several factors:

1. The need to retire most existing GPS receivers in the PBO network as they reach their end-of-life. The manufacturer is currently no longer supporting firmware development and, after 2014, will not provide spare parts for the NetRS.
2. The likelihood that aging NetRS units may begin to fail at higher than current rates (currently 3%/year).
3. The need to sustain PBO as a world-class network that will be viable beyond the end of the EarthScope project as originally proposed in order to support the community vision for decades hence. PBO serves as a cornerstone to a "Network of Geodetic Networks" along convergent margins of the western Americas.
4. And to provide all US stakeholders with a modern state-of-the-art geodetic network that is uniform in character and meets the standards of all sponsors participating in the GGOS (e.g. NASA and NOAA).

Below we develop a plan to evaluate and acquire new GNSS-capable instruments at an escalating rate of 51 to 114 units per year with an estimated unit cost of $8,000 (note that additional purchases may result in cost reductions that would further leverage this investment). This would amount to more than 400 upgraded PBO stations during the award period. Additional stations will be upgraded if prices for GNSS-capable systems are below our estimated unit cost or additional sources of funding become available.

While the case for the selective replacement of the Trimble NetRS receivers in the PBO network and the PI receiver pool is straightforward based on the discussion above, the decision to upgrade both receivers and antennae from GPS-only to GNSS-capable is not. UNAVCO has an expert D&T group, whose previous and ongoing experiments and analysis have been used to condition the selection of hardware and software prior to deployment in the PBO, GGN, and POLENET networks. We propose to focus their efforts in year 1 of GAGE to provide the appropriate data for the UNAVCO

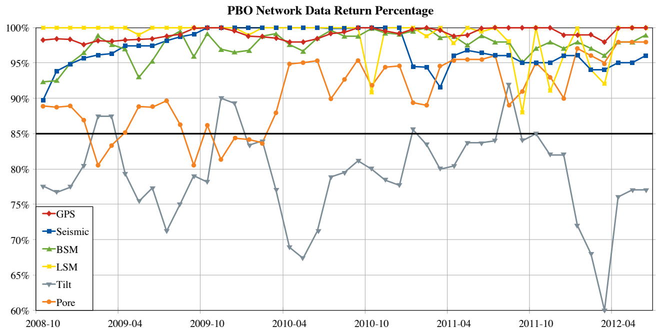


Figure 3.1-1. PBO data return. UNAVCO tailors performance metrics to the nature and scale of the project. PBO, the largest and most diverse set of networks that will be supported by the GAGE Facility, uses metrics at all stages of operations and maintenance. Through May 2012, the total quantity of archived and delivered (including streaming) data include: GPS (19.8, 47.1 Tb); seismic (3.5, 16.6 Tb); and BSM (1.6, 0.3 Tb). One important metric for PBO operations is the percentage of data returned. Most sensors exceed the 85% target. GPS, the largest component of the network, is typically well above 95% data return.

community, GAGE management, and core sponsors (NSF and NASA) to determine whether to upgrade to GNSS. The implications for this transition cannot be underestimated, given that targeted cGPS sites would need their Dorne-Margolin antenna elements replaced, which will cause an offset in the phase center of as yet unknown magnitude, in addition to having the systems record and transmit additional signals from new GNSS constellations such as GLONASS and Galileo. This transition would also have significant implications for the PBO Analysis Centers and the GAGE Geodetic Data Services program. These decisions will be driven by data obtained by the UNAVCO D&T group, with extensive and careful review and guidance provided by the GI Advisory Committee and the UNAVCO community.

3.1.1 Community and Continuously Observing Networks Plate Boundary Observatory GPS and Metpack Operations (WBS U1.1.7)

Continuous GPS (cGPS) is well suited to capture deformation occurring at time scales greater than a month, such as that associated with viscoelastic deformation following an earthquake, decadal estimates of strain accumulation and plate motion, and their spatial variations. The PBO Facility operates and maintains 1,112 cGPS stations across an area of over 10,000,000 km^2 (Figure 2.4-1), spanning Amchitka 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.

To support the goal of meeting sponsor performance standards for PBO, there are currently 10 full-time field engineers based out of four regional offices located across the Western US and Alaska. A primary metric is to ensure data return at or above the 85% requirement as set for PBO by NSF (Figure 3.1-1). Engineers visit each station every five years for scheduled battery and hardware maintenance and unscheduled maintenance is performed on a best-effort basis.

Regional offices in San Clemente, CA, Portland, OR, Anchorage, AK, and Boulder, CO will 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. Requested 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 ancillary scientific instrumentation can be added to further scientific goals of the UNAVCO community (Figure 3.1-2). Currently, 126 meteorological instruments (metpacks) are collocated 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 forecasting of weather phenomena.

Figure 3.1-2. PBO GPS station, Alaska. PBO is recognized as the highest standard for geodetic quality GPS installations. This, one of more than 100 remote PBO stations maintained in Alaska, will be maintained by the GAGE Facility. The rare sunny day belies the weather challenges when working in remote northern latitudes during the compressed summer field season. One step UNAVCO has taken is to install remote cameras at sites to provide local site condition information for helicopter operations.

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 seismic systems, will enable 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 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. Expertise in all facets of network installation and operation has made UNAVCO a primary resource for the construction of permanent geodetic networks, and we intend to maintain our global leadership in this critical area as part of the GAGE Facility. PBO engineers routinely provide support to PIs by coordinating and assisting with site access for vegetation surveys and snow depth experiments. With the merging of the current Cooperative Agreement's, field engineering expertise and deployment will be more effectively shared across the GI program. This will enhance efficiency and cross training for field engineering staff, promoting staff development for the benefit of the UNAVCO community.

Borehole Geophysics Operations (WBS U1.1.8)

Borehole strainmeters (Figure 3.1-3) 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 planning committees and include subduction zones (Cascadia), volcanic centers (Yellowstone, Mt. St. 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 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 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.

Figure 3.1-3. Borehole strainmeter installation, Cascadia. PBO undertook borehole strainmeter installations at an unprecedented scale during the MREFC installation phase of EarthScope PBO, although efforts in Asia are now even larger. Through rigorous project management, PBO overcame the technical challenges that were posed by this high-risk component of construction. The strainmeters are grouted in boreholes that are ~200m deep and collocated with other sensors like seismometers that perform very well in this environment. UNAVCO maintains the considerable technical expertise needed to install, operate, maintain, and analyze borehole geophysical sensor suites (strainmeters, seismometers, pressure sensors and associated surface meteorological measurements).

Under GAGE, UNAVCO will maintain the ability to install and operate borehole strainmeters and associated instrumentation, and to process, synthesize, and distribute these data. UNAVCO staff will 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.

GI Support for the NASA GGN (WBS U1.1.4)

The NASA Global GNSS Network (GGN), a subset of the ~230 stations that contribute to the ITRF, comprise a core of 61 GNSS stations that are operated by UNAVCO under direction from JPL. These provide a globally distributed GPS network to support NASA operations and commitments to the GGOS. Principal support provided by the GI program to GGN operations includes data flow monitoring, troubleshooting, station installation, maintenance, and operations. The GGN Project Element Manager at JPL provides technical direction for GI support of the GGN. Many of the GGN stations are currently GPS only, but the number of upgrades to full GNSS capability will continue through the GAGE award period. In addition, a growth at the rate of one to two new station installations per year is projected.

GGN data are foundational to the terrestrial reference frame and other products required by high-precision geodesists. These products include GPS satellite ephemerides, Earth rotation and orientation parameters, tracking station coordinates and velocities, satellite and receiver clock corrections, zenith tropospheric path delay estimates, and maps of the global ionosphere. These products support Earth science and other activities such as: improving and extending the International Terrestrial Reference Frame (ITRF) maintained by the International Earth Rotation and Reference Systems Service (IERS); monitoring gradual and rapid deformations of Earth; monitoring Earth rotation; monitoring the troposphere and ionosphere; determining orbits of scientific satellites such as GRACE gravity and sea surface altimetry satellites, planned SAR missions and Deep Space Network (DSN) communications equipment, and scientific, civil aviation, and commercial navigation applications. Continued commitment to these critical geodetic products along with the precise geodetic infrastructure needed to produce them was strongly endorsed by the NRC committee on *Precision Geodetic Infrastructure National Requirements for a Shared Resource* [NRC, 2010].

As NASA's primary service provider for operating the GGN, UNAVCO responds to 50 support instances per month in its daily monitoring and troubleshooting of the network. Significant repairs involve replacement of system components, system upgrades, or maintenance. UNAVCO purchases and maintains GPS receivers, communications equipment, computer hardware and local services to operate the core stations.

UNAVCO supports expansion of the GGN by installing new stations and participating in the coordination of multi-use of stations nominally supported for other projects, but that can also enhance the GGN. UNAVCO assembles, configures, tests and ships equipment and coordinates with local contacts to establish and operate new sites. Field engineering services are typically provided to new installations in order to assure use of best practices and training of local personnel in supporting operations. Driven by requirements to improve the global reference frame, we expect annual IGS planning to require additional co-location of GPS with VLBI and other space-based geodetic systems, particularly in the southern hemisphere where coverage of geodetic observations is less dense.

UNAVCO provides key sustaining engineering services to maintain the GGN and improve capabilities and performance as part of the GI program's D&T group. In the past, this support has involved improving or reducing the costs of data communications, upgrading GNSS receivers, evaluating monument or site stability issues to improve measurement precision, procedural improvements to improve efficiencies, or other activities to improve operations at specific stations. Planning for GAGE anticipates the need for continued GGN modernization for GNSS capability. Because of their role in defining reference frames, the technical issues of antenna evaluation, in situ phase–center calibrations at core stations to minimize multipath effects; site and monument stability; and site survey ties between collocated geodetic stations are particularly important. The GI D&T group will address these issues through controlled testing of equipment, specialized experiments, and contributing to best practices for upgrading to GNSS. Software and data handling enhancements will also be required.

Polar Networks: GNET & ANET - (WBS U1.1.5 and U1.1.6)

The Polar Earth Observing Network (POLENET) provides telemetered GPS and seismic data from autonomous stations at remote sites, spanning much of the Antarctic and Greenland ice sheets. The investigator-led POLENET is divided into the Antarctica Network (ANET) and the Greenland Network (GNET), with a complement of 79 core stations and 6 sister sites (LARISSA). Data from this network reveal changes in the mass balance of ice and lithosphere at a systems scale, and, taken with complementary data sets such as gravity, aid in the investigation of interactions of cryosphere, solid Earth, oceans and atmosphere [2.1.3; *Augustine et al.,* 2012; NRC, 2012; *Nyblade et al.*, 2012; *Wiens et al.*, 2010; *Zapol et al*., 2011]. Ice sheet volume change and associated rebound and change in velocity of outflow glaciers are critical constraints on models for long-term impact of climate change, and are best addressed with a combination of geodetic techniques, including GPS, InSAR, and satellite gravity. In GAGE, UNAVCO will continue to provide systems engineering, development and testing expertise for GPS and other sensor packages for deployment in the extreme polar environment, and field engineering support to various PI projects.

IRIS/UNAVCO Collaborations on Polar Efforts

IRIS and UNAVCO have supported a collaborative effort to design and develop remote polar stations, successfully completing an engineering effort (MRI funded by the NSF Office of Polar Programs) to engineer a standardized, scalable, remote power and communications system that allows for robust recording of seismic (IRIS) and geodetic (UNAVCO) data in the harsh Antarctic environment. The project developed cold hardened enclosures that integrate primary and secondary power systems with cold rated switching electronics, wind and cold hardened structures for solar panel mounts, and communications interface using Iridium satellites. These systems are capable of running continuously through the long periods of polar darkness and ensure robust operation and data return.

Using these designs, UNAVCO and IRIS participated in building POLENET, with collocated seismic and geodetic equipment throughout western Antarctica in a large, continental scale demonstration of new capabilities for these NSF facilities. Logistics coordination under the United States Antarctic Program (USAP) demonstrates how collaborative activities optimize resources during such a large experiment.

Both facilities participated in the Autonomous Polar Observing Systems workshop to share these collaborative designs with the broader science community and annually exchange ideas during the Polar Technology conferences. Recently, both facilities worked with the polar seismic and geodetic community to develop a Polar Facility Plan to help define the facility capabilities to meet the science needs in the polar regions.

IRIS and UNAVCO have a well established exchange technical information, design and logistics information to help improve scientific return while optimizing within the constraints of NSF OPP resources.

With NSF-MRI funding and in collaboration with IRIS and the community, UNAVCO developed a power and communications backbone capable of running a small instrumentation package through long periods of polar darkness, with the goal of limiting operations and maintenance site visit intervals to three years. These systems combine solar, wind and battery power with Iridium satellite communications to create a system of proven reliability for remote data collection in extreme environments.

ANET construction, led by PIs and supported by UNAVCO, installed 35 of 36 planned GPS sites, with an additional 6 sister sites installed along the Antarctic Peninsula by LARISSA. GNET now has its full complement of 44 GPS sites, supported by UNAVCO in an O&M role with scheduled visits to provide repair and incremental technology improvements. The PIs are planning for continued operations support and possible enhancements in coverage. Logistical and environmental conditions have driven different O&M strategies between GNET and ANET. GNET targets geographic sectors of approximately 17 sites per year, while ANET has broader maintenance efforts from each of its Antarctic installation hubs each year with an emphasis on older sites. The ANET was designed with longer maintenance intervals in areas with more difficult logistics.

Smaller focused cGPS networks have built on the design and success of POLENET. The most notable are WISSARD (Anandakrishnan), Recovery Lakes (Scambos) and Mount Erebus (Kyle) networks in Antarctica and GLISN (Simpson and Anderson) in Greenland. These total 12 additional telemetered GPS stations with ongoing UNAVCO O&M support planned under GAGE. UNAVCO also maintains several community cGPS stations at field stations: Summit Station, Barrow Arctic Science Consortium (BASC), Atqasuk field station, Toolik Lake field station in the Arctic and Palmer Station, McMurdo Station, and South Pole Station in the Antarctic. These sites will continue to be maintained under GAGE.

Other Community Networks: AfricaArray & COCONet

UNAVCO has built other multidisciplinary research networks, such as COCONet and AfricaArray, for the broader geosciences community. These projects demonstrate the UNAVCO expertise in logistics and diplomacy required for international fieldwork. When completed in 2014, the Continuously Operating Caribbean GPS Observational Network (COCONet) will produce high-quality, low-latency data and data products from 66 new and refurbished and 61 existing cGPS stations freely available to researchers, educators, students, and the private sector. These will be used by the US and international community to study solid earth processes, such as plate kinematics and dynamics, plate boundary interaction and deformation, and earthquake cycles. COCONet also serves atmospheric science objectives by providing more precise estimates of tropospheric water vapor and enabling better forecast of the dynamics of airborne moisture associated with the annual Caribbean hurricane cycle. The installation phase of COCONet is four years and the operations and maintenance component of the project is scheduled to continue through September 2015.

UNAVCO also supports AfricaArray, an 8-year-old initiative to promote, in the full spirit of the New Partnership for Africa's Development (NEPAD), coupled training and research programs for building and maintaining a geoscientific workforce for Africa. Under a more recent community-driven MRI award, UNAVCO engineers have installed six continuously operating GPS stations in Botswana, Namibia, Zambia, and Malawi while training international AfricaArray collaborators from the University of Witwatersrand and the Council for Geoscience in South Africa for the installation of 19 additional GPS sites across the African continent. Like COCONet, AfricaArray will provide continuous GPS and meteorological observations, and also includes seismic instruments, to address first-order questions of plate boundary tectonics and the rifting cycle, the hydrological cycle, and climate change in Africa.

3.1.2 EAR PI Project Support (WBS U1.1.3)

Campaign and Longer-Term GPS Deployments

PI project support was previously funded as part of the UNAVCO Facility Cooperative Agreement. The services are now part of the GI program in GAGE. Four components make up the PI Project support group: 1) Project planning; 2) cGPS network O&M; 3) Management of UNAVCO campaign pool instruments for PI projects; and 4) Repair of UNAVCO and community GPS instruments purchased under special agreement with various equipment manufacturers.

Ongoing demand for acquiring, distributing, and archiving high-precision geodetic data will be met, supported by activities of the GAGE Facility. UNAVCO provides comprehensive project technical support services to investigators using GPS, TLS, InSAR, and airborne LIDAR and geochronology (Figure 3.1-4). These services include equipment loan, testing, configuration, integration, new equipment design for field deployments, and technical training for campaign and permanent station deployments (Figure 3.1-5).

Specific services that UNAVCO staff provide to funded NSF and NASA PIs, and other investigators on a resource-available basis include: project management; field engineering and technical support services to plan and execute surveys and permanent station installations; network engineering services for permanent network operations; network maintenance; data flow monitoring and troubleshooting; equipment testing services to evaluate and improve performance; systems integration and software development services for developing advanced systems; technical support; consultation and training for researchers in applying geodetic technologies;

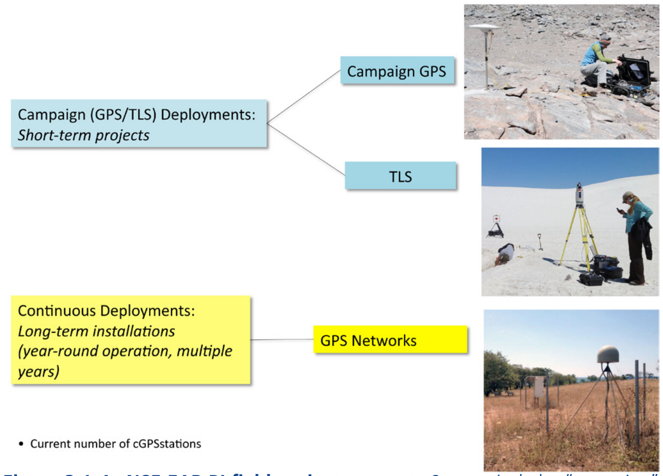


Figure 3.1-4. NSF-EAR PI field project support. Support includes "campaign" or short-term deployments of GPS or TLS in survey mode for days or weeks and "continuous" or long-term operations where instruments are deployed for months to years, typically on a permanent monument. Depicted from top to bottom: (1) a typical GPS campaign setup with portable receiver, power system and Pelican case (Atacama Desert, Chili; PI Matt Pritchard, Cornell University); (2) operation of one of UNAVCO's Reigl TLS scanners with optical targets deployed in conjunction with GPS for reference frame at White Sands, New Mexico; PI Ryan Ewing, University of Alabama; (3) a typical cGPS station in Costa Rica with power system, satellite or radio communications, and permanent drilled-braced monument at Nicoya Peninsula, Costa Rica; PI Tim Dixon, University of South Florida.

and logistics services for worldwide deployments, including property tracking and management, import/export, and shipping; and data management and archiving services.

UNAVCO manages a community equipment pool of 450 GPS and GNSS receivers and ancillary equipment (Figure 3.1-6). UNAVCO outfits, maintains, repairs, and supports these systems for PI projects. The pool consists of a variety of receiver models configured for use in campaigns and permanent stations. Most of these are newest-generation models that were purchased within the last few years. Though these systems

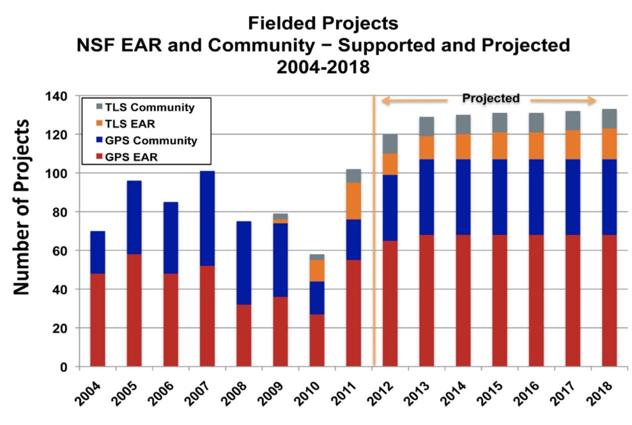


Figure 3.1-5. NSF-EAR PI projects fielded. Projects fielded each year since 2004. TLS support began in 2009 with one instrument and grew as the scanner pool grew to six instruments. Based upon past trends it is anticipated that approximately 80 GPS and/or TLS EAR-funded projects will be supported each year. When UNAVCO community members request support for projects that are not NSF-funded (e.g., startup funds or other agencies), GI provides that support on a resource-available basis. About 50 such projects are shown here.

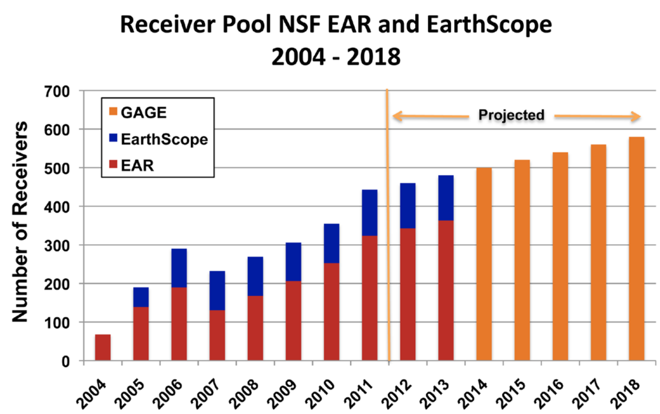


Figure 3.1-6. GPS Pool resources for NSF-EAR investigators. The UNAVCO GPS pool for NSF-EAR investigators for short-term and continuous applications has continued to grow steadily, despite a dip in 2007 that resulted from the retirement of the Trimble 4000 receivers. In 2014, the PBO GPS campaign pool will merge with the EAR pool under GAGE; the resulting pool is projected to grow at about 20 receivers each year to support new and ongoing PI projects.

are often assigned for long-term continuous-station use, they are tracked by UNAVCO as pool equipment, as they are government property owned by NSF and may be recalled for future community use with guidance from the sponsor. Many geodetic campaigns are now deployed independently of UNAVCO using both PI and UNAVCO equipment, with training and technical support commonly provided by UNAVCO.

The UNAVCO Facility currently provides O&M support to 561 continuously operating GPS stations (Figure 3.1-7). The O&M support includes data downloading, state of health monitoring and reporting, resolving communications and equipment issues, shipping replacement equipment, and working with PIs and local contacts to resolve problems.

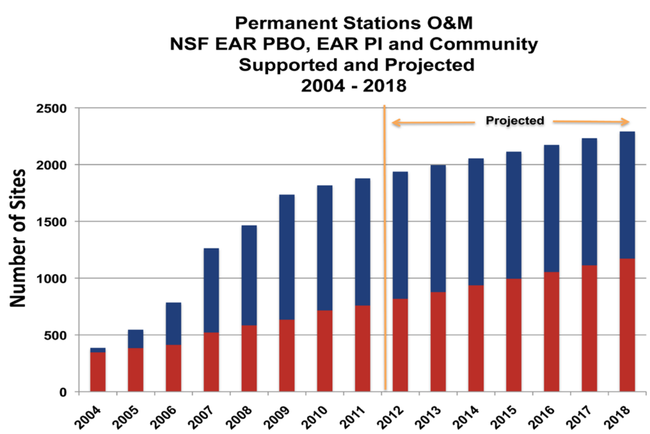


Figure 3.1-7. Continuous GPS stations for NSF-EAR investigators. Continuous GPS has grown rapidly as an investigator-preferred mode of operation for many solid Earth applications, creating time series that reveal a wealth of signals that operate over different time scales from epoch-by-epoch for earthquakes to annual and decadal for hydrogeodesy, against secular background motion within the ITRF. The number of stations that receive some form of support under GAGE is expected to continue through 2018. This preference for continuous observations has freed UNAVCO engineering effort to meet the growth in demand for TLS field support.

Most funding for PI cGPS networks comes from independent NSF and NASA projects. GAGE will continue to support these efforts with 3.3 FTE field engineers. No funds are requested as part of this proposal to upgrade or replace GPS instruments currently deployed or owned by PIs. UNAVCO plans to reevaluate the GNSS vendor selection process in the near future to ensure that PIs, UNAVCO, and the sponsors continue to benefit from community leverage in specifying and acquiring geodetic-quality systems in the evolving GNSS environment.

As community demand for long-term cGPS deployments for PI projects has increased, so has the need for centralized network engineering, installation, operation and maintenance services. Sustaining the engineering functions to improve power and telemetry systems will continue to grow in importance as we meet requirements for networked GPS stations in ever more remote locations.

Another important priority for the GI program during GAGE is to continue to provide the best available GPS equipment and a high level of support to researchers. As a result of very favorable pricing negotiated by UNAVCO for PBO, many receivers have been purchased by the community, Facility, and related projects over the last nine years. The favorable pricing relies on UNAVCO's investment in the equipment depot, where warrantee repair work is performed. The UNAVCO community has purchased an estimated 3500 receivers through the twice-yearly UNAVCO community purchase program, which includes a multi-year warranty with the stipulation that the repairs are handled by UNAVCO. This arrangement has brought the costs down for equipment purchases and enables equipment to be used for longer periods of time.

In planning for 2013 – 2018, the Engineers Support group will continue to modernize the UNAVCO community equipment pool. In each of the five years, two GNSS-capable state-of-the-art systems (currently $8k per unit, 1 each for NSF and NASA), and ten GPS-only receivers and zephyr or similar antenna systems (pending vendor selection, and estimated to continue to be available for less than $5,000) will be acquired to renew the pool. If instrument costs are significantly below current estimates we will work with UNAVCO governance to prioritize unmet needs.

Polar Services Campaign GPS

Campaign GPS support remains a large part of the geodetic support offered to the polar community (Figure 3.1-8). A range of precision GPS instrumentation is made available to PI projects, along with training, project planning, field support, system fabrication, technical consultation, data processing, and data archiving. In addition, Polar Services within GI maintains a satellite facility at McMurdo Station, Antarctica during the austral summer research season. The number of polar campaign GPS projects has remained fairly constant at about 30 per year.

The average number of receivers deployed per project has grown, and about 150 pool receivers are currently required each season (Figure 3.1-8). Various equipment types are currently in use, including Trimble R7/5700 series, NetRS and NetR9 receivers. As part of GAGE, we have requested modest funding to purchase 6 new Trimble R7 instrument packages specifically designed for polar deployment at an estimated cost of $16K per unit in each of the five years. In recent years, there has been a shift in the complexity of campaign projects toward larger networks of temporary GPS systems designed to collect uninterrupted data for an entire summer season. UNAVCO has met this demand by designing turnkey GPS systems with solar power, directed at the more common field scenarios. This has increased reliability and has decreased the engineering effort on a per station basis creating additional efficiency through expanded capacity, supporting a growing number of projects (Figure 3.1-9).

In addition to campaign GPS support, UNAVCO maintains continuously operating remote GPS stations with autonomous power systems in excess of five watts, which make use of the POLENET design, for use in long-term data collection (Figure 3.1-10) on PI projects. Use of these systems often requires modest amounts of custom project-specific engineering or integration. GAGE will support approximately 9 projects per year, with an average of 4 systems per project. About 50 receivers from the 320 OPP pool are currently required to support these intermediate-temporal scale projects (normally, 1-3 years long). These efforts will continue to be

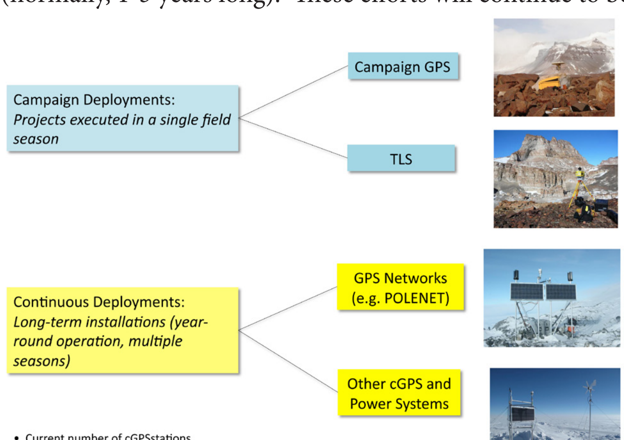


Figure 3.1-8. NSF-OPP PI field project support. UNAVCO's field support for OPP-funded PI projects, as with EAR, encompasses campaign and continuous deployments. In addition to the primary POLENET and related networks, support for other cGPS projects and non-GPS projects requiring use of UNAVCO developed power systems that can be deployed by PIs themselves. Representative technologies, from top to bottom include: (1) campaign measurements in the Beacon Valley, Antarctica; PI Ron Sletten, University of Washington, (2) TLS at an archeological site in the Shetland Islands, Scotland, part of a study of severe climate transformations; PI Gerald Bigelow, Bates College; (3) deformation measurements of Mt. Erebus, Antarctica; Phil Kyle, New Mexico Tech, (4) GPS above subglacial lakes at Recovery Lakes, Antarctica; PI Ted Scambos, University of Colorado.

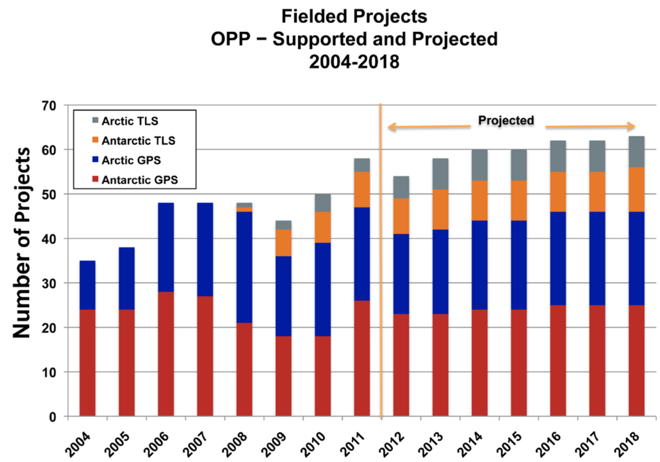


Figure 3.1-9. NSF-OPP PI projects fielded. Projects fielded each year since 2004, with TLS support beginning in 2008 with one OPP-funded instrument augmented in 2009-2010 with EAR-funding. A modest level of growth in project support is expected through 2018, reflecting self-limiting logistics capacity on the ice, limited TLS resources, and anticipated flat funding for PI projects.

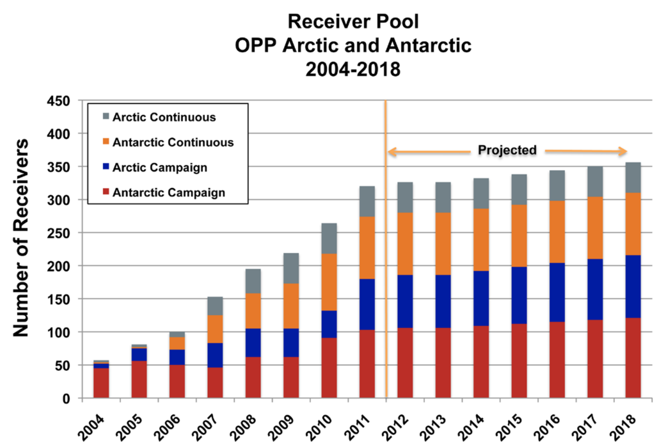


Figure 3.1-10. GPS receivers for NSF-OPP investigators. Growth of the UNAVCO GPS receiver pool for NSF-OPP investigators is expected to be modest through 2018, reflecting restrained demand based on the limits of logistics capacity on the ice. This pool reflects the UNAVCO-titled OPP-funded receivers that are used in a mix of campaign and longer-term deployments.

Terrestrial Laser Scanning (TLS) Projects

Earth science investigations increasingly require accurate three-dimensional representation of the Earth surface at a centimeter scale to quantitatively characterize and model complex processes. Since 2007, UNAVCO has supported PI's with state-of-the-art TLS equipment for campaign surveys; field engineering, and data processing services. TLS can generate high-resolution 3D maps and images of surfaces and objects over scales of meters to kilometers with sub-centimeter precision. TLS instruments are portable, relatively easy to operate, and have been used successfully to support a wide range of geoscience investigations including detailed mapping of fault scarps, geologic outcrops, lava lakes, dikes, fissures, glaciers, hill slopes, and fluvial systems. Repeated TLS measurements support surface change detection through time, making TLS even more valuable for transformative

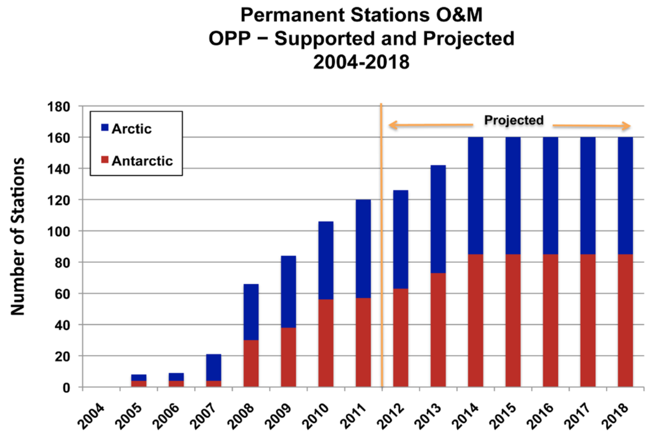


Figure 3.1-11. Continuous GPS sites for NSF-OPP investigators. UNAVCO provides support of continuous GPS observations at a variety of levels for OPP investigators, with a mix of investigator-owned and UNAVCO receivers. The number of stations that receive some form of support under GAGE is expected to continue to increase through 2014 based on projects currently in the pipeline and then level off through 2018.

science investigations. Development of new processes to propel TLS from an imaging tool to a geodetic change detection tool is an important priority within the GI and GDS programs under GAGE.

UNAVCO support for TLS was instituted through collaboration with several universities to establish the NSF-funded Interdisciplinary Alliance for Digital Field Data Acquisition and Exploration (INTERFACE) project; as a result, the TLS instrument pool and data collection expertise is now based at UNAVCO. UNAVCO acquired 6 additional TLS systems between 2007 and 2010 through a combination of two NSF MRI awards and a supplement to the Facility Cooperative Agreement. TLS resources are shared across the GI program. In order to support a range of applications, the instrument pool consists of different models with a spectrum of capabilities for range, sample rate, laser wavelength, laser spot size, physical size, weight, and power consumption.

The TLS instrument pool was used to support 87 field deployments between October 2007 and September 2011, with rapid growth during this period (Figure 3.1-12). We anticipate that the number of field deployments per year will continue to increase through 2018, but at a decreased rate of growth due to limiting factors including: 1) number of available scanners; 2) number of trained TLS operators; and 3) PI research funding. UNAVCO engineers provide PIs with TLS survey planning support, equipment preparation, field engineering, and data post-processing into common exchange formats. The PI training provided by UNAVCO staff in formal workshops and informal project settings helps to expand the TLS community.

The Polar Services group is currently serving an average of 12-14 TLS projects per year, with steady growth in demand expected in the coming years. Scheduling conflicts are emerging with growing demand. The original Optech 36D used by Polar Services reached obsolescence and is no longer in service. The GI Polar Services group will seek resources outside of this proposal to acquire new ground-based LiDAR units to continue the current level of support while meeting potential growth in demand and reducing the number of scheduling conflicts.

Enhanced instrument accessibility and capability, coupled with efficient workflows and unprecedented science applications, have catalyzed rapid community development and diversification. In response to this increasing level of community interest and the rapid evolution of technology and data availability, UNAVCO hosted an NSF-funded workshop in October 2011 that brought together 80 participants representing a spectrum of research fields with the objective of outlining a strategic vision for the future of terrestrial geodetic imaging as applied to a broad range of research activities at all levels of the community [*Phillips et al., 2012*]. UNAVCO staff and INTERFACE researchers collaborated with other NSF-supported facilities including OpenTopography and the National Center for Airborne Laser Mapping (NCALM), federal agencies including the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) and the USGS, and other universities to plan the workshop.

TLS is one of the most dynamic parts of the UNAVCO portfolio, and it will play a key role in the future growth and impact of the GAGE Facility. The recommendations contained in the TLS community workshop report provide a context and focus for UNAVCO's ongoing support of community

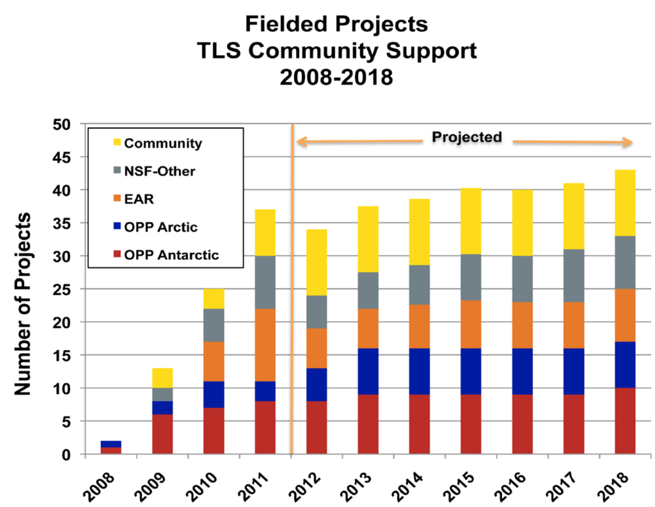


Figure 3.1-12. TLS projects fielded. TLS project support metrics show rapid growth from years 2008 – 2011, leveling off in 2012 because the TLS instruments are fully scheduled. The projected dip for 2012 reflects transitions in the pool, as the earliest instrument is now obsolete. Modest projected growth is expected to continue until 2018, as the instrument pool is renewed through ancillary proposals. In order to maintain a high level of support to the community, UNAVCO will continue to cross train engineers to provide high-level TLS field support, enhance hardware and software resources for TLS data management, processing, analysis and archiving, and expand services such as short courses and introducing TLS to undergraduate geology field camps.

TLS instrumentation and enhanced data products and training activities over the five-year duration of the GAGE Facility.

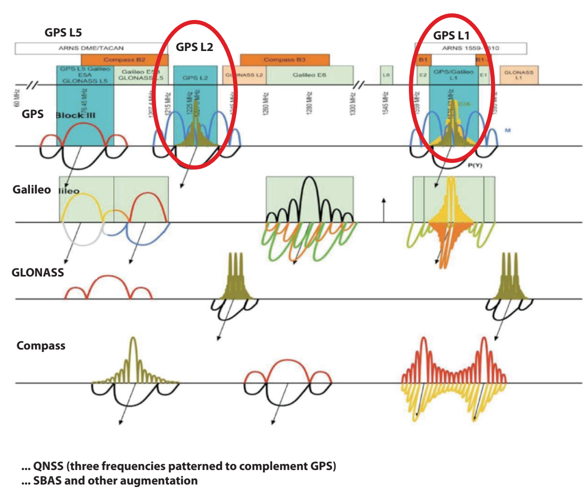
3.1.3 GI Program Development and Testing

Critical technologies used by all GAGE-supported projects, such as GNSS receivers and antennas, data communications, and power systems are rapidly evolving. Meeting project requirements for optimal system design, performance, and financial constraints requires dedicated expertise and coordination, both within the GAGE Facility, and with sponsors, community members, and hardware manufacturers. UNAVCO's recent D&T effort has been instrumental in the ongoing success of community projects of all kinds. D&T has analyzed power systems, data communications devices, and next-generation GNSS systems from different manufacturers, to evaluate features and to examine system behavior during earthquakes. Analysis of monument stability will continue during the next five years using both dedicated staff and contributions from others within the GI and GDS programs at UNAVCO. Close collaboration with the GDS on the ongoing development of teqc software to integrate new GNSS constellation capabilities is an important ongoing focus for the D&T staff.

The role of D&T becomes even more critical during GAGE 2013 – 2018, as new GNSS constellations become operational and require a new generation of antenna – receiver systems that are orders of magnitude more complex than current models. Increased reliance on real-time and high-rate data requires increased bandwidth and robust, reliable, low-latency data communications systems. Expansion of polar services requires development of robust systems better able to withstand harsh environmental conditions with lower power draw in order to deliver uninterrupted data year-round. Recent large earthquakes in Japan and Chile made clear the need to ensure that GPS/GNSS systems function properly during strong shaking and have uninterrupted data communications. And finally, cost effective data communications systems must be available to projects anywhere in the globe, with an eye to seafloor geodesy applications.

GI D&T staff members provide the specifications for community user requirements and the results of testing to GPS/GNSS manufacturers. The GI program plans to renew the pool with an escalating annual number of state-of-the-art GNSS-capable geodetic systems (51 in 2013, and growing to 114 by 2018) and an additional 6 Trimble R7 for Polar Services in each year of this five year GAGE Facility proposal. The D&T group will be primarily responsible for providing experimental data and analysis to guide UNAVCO staff, the

GPS Modernization in a Changing GNSS Environment



The scientific community has developed high accuracy satellite geodetic techniques during the past 25 years of GPS operations. Positioning precision has improved from centimeters to millimeters as tracking networks, hardware, and orbit modeling methods were perfected. The current commissioning of new Global Navigation Satellite Systems (GNSS), expected to continue over the next 5 to 10 years, includes a number of multi-frequency, constellations developed by other parties of the international community, bringing both opportunities for continued improvement in positioning precision and navigation and also technical challenges for implementation. For navigation, GNSS has the advantages of increased satellite coverage in urban and natural canyons and improved accuracy for mass market and safety-of-life applications. For science applications requiring mm-level precision, the addition of new codes and a third GPS frequency (L5) with the deployment of new GNSS constellations will enhance ambiguity resolution at global and regional scales over shorter periods of time. This will facilitate wide area precision real-time satellite orbit/clock determinations needed for kinematic applications. GPS modernization and the onset of GNSS technologies bring significant challenges, however. The signal structure, diagramed in this figure, becomes considerably more complex moving from the traditional dual frequency GPS signals of C/A on the L1 carrier and P(Y) on both the L1 and L2 carriers. This expansion is accompanied by the need for new standard formats for files and streams, development of new QC parameters, significant modifications to teqc, larger data volumes to transmit and store, modification of processing software (e.g. GIPSY, GAMIT) to handle GNSS, implementation of global GNSS tracking infrastructure, determination of GNSS antenna phase-center variations, and extensive upgrade of existing GPS infrastructure to GNSS capability. Activities of the GAGE Facility will include assessment of the impact of GNSS by the GI Development and Testing program. In addition, teqc and the GDS data archiving systems will be modified to handle GNSS signals, while steps will be taken to modernize the PBO and pool receivers. UNAVCO staff involvement in the IGS as part of GAGE will further global cooperation to implement GNSS tracking data and products as well as critically evaluate their contribution to global geodesy.

GI Advisory Committee, and community investigators to evaluate manufacturers, specific instruments, and features (GPS-only vs. GNSS-enabled) to be included in planned upgrades to the PI instrument pool and the PBO network.

The D&T group develops and supports the widely accessed Online Knowledge Base (available on the UNAVCO website) as an ongoing activity, to be continued as part of the GAGE Facility. It includes results, up-to-date firmware and software distribution, as well as UNAVCO engineering processes and best practices with community input and technical expertise. This resource is actively accessed by practitioners affiliated with Member and Associate Member institutions around the world. Results of the D&T group's efforts have been published in professional journals [*e.g., Wang et al.*, 2011] and presented at conferences such as IUGG and AGU.

3.2 GEODETIC DATA SERVICES PROGRAM (WBS U1.2)

Geodetic Data Services (GDS) program, with its subaward partners, provides a comprehensive suite of services including sensor network data operations, data products and services, data management and archiving, and advanced cyberinfrastructure (Figure 3.2-1). Like GI, GDS is a newly configured program within UNAVCO, optimized to enable access to high-precision geodetic data, products, and metadata for use by researchers, and also adapted for accessibility and interpretation for educators, policymakers, and the public. The needs of the geodesy PI community focus

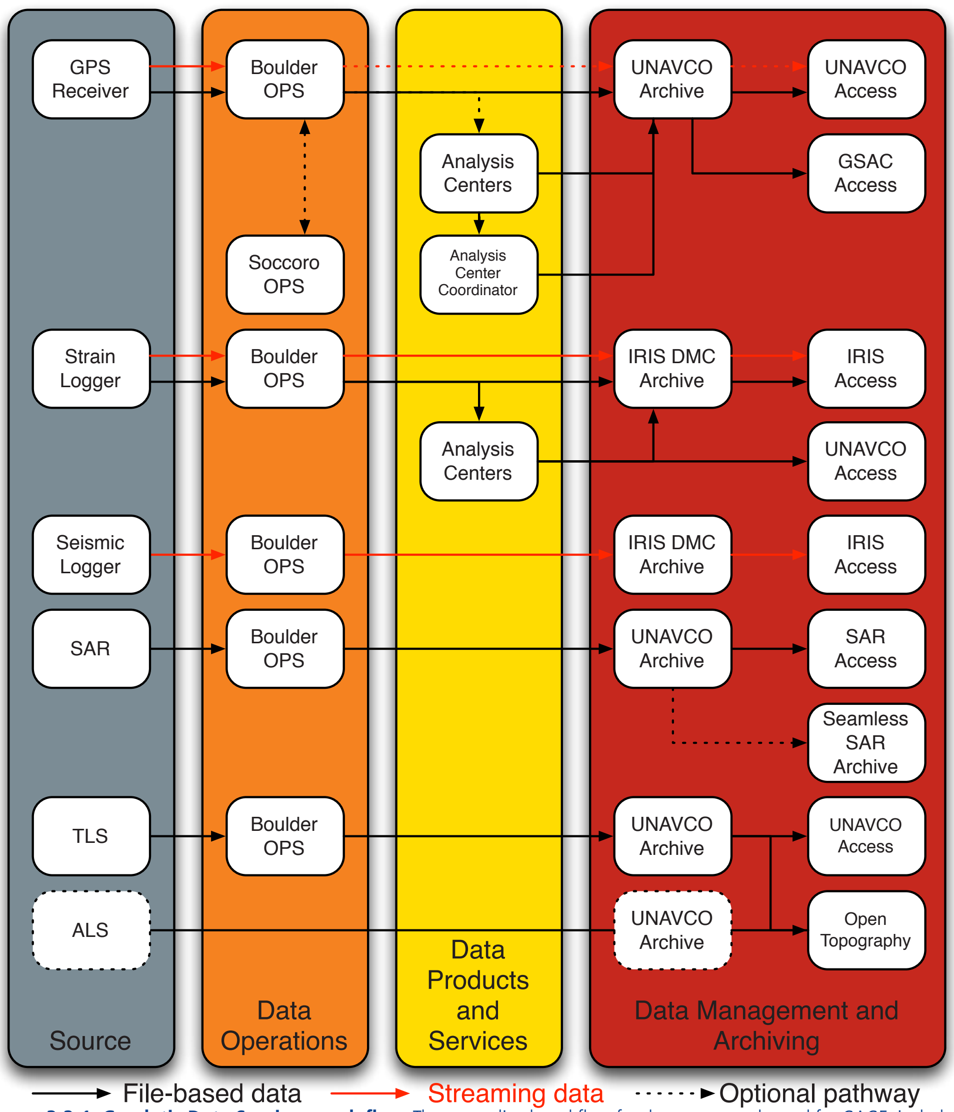


Figure 3.2-1. Geodetic Data Services work flow. The generalized workflow for data systems planned for GAGE, includes roles of subawardees and partners. The GAGE Facility will develop internal consistency and integration of data work flow to maintain and enhance its core services, to develop a new data system for TLS, to provide improved access to community data held at the facility for data users and external partners, and to develop mechanisms to acquire, track, manage and disseminate products and related provenance metadata that will enable the broadest possible use. Cyberinfrastructure developments enhance capabilities for data handling, distribution and visualization both within and external to GAGE.

enhancements for GDS, with major accomplishments under the current award. Examples include a powerful new Data Archive Interface for discovery of GPS data, web services modernization of the underlying seamless archive with key U.S. partners, and the recent rollout of a new web interface for accessing and ordering SAR data, optimized for a single point of entry to a now coordinated array of holdings with improvements to ease of data access. Close coordination of efforts formerly distributed between UNAVCO Facility and PBO programs supports better utilization of talent and enhanced effectiveness in meeting community needs.

Through community planning, governance, management review, and sponsor coordination, the groundwork has been laid to advance a number of new initiatives during the initial GAGE period. NSF's EarthCube planning process focuses on bringing the full power of cyberinfrastructure to geosciences for data discovery, access, and interaction. GDS expertise, accomplishments, and partnerships with organizations like OpenTopography and IRIS position GAGE well for these opportunities, with an increased attention to building international collaborations for data exchange.

The GDS program has significant new and newly aligned expertise in its Geodetic Imaging group (jointly managed with the GI program), with complementary depth in the Data Products group and the Data Center (for staff credentials, see Table 4.3, Budget Plan). GDS is now poised to advance TLS data products, archiving, and accessibility towards the same high standard as for GPS. TLS is a powerful tool for geomorphology and subdisciplines that are new to geodesy; this will bring new visibility for GAGE and new value to new investigators.

A number of projects within GDS will support the expansion of real-time observations in the PBO, both for its GPS and borehole geophysics networks, with enhancements to data flow operations, new standards and capacity for archiving, and support for development of data products specified by community need and prioritized through governance.

These initiatives build on the strengths of the data systems and a capable GDS staff. Current holdings exceed 70 TB of data from GPS, laser scanning, SAR, and borehole geophysical instruments (tiltmeters, strainmeters, seismometers and environmental sensors) and is expected to grow to 200 TB over the next five years (Figure 3.2-2). The GDS program vision focuses on building capacity and functionality for meeting the data and cyberinfrastructure needs of the geodetic community and the broader geosciences community. This will be achieved through contributions by the community and the GDS program for development of expanded data preprocessing, formatting, handling and visualization tools, workflow tools, migration of storage, and software to cloud-based services where appropriate and economical, continuing development of integrated web services to drive expanded accessibility for within- and cross-domain access, wrapping well-vetted community-contributed codes within a web services framework, improved EarthScope cyberinfrastructure; and strengthened data life cycle support. Tools and services will be built as modular components in order to drive flexibility and interoperability with similar efforts at other institutions.

GPS data and products are a major component of GDS data management. There are currently data from over 12,000 globally distributed GPS monuments in the UNAVCO GPS archive, with 2,376 continuous GPS sites (1,112 of these from the PBO network) and 932 GPS campaign surveys (Figure 3-1). The GPS data are stored on enterprise-class RAID systems, and on multiple tape backups; a redundant offsite data center is maintained in Socorro, New Mexico. The data from 75 PBO borehole sites (strainmeters and seismometers) and 5 long-baseline laser strainmeters are archived at the Northern California Earthquake Data Center (NCEDC) and the IRIS Data Management Center (DMC). UNAVCO's SAR archive, with its WInSAR and EarthScope collections, is accessed by the community using recently improved data tools developed by UNAVCO. With separate funding, UNAVCO and its partners are also developing web services-based seamless access tools for airborne and space LiDAR and radar data. These technologies form the groundwork for the planned TLS archive. Support for GPS data processing software, PBO data processing and analysis, and additional data collection, is provided through subawards to university partners. In its data management and archiving practices, the GDS program proactively works toward implementing the best practices for trustworthy digital repositories of the Open Archival Information System reference model [CCSDS, 2012].

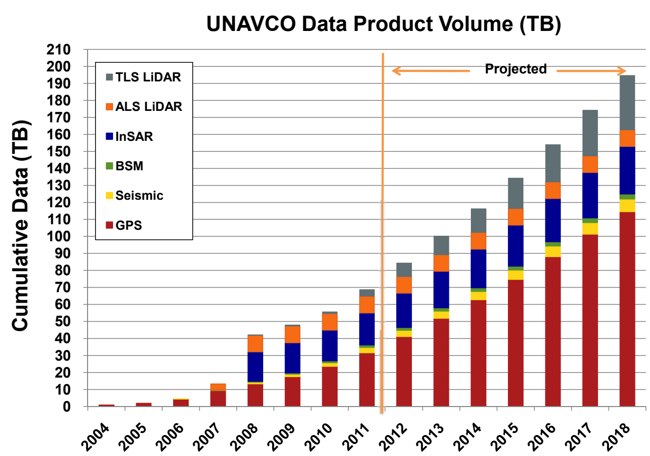


Figure 3.2-2. Cumulative data archived since 2004 with projections through 2018. The collection of GPS data volume shows steady increase from growing networks and higher rate data sampling needed for new applications. The SAR and LiDAR (ALS) collections had their largest growth during GeoEarthScope data acquisitions. The SAR holdings have continued to grow modestly. UNAVCO's SAR archives and the nascent TLS archive will continue to add data as part of the activities of the GAGE Facility. Strainmeter (BSM) and seismic data are also acquired at a steady rate.

The GDS staff brings geoscience knowledge, as well as expertise in data management, software engineering, database programming, database administration and systems administration. The GDS program has developed a highly scalable system for archiving geodetic data and for community access, featuring "teqc", a GPS data translator, editor, and quality control tool used extensively by the research and surveying communities. In addition, GDS staff develops web interfaces, application programming interfaces (APIs), and web services for on-line database access for metadata and data search and access, along with interactive map tools that support PI research and Education and Community Engagement activities.

To ensure the maximum utilization of the available data and products requires meeting the needs of a community of increasingly interdisciplinary scientists with widely varying levels of domain expertise in geodesy. UNAVCO also actively participates in the NSF EarthCube initiative, the NSF/European Union "COOPeration between Europe and US" (COOPEUS) initiative, NASA's *Earth Science Data Systems Working Groups*, and several working groups of the IGS. These activities provide avenues for the GAGE Facility to help lead the development and enhancement of data systems and associated cyberinfrastructure and provide context to ensure that GAGE's developments meet evolving community standards and best practices. UNAVCO has had a longstanding partnership with IRIS on several fronts from archiving of products, to offsite facilities, to cyberifrastructure collaborations.

Community guidance for data services is provided through the newly constituted, 2013 Geodetic Data Services Advisory Committee and the EarthScope Steering Committee. Guidance for the GDS program also is provided by the UNAVCO Strategic Plan and the 2012 EarthScope Cyberinfrastructure Preliminary Strategic Plan (ESCI). The ESCI articulates the current state of EarthScope cyberinfrastructure, and the facilities that comprise it at UNAVCO and IRIS, as well as what is needed to achieve EarthScope science goals. Users of GDS services provide additional input through solicited online surveys.

3.2.1 Data Operations and Management (WBS U1.2.3)

Network Data Flow

GDS staff and GAGE subawardees will provide data operations and management for a wide array of data and products, ensuring that high-quality data products are available to the user (Table 3.2-c). GAGE will build upon the extensive infrastructure that has been developed to support the collection of raw data, station metadata, quality control information and station state-of-health. GDS supports data and metadata flow for 1,112 PBO and an additional 1,260 GPS stations operated by NSF-funded principal investigators, the USGS, NASA's GGN and the IGS. GAGE will provide a backup capability for downloading GPS ground station data for NASA mission support. Data handling capabilities to retrieve data from specified GGN stations are maintained at UNAVCO in case of failure of primary systems at JPL.

Most of the raw (Level 0) GPS data products are generated by UNAVCO-maintained networks including the PBO and other large but regionally focused networks. Most GPS stations in UNAVCO-operated networks currently record raw data at a "standard rate" of once every 15 seconds and a "high rate" of 1 sample per second. Raw data flow to UNAVCO's facility in Boulder by direct internet, cellular modem, radio modem, and satellite transmission. Once in the Data Center

Synergies between UNAVCO and IRIS Data Centers

Both IRIS and UNAVCO operate full service data centers to manage geodetic and seismological time series data, and a wide array of geodetic and seismic imaging products. As we enter into the next five-year cooperative agreements between each organization and NSF we will continue to work together toward service integration between the data centers. IRIS and UNAVCO are involved in two significant projects where synergies between the data centers will continue to be enhanced.

- With funding from the European Commission and from NSF, the COOPEUS project is an effort to coordinate data activities in five project pairs between Europe and the United States. Of specific interest are the coordination of data management between the European Plate Observing System (EPOS) and EarthScope. UNAVCO's focus will be on vertical integration of web service techniques within geodetic data centers in the US and Europe while IRIS will work with US and European Data centers toward vertical integration of web services within seismology.
- NSF's EarthCube is a coordinated GEO- and OCI-sponsored initiative to create a data and knowledge management system in support of highly data-driven research across the geosciences in the 21st century. IRIS and UNAVCO are partners in the Service Based Integration Platform for EarthCube (SBIP-E). UNAVCO and IRIS are actively working on horizontal integrations between geodetic and seismic data, as well as data sets from other geoscience domains, as part of EarthCube.

In addition to COOPEUS and EarthCube, IRIS and UNAVCO data centers are collaborating to make high rate displacement time series derived form geodetic observations available to the seismological community. Over the course of this 5-year proposal the UNAVCO Data Center will provide the IRIS DMC with displacementgrams for distribution to the seismological community in formats and via services supported at the IRIS DMC.

Table 3.2-1. Geodetic Data Prodcuts for GAGE.

INSTRUMENT	LEVEL	PRODUCT	FORMAT	PRODUCT GENERATION FREQUENCY	PRODUCER/ DISTRIBUTOR
Global Positioning System (GPS) Receiver	0	Standard-Rate (15-sec) raw data	T00	Hourly, sub-daily or daily	UNAVCO/ UNAVCO
		High-Rate (1-sps, 5-sps) raw data	T00	Hourly (upon request)	UNAVCO/ UNAVCO
		Real-Time raw data	BINEX, RTCM	Real-time	UNAVCO/ UNAVCO
		Community continuous raw data	Varies	Hourly, sub-daily or daily	Community PI's/UNAVCO
		Survey-mode raw data	Varies	Varies	UNAVCO, Community PI's/UNAVCO
		Metadata	Database	Varies	UNAVCO
	1	Standard-Rate quality checked data	RINEX	Daily	UNAVCO/UNAVCO
		High-Rate quality checked data	RINEX	Varies	UNAVCO/UNAVCO
		Real-Time quality checked data	RINEX	Daily, varies	UNAVCO/UNAVCO
		Community continuous quality checked data	RINEX	Daily, varies	UNAVCO/UNAVCO
		Survey-mode (campaign) quality checked data	RINEX	Daily, varies	UNAVCO/UNAVCO
	2	Station position solutions	SINEX	Daily, 15-days, 3-months	MIT*, CWU*, NMT*/UNAVCO
		Station position time series	ASCII	Daily, 15-days, 3-months	MIT*, CWU*, NMT*/UNAVCO
		Station position velocity estimates	ASCII	Varies	MIT*, CWU*, NMT*/UNAVCO
		Station position offsets for significant events (e.g. coseismic)	ASCII	Varies	MIT*, CWU*, NMT*/UNAVCO
		Station position quality assurance parameters	ASCII	Varies	UNR (Blewitt)/UNAVCO
		Tropospheric Delay Parameters	ASCH	Daily	MIT*, CWU*, NMT*/UNAVCO
Borehole Strainmeter (BSM)	0	20-sps, 1-sps, 10-min raw strain series	Bottle, SEED	Hourly, daily	UNAVCO/DMC*, NCEDC*
		30 min, 1 hour instrument health series	Bottle, SEED	Hourly, daily	UNAVCO/DMC*, NCEDC*
		1-sps, 30-min environmental series	Bottle, SEED	Hourly, daily	UNAVCO/DMC*, NCEDC*
		Borehole geophysical logs, samples	Varies	During installation	UNAVCO/UNAVCO
		Station metadata	Database	Varies	UNAVCO
	2	2a Corrected and scaled strain and environmental series	XML, ASCII	Daily, bi-weekly	UNAVCO/DMC*, NCEDC*, UNAVCO
		2b Corrected and scaled strain and environmental series	XML, ASCII	4-months	UNAVCO/DMC*, NCEDC*, UNAVCO
		Station notebooks	PDF	Varies	UNAVCO
Laser Strainmeter (LSM)	0	1-sps raw strain, instrument health, and environmental series	Ice-9, SEED	Daily	UCSD*/DMC*, NCEDC*
		Station metadata	Database	Varies	Subawardee (UCSD)
	2	Corrected and scaled strain and environmental series	XML, ASCII	Bi-weekly, 4-months	UCSD*/DMC*, NCEDC*, UNAVCO
		Station notebooks	ASCII	Varies	Subawardee (UCSD)
Borehole Seismometer	0	100-sps raw data	SEED	Streaming	UNAVCO/DMC*
		200-sps raw data	SEED	Streaming (some stations)	UNAVCO/DMC*
		Seismic Metadata	DATALESS SEED	Varies	UNAVCO
Pore Pressure Meter	0	1 sps raw	SEED, ASCII	Streaming, Daily	UNAVCO/DMC*, UNAVCO
Tiltmeter	0	1-sps raw	ASCII	Streaming	UNAVCO/UNAVCO
	0	1-min raw	ASCII	Daily	UNAVCO/UNAVCO
Terrestrial Laser Scanning (TLS)	0	Scanner data (raw, proprietary format)	Varies	Varies	UNAVCO/UNAVCO
	2	Point cloud data (merged, aligned, georeferenced, unfiltered)	ASCII, LAS, other	Varies	UNAVCO/UNAVCO
Airborne Laser Scanning (ALS)	3	Point cloud data (unfiltered, filtered)	ASCII, LAS, other	Static	NCALM/OpenTopography
	3	Digital elevation model (unfiltered, filtered)	Varies	Static	NCALM/OpenTopography
	3	Hillshade image (unfiltered, filtered)	GeoTIFF	Static	NCALM/OpenTopography
Satellite Synthetic Aperture Radar (SAR)	0	Raw SAR sensor data	CEOS, ENV1	Varies (orbit dependent)	ESA, NASA (ASF)/UNAVCO**
	1	Slant range single look complex (SSC) data	COSAR	Varies (orbit dependent)	DLR/UNAVCO**
Meteorlogic Sensor	0	Temperature, humidty, barometric pressure, other	T00	Hourly/Daily	UNAVCO/UNAVCO
	1	Temperature, humidty, barometric pressure, other	RINEX	Hourly/Daily	UNAVCO/UNAVCO
	2	Soil mosture, snow depth, snow-water equivalent, NLDAS, SNOTEL, vegetation index, precipitation***	ASCII	Hourly/Daily	Community PI (Larson)/UNAVCO
	2	Time series, maps, animations	Varies	Hourly/Daily	Community PI (Larson)/UNAVCO

* Supported by UNAVCO subaward. ** UNAVCO re-distributes data to authorized users.
*** Data products are generated from combination of GPS observations (multipath), meteorologic observations, direct soil and vegetation measurements, etc.

in Boulder, Level 0 data undergo automated quality checking (QC) and archiving, creating Level 1 GPS products in RINEX format. UNAVCO also receives, archives, checks, and distributes Level 0/1 data products from a large number of GPS stations and networks operated by principal investigators and around the world.

At the nexus of several GDS systems is the PBO Operational Database (POD). This database maintains information to support station dataflow, station metadata, site logs, state-of-health data, GPS quality control data and station configuration information. It also stores level 2 strainmeter, pore pressure and temperature, tiltmeter and meteorological data that will subsequently become one part of the time series data made available by new CI tools currently under development; these include simple url-based web services and time series data presentation.

A critical operational component of the PBO is the dataflow system. This continuously operating process connects to each station on the network to retrieve GPS from 1,112 PBO stations and additional polar and Caribbean stations, totaling 1,178 stations, as well as meteorological data (138 met packs), and strainmeter (75 stations) data. Pore pressure and temperature (23 sensors), and tiltmeter (26 tiltmeters) observations are collected via the commercially licensed Antelope Environmental Data Collection (AEDC) software.

The dataflow system allows connections through cellular modem, DSL, radio, or satellite networks, and is needed to achieve EarthScope science goals. Users of GDS services provide additional input through solicited online surveys.

The Metadata Management System (MDM) is a UNAVCO-developed web-based online metadata entry system developed and maintained by GDS staff and used by various groups across UNAVCO. The MDM is used to populate the PBO Operational Database (POD) with initial station installation and subsequent maintenance metadata. Although developed for PBO, the MDM infrastructure is now providing support for stations from other networks where UNAVCO provides data and metadata support. Under GAGE, GDS will incorporate support for all non-PBO stations in the MDM. This integration will enhance the efficiency and effectiveness of systems and processes, ultimately leading to more streamlined and far-reaching data management operations.

RT-GPS Data Flow and Management

During the construction phase of PBO, 100 of the original 1,100 GPS stations were upgraded to stream GPS data at high-rate in real-time. As part of the NSF-ARRA-funded Cascadia Initiative, PBO implemented real-time streaming for an additional 232 stations, bringing the current total to 332 RT-GPS sites within the network. By the start of GAGE, data from 372 stations will be distributed in real time and archived at high rate. PBO plans to augment the set of real-time stations by adding 50 stations per year through 2018 while driving a strategic vision for the current and future needs of a broad spectrum of scientific user communities for RT-GPS raw data and position products, processing, formats, standards, analysis and distribution (Figure 3.2-3).

Campaign Data Flow: GPS, TLS

GPS campaign data are typically submitted by the project PIs to the GDS Data Center group where data and metadata are ingested into the archive and checked for quality through a well-established process. Management of campaign TLS data, however, is still relatively new and GDS is developing archiving standards and processes in response to recommendations from the 2011 Management Review and TLS community workshop. Currently, raw data collected during TLS campaigns are stored in the GDS data archive and made available to UNAVCO field engineers, project PIs, and students for processing and generation of higher-level data products, including the standard UNAVCO deliverable of a merged, aligned, georeferenced point cloud. Development is ongoing and will continue under the GAGE facility to support TLS data with a system for field-based metadata capture and synchronization of field metadata and raw data products with a centralized, "RAMADDA" content management repository-based, TLS data management system; this will be used throughout the data processing, archive, and distribution workflow.

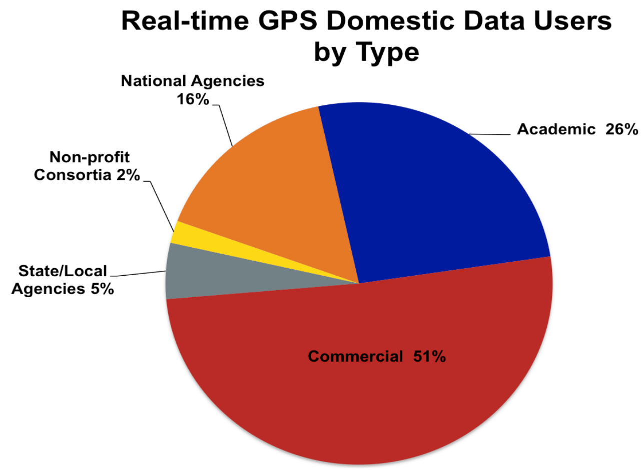


Figure 3.2-3. Real-time GPS data users. Real-time data distribution uses the Trimble VRS3 system and Ntrip caster, 1 Hz data is streamed with average latencies of 0.5 second and over 95% data completeness. These high quality data streams are made available to approximately 160 subscribers. Approximately 51% of these users are from the commercial sector demonstrating the broader impact of these PBO data.

3.2.2 Data Products (WBS U1.2.4)

GAGE will provide a variety of high-quality geodetic data products from a diverse suite of instruments as outlined in Table 3.2-1. Depending on data type, UNAVCO provides everything from raw data (Level 0) to fundamental derived products (Level 3), which allows us to serve a range of users from experts in raw data analysis to those whose research requires reliable derived products such as geodetic time series. To date, UNAVCO has collected over 70 TB of GPS, strain, seismic, tilt, LiDAR, SAR and meteorological data, and has delivered over 90 TB of data to educational institutions, government agencies, and commercial organizations in the United States and internationally. We anticipate that UNAVCO will generate ~200 TB of data products by the end of FY18 (Figure 3.2-2).

In addition to these Level 0-3 data products, UNAVCO provides a suite of tools that allow community users to explore and analyze data directly and easily. These tools will be used as part of GAGE ECE activities (see 3.3 below). For example there are web-services-based tools that support requests for GPS data, station position time series, raw and level 2 strain meter data, station metadata, and earthquake and seismic data retrieved from IRIS. We have recently developed a site-position animator that displays its 2-dimensional position change over time and are developing a generalized time series plotter. These tools will be rolled out to the UNAVCO community and improved with community feedback during GAGE.

GPS Data Products

GAGE will provide a continuum of GPS data products, including raw data, RINEX files, velocity solutions, position time series, and other derivative products as summarized in Table 3.2-1.

Level 2 GPS products are generated by analysis centers that are funded through subawards. These products include station position and velocity solutions, position time series, station velocity estimates and coseismic offsets for significant events. The separate analysis centers (AC) at Central Washington University and the New Mexico Institute of Mining and Technology use different GPS analysis software packages (GIPSY and GAMIT, respectively) to process all PBO Level 1 RINEX data into initial Level 2 products. The Analysis Center Coordinator at MIT then merges the loosely constrained position estimates into a unified set of high-quality combined products (Table 3.2-1). The PBO analysis centers will process ~1700 stations from PBO and associated networks by the beginning of GAGE. UNAVCO based the AC structure on that of the International Global Navigation Satellite System Service (IGS) and SCIGN, which showed conclusively that having multiple independent processing strategies that are independently coordinated produces the highest quality GPS solutions. GPS position estimates produced in this exacting manner are nominally precise to within 2 mm horizontally and 5 mm vertically; after several years of continuous operation, PBO network solutions exceed this high standard.

QC parameters for GPS data range from receiver tracking performance to continuity of data supplied to the end user. New post-processed QC parameters developed under the GSAC project will continue to be provided by Geoff Blewitt (University of Nevada, Reno) at no cost to GAGE. UNAVCO has used its deep understanding of the fundamental data observables and excellent relationship with vendors to develop and support the teqc translation, editing and quality-checking program that is widely used around the world to assess the quality of GPS data. teqc is used to generate data completeness, signal-to-noise, multipath and other QC parameters that are easily accessed through the archive Data Archive Interface (DAI).

GAGE staff will continue to develop teqc so that it can handle the greatly expanded set of observables produced by new GNSS constellations while managing the user interface complexities these new signals entail. The GDS Director serves on the IGS Governing Board and will evaluate emerging data format trends as they arise during GAGE. GDS staff will also continue to support the implementation of new BINEX standards by receiver manufacturers as a raw format alternative. teqc will be expanded to have the ability to read the GNSS-capable RINEX 3.0 data format as well as BINEX, and will define and implement QC for expanded GNSS observables.

PBO Strain, Seismic and Tilt Products

Data products for PBO strainmeters include processed strain time series and accompanying metadata. Both BSM and LSM processed data sets include strain time series in geophysical units and corrections for Earth tide and ocean load at each site, barometric pressure response and estimates of static offsets in the data. The BSM data also are corrected for long-term borehole deformation trends. The standard sample interval for the processed data is 5-minutes though a 1-Hz data set is generated for the BSMs after significant geophysical events or upon user request. The LSM data set is updated at least once every two weeks while BSM data are updated daily.

UNAVCO collects seismic data at 79 borehole sites across the PBO network; all but five are installed in the same borehole as the strainmeters. Data are recorded by 3-component Sonde-2 seismometers at sample rates of 100 and 1 sps on a Quanterra Q330 digitizer with a Marmot data logger providing up to one year of data storage at each site. The data are downloaded via the Antelope system and arrive at UNAVCO and the IRIS DMC (the archive for PBO seismic data) in near real time. UNAVCO creates and maintains the dataless SEED for each of the seismic sites sending updates as needed to the DMC. Once at the DMC the seismic data are available to the community in full SEED, miniSEED or SAC format. UNAVCO's Seismic Data Products web page provides links to the current data download performance, data recovery rates and daily webicorder plots.

Tilt data are recorded at 26 sites in volcanic regions: Mt. St. Helens, Yellowstone, and Akutan and Unimak Islands in Alaska. Sites at Yellowstone and Mt. St. Helens are collocated with PBO borehole strainmeters and seismometers and sample at 1 sps. The data are downloaded using the Antelope system along with the seismic data. Tiltmeters installed at non-BSM sites usually have a sample interval of 600 s, are recorded by GPS receivers and downloaded in BINEX format. All tilt data are parsed and read into the PBO's POD database. The data are made available as full sample-rate hour-long files and as decimated, 10-minute interval, year-long files. Data are pushed daily to an anonymous FTP server at UNAVCO. Tilt plots, raw data and site information can be accessed through the DAI.

Meteorological and Hydrologic Data Products

Precipitable water vapor in the troposphere delays radio waves, providing the basis for estimates of a number of tropospheric parameters, and are generated while processing daily position solutions in GAMIT and GIPSY. These are routinely provided by the PBO Data Analysis Centers and distributed in daily files from the Data Center.

In 2012, new "H2O" data products were added to the suite of UNAVCO-distributed data products. These include soil moisture, snow depth, and vegetation sensing measurements derived from 1-Hz GPS data from select PBO sites that are discussed in Section 2.1. Products are produced and provided by Dr. Kristine Larson (University of Colorado).

Hydrologic loading models, determined from GPS position time series will soon be available to users. Large seasonal variations in water storage as groundwater, in surface reservoirs, snowpack, oceans, and atmosphere, cause large vertical motions (and often lesser horizontal motion) that are measured by GPS. Hydrologic loading models will support more sophisticated GPS time series analysis and hydrogeodesy applications by the research community, and these will be developed into a more complete service under GAGE.

LiDAR – Terrestrial and Airborne Laser Scanning Products

Since 2007, UNAVCO has been providing the community with Terrestrial Laser Scanning (TLS) instrumentation and field engineering support for campaign surveys, with additional processing services available upon request. Standard products for all supported TLS projects include raw (Level 0) scanner data in the instrument manufacturer's proprietary format, as well as a standard processed product (Level 2) consisting of merged, aligned, georeferenced, unfiltered point cloud data in ASCII or LAS format. GDS staff will be partnering with OpenTopography to make TLS data available through their web-based data access and processing system.

The 2011 TLS Community Workshop Report articulates several requirements of the Earth science TLS community and will guide the work of the GAGE Facility. Recommendations include augmentation of training materials and best practices for TLS field data collection, development of domain-specific data processing, and analysis workflows will be developed in collaboration with community TLS experts. These contributions will be available via the UNAVCO online Knowledge Base. Regular short courses for TLS data collection and processing have been very effective in supporting new investigators.

As part of GeoEarthScope (2003 – 2008), UNAVCO managed the acquisition of nearly 6,000 km2 of high resolution Airborne Laser Scanning (ALS), airborne LiDAR data collected by the National Center for Airborne Laser Mapping (NCALM). The GAGE Facility will have legacy responsibility for management of the data and providing metrics of its use. Level-3 data products delivered by NCALM are currently freely available through the OpenTopography portal. GAGE will also facilitate future community ALS data acquisitions as needed.

3.2.3 Data Management and Archiving (WBS U1.2.5)

The GDS program provides resources to scientists, educators, and the public through the Data Center that manages, archives and distributes geodetic data and products. Data Center procedures ensure full life-cycle support for the geodesy data holdings by following established practices for data and metadata curation, long-term preservation, updating, accessibility, and distribution for GPS data and data products and SAR imagery. GDS is now applying these practices to TLS point clouds and ancillary data. PBO laser strainmeter, tilt, borehole seismic, strain and meteorological data are held locally at UNAVCO to facilitate product development and display and exploration tools, while their official archives are elsewhere (Northern California Earthquake information Center for strain and IRIS for seismic and tilt). UNAVCO is working to promote best practices in giving attribution to dataset creators and enabling technologies to ensure reproducibility and traceability of datasets. At the time of this submission, UNAVCO has a developed prototype software system for assigning Digital Object Identifiers (DOIs) to data sets within the GPS Archives. Under GAGE, GDS staff will deploy this system for GPS data and products and will develop analogous DOI systems for holdings of SAR products and for LiDAR collections.

GPS Data Archiving

The GPS archive has been in existence since 1992 and has archived a cumulative total of 24 TB of level 0/1 data and 5 TB of level 2 and higher products. The amount of data archived annually has steadily increased through time and in 2011, 970,000 files and 7 TB of level 0/1 GPS data were archived. The value of these data to the scientific community can be assessed through community usage rates; delivery volumes for GPS standard rate data files show a gradually increasing reuse factor (ratio of aggregate pickup volume to archived volume) that averages 6:1 over a 16-month interval. Data users are mainly from the .edu and .gov Internet domains.

Almost 10 years ago, the Data Center committed to the use of highly scalable hardware architecture with supporting software, which has proven invaluable for handling the fifteen-fold increase in data volume (1 Hz vs. 15 s) for high-rate data that is increasingly being utilized. Archiving systems are currently being transitioned to virtual machines that further simplify hardware scalability; the scalable software architecture continues to reap benefits in this new hardware environment. Under GAGE, UNAVCO will explore and implement the use of cloud services to accommodate the increased IT demands (storage, data formatting, and data delivery bandwidth) stemming from the increasingly high volume data streams. Figure 3.2-4 illustrates how the Data Center, like other areas of UNAVCO, provides increased cost efficiency and service effectiveness by building on a scalable system.

Archived data reaches its maximum utility when the larg-

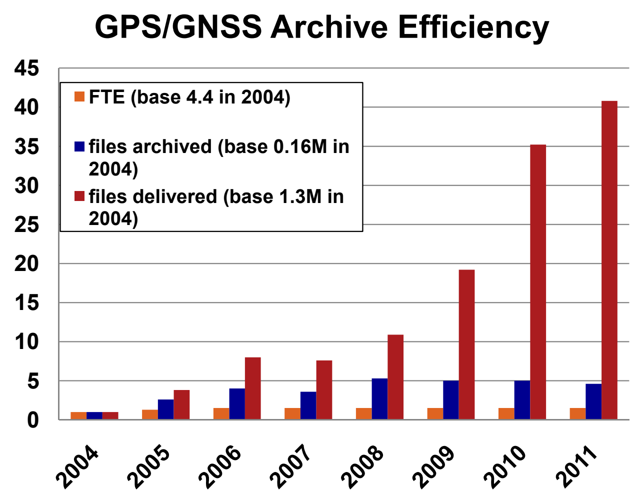


Figure 3.2-4. Archive efficiency. One of the biggest assets that large facilities provide to sponsors and investigators is development of robust and extensible solutions to infrastructure needs. This chart compares archive effort (FTE) expended each year with data throughput (data delivered to the user community) using 2004 as a baseline to illustrate increased efficiency and robust scalability. Charted FTE includes personnel engaged in tasks that span GNSS data operations to final deposition in the archive.

est possible audience accesses it. The Data Archive Interface (DAI) web-based Graphical User Interface tool facilitates GPS data discovery and access. Version 2 of the DAI, introduced in 2008, has been widely accessed and has greatly improved the efficiency of data discovery by enabling complex spatial and temporal queries to be posed by researchers and allowing the results to be explored visually. Software-driven exploration tools based on web-service APIs are also a component of the DAI.

PBO Strain, Seismic and Tilt Data

PBO collects Borehole Strainmeter (BSM) data plus several ancillary data sets, e.g., barometric pressure and rainfall at each site and transmits the data and processed products to the Northern California Data Center (NCEDC) and the IRIS Data Management Center (DMC) via SEEDLink for archiving. Once in the NCEDC and DMC archives, the data are available as SEED data and can be accessed using web services and tools provided by these data centers. Under normal operations the latency between onsite data collection and avilability to the community is about 2 to 3 hours. Work in progress will implement real-time data streaming. The Laser Strainmeter (LSM) data are archived in a similar manner.

Terrestrial and Airborne Laser Scanner Data

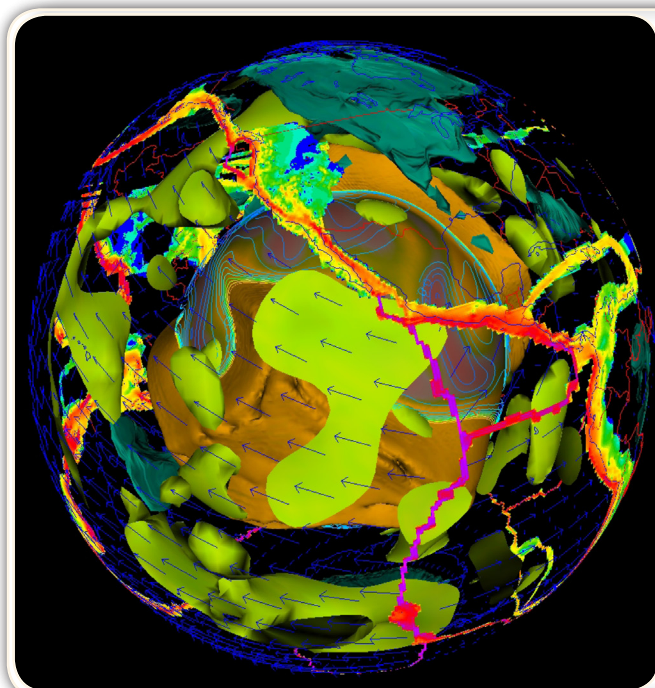
The growth of TLS scanning at UNAVCO has driven a high volume of scanner and ancillary data products that must be managed by GDS. Different TLS manufacturers have yet to develop a standard, open raw data format. This and the range of project types, requires a flexible, but comprehensive data repository for a diverse set of information for effective investigator support. We have drafted an initial project archive data and product (e.g. merged point clouds) list including TLS scans, merged scans, scan photos, field photos, maps, GPS data, project workflow directories, software and other data and metadata. Development of a TLS data project management and archive capability on the RAMADDA scientific content management platform is ongoing. The proposed archive capability will also work with the OpenTopography project to allow data discovery and access by the LiDAR community. This work will be an important focus for the GAGE Facility.

SAR Data

The SAR Archive component of the UNAVCO Data Center was initiated in 2006 when the WInSAR Consortium voted to transition its operations and management to UNAVCO. During the EarthScope MREFC, a large collection of EarthScope-related SAR data was amassed as a resource for the community. Together the WInSAR and EarthScope SAR collections total ~20 TB. As part of this proposal, WInSAR support will be integrated with core GDS funding. Because SAR data primarily comes from the space agencies that have deployed SAR satellites (e.g. ESA and JAXA), the GAGE GDS activities will include satellite tasking, ordering data, and managing metadata.

When the European Space Agency (ESA) initiated a free and open data distribution in 2010, UNAVCO upgraded its hardware and software to enable PI access to new holdings. This included a redesign of the complete database schema, migration to a new relational database management system, upgrade of data ingestion scripts, construction of a Web services based API, and revision of relevant web pages. Due to recent loss of the ALOS, ESA's Envisat and ERS2 SAR satellites, the activities of the SAR Archive have shifted focus to the German Space Agency (DLR) X-band SAR satellite, TerraSAR. Data costs are high for TerraSAR-X and the other active SAR satellites (the Italian Space Agency's COSMO-Skymed, and the Canadian Space Agency's RadarSAT-2), and large volumes of these data are not expected to reside in the UNAVCO's SAR Archive. Tasking of the TerraSAR-X satellite, together with purchase of small quantities of scenes have become a principal activity in support of SAR data acquisition, along with steady ordering of older ERS2 and Envisat scenes and coordination with ESA UNAVCO's role in facilitating access to the upcoming Sentinel mission.

UNAVCO has also developed support for the GEO online GeoHazards Supersites, sustaining data management and website support integral to this international effort in data sharing. New activities in the SAR area for the GAGE Facility will dovetail with and support cyberinfrastructure activities described in the next section.



Cyberinfrastructure integrates data accessibility vertically for geodesy applications, and horizontally for interactions between geodesists and other geoscientists.

In this example, UNAVCO has developed a plugin to the UNIDATA Integrative Data Viewer called the GEON IDV that allows users to access, visualize, and interact with local and distributed geophysical data and models. This tool is extremely capable - but the lack of sufficient and standard metadata sources, the lack of standard formats, difficulties in discovering data, and the sheer volume of data limit effective use. These challenges will be taken on by GAGE cyberinfrastructure developments in the context of EarthCube. This image shows mantle tomography data [*Megnin and Romanowicz, 2000; Shapiro and Ritzwoller, 2002]*; the final time step of the geodynamics model [*McNamara and Zhong*, 2005]; and Global Strain Rate Map and associated tectonic plate motions [*Kreemer and Holt,* 2001].

3.2.4 Cyberinfrastructure (WBS U.1.2.7)

In the 30 years since the development of the Internet began, all branches of science have embraced digital data; geodesy is no exception. While data and metadata are more easily accessible, and the tools to analyze, manipulate, and transform data into knowledge products have proliferated, the complexity increases, often compromising efficiency in manipulating data. Cyberinfrastructure efforts planned for the GAGE Facility simplify access to data at all levels, create higher-level products, and enhance usability both within and outside of geodesy. The current data and metadata access, software, databases, and hardware resources available at UNAVCO and through external partnerships can improve utilization of data resources to advance the science challenges. These core resources will also provide a foundation for UNAVCO's participation in COOPEUS and EarthCube initiatives.

The EarthScope Cyberinfrastructure Plan [*Gurnis et al.,* 2012] identified a set of CI challenges and targeted web services that are foundational to enhanced data access and thus necessary to realize the benefits of modern data sets. UNAVCO began building web services to facilitate exchange of metadata in part to support the EarthScope Portal. Evolution in web services methodologies have led UNAVCO to focus on simple URL-based web services to interoperate with external CI efforts. UNAVCO's web services also form the basis for an Application Programming Interface (API) for internal processes and external clients that must exchange metadata.

Over the last two years, UNAVCO staff has worked with partner data centers at SOPAC and CDDIS to rebuild the Geodesy Seamless Archive Centers (GSAC) using web services as the underlying information exchange mechanism. Federated queries for metadata and data access all three data repositories. GDS staff members have also designed web services to serve users interested in a generalized API for accessing time series, including GPS positions, strain, tilt, and meteorological sensor data. The time series are delivered in XML and can be consumed by a variety of tools and clients, including the time series viewer discussed above. Through an NSF award to the WInSAR Consortium UNAVCO has also built web services to support SAR search and access to its WInSAR and EarthScope SAR collections. Enhancements from the recently-funded ROSES Seamless SAR Access (SSARA) project will enable a workflow to produce interferograms from raw SAR data, bringing in ancillary terrain and meteorological information via Web services to correct the SAR images for these effects. Similar CI development to support web-service-based access to LiDAR data has been ongoing in the UNAVCO-led NASA ROSES LiDAR Access System (NLAS) project that is developing Web service access for high altitude airborne and satellite laser altimetry data. The NLAS achievements provide a framework for the development of services to access to TLS data products hosted in the UNAVCO archive.

As a NASA-funded task of the GAGE Facility, GDS will continue to provide CI support to the IGS Central Bureau and to facilitate the exchange of IGS network metadata in support of network operations. UNAVCO's CI expertise will strengthen the integrity of metadata and provide web tools for viewing station and QC metadata and the state of data flow within the

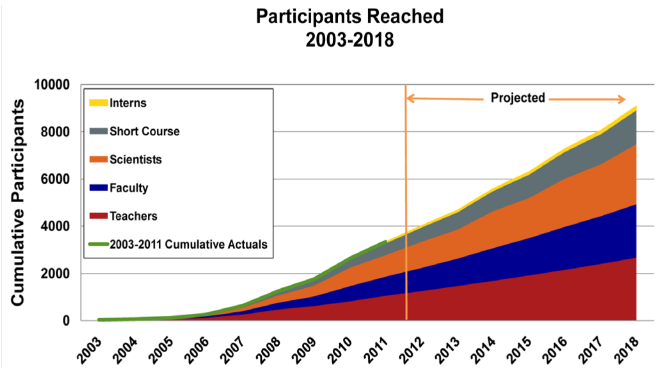


Figure 3.3-1. Education and Community Engagement impact. The cumulative number of participants reached through Education and Community Engagement activities including internships (RESESS), short courses, workshops, and related outreach activities.

IGS network. Use of GSAC web services in conjunction with IGS network operations is anticipated.

3.3 EDUCATION AND COMMUNITY ENGAGEMENT

Since its establishment in 2004, activities of the UNAVCO Education and Outreach program have supported the geodetic and broader geosciences community and other focused public constituencies (Figure 3.3-1). The program now operates as Education and Community Engagement (ECE), renamed to better reflect the participatory nature of current and planned initiatives. Ongoing core support by ECE includes: communicating scientific results from the geodetic community; fostering education through workshops, short courses, and online materials; providing professional development for secondary and higher educators; supporting workforce development including increasing diversity in the solid Earth sciences; and coordinating communications and showcasing results during community-driven response to earthquakes.

The National Research Council [2010] asserts the importance of supporting the geodetic infrastructure, including fostering education. During the next five years, in addition to continuation of strategic core activities, ECE will embark on four new community-focused initiatives, made possible by increased internal efficiencies, strong working relationships with the community, and established key partnerships. These proposed initiatives are the result of community input including survey results from the Education and Outreach Advisory Committee, community feedback during the 2012 Science Workshop, and a formal NSF-sponsored Education and Outreach evaluation [*NSF*, 2011].

Increasing international engagement and partnerships will be a priority of the UNAVCO ECE Program during the next five years. Community and capacity building in underserved areas of the world is a new UNAVCO focus that will extend to its management of GAGE Facility, initially linked to the needs articulated by UNAVCO's local and regional partners in the COCONet project, but extending to other areas of the globe as community activities dictate, such as Africa (see 3.1.1). This effort parallels UNAVCO's recent expansion of involvement in and support for international organizations such as the IGS, and aligns with the ongoing growth of UNAVCO's international Associate Membership. International opportunities for professional development have recently become a priority for UNAVCO, beginning with a GAMIT/GLOBK GPS processing course taught in Lima, Peru in 2011. Since then, instructors from MIT and UNAVCO have travelled to Turkey, South Africa, the Philippines and Montserrat to teach this material at UNAVCO-organized short courses.

UNAVCO ECE will support events such as international training workshops on emerging geodetic technologies, drawing on the varied expertise of community (Figure 3.3-2). ECE will also work with the community and draw on research results of others [e.g., *Biermann et al.*, 2010; *Leemans et al.*, 2009] to determine the preferred mechanism

Coordinated IRIS, UNAVCO, and ESNO education and outreach activities.

The UNAVCO Education and Community Engagement and IRIS Education and Public Outreach programs have collaborated extensively over the past 7 years and it is proposed to continue the successful partnership. The partnership has been particularly valuable for EarthScope-related activities, where UNAVCO and IRIS work closely with the EarthScope National Office (ESNO) to bring EarthScope science to national, regional and local audiences within the EarthScope footprint.

- Collaborations have ranged across each group's products and services, including:
- EarthScope-focused teacher workshops
- EarthScope interpretive workshops for informal educators (led by ESNO)
- Development of content for the IRIS Active Earth Monitor
- Preparing PBO-, USArray- and EarthScope-focused materials on topics such as Episodic Tremor and Slip for wider distribution through print, web, and mobile information technologies
- Cooperation on diversity initiatives, including research experiences for undergraduates, and shared booths and student field trips at professional meetings that promote diversity.

Coordination is further enhanced through the E&O advisory committees of EarthScope, IRIS and UNAVCO, with ex-officio participation in each by the three Program Directors.

Figure 3.3-2. Geodesy short courses for international reach. Each year, UNAVCO offers a series of short courses designed to support community inclusivity. New investigators in need of geodetic tools to advance their research can acquire the technical knowledge to use and interpret any of the toolbox basics: GPS data processing, TLS results manipulation, strain meter data analysis, and the production of SAR interferograms. The short courses are offered at no cost to participants, with further support extended to graduate students, post-doctoral scholars, and early career faculty. 2012 saw the long-awaited return of the GIPSY short course at UNAVCO.

for dissemination of research results and training tools in more accessible and informative ways to stakeholders including policymakers, the public, and the scientific community. We anticipate leveraging existing (interactive web tools for training and data acquisition and analysis) as well as emerging technologies (e.g., 3D displays, mobile platforms for collaboration, social media).

An important component of GAGE will be the implementation of a *web-based learning environment* cutting across all elements of the GAGE Facility and UNAVCO. Using the web as a tool for informing, educating, serving data and communicating on topics of community science and geodetic techniques will support engagement by broad spectrum of stakeholders ranging from scientists to policymakers and the general public. ECE will emphasize leveraging established and emerging web technologies to provide materials, online tools, multimedia, workshops and short courses via a web-based learning environment.

This will empower the community to communicate and contribute within the UNAVCO website resulting in a community-enhanced resource with rich content, thus allowing UNAVCO's international community to actively participate

Advancing TLS Science and Diverse Workforce Development with RESESS

RESESS Intern Melissa Carnicle, center, mentoring a peer undergraduate student on a UNAVCO TLS field campaign to Italy.

UNAVCO contributes to building a geoscience workforce that is both diverse and technically skilled in the cutting edge field of TLS (Terrestrial Laser Scanning) by supporting RESESS interns and mentors in their investigations. RESESS enables students on their path to graduate school by engaging them in geoscience research. During the summer of 2012, UNAVCO trained two RESESS interns to operate state-of-the-art TLS instruments and process the data. The interns participated in UNAVCO's week-long TLS workshop, scanned a rock glacier in Colorado with the guidance and support of UNAVCO field engineers, and were guided through the processing of the large data sets that they had collected. One intern worked with her home institution advisor to conduct a TLS field campaign in Italy on glacial geology. The RESESS interns use their results to characterize rock glacier deformation and differentiate between glacial advances and their deposits in ways that have never before been applied.

New collaborations crystallize around the RESESS projects, including partnerships between UNAVCO and the USGS, and the University of Minnesota Morris. These are only made possible because of the strong support that UNAVCO gives the RESESS Internship Program by providing training and assistance in collecting field data with complex and powerful field instruments like TLS. Science investigations and mentoring educate a new generation of diverse geoscientists for careers that will embrace technology innovation for transformative science.

and also supports our role as a facility to engage the community in a scalable way.

A third new initiative will be focused on exploration and development of innovative approaches to strengthening workforce development and improving diversity in the solid Earth sciences and specifically geodesy. This work will build on the highly successful RESESS program (Research Experiences in Solid Earth Science for Students; Figure 3.3-3) [*Eriksson*, 2008; *Eriksson and Hubenthal*, 2009; *Sloan et al.*, 2011] managed by ECE. This program was the first step for UNAVCO in addressing the call for a "quantitative assessment of the workforce required to support precise geodesy in the United States and the research and education programs in place at U.S. universities" [NRC 2010, p. 9]. ECE will complete the currently emerging sustainability plan for RESESS while continuing to support and manage the program. Emphasis will be on developing additional mechanisms and activities to encourage and support diversity in solid Earth sciences. ECE will continue to work internally with the UNAVCO GI and GDS programs to support and mentor promising undergraduates aspiring to work professionally in the field of geodesy. By working closely with industry and government partners, such as USGS, we will develop a framework for reaching out to women, men, underrepresented minorities, and persons with disabilities, involving them in the field of geodesy.

The geodetic community, through the UNAVCO strategic planning process and consequent collaborations, identified the need for 21st century undergraduate *geodesy curriculum*. Initial planning on this fourth new initiative began at a workshop held in May 2011 at the EarthScope National Meeting. Education experts from the UNAVCO community convened to identify resources and a process for development of an effective community-reviewed geodesy curriculum. The established framework includes enhancing existing resources with new activities to provide a flexible web-based conceptual framework to sequence geodesy learning modules and linking with complementary content from partners and community contributors. The geodesy curriculum will be a community-driven effort coordinated by UNAVCO ECE. Additional funding sources will be explored to support the full development of a formalized, systematic suite of undergraduate modules integrating geodetic technologies beyond the current high-precision GPS tool set, which will provide a common basis for the geodesy and Earth system sciences communities. Elements of the geodesy curriculum and accompanying media materials will be evaluated and extended to a more public audience as appropriate, thus providing a resource for increasing public understanding and appreciation of geodesy and its relevance to society.

Figure 3.3-3. Faces of the future of geosciences. The 2011 cohort of RESESS interns concluded their summer research internship in Boulder, Colorado. Several returned for a second year, while many have gone on to graduate school

3.4 RESULTS OF PRIOR NSF SUPPORT

UNAVCO Community and Facility Support: Geodesy Advancing Earth Science Research PIs: M. Miller, C. Meertens. Award #: EAR-0735156; Award: $23,050,890; Period: 01/08 – 12/12.

Collaborative Research: EarthScope Facility Operation and Maintenance (PBO/SAFOD): PIs: M. Miller, G. Mattioli. Award #: EAR-0735156; Award: $44,310,299; Period: 10/08 – 9/13.

Track 2: Research and Education in Solid Earth Science for Students (RESESS): Developing a Sustainable RESESS Program, PIs: M. Meghan Miller, Donna Charlevoix, and others. Award #: OEDG-0914704, Amount: $1,179,864. Period: 9/09-8/14.

These three awards are the most closely related to this proposal for a GAGE Facility, which will integrate UNAVCO's core Facility, PBO and ECE activities into a single award starting in 2013. The accomplishments described here are summarized by the performance metrics throughout sections 3.1, 3.2 and 3.3.

Under the first award, UNAVCO extends support to both PI-led efforts and major community projects such as POLENET and AfricaArray. To date (1/1/08-5/31/12) 758 PI projects for EAR, OPP, and the community have been supported. There are 2,376 active cGPS (continuous GPS) sites with data being archived at UNAVCO; over 700 of these have their operations and maintenance supported by UNAVCO.

Under the PBO award and its supplements, UNAVCO operated and maintained 1,112 GPS stations, 76 borehole strainmeters, 79 borehole seismometers, 6 laser strainmeters, 26 tiltmeters and 125 meteorological stations (102 core, 23 NOAA). UNAVCO oversaw management of SAFOD as the SAFOD Management Office, including support for the failure analysis borehole instruments. UNAVCO also collects and distributes high-rate (1 Hz), low-latency (<1 s) GPS data streams (RT-GPS) from approximately 350 stations in PBO, including 232 stations upgraded as part of the NSF-funded ARRA Cascadia initiative.

Broader Impacts. UNAVCO Education and Community Engagement (ECE) hosted three biannual UNAVCO Science Workshops (2008, 2010, and 2012), engaging a total of 583 participants; provided 20 technical short courses for researchers in the UNAVCO community reaching 482 participants, and engaged seven master teachers and faculty in the one week Master Teacher- and Faculty-in-Residence Program to develop and refine educational materials for wide dissemination.

The RESESS internship program pairs minority undergraduate students with geoscience researchers (e.g., Sloan et al., 2011). The 2012 applicant pool was the largest, most diverse, and most academically qualified one to date with 17 interns selected from 130 applicants. Since 2005, RESESS has sponsored 37 student interns. Of those, 21 are still undergraduates, 16 have bachelors' degrees, two are working as geoscience professionals and 12 are in graduate school (10 in the geosciences).

Broader impact also extends to the technical community. Land surveyors and civil engineers routinely request PBO data sets and enhanced data rates, using the 800 number on site installations. During 2011, the GPS data editing and quality control software teqc was downloaded 13,938 times from the UNAVCO website, and the Knowledgebase was accessed 391,235 times by a monthly average of 5,848 unique users.

Publications. UNAVCO support for community and PI-led projects, development and testing, software, and data support, has contributed directly and indirectly to numerous publications. Metrics derived from searches on the Web of Science indicate at least 2,796 papers on global geodesy published from 2008 – 2011; most rely on UNAVCO infrastructure, software, data, and data products. A small sample of these have been highlighted above, and are included as references.

Evidence and availability of research products. UNAVCO's archive includes raw data, quality-control data, and level 2 products contain over 30 terabytes are openly available research products on the web or anonymous ftp.

Renewed support. The proposed work extends work under these two cooperative agreements to establish a new facility, GAGE, for integration of geodesy services for broad PI support, upgrade and renewal of about 400 GPS from GPS-only to GNSS-capable instruments as well as upgrade of an additional 250 sites to RT-GPS within PBO, and continued O&M for all 1,112 PBO sites from October 2013 to September 2018.


Beatrice Christopher records necessary survey information while local village people watch the installation of a campaign GPS site in eastern Tanzania. Photo: B. Hodge 2010.

4. Budget Plan

This budget plan describes resources required to accomplish the work that is proposed for GAGE, both new initiatives and the continuing work scope performed under the PBO and UNAVCO Facility Cooperative Agreements. In addition to providing integration and refocusing of two legacy programs, the single cooperative agreement and integrated budget will support a single streamlined management entity, promoting efficiencies and opportunities to leverage staff and other resources. UNAVCO has been funded by a variety of sponsors and funding vehicles in the past, some of which continue into the GAGE period (Figure 4-1).

UNAVCO has existed since 1984 under various management structures, and was incorporated as a non-profit in 2002. This was done in anticipation of extending UNAVCO's well-honed investigator support capabilities to construction, operations, and maintenance of the EarthScope Plate Boundary Observatory. The founding president laid the groundwork for this transition in 2002 under a seed award; UNAVCO staff migrated to the new structure in October 2003 at the onset of the EarthScope award and renewal of I&F support to the EAR PI community. PBO construction was closed out in 2009; O&M had initiated early in the project with the first station completions and was fully functional and fully funded by 2009. Since 2003, EAR and NASA funding came as a single award through NSF. NSF - OPP began to support Arctic and Antarctic projects as supplements to the core through EAR, but are not tracked separately in this figure until 2008. During 2008, renewal of the UNAVCO Facility award was formally co-funded by OPP, in addition to the EAR and NASA contributions. ARRA-funded augmentations came from the USGS and NASA-ROSES during 2010 and 2011. "Other" includes a variety of small awards and contracts such as NOAA augmetation of the PBO sites with meteorological observations.

Projections for October 2013 and beyond anticipate integration of EAR (both EarthScope and Instrumentation & Facilities Programs), OPP (both the Arctic and Antarctic Programs), and NASA funding in a single GAGE award. The request further reflects sponsor guidance for the initial annual request and restrained projections for annual increases. Current RESESS and COCONet awards expire during the first or second year of GAGE; sustaining levels of funding projected from 2015 forward are shown (Figure 4-1).

Building on this history, this section outlines the budget structure and costs planned to accomplish the operational activities described in the Project Description. Table 4-2 outlines the budget by year for GAGE; the WBS dictionary (in supplementary documents) provides further information about the task definitions and the bases of estimate for the planned elements.

4.1 GAGE BUDGET OVERVIEW

The GAGE Facility represents the integration of two legacy NSF cooperative agreements: one to operate the UNAVCO Facility in support of broad geodetic research and data archive, and the other to construct (2003-2008) and operate and maintain the Plate Boundary Observatory of Earthscope (2008-2013, with plans to continue EarthScope until 2018), both on behalf of the science community. Figure 4-2 illustrates the integration of scope under previous awards and the new initiatives undertaken as a result of the efficiencies achieved through combination, and the retirement of certain tasks.

UNAVCO's governance-vetted reorganization was internally motivated by opportunities to strengthen staff, performance,

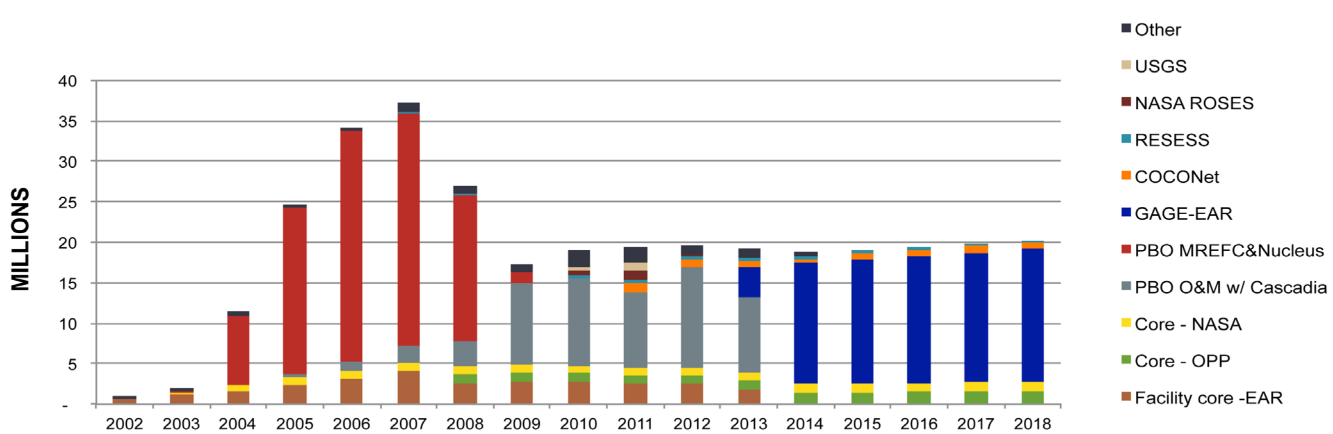


Figure 4-1. Funding of UNAVCO since incorporation. 2002 - 2012 indicates actual awards. 2013 - 2018 include a mix of continuing grants, pending support, and a few anticipated renewals.

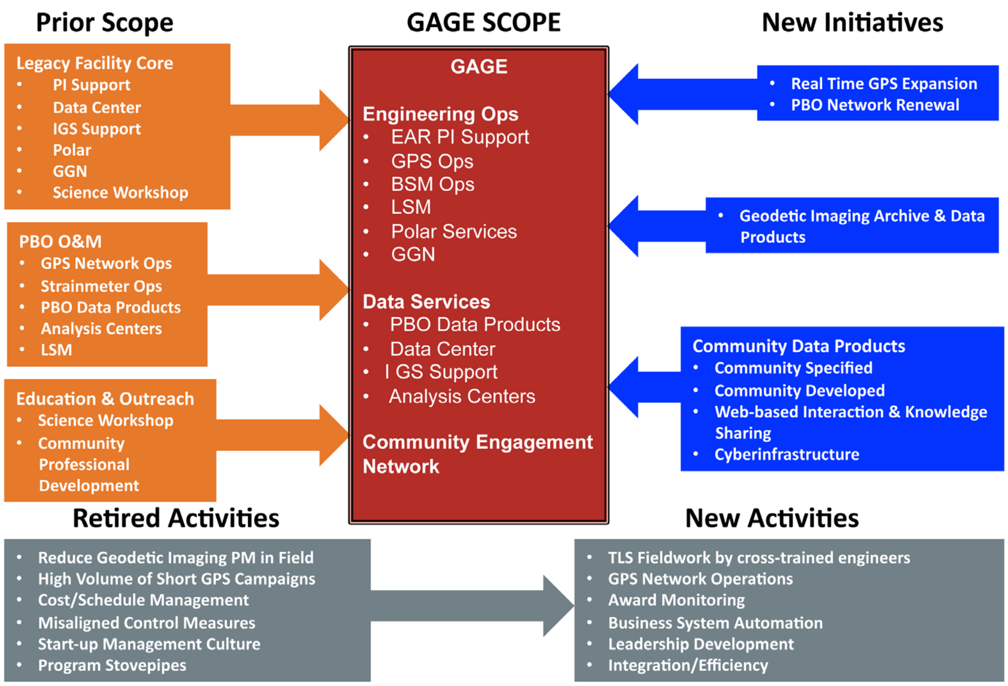


Figure 4-2. Relationship of continuing activities to GAGE work plan. This schematic indicates legacy activities (orange) that are integrated into planning for GAGE (red). New and enhanced initiatives (blue) are possible through efficiencies under the new organizational structure and single planned cooperative agreement. Efficiencies realized by UNAVCO's transition from a "start-up" management culture (gray-left) to a mature and sustainable management culture (gray-right).

and the working environment through integration of parallel activities. The organizational structure described here will benefit from operations under a single core cooperative agreement. The integration of the awards will support efficiencies by reducing duplicative management reporting and review, combining parallel efforts, and leveraging organizational strengths in (1) geodetic observing systems, and data acquisition (with new emphasis on geodetic imaging tools like TLS, and on network operations as PI and other networks proliferate), (2) data operations, archiving, discovery, and accessibility (with new emphasis on community-specified and community-contributed data products, and on realizing the benefits of advancements in cyberinfrastructure), and (3) education and outreach activities that build on the foundation of successful core activities and add strengths that respond to 2011 Management Review recommendations. The new organizational alignment is reflected in the Work Breakdown Structure now comprises three programmatic elements: Geodetic Infrastructure, the observing systems and engineering support element; Geodetic Data Services, the data flow, archiving and data products element; and Education and Community Engagement, the community, workforce development, and public outreach element.

Each of these three programs draws resources from a variety of sources and meets the needs of multiple sponsors and communities. GI has a major focus on sustaining PBO and the subaward Scripps operation of the LSM array (Figure 4-3). Project support for both EAR and OPP PIs is also a significant effort in this program, as well as maintenance of the NASA GGN. The allocation in GDS is different mix (Figure 4-4), with a number of tasks that track data operations to distribution, and improvements to discovery, access and interaction via rapidly evolving cyberinfrastructure. As a smaller program, ECE work is reported under a single task, with WBS elements that allow for allocation of costs to each of the benefitting sponsor programs (Figure 4-5). Because this program was largely funded by indirect costs in the predecessor awards, the GAGE Facility allocation is offset by a reduction in the overall UNAVCO G&A indirect cost rate.

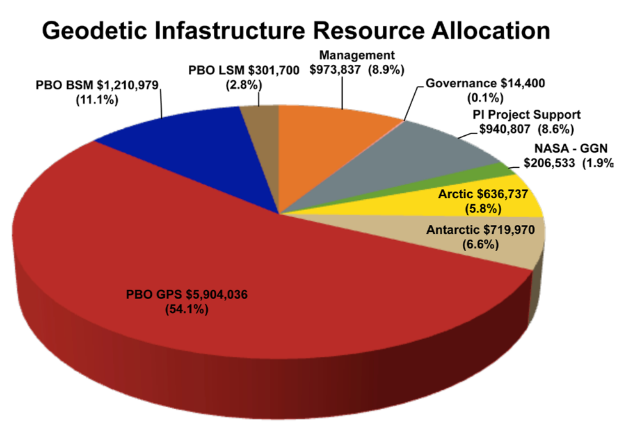


Figure 4-3. Geodetic Infrastructure Resources Allocation. Resource allocation by WBS element for geodetic observing systems and their technical, engineering support.

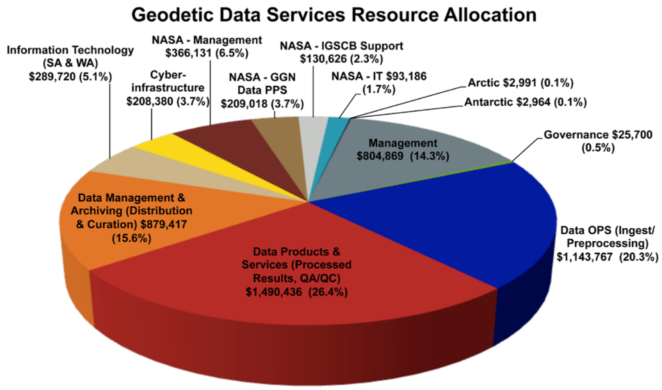


Figure 4-4. Geodetic Data Services Resource Allocation. Resource allocation by WBS element for data services.

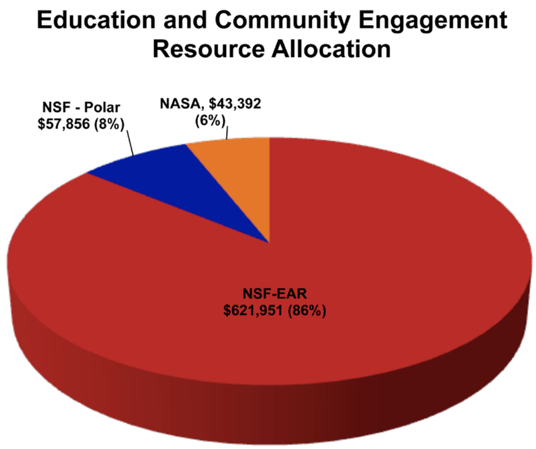


Figure 4-5. Education and Community Engagement Resource Allocation. Resource allocation by WBS element for education and outreach activities.

4.2 INVESTMENT ALLOCATION

The investment allocation can also be viewed from a programmatic perspective, where governance and program management are shown separately from the direct work of each of the three programs (Figure 4-6). Support for observing networks and PI science (collectively, infrastructure) dominate the investment allocation, followed by data services that are provided to the investigator community. Management, ECE, and governance play supporting mission-critical roles.

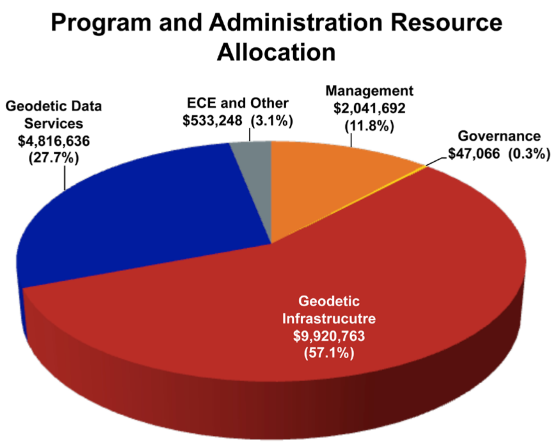


Figure 4-6. Program and Administration Resource Allocation. Resource allocation is shown by GAGE Faclity program and UNAVCO administrative function.

4.3 STAFFING GAGE

Staff support: UNAVCO maintains a highly qualified and experienced staff to meet the needs of the science community, to develop solutions for innovation with evolving technologies (GNSS Rf environment, TLS, etc.), to manage NSF's national geodesy archive and data services, and to ensure forward-looking broad impact (Figure 4-1).

Refinements to UNAVCO's recent program reorganization are anticipated between now and the launch of GAGE. This new structure includes a number of efficiencies that will resource new initiatives in GAGE. The improvements result from re-aligning the work of functional groups into new expert teams, to support UNAVCO's strategic plan. For instance, the field engineering staff is now cross-trained to support TLS instruments and perform network engineering, responding to new needs and new investigators in the science community. Until quite recently, the geodetic imaging project manager helped define and build a community interested in the instrumentation largely supported TLS field deployments. That responsibility has now been assigned to engineering staff whose primary focus is PI field support, freeing up a significant resource to develop TLS-Geodetic Imaging data products and archiving conventions, in response to a management review recommendation (Table 4-2). The new structure has helped managers recognize a significant shift in technical staff priorities to support process improvement: investigators increasingly require continuous GPS observations, and the number of short-term GPS campaigns has decreased. UNAVCO is meeting the commensurate demand for network engineering and monitoring responsibilities, and From November 2010 to January 2011, UNAVCO management was reviewed by NSF-EAR, culminating in a panel of experts who formulated five recommendations. UNAVCO has acted on these recommendations within its current resource allocation, relying on efficiencies like those described here and schematically shown in Figure 4-2.

UNAVCO has committed to the continued growth of its staff by creating and encouraging a professional development opportunities including tuition reimbursement for work-related university courses, on-line and classroom training for various technical and management skills (Excel, Cisco networks, technical writing, project management, etc.), and has partnered with UCAR to launch a pilot leadership development curriculum for NSF facility managers. These investments are aimed at keeping a technically current and managerially adept workforce to meet future challenges and opportunities.

Table 4-1. GAGE Staff and Credentials.

NAME	TITLE	CREDENTIALS and UNIVERSITY/COLLEGE
Executive Office & Business Affairs		
Miller, Meghan	**President**	**Ph.D. Geology, Stanford University**
Rowan, Linda	Director, External Affairs	Ph.D. Geology, California Institute of Technology
Magliocca, Jaime	Executive Assistant	
Strobel, Gail	**Director, Business Affairs**	**B.B.A. Accounting, CPA, Cleveland State University**
Meyers-Wagner, Laura	Human Resources	M.B.A Golden Gate University
deBourgoin, Celine	Contracts Administrator	B.A. Communication & Advertising, University of Cambridge, UK
Deitesfeld, Carol	*Controller*	*M.B.A. Business, University of Denver*
Donato, Judy	Staff Accountant	B.A. Business Administration, Loyola University-Chicago
Burkholder, Bethe	Accounting Clerk	B.S. Finance, Regis University
Stephanus, Blaise	Award Monitoring Administrator	M.S. Telecommunications, PMP, University of Colorado
Krantz, Angela	Budget Analyst	Undergraduate Course Work
Schissler, Megan	Budget Analyst	B.A. History, Colorado State University
Reeme, Tim	Purchasing Agent	B.S. Business Administration, Metropolitan State College of Denver
Schaub, Eric	Property & Building Coordinator	B.A. Education, Michigan State
Zilling, Holly	Human Resources Assistant/	B.A. Management & Economics, Marietta College
Geodetic Infrastructure		
Mattioli, Glen	**Director, Geodetic Infrastructure**	**Ph.D. Geological Sciences, Northwestern University**
Feaux, Karl F	Project Manager, EarthScope & Related	M.S. Aerospace, University of Colorado
Luevano, Taunia	Administrative Assistant	
Bohnenstiehl, Kyle R	Permitting Coordinator	B.A. Geography, Northern Arizona University
Austin, Kenneth E	*NW Regional Manager, GPS*	*M.S. Geology, Central Washington University*
Woolace,Adam C	Field Engineer	M.S. Geology, Humboldt State University
Dittmann, Stephen T	*Eastern US Regional Manager, GPS*	*B.S.E. Geological Engineering, Princeton University*
Dausz, Korey M	Field Engineer	B.S. Earth Science, University of Colorado
Jenkins, Fred L	Field Engineer	B.S. Engineering Science, Montana Tech of The University of Montana
Kasmer, David M	Field Engineer	B.S. Civil Engineering, University of Wisconsin
Enders, Max L	*Alaska Regional Manager, GPS*	*B.S. Geology, Central Washington University*
Boyce, Eleanor S	Field Engineer	M.S. Geophysics, University of Alaska
Bierma, Ryan	Field Engineer	M.S. Earth Science, University of North Carolina-Charlotte
Willoughby, Heidi	Permitting Assistant	B.S. Communications - Digital & Mass Media, Castleton State University
Walls, Christian P	*SW Regional Manager, GPS*	*M.S. Geology, San Diego State University*
Mann, Doerte	Field Engineer	Ph.D. Geophysics, University of Alaska
Basset, Andre J	Field Engineer	B.S. Geology, University of California-Davis
Jarvis, Chelsea	Permitting Assistant	B.A. Geography, University of Colorado
Sklar, Jacob R	Field Engineer	B.S. Geology, Rensselaer Polytechnic Institute
Pitcher, Travis	Field Engineer	B.S. Geological Engineering, Colorado School of Mines
Nolting, Robert	Equipment Technician	Undergraduate Course Work
Blume, Frederick	*Project Manager, Development & Testing*	*Ph.D. Geological Sciences, University of Colorado*
Berglund, Henry	Test Engineer	M.S. Geology, University of Colorado
Gallaher, Warren	Test Engineer	Undergraduate Course Work, University of Missouri
White, Seth	Test Engineer	M.S. Mechanical Engineering, Purdue University
Prantner, Andrea	Test & Field Engineer	M.S. Geophysics, Ludwig Maximilian University of Munich
Pettit, Joseph R.	*Project Manager, Polar Projects*	*B.S. Electrical Engineering, New Mexico State University*
Hodge, Brendan	Field Engineer	M.S. Geology, Fort Lewis College
Nylen, Thomas	Field Engineer	M.S. Geology, Portland State University
Okal, Marianne H.	Field Engineer	M.S. Geological Sciences, University of Chicago
Miner, Jeremy	Field Engineer	B.S. Environmental Science, University of Alaska
Coleman, Scotty B.	Equipment Technician	Undergraduate Course Work
Normandeau, James	*Program Manager, Engineering Support*	*B.S. Survey Engineering, University of Maine*
Morrison, Abraham	Field Engineer	B.S. Aeronautical Engineering, Purdue University
Doelger, Sarah E.	Field Engineer	B.S. Geology, Western Washington University
Sandru, John	Field Engineer	B.S. Geology, University of Nevada-Las Vegas
Williams, Keith	Field Engineer	M.S. Civil Engineering, Oregon State University

Table 4-1. GAGE Staff and Credentials.

NAME	TITLE	CREDENTIALS and UNIVERSITY/COLLEGE
Geodetic Data Services		
Meertens, Charles	**Director, Geodetic Data Services**	**Ph.D. Geophysics, University of Colorado**
Boler, Frances	*Manager, Data Center & Cyberinfrastructure*	*Ph.D. Geophysics, University of Colorado*
Estey, Lou	Senior Software Engineer	Ph.D. Geophysics, University of Colorado
Trochim, Eddie	Software Engineer	B.S. Computer Science, University of Alaska
Wier, Stuart	Software Engineer	Ph.D. Geology & Geophysics, Princeton University
Maggert, David	*Project Manager, Data Operations*	*M.S. Information Science, Metropolitan State University*
Jay, Cassidy	Data Technician	B.A. Geosciences, Hamilton College
Flores, Nicandro	Engineer	M.S. Mathematics, University of Colorado
Braddy, Tim	Data Technician	A.S. Computer Information Systems, Columbia College
Williamson, Hans	Data Technician	B.A. Environmental Health, Colorado State University
Shenefelt, Cassandra	Student Assistant	Pursuing B.A., Metropolitan State University
Mencin, David J	*Project Manager, Borehole Geophysics Operations*	*M.S. Nuclear Engineering, University of Missouri; Ph.D. in Progress*
Fox, Otina C	Data Engineer	M.S. Geology, University of Colorado
Looney, Karen T	Data Technician	B.S. Electrical Engineering, University of Florida
Sievers, Charlie	Data Engineer	M.S. Physics, University of Colorado
Gottlieb, Michael H	*Project Manager, Borehole Operations*	*B.S.E. Environmental Engineering, Princeton University*
Johnson, Wade C	Field Engineer	B.A. Geology, University of California-Berkeley
Van Boskirk, Elizabeth J	Field Engineer	M.S. Geology, University of Arkansas
Pyatt, Chad	Field Engineer	B.S. Geology, California State University-Fresno
Snett, Lee D	*Project Manager, Software Engineering & IT*	*B.S. Biology, University of Arizona*
Smith, Jeremy A	Software Engineer	M.S. Geophysics, University of Washington
Blackman, Brian L	Web Administrator	Undergraduate Course Work
Riley, Jim	Web Administrator	B.S. Computer Science, Regis University
Jeffries, Susan	Database Analyst	B.A. Information Systems, University of Texas
Hanzel, Karl	Systems Administrator	B.S. Natural Science, Lewis & Clark College
Leeds, Roland	IT Help Desk Specialist	B.A. Filmmaking, University of Oklahoma
Duncan, Stuart	Systems Administrator	M.S. Information Technology, Pennsylvania State University
Torrez, Damian L	Software Engineer	Pursuing B.A., Regis University
Petzke, William	Software Engineer	M.S. Computer Science, University of Colorado
Phillips, David	*Project Manager, Data Products*	*Ph.D. Geophysics, University of Hawaii*
Puskas, Christine	Data Engineer	Ph.D. Geophysics, University of Utah
Gross, Susanna J.	Data Engineer	Ph.D. Geophysics, University of Colorado
Hodgkinson, Kathleen M	Data Engineer	Ph.D. Geophysics, Durham University, UK
Henderson, David B	Data Technician	B.S. Geology, New Mexico Institute of Mining & Technology
Chris Crosby	*Project Manager, Geodetic Imaging*	*M.S. Geological Science, Arizona State University*
Baker, Scott	Software Engineer	Ph.D. Marine Geology & Geophysics, University of Miami
Education & Community Engagement		
Charlevoix, Donna	**Director, Education & Community Engagem**	**Ph.D. Science Education, University of Illinois**
Olds, Shelley	Education & Community Engagement Specialist	M.S. Instructional Systems Design, University of Maryland
Sloan, Valerie	GeoScience Education & RESESS Specialist	Ph.D. Geology, University of Colorado
Berg, Megan	Education & Community Engagement Generalist	B.A. History, University of Otago, Dunedin, New Zealand
Weber, Melissa M	Administrative Assistant	Undergraduate Course Work
Schiffman, Celia R	Education & Community Engagement Specialist	M.S. Geology, Ph.D. in progress, University of Colorado
Subaward Key Personnel		
Agnew, Duncan	Ph.D. Geophysics	University of California-San Diego
Allen, Richard	Ph.D. Geosciences	Princeton University
Bock, Yehuda	Ph.D. Geodetic Science	Ohio State University
Dreger, Douglas	Ph.D. Geophysics	California Institute of Technology
Herring, Thomas	Ph.D. Earth & Planetary Sciences	Massachusetts Institute of Technology
King, Robert	Ph.D. Atmospheric & Planetary Sciences	Massachusetts Institute of Technology
Melbourne, Timothy	Ph.D. Seismology & Tectonics	California Institute of Technology
Murray, Mark	Ph.D. Geophysics	Massachusetts Institute of Technology
Wyatt, Frank	Ph.D. Earth Sciences	University of California-San Diego

4.4 MANAGING TO SUCCESS

UNAVCO Performance Management

Governance and Management of UNAVCO hold themselves to a high standard of performance and transparency by measuring performance and progress. UNAVCO operates with the guidance of its Strategic Plan, initially drafted in 2008 and refreshed for accomplishments and new challenges in 2011.

The critical success factors measured each year and reported to the board and consortium members mark progress against those strategic objectives. Each program also maintains a set of metrics for its work, as laid out in the Facility project description.

Business Systems for Award Support

In addition to reporting progress on award objectives to sponsors and the UNAVCO board of directors, each board meeting includes topics to inform their oversight of management self-assessment of internal business controls. Topic areas are rotated such that each critical control function is reported at least annually:

- Human Resources: recruiting, turnover, days to fill positions, benefits costs vs. competing employers, etc.
- Finance: audited financials, A-133 comments and resolutions, review of Form 990 filings, forecasted rate performance, budget and rate proposals for coming year, etc.
- Procurement: small business utilization, competed procurements vs. single source, competitions completed, savings captured, etc.

Award and subaward monitoring is a major new focus of the NSF Large Facilities Office (LFO); UNAVCO Business Affairs has contributed to the structures LFO will use to ensure compliance and accountability in area. The UNAVCO plan for meeting this requirement will escalate this topic to annual board review.

Top to Bottom Review of Control

As PBO construction drew to a close, UNAVCO board of directors initiated a sweeping change of the organization's business practices. In 2008, a new president was brought on board, who undertook an effort right-size the organization and make the business operations that supported the awards more effective. After due analysis and review, a restructuring was undertaken that provided for fewer business affairs director-level positions and a more cost-effective mix of supporting staff. This coincided with the end of PBO construction, supporting the goals of low overhead and nimble management structures.

Efficiencies realized as a result of the restructuring positioned UNAVCO to focus on completing all necessary corrective actions from the Business Systems Review conducted by the NSF Large Facilities Office in 2009. Those findings required a significantly increased focus on subaward monitoring and management, improved equipment monitoring and reporting, improved financial control and audit standards, award monitoring, documented processes for all aspects of human resource management, and substantially improved procurement documentation that includes small business utilization monitoring and documentation of vendor selection and oversight. These were all completed within the allocated 12 months, to the satisfaction of the LFO.

On the operational level, a complete review of internal controls by function was undertaken and control measures assessed for effectiveness and efficiency. UNAVCO strives for an appropriate mix of employee empowerment and accountability, resulting in adequate internal control that does not excessively burden operations. Processes continue to

Table 4-2. 2011 Management Review

2011 Panel Recommendation	UNAVCO implementation
(1) Because the scientific community served by UNAVCO is rapidly expanding beyond its core GPS users, UNAVCO management and governance should develop processes and take actions to ensure sufficient inclusivity of this broadening community.	• Develop member, investigator recruitment and support plan [ongoing] • Board to note the need for broad representation to Board Nominating Committee [done for 2012; ongoing] • Implement and populate the community member database for diversity metrics [piloted March 2012; full implementation for 2013] • Address discipline diversity in appointing the 2011 Membership Committee [committee charge revised]
(2) UNAVCO management and governance should develop a *proactive* strategic vision for expansion of the organization's services and competencies. UNAVCO should develop specific mechanisms for prioritizing potential new capabilities, and for identifying the resources required to provide services to end users of these capabilities comparable to those currently being provided to the GPS community.	• Refresh the strategic plan for GAGE proposal [completed 2011] • Continue Action Planning for annual implementation of the strategic plan for governance and staff [ongoing each February] • Schedule annual board review of emerging technologies [done] • Formalize strategic evaluation of new directions and technologies [process under review] • Develop an implementation plan when new technology is adopted, to address user outreach, user requirements, facility support, and required resources as appropriate [in place for TLS; tripod radar and seafloor geodesy on the "watch" list]
(3) UNAVCO management should place emphasis on assessing existing and new community needs for TLS, and should focus additional resources on bringing UNAVCO's TLS capabilities as rapidly as possible to the point that they can provide end users with research-grade data products.	• TLS users proposal, workshop, & report [complete] • Submit TLS implementation outline for sponsor review [completed 2011] • Charge the Facility Advisory Committee to review UNAVCO's role in INTERFACE [completed, but now evolving] • Interface II proposal submission [in progress, INTERFACE PIs] • Integration of TLS support into the next UNAVCO Cooperative Agreement [proposed here; field engineering support through efficiencies; new Geodetic Imaging manager on board]
(4) UNAVCO management and governance should take a greater and more proactive role in establishing international partnerships for geodetic research, data management and sharing, and capacity building.	• Formal planning of international goals and supporting activities [ongoing] • Develop an NSF-Research Coordination Networks proposal to support international collaboration for COCONet [RCN-SEES was not a fit; two PASI proposals pending, other resources identified] • UNAVCO geodesy short courses in international venues with a focus on foreign participation as funding allows [GAMIT in South Africa, Peru, and Nepal most recently; proposed here] • Outreach plan for associate member and other international partners, focused on centralized technical resources for international networks [Community Engagement Network proposed here (enGAGE), new External Affairs Director – August 2012; ongoing collaborations] • Use annual action planning process to strengthen efforts in international geodesy [annual, ongoing]
(5) UNAVCO management should partner at high levels with other closely allied organizations such as IRIS to develop effective information conduits to the public and policymakers.	• Seek guidance to resourcing this goal [External Affairs Director position created; filled, August 2012] • Establish dialog with associate member and other international partners, for technical resources and international networks [ongoing project embedded efforts (COCONet, Africa Array, COOPEUS); External Affairs Director appointed; enGAGE proposed here for 2013]

be targeted for automation of workflow and streamlining of process (electronic purchase requisitions, etc.) in ways that ensure access and accountability of all staff regardless of their geographic assignment.

Risk management addresses both technical programmatic as well as organizational risks. Risks to the PBO network operation are reviewed annually and documented in a risk register provided to the NSF program officer. Technical risks are assessed: critical equipment obsolescence, vendor risks (single supplier) and, staffing-related including employee and subawardee personnel with hard-to-replace domain expertise.

Risk is also assessed to support corporate viability. Corporate insurance programs are secured through a broker who conducts a semi-annual review with Business Affairs managers of operational needs and emerging threats. It was through this process that the opportunity to protect the TLS scanners with cost-effective insurance was identified and ultimately approved by NSF for the unique risks of high cost, highly mobile instruments. Corporate general liability, automobile, foreign travel, directors and officers liability and employment law insurance is maintained. At its most recent meeting, the board directed management to develop a financial exigency plan; this will be undertaken in the coming months.

A succession plan for key management positions is in place to protect the organization from the sudden loss of key personnel. The plan provides for prioritizing mentoring and training needs to sustain UNAVCO through unanticipated vacancies.

Business Systems for Public Stewardship

Most Business Systems controls are the purview of Business Affairs, which is primarily funded through the General & Administrative indirect cost pool. Combining effective staffing and right-sized control measures has allowed UNAVCO to maintain its historically low rate and not adversely impact program ability to complete award objectives. The organization chart shows the primary functions in Business Affairs.

An exhaustive NSF-LFO Business Systems Review of UNAVCO's administrative and financial practices during PBO construction (2003-2008) affirmed the need for changes; many were already in progress; UNAVCO was able to address and retire all of the concerns of the LFO within the allocated 12 months of the review. The administrative realignment has helped UNAVCO control the G&A rate, which is very competitive despite the erosion of base funding (Figure 4-1) and the enhancement of UNAVCO's compliance and accountability, marking the transition to a management culture that is professional, sustainable, and holds to the standard of self-examination and improvement for both right-size compliance and efficiency (Figure 4-2).

4.5 KEY BUDGET ASSUMPTIONS

The GAGE budget request totals $92,154,662 for the five-year period October 1, 2013 through September 30, 2018. This includes funding from NSF EAR, NSF-OPP, and NASA consistent with guidance received from the agencies and divisions and with known costs of operation. A management fee of $80,000 per year is included, also consistent with prior cooperative agreements.

UNAVCO's nearly ten-year operating history under its current management umbrella form the basis for developing the GAGE Facility budget for 2013 – 2018.

General: Costs for the five-year period 2013 through 2018 are based upon historical costs from nearly five years of experience with PBO Operations & Maintenance and the current UNAVCO Facility cooperative agreements. Multi-year averages were used to determine non-labor costs, and were adjusted for changes that are planned in GAGE. Cost escalation has been provided in out-years based upon Gross Domestic Product Deflator as recommended by the Office of Management and Budget ("OMB"). Accordingly, labor is escalated by 2.6% per year and non-labor budget elements by 2%. Sponsor guidance allows for 3% annual increases. For years two to five, the difference between these escalation factors and the 3% guidance is programmed for the increased costs of sustaining aging infrastructure, particularly within PBO.

Salaries are based upon current, ongoing staffing levels. Note that in years 4 and 5 of the current awards, UNAVCO is

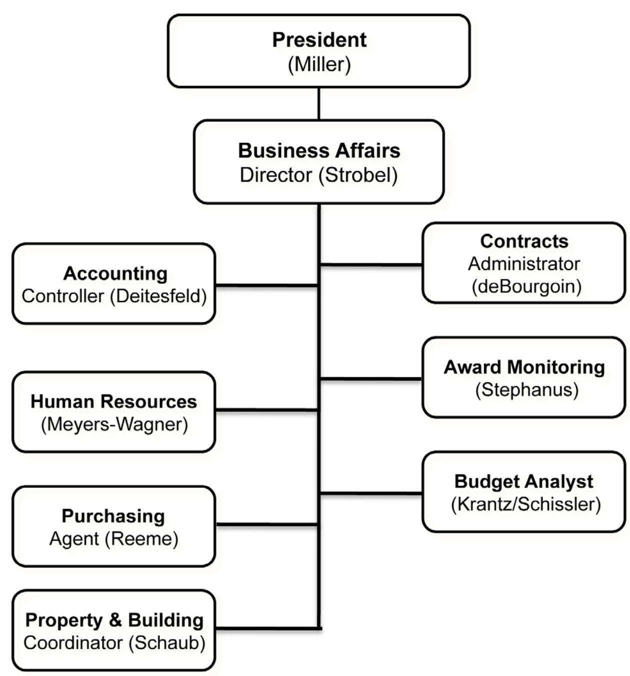


Figure 4-7. UNAVCO's Business Affairs Organizational Chart. Since 2008 and the end of PBO construction, Business Affairs has been realigned to meet ongoing organizational needs.

managing some surge capacity that was required to meet the needs of ARRA work and to make up deferred scope during the second half of the period of the current award. This surge FTE effort is excluded from the GAGE Facility budget. 2012 salaries are planned for annual adjustments of 2.6%, as noted above. UNAVCO is located in Boulder, CO with a number of other scientific organizations; the need for cost control exists in balance with retention risk for high caliber, highly trained staff members. Market surveys of salary increases in the area are performed each year and UNAVCO management recommends the salary pool adjustment required to retain skilled staff, for approval by the board of directors. The cost of increases to salaries of employees who demonstrate increased value to the organization is partially offset with turnover, if a departing staff member is replaced with a candidate lower in the salary grade for that position. The board and management are mindful of the tension between federal budget outlook, the need for cost control, and the mission impact of losing highly qualified technical staff.

The cost of benefits is applied to salaries based upon the expected fringe rate, which includes medical and retirement benefits, paid time off and payroll taxes. Benefits are assumed to increase at approximately the same rate as salaries and the percentage rate is therefore held to the 2012 level. When that assumption is not true, the cost of benefits shifts incrementally to the employee as is common in many employment sectors. UNAVCO uses a Professional Employment Organization ("PEO") that leverages medical and other benefit plans across approximately 250,000 employees and has allowed a competitive benefits package to be maintained cost effectively for staff in a half-dozen states.

Staff-driven costs that provide basic tools and professional development have been estimated on a per employee basis for consistency. Staff members are managed by unit and directorate, and associated costs vary by position and need (Table 4-5). Staff driven costs are included in the Management WBS elements for Geodetic Infrastructure (U1.1.1) and Geodetic Data Services (U1.2.1) and to the Education and Community Engagement element (U1.3) (Table 4-3).

Support staff of (3 FTE) systems administrators (servers, networks, etc.), (1 FTE) desktop help desk, (2 FTE) budget analysts, (2 FTE) administrative assistants and (1 FTE) award and subaward monitoring are shared by all programs. They have been allocated based upon a mix of headcount, servers, and managers supported.

Facility (occupancy) cost is approximately $950,000 per year and is allocated based upon space occupied by each program and/or sponsor program, including the G&A pool (Table 4-4). The pool cost includes an annual provision of approximately $150,000 to maintain the currency and efficiency of the computing infrastructure: data center back-up power and air handling, business system servers such as email and calendars, web-based meeting tools, etc. This level of ongoing investment has allowed UNAVCO to manage the impact of necessary upgrades in increments that do not adversely affect program operations.

4.6 FLEXIBLE STAFFING STRATEGY

Over the last decade, UNAVCO, Inc. has matured as a large facility, evolving from a series of affiliated projects into a cohesive organization capable of leveraging across programs, projects, technical specialties and techniques. Today, all key staff members (direct reports to the president) are in place, all but one of them new since the last cooperative agreements were initiated. As a result of the recent reorganization and greater horizontal transparency and communication at all levels in the organization, improved accountability, transparency and collaboration have been achieved.

Emerging Trends: Guided by consortium stakeholders, UNAVCO monitors demand for services in the community. We observe: 1) increasing calls for data products and visualization tools, 2) desire for real-time/high frequency data, 3) fewer PI short-duration campaigns and more long-term observations (networks to support), 4) new technologies (TLS) and 5) the drive to integrated data for use by multiple disciplines. Staff effort has been reallocated to meet these changing needs.

Known Impacts: As plans for the modernization of the PBO network evolve, the work of field engineering staff will change and may have workforce impacts. Staffing will evolve to meet the needs of an increasingly real-time PBO network, and evolving needs in other projects over the period of the cooperative agreement. Similarly, more PI network operations demands replace support formerly directed to campaigns. Real-time data handling and product development will require flexibility to respond to changes in techniques and practices.

Table 4-3. Annual Costs Related to Number of Staff.

Staff Driven Costs		$000's per year		
	Per FTE $	GI	GDS	ECE
Training (technical, management, skills, etc,)	$2,500	109.9	77.6	9.9
Desk/Laptop computers and related tools	$1,100	24.7	17.4	2.2
Cellular/Smart phone cost-share w/ employee	$840	9.7	6.8	0.9
Office and other supplies	$400	9.7	6.8	0.9

Table 4-4. Facility and Occupancy Charges.

Square Footage		Facilities Cost	
7,627	35.66%	$337,111	GDS-EAR
1,711	8.00%	$75,626	GDS-NASA
671	3.14%	$29,658	GI-Antarctic
671	3.14%	$29,658	GI-Arctic
6,039	28.24%	$266,922	GI-EAR
1,175	5.49%	$51,935	ECE
3,492	16.33%	$154,345	G&A pool
21,386	100.00%	$945,255	

In the technical programs, a deliberate recruitment strategy focuses on a staffing mix that balances geodesy or geosciences domain knowledge with high levels of technical expertise in software or infrastructure engineering, project management, or other areas of UNAVCO need. Such highly a qualified staff is capable of adapting to new requirements as work changes.

The staffing plan for GAGE totals 90 FTE, and excludes current surge capacity. Plans are to manage this workforce to meet evolving community needs and efficiencies for sponsors. A mix of management strategies now supports staffing in temporary, on-call and fixed-term positions, in addition to regular ongoing appointments. This mix provides flexibility to respond to evolving needs. Management is committed to aligning UNAVCO's work force with community needs using a flexible staffing model responsive to change. Each vacancy is reviewed in light of the potential to reconfigure duties for greater leverage, impact, efficiency, or enhancements to strategic direction. Targeted use of flexible positions will allow us to take on smaller projects that are outside the scope of the cooperative agreement (such as recent NASA ROSES efforts to enhance GPS, SAR, and LiDAR archives), without negative impact on core activities.

4.7 BUDGETING NON-LABOR

Non-labor costs have been estimated based on similar scope in the existing awards, planned initiatives and known changes. Where sufficient history is lacking, estimates are based upon vendor input or other resources available. Travel has generally been estimated on a per-trip basis, depending on usual lengths of stay and destinations.

Special Budget issues

Cloud Computing

A new initiative included in the budget is "cloud" computing. The "cloud" has become the term for remote storage and computational services, popularized in recent years by Apple, Amazon, Microsoft and other commercial entities. But UNAVCO is also "the cloud". UNAVCO cyberinfrastructure (servers and software) support community data storage and archiving provide web services-enabled data access, and make available computational resources and other services over the Internet. In order to assess offsite cloud resources for cost effectiveness, convenience, broader access, reliability, and security, UNAVCO has explored commercial and academic options.

The first venture was with the European Space Agency's Centre for Earth Observation (ESRIN), the source of Envisat and ERS SAR data for WInSAR and Supersites. ESRIN contracts Level 3 for cloud storage services and UNAVCO manages the content including uploading SAR images for distribution for Supersites. Once in the Level 3 cloud, data are replicated to servers around the world to provide high-speed access to international Supersites users. This cloud service has proven to be effective for ESRIN purposes but relatively costly. ESRIN is pursuing other longer-term cloud options as part of a new project "Helix Nebula – the science Cloud". UNAVCO will continue to work with ESRIN as the concept is realized.

Closer to home, UNAVCO is also pursuing for PBO and GAGE cloud computing options from the San Diego Supercomputing Center (SDSC). SDSC has partnered with UNAVCO in a number of projects (GEON, NASA ROSES, OpenTopography, and GeoEarthScope) and is a leader in academic cloud research and services. SDSC Cloud Storage services, available to academic and research partners, are designed to be a convenient and affordable way to store, share, and archive data, including extremely large data sets such as UNAVCO's.

A pilot project for backup of real-time streaming data from PBO on the SDSC Cloud is under way. Reliability, access speeds, and other metrics will be assessed and evaluated. UNAVCO contributes to SDSC's cloud research project as a large-scale user. SDSC provides UNAVCO a significant value – expert support to ensure long-term security of data and advance notice on service changes. For GAGE we anticipate a positive pilot outcome and have budgeted long-term cloud

Table 4-5 PBO 5-Year Equipment Investment.

PBO 5-year Equipment Investment	GFY14 Units	GFY14 Dollars	GFY15 Units	GFY15 Dollars	GFY16 Units	GFY16 Dollars	GFY17 Units	GFY17 Dollars	GFY18 Units	GFY18 Dollars	Total Units	Total Dollars
Equipment (unit price over $5,000)												
GNSS Capable (receiver and antenna)	49	$394,842	64	$526,026	80	$670,683	96	$820,917	112	$976,891	401	$3,389,359
Fuel Cell	3	$33,357	3	$34,024	3	$34,705	3	$35,399	3	$36,107	15	$173,591
Tiltmeters	1	$8,517	1	$8,687	1	$8,861	1	$9,038	1	$9,219	5	$44,323

Table 4-6. GAGE Budget by WBS Element.

U1. GAGE	GFY14	GFY15	GFY16	GFY17	GFY18	Total
	$17,359,404	$17,875,665	$18,414,462	$18,968,117	$19,537,014	$92,154,662
U1.1 GAGE Geodetic Infrastructure (GI)	$10,909,000	$11,278,532	$11,667,036	$12,066,742	$12,477,950	$58,399,260
U1.1.1 GI Management	$973,837	$995,576	$1,017,808	$1,040,546	$1,063,799	$5,091,567
U1.1.2 GI Governance	$14,400	$14,688	$14,982	$15,281	$15,587	$74,938
U1.1.3 GI PI Project Support	$940,807	$963,853	$987,469	$1,011,670	$1,036,471	$4,940,269
U1.1.4 GI NASA	$206,533	$211,727	$217,054	$222,515	$228,115	$1,085,944
U1.1.4.2 GI NASA GGN O&M	$206,533	$211,727	$217,054	$222,515	$228,115	$1,085,944
U1.1.5 GI Arctic	$636,737	$652,123	$667,886	$684,035	$700,579	$3,341,360
U1.1.6 GI Antarctic	$719,970	$737,123	$754,690	$772,682	$791,109	$3,775,573
U1.1.7 PBO Component (GPS OPS)	$5,904,036	$6,157,881	$6,427,977	$6,706,491	$6,993,652	$32,190,038
U1.1.7 Labor, Fringe	$1,833,956	$1,881,639	$1,930,561	$1,980,756	$2,032,255	$9,659,167
U1.1.7 Travel	$488,591	$498,363	$508,330	$518,497	$528,867	$2,542,648
U1.1.7 Equipment, Material, and Supplies	$1,021,370	$1,165,085	$1,322,523	$1,485,793	$1,655,065	$6,649,837
U1.1.7 Communication	$715,586	$729,898	$744,496	$759,386	$774,573	$3,723,938
U1.1.7 Helicopter	$435,000	$443,700	$452,574	$461,625	$470,858	$2,263,757
U1.1.7 Other Costs, R-Offices, Trucks, Permitting, Storage etc.	$763,908	$779,186	$794,770	$810,665	$826,879	$3,975,409
U1.1.7 Indirect	$645,625	$660,011	$674,723	$689,768	$705,155	$3,375,282
U1.1.8 PBO Component (Borehole Instrumentation OPS)	$1,210,979	$1,237,838	$1,265,302	$1,293,386	$1,322,104	$6,329,608
U1.1.8 Labor, Fringe	$387,878	$397,963	$408,310	$418,926	$429,818	$2,042,897
U1.1.8 Travel	$161,126	$164,349	$167,636	$170,988	$174,408	$838,506
U1.1.8 Equipment, Material, and Supplies	$332,297	$338,943	$345,722	$352,636	$359,689	$1,729,286
U1.1.8 Other Costs (Communications, R. Office, Indirect etc.)	$329,678	$336,583	$343,635	$350,835	$358,189	$1,718,920
U1.1.9 PBO Component (Long Baseline Strainmeter)	$301,700	$307,723	$313,868	$320,138	$326,534	$1,569,963
U1.1.9.1 UCSD SIO Subaward	$292,348	$298,128	$304,023	$310,037	$316,170	$1,520,705
U1.2 GEODETIC DATA SERVICES (GDS)	$5,647,205	$5,776,803	$5,909,554	$6,045,538	$6,184,832	$29,563,932
U1.2.1 GDS Management	$804,869	$822,316	$840,148	$858,371	$876,997	$4,202,702
U1.2.2 GDS Governance	$25,700	$26,214	$26,738	$27,273	$27,819	$133,744
U1.2.3 GDS Data Operations (Ingest/Preprocessing)	$1,143,767	$1,172,860	$1,202,696	$1,233,295	$1,264,676	$6,017,293
U1.2.3 Labor,Fringe	$913,884	$937,645	$962,023	$987,036	$1,012,699	$4,813,287
U1.2.3 Other	$229,883	$235,215	$240,673	$246,259	$251,977	$1,204,007
U1.2.4 GDS Data Products & Services (Processed Results QA/QC)	$1,490,436	$1,519,894	$1,550,066	$1,580,970	$1,612,624	$7,753,991
U1.2.4 Labor,Fringe	$705,890	$724,243	$743,073	$762,393	$782,215	$3,717,813
U1.2.4 Subawards	$511,788	$517,139	$522,596	$528,163	$533,842	$2,613,528
U1.2.4 Other	$272,758	$278,513	$284,397	$290,414	$296,567	$1,422,650
U1.2.5 GDS Data Management & Archiving (Distribution and Curation)	$879,417	$900,706	$922,512	$944,847	$967,724	$4,615,206
U1.2.6 GDS Information Technology (SA and WA)	$289,720	$297,102	$304,674	$312,439	$320,403	$1,524,338
U1.2.7 Cyber-Infrastructure	$208,380	$213,721	$219,200	$224,819	$230,582	$1,096,702
U1.2.8 GDS NASA	$798,961	$817,879	$837,253	$857,092	$877,408	$4,188,592
U1.2.8.1 GDS NASA Management	$366,131	$374,144	$382,336	$390,710	$399,270	$1,912,592
U1.2.8.2 GDS NASA GGN Data Operations	$209,018	$214,378	$219,877	$225,516	$231,301	$1,100,090
U1.2.8.3 GDS NASA Support of the IGSCB	$130,626	$134,011	$137,485	$141,048	$144,704	$687,873
U1.2.8.4 GDS NASA Information Technology	$93,186	$95,345	$97,555	$99,818	$102,133	$488,038
U1.2.9 GDS Arctic	$2,991	$3,069	$3,148	$3,230	$3,314	$15,752
U1.2.10 Antarctic	$2,964	$3,041	$3,121	$3,202	$3,285	$15,613
U1.3 EDUCATION AND COMMUNITY ENGAGEMENT (ECE)	$723,199	$740,330	$757,872	$775,836	$794,233	$3,791,470
U1.3.1-7 ECE NSF - EAR	$621,951	$636,684	$651,770	$667,219	$683,040	$3,260,664
U1.3.8 ECE NASA	$43,392	$44,420	$45,472	$46,550	$47,654	$227,488
U1.3.9 ECE Arctic	$28,928	$29,613	$30,315	$31,033	$31,769	$151,659
U1.3.10 ECE Antarctic	$28,928	$29,613	$30,315	$31,033	$31,769	$151,659
MANAGEMENT FEE	$80,000	$80,000	$80,000	$80,000	$80,000	$400,000

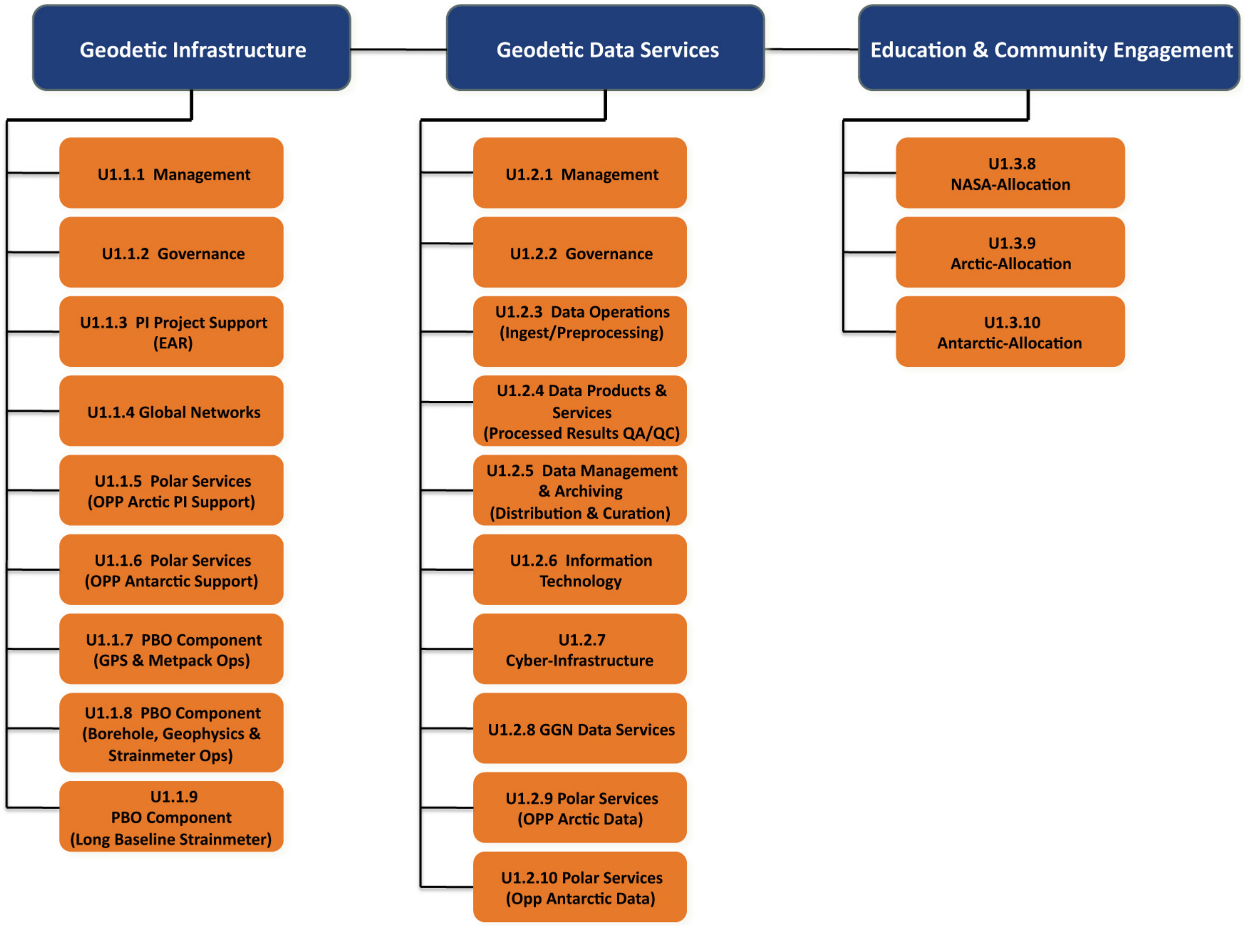


Figure 4-8. Work Breakdown Structure (WBS). The WBS provides a framework for tracking, charging, and reporting effort for each task. The structure for the GAGE Facility, here shown to level 3, identifies specific tasks under each of the major areas of work, as well as elements for charging to non-EAR tasks. The next level of the GI and GDS WBS details tasks for each of the contributing sponsors in OPP and NASA, providing transparency and task reporting for those elements and alignment of tracking and charging practices.

storage at SDSC. The initial goal is to assess and migrate to cloud storage for back-up archiving. The possibility of cloud storage for primary storage, now hosted at UNAVCO, will be evaluated for economies in this quickly changing landscape.

A second component is cloud computing – using remote computers for processing, analysis, and other applications. UNAVCO currently has 50+ servers performing the tasks required to operate the data center. In anticipation of GAGE, UNAVCO is systematically migrating from SUN servers and Operating System ("OS") to standardized Virtual Machines ("VM") that can operate any OS. This will not only allow more efficient management of server resources, but will enable transfer to remote VM cloud computing services. Cloud computing and storage landscapes are evolving rapidly. UNAVCO is moving cautiously but steadily to evaluate cloud services in order to optimize their capabilities.

Earthscope/PBO network sustainability and upgrade: As part of the work of the GAGE Facility, the UNAVCO community will develop its recommendation for the future of PBO beyond the initial 15-year plan for Earthscope. UNAVCO staff anticipates that a significant portion of the PBO will be recommended for continued operation beyond 2018; requiring upgrades of existing GPS-only instruments and ancillary equipment in the PBO network. The current PBO site configuration standard includes a Trimble NetRS GPS receiver that has already reached "end-of-life" and will reach "end-of-service" by early 2014, well before the end of the 15-year plan period. It will no longer receive support or service including spare parts or firmware upgrades responsive to the changing GNSS environment from Trimble. As of the time of this submission, Trimble no longer supports any firmware updates for the NetRS. Therefore, a plan to renew selected receivers to sustain PBO to 2018, and to position successor projects is under development. This process will involve the UNAVCO science community and governance, and EarthScope Science Committee. UNAVCO staff will track detailed technical documentation for different receiver brands, types, and features (for example, whether to switch on GLONASS data acquisition), the impact of upgrading choke ring antenna elements, as well as an evaluation of the data quality metrics for specific sites within PBO, but the plan will be driven by community science goals.

Selection of the "next generation" PBO receiver and the appropriate time to adopt a new standard depends on future developments of the constellations of navigation satellites (GNSS) as well as the capability to demonstrate that using these enhanced signals will improve site position precision. Receiver testing options will be conducted with the objective to develop a replacement recommendation during 2013. A science-driven plan for updating the PBO will be shaped by governance. In parallel with site prioritization, another process to evaluate various receivers, will led by UNAVCO Development & Testing staff will inform the decision regarding the timing and necessity of upgrading from GPS-only to GNSS-enabled receivers and antennae.

Equipment price estimates, particularly for GPS/GNSS receivers, are based upon current pricing. It is anticipated that once the testing of next generation receivers is complete and an informed plan for how and when to upgrade the PBO network is also complete, an new agreement can be negotiated with the manufacturers for prices and quantities, which may be more advantageous than currently available pricing. In this proposal, current pricing for Trimble R9 GNSS receivers is used. Any leverage that comes out of the new vendor competition will enhance upgrade plans. Below we summarize an annual plan under GAGE that results in a total of 406 PBO site upgrades by 2018.

The Work Breakdown Structure (WBS), detailed in Supplementary Documentation, was developed in conjunction with IRIS, the sister consortium in Earthscope (Figure 4.8). The WBS provides a structure to track and charge the work planned for the GAGE Facility (Figure 4.6). At the highest level, it reflects the UNAVCO program structure. Within each program, the structure identifies core tasks required to sustain geodetic observations and infrastructure, data systems and services, while providing transparency to individual sponsor agencies that contribute to the cooperative agreement. ECE activities are more cross-cutting in nature and the small program does not warrant differentiation of tasks. Program work will be proportionally allocated to each sponsor, to appropriately reflect the benefit of the work.

4.8 ACRONYMS USED IN GAGE PROPOSAL

ASTER: Advanced Spaceborne Thermal Emission and Reflection Radiometer

BARGEN: Basin and Range Geodetic Network

BASC: Barrow Arctic Science Consortium

BIFROST: Baseline Inferences for Fennoscandian Rebound Observations, Sea level, and Tectonics

BINEX: Binary Exchange Format

BSM: Borehole Strainmeter

CBN: Cooperative Base Network

CCSDS: Consultative Committee for Space Data Systems

CDDIS: Crustal Dynamics Data Information System

cGPS: Continuous GPS

COCONet: Continuously Operating Caribbean GPS Observational Network

CONACyT: Consejo Natcional de Ciencia y Tecnologia, the National Council on Science and Technology (Mexico)

COOPEUS: COOPeration between Europe and US initiative

COSMO-Skymed: COnstellation of small Satellites for the Mediterranean basin Observation

CRREL: U.S. Army Cold Regions Research and Engineering Laboratory

CRTN: California Real Time Network

CSR: Center for Space Research

CU: University of Colorado

CUAHSI: Consortium of Universities for the Advancement of Hydrologic Science, Inc.

CWU: Central Washington University

DAAC: Distributed Active Archive Center (NASA)

DAC: Data Archive Center

DAI: Data Archive Interface

DESDynI: Deformation, Ecosystem Structure and Dynamics of Ice

DLR: Deutsches Zentrum fur Luft- und Raumfahrt (German Aerospace Center)

DOI: Digital Object Identifier

DORIS: Doppler Orbitography and Radiopositioning Integrated by Satellite

DSL: Digital Subscriber Line

DSN: Deep Space Network

EAR: Division of Earth Sciences (NSF)

ECE: UNAVCO Education and Community Engagement Program

ECMWF: European Centre for Medium-range Weather Forecasts

EDC: EROS Data Center

EGU: European Geosciences Union

enGAGE: Proposed online portal for the GAGE Facility

EROS: Earth Resources Observation System

ERS-1, -2: European Remote Sensing satellite 1 or 2

ESA: European Space Agency

ESCI: EarthScope Cyberinfrastructure Preliminary Strategic Plan

ESNO: EarthScope National Office

ESSP: Earth System Science Partnership

ETS: Episodic Tremor and Slip

EUREF : IAG Reference Frame Sub-Commission for Europe

FA: Flexible Array

FTE: Full-Time Equivalent

FTP: File Transfer Protocol

FY18: Fiscal Year 2018

GAGE: Geodesy Advancing Geosciences and EarthScope

GAMIT: GPS Analysis MIT GPS Processing Software

GBIR: Ground Based Interferometric Radar

GCOS: Global Climate Observing System

GDS: UNAVCO Geodetic Data Services

GEO: Group on Earth Observations

GeoPRISMS: Geodynamic Processes at Rifting and Subducting Margins

GEOSS: Global Earth Observation System of Systems

GGN: NASA Global GNSS Network

GGOS: Global Geodetic Observing System

GI: UNAVCO Geodetic Infrastructure Program

GIA: Glacial Isostatic Adjustment

GIPSY: GNSS-Inferred Positioning System, JPL

GLISN: Greenland Ice Sheet Monitoring Network

GLOBK Global Kalman: MIT Space Geodesy Combination Analysis Software

GLONASS: Globalnaya Navigatsionnaya Sputnikovaya Sistema/GLObal NAvigation Satellite System

GMT: Generic Mapping Tools

GNET: Greenland Network

GNSS: Global Navigation Satellite System

GOES: Geostationary Operational Environmental Satellite

GPS-A: GPS-Acoustic for seafloor geodesy

GPS: Global Positioning System

GRACE-II: Planned GRACE follow-on satellite (next generation)

GRACE: Gravity Recovery and Atmospheric Change Experiment

GREAT: GPS Real Time Earthquake And Tsunami alert system

GRGS: Groupe de. Recherche de GÈodÈsie Spatiale

GSA: Geologic Society of America

GSAC: Geodesy Seamless Archive Centers

GSFC: Goddard Space Flight Center

GTOPO30: Global Digital Elevation Model at 30 arc seconds resolution

IAG: International Association of Geodesy

ICESat: Ice, Cloud, and land Elevation SATellite

ICESat-II: Planned ICESat follow-on satellite (next generation)

IDS: International DORIS Service

IEEE: Institute for Electrical and Electronics Engineers

IERS: International Earth Rotation and Reference Systems Service

IGCP: International Geoscience Programme

IGS: International GNSS Service

IGSCB: IGS Central Bureau

IHOP: International H2O Project

IJ05 Ivins and James ice model for Antarctica (2006)

ILRS: International Laser Ranging Service

InSAR: Interferometric Synthetic Aperture Radar

INTERFACE: INTERdisciplinary Alliance for Digital Field Data ACquisition and Exploration, a science community collaboration for TLS implementation

IPCC: Intergovernmental Panel on Climate Change

IRIS: Incorporated Research Institutions for Seismology, an NSF-EAR facility

IRIS DMC: IRIS Data Management Center

IT: Information Technology

ITRF: International Terrestrial Reference Frame

IUGG: International Union of Geodesy and Geophysics

IVS: International VLBI Service

JAXA: Japan Aerospace Exploration Agency

JPL: NASA Jet Propulsion Lab

LARISSA: LARsen Ice Shelf System

LAS: LiDAR Access System

LiDAR: LIght Detection and Ranging

LOS: Line-of-Sight between a geodetic instrument and its target

LSM: Laser Strainmeter

MDM: Metadata Management System

MEMS: Micro-Electro-Mechanical Systems

miniSEED: SEED format without header information

MIT: Massachusetts Institute Technology

MP1: Multipath (GPS L1)

MREFC: NSF Major Research Equipment and Facilities Construction program

MRI: NSF Major Research Instrumentation program

NAME: North American Monsoon Experiment

NASA: National Aeronautics and Space Administration

NCALM: National Center for Airborne Laser Mapping, an NSF-EAR facility

NCEDC: Northern California Earthquake Data Center

NDVI: Normalized Difference Vegetative Index

NEPAD: New Partnership for Africa's Development

NLAS: NASA ROSES LiDAR Access System

NMT: New Mexico Institute of Mining and Technology

NOAA: National Oceanic and Atmospheric Administration

NRC: National Research Council

NROES: New Research Opportunities in the Earth Sciences, NRC report

NSF: National Science Foundation

NSIDC: National Snow and Ice Data Center

NSTA: National Science Teachers Association

OAIS: Open Archival Information System

OASIS: Orbit Analysis Simulation Software

OEDG: Opportunities for Enhancing Diversity in the Geosciences (grant designation)

OOI: Ocean Observatory Initiative, an NSF-MREFC facility new start

OPP: Office of Polar Programs

OT: OpenTopography, an NSF-EAR facility

PANGA: PAcific Northwest Geodetic Array

PBO-H2O: Plate Boundary Observatory Water Cycles studies

PBO: Plate Boundary Observatory, the geodetic component of EarthScope built and operated by UNAVCO

PI: Principal Investigator

POD: PBO Operational Database

POLENET: Polar Earth Observing Network

PRN: Pseudorandom noise (Unique GPS Satellite Transmitted Code)

PVW: Precipitable water vapor

QC: Quality Control

RADARSAT: constellation of SAR satellites

RAID: Redundant Array of Independent Disks

RAMADDA: Repository for Archiving, Managing and Accessing Earth Sciences Data

RAPID: Rapid Response Research (NSF grant designation)

RESESS: Research Experiences in Solid Earth Science for Students

RINEX: Receiver Independent Exchange Format

ROSES: Research Opportunities in Space and Earth Sciences (NASA)

RT-GPS: Real-time GPS (1 Hz or more frequent sampling, 1 s or less latency)

SAC: Seismic Analysis Code

SAFOD: San Andreas Fault Observatory at Depth

SAGE: Seismology Advancing Geosciences and EarthScope

SAR: Synthetic Aperture Radar

SCEC: Southern California Earthquake Center

SCIGN: Southern California Integrated GPS Network

SCP: secure copy

SEED: Standard for the Exchange of Earthquake Data

SEEDLink: SEED data transfer protocol

SERC: Science Education Resource Center, Carlton College

SIO: Scripps Institution of Oceanography

SIR-C/X-SAR: Spaceborne Imaging Radar-C/X-band Synthetic Aperture Radar

SLR: Satellite Laser Ranging

SMN: Servicio Meteorológico Nacional. México; Mexico's national weather service.

SMO: SAFOD Management Office

SNOTEL: SNOw TELemetry

SOARS : Significant Opportunities in Atmospheric Research and Science

SOPAC: Scripps Orbit and Permanent Array Center

SSAI: Science Systems and Applications

SSARA: Seamless SAR Access (NASA ROSES award to UNAVCO)

SUOMINet: Mid-continent and Caribbean CGPS network focused on meteorological and severe weather observations in near real-time.

SWE: Snow Water Equivalence

TA: Transportable Array

TB: Terabytes

TEC: Total Electron Content of the ionosphere

teqc : Translation, Editing, Quality Checking software from UNAVCO

TerraSAR-X: German X-band SAR Satellite (not an acronym)

TLALOCNet: Trans-boundary Land and Atmosphere Long-term Observational and Collaborative Network

TLS: Terrestrial Laser Scanning

TOPEX/Poseidon: Laser altimetry satellite to map the sea surface and topography

TOTLE: Teachers on the Leading Edge

UCAR: University Corporation for Atmospheric Research

UCERF3 : Uniform California Earthquake Rupture Forecast v3

UNAVCO : Originally University Navstar Consortium, now simply UNAVCO, an NSF-EAR facility

UNFCCC: United Nations Framework Convention on Climate Change

UNR: University of Nevada-Reno

URL: Uniform Resource Locator

USArray: Seismic component of EarthScope, managed by IRIS

USC: University of Southern California

USGS: U.S. Geological Survey

VEI: Volcanic Explosivity Index

VLBI: Very Long Baseline Interferometry

VRS3: Trimble RT-GPS Software

VSAT: Very Small Aperture Terminal

WBS: Work Breakdown Structure

WInSAR: Western North America InSAR Consortium

WISSARD: Whillans Ice Stream Subglacial Access Research Drilling

XML: Extensible Markup Language

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i. Work Breakdown Structure Dictionary and Personnel Table

Work Breakdown Structure Dictionary

NSF selected Work Breakdown Structure, a Project Management Institute standard, as the budgeting methodology for GAGE. The purpose of the Work Breakdown Structure Dictionary is to define all the elements of the work included in the proposal and to substantiate the basis of estimate for each item. It is designed to organize the scope and associated budget into agreed upon categories to facilitate efficient and transparent management of both scope and budget.

This UNAVCO project management tool was foundational to the success of EarthScope PBO construction, and has been implemented throughout Operations and Management. There are nuances in extending this tool to all of the activities planned under the GAGE Facility and UNAVCO's new, integrative organizational structure. In particular, the need to track and cost tasks by each of GAGE's four sponsor programs adds complexity to the WBS. We recognize the need to implement a program-level overarching task and an allocation basis for program-wide tasks to support each of the programs: Geodetic Infrastructure, Geodetic Data Services, and Education and Community Engagement.

For budgeting purposes, we have made simplifying assumptions in the interests of transparency. Most of the management effort in GI is driven by the work for EAR, OPP-Arctic, and OPP Antarctic. Most of the management effort for GDS benefits EAR and NASA. Whereas ECE brings benefit to all sponsors of the GAGE Facility. We have based the Management task under each of these programs to reflect these planned efforts and the beneficiary sponsor.

To first order, the WBS presents a hierarchy wherein budgets are summarized at each level, but all dollars are estimated at the lowest level of the structure. Therefore, each summary level contains only the sum of the lower elements. Note that in the case of ECE, however, there is a single task because of the size and simplicity of the program (WBS 1.3). The allocations to non-EAR sponsors are applied as a percentage to the overall allocation at the third WBS level. EAR, which funds 86% of the program (as the EAR proportion of GAGE), is not specifically called out at level 3. The EAR contribution is the difference between the WBS 1.3 rollup and the proportional allocations NASA, OPP-Arctic and Antarctic. This plan will have negligible impact on sponsors, who previously supported this program as part of UNAVCO's overall indirect cost rate.

In practice, between now and the onset of the GAGE Facility cooperative agreement, we will track current work under UNAVCO's new organizational structure to the WBS proposed here to confirm the appropriate basis for allocation. If needed, we will refine the implementation to ensure that each sponsor will receive the full benefit and appropriate allocation for each Management task (WBS 1.1.1, 1.2.1, and 1.3.1) as budgeted in this proposal. Any refinement will build on the successful implementation of WBS project management during EarthScope construction as well as Operations and Management, and the multi-sponsor work of the UNAVCO Facility under a WBS that incorporates accountability to a mix of sponsors.

Below, the dictionary provides the definition of the scope in each element and an explanation of the basis of estimate used to develop the budget, for each element of the WBS. The bases of estimate describe the elements of cost and how the dollar amount of each estimate was derived.

U1. THE GAGE FACILITY (GEODESY ADVANCING GEOSCIENCES AND EARTHSCOPE)

Definition: The highest summary of the work to be performed by UNAVCO under GAGE combines tasks previously performed under two Cooperative Agreements and includes the mission of NSF-EAR, NSF-OPP and NASA for the UNAVCO community facility and the PBO mission of Earthscope. The WBS includes three program areas as shown in Table 1.

Table 1. WBS Dictionary

WBS Reference	Description	FTE
U1.1	Geodetic Infrastructure	44
U1.2.	Geodetic Data Services	33
U1.3.	Education and Community Engagement	4
Details of FTE in the various program areas by scope and sponsor is included in WBS Dictionary Appendix 1.		

Basis of Estimate: No cost is estimated at this level. It represents the sum of the scope and budget included in the detailed estimates and work breakdown structure below.

U1.1 Geodetic Infrastructure (see Part I, Section 3.1)

Definition: This is one of three program directorates in the UNAVCO organization. It includes the following areas of responsibility: construction, operation and maintenance of permanent networks of GPS and borehole instruments (e.g., PBO, COCONet); coordination and execution of PI campaign projects and support of PI networks (i.e., Africa Array, POLENet); development and testing of instrumentation, monuments, power systems and communications; field support for the Arctic and Antarctic programs of NSF; and logistical support of all field operations.

Basis of Estimate: The estimates for each task under this element are described more fully below by WBS element (See Table 2). Staffing requirements have been estimated from the currently assigned employee base and periodic use of shared staff from other projects. Shared staff members

Table 2. Summary of Geodetic Infrastructure Task Elements

U1.1.1	Management	Resources that benefit the entire Geodetic Infrastructure WBS task including direction of GI activities and administrative and budget support.	(3.7 FTE)
U1.1.2	Governance	Geodetic Infrastructure Advisory Committee, PBO Working group advisors to program.	(none)
U1.1.3	PI Project Support	Field support to PI projects funded by NSF and/or NASA.	(6.7 FTE)
U1.1.4	NASA GNSS Networks	Field support for NASA's GNSS networks.	(1.4 FTE)
U1.1.5	Polar Services (Arctic)	Field support of OPP Arctic program and PI's	(4.05 FTE)
U1.1.6	Polar Services (Antarctic)	Field support of OPP Antarctic program and PI's.	(4.25 FTE)
U1.1.7	PBO GPS Operations	Operation and maintenance of 1112 permanent GPS stations in PBO.	(19.45 FTE)
U1.1.8	PBO Borehole Geophysics	Operations & maintenance of borehole strainmeters, seismometers and tiltmeters.	(4.1 FTE)
U1.1.9	Long Baseline Strainmeter	Operate & maintain 6 laser strainmeters in Cooperative Agreement (by subaward).	(0.05 FTE)
		Total Geodetic Infrastructure Total:	(44 FTE)

are not double-counted; they are decremented from primary assignments if they have been assigned in other areas. Where deviations from historical averages are also made, the rationale has been provided for such a decision.

U1.1.1 GI Management (See Part I, Section 3.1)

Definition: Management includes activities that benefit the entire Geodetic Infrastructure WBS task. Included are directing the various engineering efforts, interacting with and preparing reports for NSF Program Officers, project advisory and UNAVCO governance committees, reporting of technical and financial information and the support staff to enable these high level responsibilities to be met. Key elements are:

- Geodetic Infrastructure ("GI") director, administrative, support staff (budget analysis, system administration (IT) and administrative assistance), travel, office supplies, cell phones and other costs to support the productivity of the same staff members are included.
- Employee/manager training, office supplies, computers, cell phones and office and warehouse space in Boulder for all GI staff.

Basis of Estimate - *Labor (3.5 FTE):* The GI director is included at 0.9 FTE for GAGE with the remaining 0.1 FTE assumed charged to other projects and the bid & proposal account (in accord with current Cooperative Agreement and charging practices).

Of this 0.9 FTE, 0.7 of the director is charged to this task with the remaining 0.2 being charged to polar services. A total of 2.8 FTE of support staff are allocated to this task. Managers who supervise the line staff are included in the WBS elements where their efforts are directed. Responsibilities are the supervision of tasks and personnel as well as the direct effort of domain expertise in their area.

Other Costs: Certain staff-driven costs are included in this management element. The per person estimates were developed based upon average cost from the two existing cooperative agreements with NSF. Computers and phones are presumed every three years, with $1100 per staff member provided each year. Cell phone monthly cost is estimated at an average $70 per employee, which is the average based on UNAVCO's cost sharing policy with staff.

Office expense includes space occupied in the Boulder facility for both offices and warehouse and logistical support for EAR, OPP, and NASA projects, which is allocated entirely to GI, resulting in an annual allocation of $326,328, with $29,658 allocated to OPP-Arctic and the same to OPP-Antarctic.

Employee training (except field-specific training such as helicopter or bear safety) is included in this task at an annual average of $2500 per person. Also included are management, technical and policy training for all personnel consistent with position responsibilities and to support career and professional development. This estimate is based upon recent experience as UNAVCO has made deliberate investments in various training programs. It further assumes a successful pilot for leadership development training coordinated with UCAR, NEON and other NSF large facilities.

Travel: The travel budget of $46,609 is based on history. $24,109 is the director travel budget and includes $6,000 of international travel. $22,500 is for monitoring visits to subawardees and/or the NSF permitting trips to remote office and field sitesIT support of the remote office, and IT systems.

U1.1.2 GI Governance (See Part II, Section 1.1)

Definition: The advisory groups provide community input to both management and the UNAVCO board of directors. A board member is designated as liaison to each advisory committee. Advisory groups help prioritize UNAVCO efforts based on developments in science, technology and public interest. All advisory group members serve without compensation. While governance is being reconfigured with the concurrence of the UNAVCO board of directors and management, it is anticipated that there will be two advisory committees to this directorate: Geodetic Infrastructure Advisory Committee (AC) and a PBO Working Group.

Basis of Estimate: *Participant Support:* The Geodetic Infrastructure AC is expected to have nine members and meet once a year at a cost of $8,100 ($900 per member) and the PBO working group to be comprised of seven members who meet once a year for $6,300 ($900 per member). This is based upon forecasted airfare from various consortium member locations to Denver, plus hotels and meals. Additional meetings are conducted by telecom, with minor costs solely related to the maintenance of appropriate toll-free telecommunications accounts by UNAVCO.

U1.1.3 EAR PI Project Support(See Part I, Section 3.1.2)

Definition: PI Project support includes comprehensive project technical support services to UNAVCO community principal investigator ("PI") funded projects centered on acquiring, distributing, archiving and applying high precision geodetic data. These services range from technical proposal planning and budgeting, in-field engineering services for permanent station deployments, data collection, technical training and on call support. In addition, PI Project support includes NSF-EAR asset management and equipment loans, testing, repair, configuration, integration, and development of new equipment designs for specific PI projects. PI Project support also includes operations and maintenance ("O&M") in coordination with PIs and local collaborators for continuously operating stations installed by PIs, primarily with independent NSF and NASA funding. In GAGE, the EAR PI and PBO receiver pools will be merged and jointly managed to achieve maximum efficiency in response to community demand,

Basis of Estimate: *Labor (6.70 FTE)*: Led by a manager (1 FTE) who coordinates the work of 3.3 FTE field engineers and 1 FTE technician, who together support an average of 110 PI projects each year. Allocated to the task are 0.25 FTE for TLS field support expertise, and 1.15 FTE who perform development and testing tasks. (See cross cutting D&T description). Staff currently supports 561 PI cGPS stations for O&M as a consequence of growth of approximately 50 new sites per year. The technician repairs approximately 120 receivers per year.

Equipment, Materials, and Supplies: Ten receiver replacements/additions to the PI receiver pool are planned plus additional costs to outfit them appropriately for campaign surveys; engineering tools and small hardware for PI GPS stations. This consists of one GNSS capable receiver and antenna set per year as equipment($8,058) and $151,051 in materials and supplies, including the 10 replacement pool receivers with required peripherals such as wires, cables, cases, etc., whose value is under $5,000. This is based on the past Cooperative Agreement's average annual costs for these activities, projected replacement needs and actual per unit cost experience from the past Cooperative Agreement.

Travel: $8,400 per year is estimated for domestic travel to meetings, conferences and workshops to support interactions with the PI community. International travel is planned at $3,000 per year to attend one science meeting.

Other Costs: $9,000 is included for insurance for TLS scanners (approved by NSF) and $17,000 for ownership, maintenance and fuel of a field vehicle. The remaining $12,530 includes field communications, shipping of receivers and parts, and other needs to support PI campaigns based upon 4 years of recent history.

U1.1.4 NASA Global GNSS Networks (GGN) (See Part I, Section 3.1.1)

Definition: Engineering support to NASA GGN includes operation, maintenance and upgrading of 61 GNSS field stations around the world, and installation of new stations when required. Tasks include basic operations, budget management, hardware and computer configuration and shipping, coordination with local station operators, and field visits.

Basis of Estimate - *Labor (1.9 FTE):* Staff consists of 0.5 FTE shared with NASA Development and Testing and 0.5 FTE shared with NASA GGN Data Services, managed by 0.25 FTE with network and engineering expertise and supported with 0.15 FTE test engineer. Staffing is based on historic levels needed to successfully operate the GGN. The shared resources provide the specific network knowledge to support the NASA stations and perform development and testing to maintain highest standards demanded by the GGN. See development and testing cross-cutting description.

Equipment ($8,058), Materials and Supplies ($10,332), Travel ($5,008) and Other ($1,196): Costs are projected to be consistent with recent expenditures, and include shipping, replacement and upgrade hardware, travel to field sites, travel to scientific conferences, travel to JPL to meet with project sponsors and managers, and data communications.

U1.1.5 Polar Services (OPP Artic-PI Support, See Part I, Section 3.1.1)

Definition: NSF-OPP Arctic funds research programs including engineering technical support to PI projects: campaign GPS, Terrestrial Laser Scanning (TLS), hands-on training courses to researchers, installation and O&M of remote cGPS deployments with associated power and telemetry systems, and post-season data processing and data archival support. The Polar team provides oversight and O&M support for several continuously operating polar GPS networks, including POLENET with established remote GPS stations operating autonomously in Greenland and Antarctica. UNAVCO maintains dedicated engineering and equipment resources for OPP due to the unique technical and logistical challenges associated with extreme environments. OPP also requires coordinated field season planning and survey systems at various polar research stations. GAGE fully integrates the former Enhanced Polar award, including TLS project and Polar networks support.

The Polar equipment pool has grown to 320 GPS receivers, with 123 OPP-Arctic owned. This is substantial growth, which occurred in the last three years, in response to increasing size and complexity of projects. The oldest receivers are approaching end of life, thus replacement is planned. Two real-time, kinematic-capable GPS receivers and five CORS receivers will be purchased annually to meet manufacturer lifecycle estimates of five years. Ancillary support gear will be refreshed as needed to continue meeting support requirements.

Basis of Estimate - *Labor (4.05 FTE):* Project Manager (0.5 FTE) supervises assigned staff and plans, delegates and oversees project tasks. The cost is split between Arctic and Antarctic with 0.5 FTE to each program. Polar engineering staff (2.0 FTE) for the Arctic program perform TLS support, PI field support and training, installations and other scope described above in the definition. A Polar technician (0.5 FTE) prepares the various instruments and station components for deployment in the field and interfaces with logistics contractor to ensure delivery. GI Director (0.12) and support staff (0.32) provide the balance of labor for this program.

Development and testing is budgeted at 0.625 FTE per year to focus on improving engineered systems, and providing network monitoring to ensure problems are identified early and best practices applied in unique polar situations. See Development & Testing cross-cutting task.

Travel: Field deployments in support of Arctic PI projects not covered by PI grants, and to relevant meetings and conferences include: Foreign travel: 1) $1,500 Greenland Summit or KAGA maintenance, and 2) $4,000 for two meetings or workshops. Domestic travel: 1) $3,000 maintenance trip for forward-placed GPS equipment to Polar Barrow, Toolik Lake, etc. and 2) $4,500 for 3 meetings or workshops at $1,500/trip.

Governance: Four Polar Networks Science Committee (PNSC) meeting participants at $1,500 each for a total of $6,000, based on past experience.

Equipment: Funding planned is for 2 Trimble R7's configured for Polar applications at $16,000 each.

Materials and Supplies (Equipment Pool Maintenance): Arctic pool of 123 receivers requires replacements for lifecycle and other attrition losses to meet ongoing demands. Table 3.summarizes the items planned to keep the equipment pool current to the needed standard.

Other Costs: Shipping and Facilities

- $29,658 allocated share of UNAVCO facility.
- Other costs of $19,153 consisting of TLS peripheral equipment, mailing/shipping fees, based on average costs in the current grant.

Table 3. Arctic Materials and Supplies

ARCTIC		
Product	**Quantity**	**Annual Costs**
Base Station Reference GPS receivers	5 @ $4,999	$24,995
GPS Survey Controller	1 @ $4,000	$4,000
Ancillary Materials for GPS Core Project Suppo	Misc	$15,000
TLS Intrument Support & Maintenance	Misc	$10,000
TLS Software	1 @ $2,500	$2,500
Computers/Laptops	1 @ $2,000	$2,000
Hardware for incremental technology developm	Misc	$5,000
Ancillary Networks IT Infrastructure	Misc	$1,000
Misc Other Consumables	Misc	$500
Product	**Quantity**	**One Time Purchase Cost**
TLS Field Computer - Hardened	1 @ $4,000	$4,000
TLS High-Speed Desktop Processor	1 @ $1,500	$1,500
KAGA cGPS Rebuild Materials & Supplies	Misc	$6,000
		$76,495

U1.1.6 Polar Services (OPP Antarctic-PI Support, See Part I, Section 3.1.1)

Definition: See U1.1.5 Polar Programs (OPP Arctic) above for definition. The program description is identical, except that this WBS element focus on the southern Polar region. Note, however, that there are cost differences based on geography, which are described in the basis of estimate.

Polar equipment pool has grown to 320 receivers, with 197 OPP-Antarctic owned. Growth is a response to increasing project size and complexity. The oldest receivers are approaching end of life and therefore replacement is planned. Four real-time, kinematic-capable GPS receivers and nine CORS receivers are planned annually pursuant to manufacturer lifecycle estimates (5 years). Ancillary support gear will be refreshed as needed to continue meeting support requirements.

Basis of Estimate - *Labor (4.25 FTE):* Antarctic staffing is the same as Arctic (U1.1.5) with the addition of 0.2 FTE field engineer assigned from the UNAVCO engineering staff for deployment to Antarctica.

Travel: Staff travel to the field in support of Antarctic PI projects each year. Foreign Travel of $14,500 consists of engineering team deploys to McMurdo Station via New Zealand or Punta Arenas incurring foreign travel for five staff (5 x $1,500 = $9,000) and 1 additional POLENET deployment of $1500, plus 2 foreign meetings or workshops ($4,000 total). Domestic travel of $4,500 is for participation in three workshops at $1,500 each.

Governance: Four PNSC meeting participants at $1,500 each for a total of $6,000.

Equipment: 4 Trimble R7's configured for Polar applications at $16,000 each.

Materials and Supplies (Equipment Pool Maintenance): Antarctic pool of 197 receivers requires replacements for lifecycle and other attrition losses to meet ongoing demands. Table 4 summarizes the items planned to keep the equipment pool to maintain it to standard.

Other Costs: Shipping and Facilities:

- $29,658 allocated share of UNAVCO facility
- Freight costs to and from Pt. Heuneme, for TLS and GPS instrumentation, $7,500
- TLS peripheral supplies (range finders, etc)
- Mailing/shipping fees, $600 per year based on current costs.
- Medical services / Antarctic medical qualification, $800 per year, based on actual cost.

Table 4. Antarctic Materials and Supplies

ANTARCTIC		
Product	Quantity	Annual Costs
Base Station Reference GPS Receivers	9 @ $4,999	$44,991
GPS Survey Controller	1 @ $4,000	$4,000
Ancillary Materials for GPS Core Project Support	Misc	$25,000
TLS Intrument Support & Maintenance	Misc	$10,000
TLS Software	1 @ $2,500	$2,500
Computers/Laptops	1 @ $2,000	$2,000
Hardware for Incremental Technology Development	Misc	$5,000
Ancillary Networks IT Infrastructure	Misc	$1,000
Misc Other Consumables	Misc	$500
Product	Quantity	One Time Purchase Cost
TLS Field Computer - Hardened	1 @ $4,000	$4,000
TLS High-Speed Desktop Processor	1 @ $1,500	$1,500
		$100,491

U1.1.7 PBO Component (GPS & Metpack Operations, See Part I, Section 3.1.1)

Definition: PBO-GPS Operations supports the operation and maintenance of 1112 permanent Earthscope GPS stations located across the US, Puerto Rico, and Baja California with a required 85% uptime standard for the network. Major cost categories are labor, travel, helicopter operations, cellular and satellite-based data communications, replacement equipment, materials, staff safety training, safety equipment, vehicle maintenance, shipping-within region, remote office/storage leases, and other miscellaneous costs related to GPS station maintenance.

U1.1.7 (Labor)

***Basis of Estimate** - Labor:* 19.45 FTEs are planned for this task, comprising of 15 full time and 9 part time staff members. In addition to engineering staff, there are three part time permit experts and one technician. Surge capacity is provided with at least two "on-call" engineers, with one shared with the borehole geophysics program to maximize productivity. Staff duties include field engineering, logistics, project planning, campaign support, equipment testing, shipping, administrative, and project management activities. Staffing levels are based on experience during the first four years of operations and maintenance of the PBO-GPS network to support both scheduled and unscheduled maintenance, yielding the expected number of trips per year, average days per trip, and the number of field engineers per station visit. Labor includes regional project managers, field engineers, permitting support, development and testing, administration, and a manager to oversee activities of the staff.

Operations Manager (1 FTE): coordinates among regional offices, oversees operations and maintenance activities within the GPS network; directly manages regional project managers and supports project reporting requirements. The GPS operations manager also provides documentation to the Director of GI for required quarterly and annual project reporting to NSF.

Regional Project Management (3.9 FTE): The PBO network is divided into four regions: Southwest, Northwest, Alaska, and Eastern, each with a regional manager who is responsible for managing the engineering staff, the office/warehouse/storage facilities, equipment, station documentation, and vehicles. Regional managers perform station monitoring, trouble-shooting, maintenance and safety issues for their region as well as completing any specific field work as required.

Field Engineering, Interns, On-Call Engineers (9.9 FTE): provide the field support for approximately 110 stations per FTE. Based on experience from the first four years of PBO O&M, this is the required field engineering staffing level to maintain approximately 50% engineering staff time in the field. Engineers perform the on-location repairs, replacements, brush clearing, battery change-outs, etc. to keep PBO GPS stations operating to the mandated NSF standard of 85% uptime. Engineers monitor their assigned stations for trouble-shooting when not in the field.

Permitting (1.35 FTE): Permit Coordinator and staff base are responsible to ensure that regulatory and statutory obligations for site permits are met. Permits need to be renewed at least once for most of the PBO GPS stations during FY2013-FY2018. The staff meets reporting equirements for federal, state, municipal and other landowners, as well as managing on-going relationships with landowners.

Technicians/Senior Engineer (1.3 FTE): A full-time technician provides equipment preparation, testing, and tracking, manages the materials and equipment inventory in the Boulder warehouse and maintains vehicle records for field vehicles. A senior engineer provides testing and development activities related to PBO equipment, power systems, data communications, and VPN networks.

Campaign, Development and Testing Engineers (1.5 FTE): Currently, a 0.5 FTE engineer manages the 100 GPS receiver pool for EarthScope-funded PI projects, assisting PIs in the technical and scientific aspects of project development, proposal preparation, and performing equipment pool oversight. As discussed in U1.1.4, the distinction between EAR and PBO receiver pools will not continue under GAGE. All GPS assets will be managed to achieve maximum efficiency on behalf of the UNAVCO community, 1.0 FTE supports D&T efforts for EarthScope, such as receiver, power, data communications, and systems integration testing. See Development and testing cross-cutting description.

Administration Staff (0.5 FTE): Anchorage office support for 6 months during Alaska field season. Duties include supporting engineering teams in the field with shipping/receiving tasks, providing helicopter check-in support, light permit-renewal tasks, as well as providing an office presence during the Alaska field season, when surge staffing is on hand.

U1.1.7 (Travel)

Definition: Travel is incurred for scheduled and unscheduled maintenance visits to PBO GPS stations including non-helicopter air travel, boat rental, snowmobile /pack horse rental, per diem, lodging, and transportation Travel for training and meetings also are included in this WBS element.

Basis of Estimate: *Travel:* Costs of $488,591 are generally based on actual expenses for the first four years of PBO-GPS O&M. A total of 1,433 engineer-field days per year are planned for scheduled maintenance (each station visited every 5 years), unscheduled maintenance (each station visited every two years), two weeks of required safety and other training, and two weeks of workshops and meetings. Planned visits are to clusters of stations at 1-3 days per site (depending on work performed), saving travel expense. For safety reasons, maintenance trips in the winter require two field engineers, and all Alaska visits require a second field engineer.

U1.1.7 (Equipment, Materials, and Supplies)

Definition: Repair and replacement of GPS station hardware results from equipment failure, theft, vandalism, and routine wear and tear. Equipment (over $5,000) includes replacement GNSS receivers, tiltmeters, and fuel cell generators used to provide backup power at several GPS stations within the network. Also included are periodic replacement of safety equipment (satellite phones, survival gear, hand-held GPS, etc.) and tools (generators, welders, power and hand tools).

Basis of Estimate: Refer to Table 5 for details of items and costs. Battery replacement on a 5-year schedule requires 1,471 batteries each year. Based on past failure rates, 3% of GNSS receivers and 1% to 5% for various other components are planned for replacement. As discussed above and in the Facility Plan, upgrading and replacing the GPS-only Trimble NetRS receivers currently deployed throughout PBO to GNSS-capable receivers is planned as part of GAGE. Upgrades to the next generation cellular hardware, at 50 units per year, are planned support to RT ("real time") GPS requirements.

U1.1.7 (Data Communications)

Definition: Data communications costs are monthly cellular (AT&T, Verizon, Sprint), VSAT, DSL, and BGAN connections for the transmission of data from stations to processing centers and ultimately to archive.

Basis of Estimate: Station communications are currently 60% cellular, 10% VSAT, 4% DSL, 1% BGAN, and 25% other non-fee (manual downloads, radio networks, shared IP connection). Cost estimates are based on current plan charges and include GPS stations and data communications relays. Recent results with vendor competition indicate possible savings by migrating some stations to alternative carriers allow savings to offset the impact of streaming more high-frequency, low latency data as more real time stations come on line during GAGE.

U1.1.7 (Helicopter Operations)

Definition: Helicopter operations support for volcano and other GPS stations not accessible by maintenance vehicles.

Basis of Estimate: Helicopter use is a combination of daily availability rates, hourly fly-time rates, fuel, and crew travel plus OT hours for pilot and mechanic. Costs are based on 2012 operations, with an expectation of a 5-10% increase in daily and hourly rates starting in FY2014. (Negotiated prices were held flat for 2010-12) Eighty-six stations require helicopter operations in the PBO network. Fifty-eight helicopter days, including fuel and hourly rates for 216 hours of flying are planned for each year.

U1.1.7 (Other Costs)

Definition: Other costs include leases for remote office/ warehouse ad storage facilities, truck maintenance, insurance and replacement, permitting fees for renewals, and shipping expenses in Alaska.

***Basis of Estimate** – Leases:* These include the three regional offices in San Clemente, Cooperative Agreement, Anchorage, AK, and Portland, OR. To achieve some cost-saving, field engineers are also based in home offices in San Jose, Cooperative Agreement, Salt Lake City, UT, Arcata, Cooperative Agreement, and Fairbanks, AK. Fees for remote storage for equipment and vehicles at 10 facilities near airports across the western US, including Arcata, Cooperative Agreement, Salt Lake City, UT, San Jose, Cooperative Agreement, and Reno, NV are included. The storage and office lease costs are based on actuals paid during the fourth year of the O&M phase of PBO. The average cost for each of the three regional offices is $2,977 per month. The average cost for each storage unit is $319 per month.

Table 5. PBO Component (GPS & Metpack Operations) Materials, Supplies, and Equipment

MATERIALS AND SUPPLIES	Budget Qty.	Budget Cost/per item	Budget	Comments
Lan Cell 3	50	$599	$29,950	Upgrading for RTGPS
Cell Cards	50	$179	$8,950	
Radios	11	$1,650	$18,150	
VSATs	8	$1,500	$12,000	
BGANs	3	$3,000	$9,000	
Huts-Alaska	2	$3,000	$6,000	
Enclosures	6	$848	$5,088	F4, 4 battery enclosures
Batteries	1470	$179	$263,130	Average per year for battery replacements, 9% increase from 2011 to 2012
Solar Panels	50	$375	$18,750	
Domes/Mounts	22	$465	$10,230	
Metpacks	6	$2,464	$14,784	
Metpack Repair2	6	$850	$5,100	
Solar Panel Mounts	11	$300	$3,300	
Cisco Routers	3	$800	$2,400	
Helicopter Gear - Slings, Helmets, Flight Suits	15	$300	$4,500	
Webcam	2	$1,200	$2,400	
Miscellaneous (cable, lightning protection, web switches, back panels, storage, etc.)	1	$60,000	$60,000	
Subtotal Material and Supplies			$473,732	
CPI-W to escalate prices for 2012	2.0%		$9,475	
Regional/Office Materials & Supplies			$0	Locally Purchased Materials and Supplies for 3 Regions
TOTAL MATERIALS AND SUPPLIES			**$483,207**	
EQUIPMENT (unit price over $5,000)				
GNSS Capable (receiver and antenna)	49	$7,900	$387,100	4.5% replacement*
Fuel Cell	3	$0	$0	
Tiltmeters	1	$0	$0	
Subtotal Equipment			$387,100	
CPI-W to escalate prices for 2012	2.0%		$7,742	
TOTAL EQUIPMENT			**$394,842**	
TOTAL COMBINED EQUIPMENT, MATERIALS, AND SUPPLIES W/ ESCALATION			**$878,049**	

Basis of Estimate - *Trucks/Insurance:* Liability and physical damage insurance is maintained for the trucks used for PBO field operations. Costs have been stable over the prior three years and are competed by the insurance broker each year. Cost is estimated at $20,000 annually with GAGE.

Basis of Estimate - *Permitting Fees:* Permit renewals occur over the life of the period in varying numbers and costs per permit. The expected total is based upon most recent renewal and has been averaged across the five years at a total of approximately $1,138,000.

Basis of Estimate - *Alaska Shipping:* Based on actual costs of $40,000 per year from past experience, the plan includes shipping of helicopter fuel, batteries, and other hardware from the Anchorage office to various locations throughout Alaska.

U1.1.8 PBO Component (Borehole Geophysics & Strainmeter Operations, See Part I, Section 3.1.1)

Definition: PBO-BSM includes the operations and maintenance of 75 borehole strainmeters, 79 borehole seismometers, 26 borehole tiltmeters, and ancillary sensors (pore pressure, met data, etc.) and support equipment. The instruments are at 80 different sites (five without strainmeters). Labor, travel and office/warehouse space, for 5.5 FTE's are planned, as well as materials, equipment and supplies for scheduled and unscheduled maintenance site visits. Monthly costs associated with station communications and power are included. Recurring permit costs are included based on stations permitted. See permitting in U1.1.7 above.

Basis of Estimate - *Labor (4.1 FTE):* Field engineer (3.4 FTE) time is divided between field visits (50%) and network monitoring, equipment preparation, and other support activities. Staffing needs are estimated from past experience to maintain the borehole network to the 85% uptime NSF standard; a network engineer (0.4 FTE) performs various state of health checks, works in the development and test function to identify efficiency and technological enhancements.

Table 6. PBO Component (Borehole Geophysics) Materials, Supplies, and Equipment

EQUIPMENT, MATERIALS, AND SUPPLIES	Unit Cost	Percent Failure Rate/Yr	Fractional Replacement	Comments
Marmot	$5,445	5.0%	$272	
Q330	$8,465	5.0%	$423	
VSAT	$1,450	15.0%	$218	Assumes a 10 yr lifetime (whole assembly)
BSM Electronics	$10,000	15.0%	$1,500	
Batteries, CONUS (DEKA 8G31, w/stud terminal)	$179	5.0%	$9	
Cables, Hardware, Misc	$300	25.0%	$75	
Optical Modems x 2	$458	5.0%	$23	
Cisco Router	$396	5.0%	$20	
Intuicom Radios	$1,195	2.0%	$24	
Charge Controller/LVD/DC Iso	$150	5.0%	$8	
LVD	$245	5.0%	$12	
Hydrogen Fuel Cell	$10,901	5.0%	$545	
Rain Gauge	$298	5.0%	$15	
Barometer	$1,704	5.0%	$85	
GPS Antennas	$29	5.0%	$1	
Solar Panels	$395	5.0%	$20	
WiLan radios	$1,987	5.0%	$99	
Three Panel Mount	$350	5.0%	$18	
Per Station Replacement Per Year			$3,366	
Number of Stations			80	
TOTAL UNSCHEDULED MAINTENANCE			**$269,317**	
MATERIALS, AND SUPPLIES	**Unit Cost**	**Percent Replacement Rate/Yr**	**Fractional Replacement**	
Batteries, CONUS (DEKA 8G31, w/stud terminal)	$1,790	25.0%	$448	
Per Station Replacement Per Year			$448	
TOTAL SCHEDULED MAINTENANCE			**$35,800**	
Tiltmeters (Total Replacement Per Year)	**$8,350**	**40.0%**	**$3,340**	
Total Equipment, Materials, and Supplies/Yr			**$308,457**	
CPI-W to escalate prices for 2012			2.0%	
Miscellaneous Local Materials			$0	
TOTAL EQUIPMENT, MATERIALS, AND SUPPLIES/YR W ESCALATION			**$314,626**	
Less Annual Equipment Estimate				
Marmot	4	$5,445	$21,780	
Q330	4	$8,465	$33,860	
Hydrogen Fuel Cell	4	$10,901	$43,604	
Total Equipment			$99,244	
CPI-W to escalate prices for 2012			2.0%	
TOTAL EQUIPMENT W/ ESCALATION			**$101,229**	
MATERIALS AND SUPPLIES ONLY			**$215,382**	

The operations manager (0.3 FTE) supervises the staff as well as managing borehole instrument community interface and development.

Travel: Travel, per diem, and lodging costs are for scheduled and unscheduled maintenance visits for the 80 borehole strainmeter stations. Assumptions on the number of visits are derived from the maintenance schedule and actual experience during the PBO O&M phase, with the bulk of planned visits being twice yearly. Costs per visit are based upon historic actual cost. Visits are planned to cover a sub-network in order to be cost- and time-effective. A typical visit requires approximately 2.25 days per site, depending on the actual maintenance that must be performed. An average trip requires 500 miles of driving, 50% require air travel, and 25% of the visits require an additional field engineer.

Equipment, Materials and Supplies: Individual unit costs are based on manufacturers' estimates and costs encountered during the initial PBO O&M phase. The predicted equipment failure rates of 2–6% per year for most system components are based on past experience with the stations. There is a small component included (1–2%) for scheduled replacement. Refer to table Table 6 for detailed pricing and replacement rates.

Other Costs: The data communication and power costs are based on actual costs incurred over the prior three years as part of PBO O&M.

U1.1.9 PBO Component

(Long Baseline Strainmeter Subaward, See Part I, Section 3.1.1)

Definition: The long baseline strainmeter is managed entirely by UCSD under a subaward from UNAVCO.

University of California San Diego

Scope: measuring crustal deformation using longbase strainmeters (LSM's): six instruments at four locations in Central and Southern California.

Basis of Estimate: Refer to subaward budget justification for the basis of estimate.

U1.2 Geodetic Data Services (See Part I, Section 3.2)

Definition: This is the second of three program directorates in the UNAVCO organization. It includes a continuum of activities that are broken down into the following areas of responsibility: the operations supporting the acquisition of data and maintenance of metadata from PI- and PBO-managed daily and real-time sources (including data quality and state-of-health monitoring); generation and handling of data products (including management of PBO analysis center subawards); maintenance and enhancement of the UNAVCO archive; administration of IT systems; development and coordination of cyberinfrasturcture projects; NASA global data operations; and polar program data archiving. Resources include data technicians, data and software engineers, project managers and associated staff for operations, maintenance, and further development of GDS systems. Integration of previously independent data services (PBO and Facility) is a focus of effort during the first year of GAGE. Resources for maintenance and development of software are partitioned by task but will be optimized by a modified "Agile" process. Table 7 summarizes the activities and resources for each task. Details regarding the specific work efforts are described in the lower level elements described below.

Basis of Estimate: The estimates for each task are described more fully at the next WBS level. Staffing has been estimated from the current employee popultion and recognizing periodic use of staff on other projects. Where deviations from history have been made, the rationale has been provided for such a decision.

Table 7. Summary of Geodetic Data Services Task Elements.

U1.2.1	Management	Resources that benefit the entire Geodetic Data Services WBS task including direction of GDS activities and administrative and budget support.	(2.00 FTE)
U1.2.2	Governance	Geodetic Data Services Advisory Committee, TLS Working Group and the WInSAR Executive Committee	(none)
U1.2.3	Data Operations	Sensor network data operations (PBO and PI networks); campaign (GPS and TLS) data handling; SAR tasking and acquisition; geodetic data ingestion and preprocessing.	(10.42 FTE)
U1.2.4	Data Products and Services	Data translation; generation of QC/QA, time series, velocities, strainmeter, and other data products; monitoring and analysis for quality control and product enhancement.	(6.7 FTE)
U1.2.5	Data Management and Archiving	Management, distribution and curation of geodetic data.	(3.85 FTE)
U1.2.6	Information Technology	Administration of UNAVCO's ~60 servers, 100+ staff systems, web administration	(2.35 FTE)
U1.2.7	Cyberinfrastructure	Development, and maintenance of data web services. Project management with national and international stakeholders.	(1.47 FTE)
U1.2.8	NASA GNSS	GGN network data operations, support of the IGSCB, project direction and management, IT	(4.19 FTE)
U1.2.9	Polar Programs (OPP Arctic)	Archiving of OPP Arctic Data	(<.1 FTE
U1.2.10	Polar Programs (OPP Antarctic)	Archiving of OPP Antarctic Data	(<.1 FTE)
Total: (31 FTE)			

U1.2.1 Management (See Part I, Section 3.2)

Definition: Management includes the following resources that benefit the entire Geodetic Data WBS task such as directing the various data tasks, ensuring integration of data services, interfacing with the NSF Program Officer, governance committees, reporting of technical and financial information, and providing the support staff to enable these high level responsibilities to be met. Key elements are:

Geodetic Data Services ("GDS") director, administrative, and budget analyst staff. Travel, office supplies, other costs to support the productivity of these staff members are included.

Also in this element are staff-driven costs: 1) employee/manager training, 2) office supplies, 3) computers, 4) cell phones and 5) office and data center space in Boulder for all GDS staff.

***Basis of Estimate** - Labor:* The GDS director is included a 0.90 FTE (0.55 EAR and 0.35 NASA) with 0.10 assumed charged to other projects and the bid & proposal account in accord with current Cooperative Agreement and charging practices. A total of 1.7 FTE of support positions are allocated to this task (Budget and cost analysis, administrative support and systems administration (IT)). Managers who supervise the line staff are included in the WBS elements where their efforts are directed. Responsibilities are the supervision of tasks and personnel as well as the direct effort of domain expert in their area.

The director is allocated at 0.35 FTE and other support staff at 0.27 FTE to NASA which benefits from their efforts. (Task U1.2.8) The balance is allocated to EAR.

Other costs: Other costs were developed based upon average cost experience in the two existing cooperative agreements with NSF. Computers and phones are presumed replaced every three years, with $1,100 per staff member provided each year. Cell phone monthly cost is estimated at an average $70 per employee, which is the average based on UNAVCO's cost sharing policy with staff.

Office expense includes space occupied in the Boulder facility for both offices and data center. The data center is allocated entirely to GDS, resulting in an annual allocation of $412,737.

Employee training is planned in this task at an annual average of $2,500 per person. Included are management, technical and policy training for all personnel consistent with position responsibilities and to support career and professional development. This estimate is based upon recent experience as UNAVCO has made deliberate investments in various training programs. It further assumes a successful pilot for leadership development training coordinated with UCAR, IRIS, NEON and other NSF large facilities.

Travel: The travel budget is based on recent history. Director travel includes one international workshop or science meeting and visits to NSF, remote offices, meetings of AC's, board of directors meetings, etc.

U1.2.2 Governance (See Part I, Section 1.2)

Definition: Advisory groups provide community input to both management and the UNAVCO board of directors. A board member is designated as liaison to each advisory committee. Advisory groups help prioritize UNAVCO efforts based on developments in science, technology and public interest. All advisory group members serve without compensation.

Governance is being reconfigured by the UNAVCO board of directors and management as a result of the recent reorganization. It is anticipated that there will be several advisory groups for this directorate: Geodetic Data Services Advisory Committee, TLS Working Group and the WInSAR Executive Committee.

Basis of Estimate: The Geodetic Data Services advisory committee is expected to have nine members and meet once a year at a cost of $8,100 ($900 per member), TLS working group to be comprised of seven members who meet once a year for $6,300 ($900 per member), the WInSAR Executive Committee to have 7 members meeting once a year ($6,300) and the WinSAR Consortium annual meeting held at AGU is budgeted at $5,000 (based on recent actual cost experience). The $900 per person is based upon forecasted airfare from various consortium member locations to Denver, plus hotels and meals.

U1.2.3 Data Operations (Ingest/Preprocessing. See Part I, Section 3.2.1)

Definition: Data Operations encompasses the processes and information technology hardware, software and communication systems responsible for the preprocessing of geodetic data and providing of accurate, validated metadata. Ingestion uses the multiple dataflow systems that regularly and automatically communicate with GPS, borehole strainmeter, tiltmeter, and other instrument sensors to download data to the UNAVCO data center in Boulder.

State of health systems monitor the connectivity, download history, and data patterns to provide field engineers with information about possible problems that drive troubleshooting. Engineers use metadata systems to record location, installation parameters, operational status, communication setup, maintenance activities and equipment configurations and replacement.

These systems are supported by data engineers, data technicians, software engineers, system administrators and database administrators to ensure high-quality geodetic and metadata is complete, delivered as required, that systems continue to operate, and are enhanced to expand and improve their capabilities.

Data technicians and data engineers perform TLS data transfer and pre-processing and SAR data tasking, ordering, and downloading.

PI-operated GNSS stations require significant data and metadata intake if the stations that do not leverage the ingestion systems used by UNAVCO-operated networks described above. As a result, quality data depends upon QC monitoring of state of health for stations delivering GNSS data. Software engineers maintain and enhance UNAVCO's TEQC software --used by GAGE as well as institutions around the globe for QC. A new level of post-process QC parameters, developed for GSAC, will be distributed from the Data Center as part of GAGE.

***Basis of Estimate** -Labor (10.42 FTE):* UNAVCO-managed GPS, borehole instruments, and meteorological sensor network operations (3.30 FTE): Management of staff and systems requires 0.45 FTE. An estimated 0.45 FTE Software Engineer is planned to maintain the current Dataflow System (DS) used for PBO and COCONet. Additional applications for PI-operated networks will be developed over the 5-year period. The metadata management (MDM) and state-of-health systems will be enhanced with new functionality and growth to handle additional networks, consuming 1.15 FTE Software Engineer. A data technician (0.25 FTE) performs GPS metadata management. Database administration required to manage growth and develop enhancements to support new features, data growth and improved performance will be fulfilled by 0.65 FTE. Enhancements to the web site to display new information related to station metadata and state-of-health will consume 0.35 FTE. These staffing estimates are based on past maintenance and planned enhancements to the corresponding systems.

Data intake from PI-operated GNSS instruments (2.92 FTE): requires data technicians (1.64 FTE), a data engineer (0.48 FTE), and a software engineer/database analyst (0.5 FTE). The data engineer works with the software engineer/database analyst to ensure intake and flow software is designed and operates to meet requirements; the data engineer ensures that the software operates correctly in production. Data technicians ensure that all required metadata meet standards for quality and completeness. Technicians also monitor automated processes, generate reports and help the data engineer troubleshoot problems with data and metadata intake and data flow. Technicians also ingest campaign GPS data. TEQC implementation, development and maintenance for operations are performed by (0.77 FTE) software engineer.

Real time GPS utilizes 0.85 FTE: led by an operations manager-(0.1 FTE) and including a data technician (0.5 FTE) and data engineer (0.25 FTE). Staff operate the real-time GPS data collection system, monitor state-of-health, distribute raw data streams in multiple formats, and manage user access subscriptions. Real-time (low latency), high-rate GPS raw GPS data is being distributed from approximately 350 stations. Real time is expected to grow by 50 stations per year through the life of this proposal. Data archiving of this raw and processed data is included in a separate element. Staffing and other costs are estimated based on real time requirements during the Cascadia (PBO) initiative.

Geodetic imaging including LiDAR and InSAR: requires 0.83 FTE for data operations including manager (0.15 FTE), data technicians (0.3 FTE), data engineers (0.5 FTE) and software engineers (0.18 FTE). TLS tasks include data transfer of raw data; processed point clouds and metadata; and data management. SAR operations are data tasking, ordering and downloading, and are performed by data technicians and data engineers. Software engineers support associated data operations software.

Borehole instrument (strainmeter, seismic, tilt, pore pressure, and meteorology) data operations (1.25 FTE) utilize a manager (0.2 FTE), data engineers (0.25 FTE) and data technicians (0.80 FTE). Staffing to operate the real-time and file-based borehole instrument data collection system, to monitor state-of-health, and to maintain metadata is based upon 3 years of actual operating cost history.

Travel: Planned travel includes two three-day trips from Seattle to Boulder for 3-5 days $3,600 (Smith) and 3 attendees to AGU (or other conference) at $7650.

Materials and Supplies: One Antelope software annual license of $18,000 is planned.

Equipment: 4.6 annual average new or replacement servers at $10,000 each.

Other costs: Real-time software licenses ($25,000) are planned plus related costs for real-time processing of $20,000.

U1.2.4 Data Products and Services - Processed Results, QA/QC, See Part II, Section 3.2.2)

Definition: Data Products and Services support various geodetic instruments and techniques. Products include raw GPS data (Level 0,1), processed GPS data (Level 2) performed by subawardee institutions, strain data (Level 0,2), seismic data (Level 0), terrestrial laser scanning data (Level 0,1,2), and synthetic aperture radar data (Level 0). Services include the development, implementation and distribution of automated and interactive tools, web services and associated web support, as well as processing by subawardees, to generate, quality-check, curate, and analyze these data products.

- GPS products include Level 0 data such as 15-sec and 5-sps raw receiver files and streams, Level 1 data such as quality checked RINEX files, and Level 2 data such as station position and velocity solutions, time series, and co-seismic offsets of significant events are produced by subawardees: MIT, CWU, NMT and distributed by the Data Center.
- Borehole strain products include Level 0 data such as 20-sps, 1-sps, 10-min raw strain series in Bottle and SEED files, and Level 2 data such as corrected and scaled strain and environmental series. Laser strain products, produced (by subaward) by UCSD include Level 0 data such as 1-sps raw strain data in Ice-9 and SEED format, and Level 2 data such as corrected and scaled strain and environmental series in XML and ASCII formats.
- Seismic products include Level 0 data such as 100-sps and 200-sps raw data in SEED format.
- Terrestrial laser scanning products include Level 0 data such as raw scanner data, Level 1 data such as unclassified point cloud files in ASCII or LAS format, and Level 2 data such as merged, aligned, geo-referenced, unclassified point cloud files in ASCII or LAS format.
- InSAR products include Level 0 raw SAR sensor data in CEOS or ENV1 format.
- Numerous other products are also supported including borehole pore pressure, borehole tiltmeter and meteorological products. Services include the development, implementation and distribution of automated

and interactive tools, web services and associated web support, and the work of subawardee institutions, to generate, quality-check, curate, and analyze the above data products.

Basis of Estimate - *Labor (6.70 FTE)*: Based on current and projected staffing, and distributed as follows:

Standard GPS data products and services (3.45 FTE) requires managers (0.70 FTE), data engineers (1.10 FTE) data technicians (0.25 FTE), and software engineers (1.4 FTE). Managers coordinate and oversee all activities conducted by and for UNAVCO; serve as primary interface with community members and the subawardees that process data; and supervise staff. Data engineers operate and maintain existing systems critical for data products and services; manage data and data quality assurance activities including station state of health ("SOH"), station position and velocity solutions, and time series; work closely with subawardees who process data and help ensure the quality of generated data products; work closely with software engineers to help develop and maintain tools and services related to GPS, and are responsible for overall data quality assurance, metrics tracking and reporting. Software engineers develop and maintain tools for the community such as web services to provide easier access to and presentation of geodetic data to meet evolving needs for data products. Engineers design web enhancements for documentation and additional entry points to services and displays and develop tools and visualizations such as time series viewers and station position animations. Staffing is estimated based on experience during the past and current UNAVCO Facility, PBO MREFC and PBO O&M cooperative agreements.

Real time GPS data services utilizes (0.95 FTE): led by an operations manager (0.2 FTE) and including a data technician (0.25 FTE) and data engineer (0.5 FTE). Staffing is estimated based on real time requirements experience during the Cascadia (PBO) initiative. Staff perform in-house processing for real-time position streams as well as providing resources to compare data from outside-processed, contributed streams.

Borehole geophysics (strain and seismic) data products and services (0.80): requires managers (0.1 FTE), data engineers (0.5 FTE) and data technicians (0.2 FTE). The manager coordinates and oversees the various borehole data activities , including staff supervision, and is the primary interface with community members and the subawardees that process data. Data technicians assist with production and web display of strain data products. Data engineers develop and maintain software to generate processed strain data and related products such as tidal modes, barometric response coefficients, and time series analysis, and assist the user community with analysis. Staffing is estimated based on requirements experience during the UNAVCO Facility, PBO MREFC and PBO O&M cooperative agreements.

TLS geodetic imaging data products and services (0.75 FTE): requires managers (0.45 FTE), data technicians (0.15 FTE) and software engineers (0.15 FTE). Managers coordinate and oversee all activities; serve as primary interface with community members; teach community classes; and supervise staff. Data technicians operate and maintain systems for data products and services and assist with data and data quality assurance. Software engineers maintain tools for the community such as RAMADDA and web services to provide enhanced data management and flow, easier access to and presentation of geodetic data to meet evolving needs for data products. Engineers create web enhancements for documentation and additional entry points to services and displays. Staffing is estimated based on experience during the UNAVCO Facility cooperative agreements and INTERFACE project, as well as community recommendations from the 2011 TLS Workshop.

InSAR geodetic imaging data products and services (0.80 FTE) requires project managers (0.3 FTE), data technicians (0.15 FTE) and software engineers (0.35 FTE). Managers coordinate and oversee activities, supervise staff, and serve as primary interface with community members and subawardees that process data. Data technicians operate and maintain systems critical for data products and services for WInSAR and GeoEarthScope; perform data quality assurance, help develop and maintain tools and services, and create the metrics for tracking and reporting. Software engineers develop and maintain tools for the community such as web services to provide easier access to and presentation of geodetic data to meet evolving needs for data products as well as web enhancements for documentation and additional entry points to services and displays. Engineers develop InSAR products such as interferograms and tools to manage and visualize such products. Staffing is estimated based on experience during the UNAVCO Facility, PBO MREFC and PBO O&M cooperative agreements as well as the SAR upgrade project.

Travel: Travel of $40,800 ($900-$1200 each trip) domestic and $10,400 (~$3,300 each trip) foreign is based upon deep participation in science meetings and workshops as follows:

- GNSS - 4 conferences per year (manager) 1 conference per staff, 1 international for manager.
- Remote borehole data staff make 2 total trips to Boulder office and attend a total of 4 domestic conferences for the manager and one conference for staff. and one international meeting every other year.
- TLS staff attends a total of 3 domestic meetings & conferences: one staff member attends one domestic meeting per year and one international meeting every other year.
- InSAR one staff member attends 2 domestic meetings per conferences annually, the other attends one per year.

Materials and Supplies: Hardware storage devices will be aquired to support the productivity of the engineers, technicians and managers. They are estimated at $13,600 per year.

Other Costs: Software licenses and maintenance ($20,000) are planned. $50,000 is estimated per year for robust cloud storage of data and data products.

Equipment: Equipment is exclusively servers based upon expected data growth and life-cycle replacements estimated at $10,000 each (average 1.2 per year).

Subawards: GPS data processing and analysis services and products provided to UNAVCO by the subaward institutions as follows:

Central Washington University (CWU)

Scope: PBO and supplemental GPS data processing within the CWU Geodesy Lab with GIPSY and ongoing operation of daily, weekly, supplemental processing of PBO GPS and reprocessing of Nucleus time series.

New Mexico Institute of Mining and Technology (NMT)

Scope: The processing and analysis of data from the PBO permanent GPS network of sites installed as of 30 September 2008 (the "PBO core network"), and additional permanent GPS network sites agreed upon.

Massachusetts Institute of Technology (MIT)

Scope: Analyze and integrate the PBO products streams being generated by the PBO Analysis Centers with focus on ensuring that PBO data products are of high quality and are generated in a timely fashion.

Scope: Maintain and further develop the GAMIT/GLOBK software used by U. S. (and other) investigators to obtain maps of crustal motion from GPS measurements in deforming areas throughout the world.

MIT also develops, maintains and provides technical support and training for the GAMIT/GLOBK GPS processing and analysis code.

Basis of Estimate: Subaward costs are based on proposals submitted by CWU, NMT and MIT.

U1.2.5 Data Management and Archiving (Distribution and Curation, See Part I, Section 3.2.3)

Definition: Data management, archiving, distribution, and long-term curation are performed by the Data Center with its archives for GNSS, SAR, and LiDAR data. Seismic and strain data and metadata are prepared for archiving at subawardee institutions.

Staff develop and/or operate software for manual archiving (TLS, InSAR, and campaign GNSS) and for automated archiving to handle network GNSS data with low latency, with load balancing and with failover capability, and for high availability data search and access through application programming interfaces, ftp, and web interfaces and tools. Activities significantly interface with and leverage certain data operations under element 1.2.3, especially in data flow to the archive and metadata management.

Strain data are downloaded, converted to miniSEED, and transferred to the IRIS Data Management Center ("DMC") and U. C. Berkeley Northern California Earthquake Data Center "NCEDC" at hourly intervals; seismic data flow to the IRIS DMC in miniSEED format in near real time. NCEDC performs archiving under a subaward. Metadata are maintained by UNAVCO and provided to the DMC and NCEDC. Once time-series and metadata are at the DMC and NCEDC, web tools allow users to search, explore and retrieve time series. Archiving the strain, seismic and ancillary data in SEED form at leverages data distribution systems and tools available for seismic data, simplifies the integration of the data sets and makes the data sets readily accessible to both the geodetic and seismic communities. SOPAC at UCSD provides additional archive data.

University of California Berkeley

Scope: Translates archive and distribute PBO strainmeter data including levels 0, 1 and 2.

University of California San Diego

Scope: SOPAC provides additional GPS archive data and participates in GPS Seamless Archive Centers ("GSAC").

Basis of Estimate: See budget justifications of subawards for estimates.

Basis of Estimate: The GPS, GNSS, and InSAR archives have been operational for 16 and 6 years respectively. As has been done since inception of PBO, archiving of borehole strain and seismic data occurs through subawards with supporting in-house labor to prepare data for archiving. Actual costs over the past 5 years are the basis for labor, hardware, materials and supplies, and software licenses estimates. Costs for LiDAR (primarily TLS) archiving are estimated from projected data volumes and archiving processes in place and under development. Storage needs associated with additional instrumentation and expanded high rate data archiving for GNSS have been budgeted, with some storage costs accommodated through migration to cloud services. Moderate increases to data storage requirements are projected for SAR and TLS.

Labor (3.85 FTE): Staff time in this task includes 0.65 FTE management, 1.9 FTE database analyst/software engineers; 0.5 data engineer; 0.5 student /intern; and 0.3 FTE web administrator. Managers supervise staff and plan and organize the work. Software engineers develop and support complex software and database systems for automated archiving with failover capability and redundant storage. They develop web user interfaces; application programming interfaces for data search and access; and supporting scripts. A software engineer (0.25) FTE performs TEQC development and support. Data engineers prepare strain and seismic data for archiving under subawards. A web administrator works with the user interface software developers for web deployment. The student assistant/intern supports the data engineers and managers.

Staffing is estimated based on experience during the UNAVCO Facility, PBO MREFC and PBO O&M cooperative agreements as well as associated projects.

Materials and Supplies: Estimated costs are for lower capacity RAID systems, replacement RAID disks, development systems, memory, LTO backup tapes, system accessories (rack mounts, cables, etc.), and is budgeted at $36,000 based on prior actual costs and planned expansions in archiving for real-time GNSS ($27,000), InSAR ($5,000) and LiDAR ($4,000).

Equipment: Information technology components including storage RAID and SAN; tape backup appliances; servers for database, ingestion processing, reformatting, quality checking, and data access via ftp and http. For all archiving activities, $118,200 is budgeted per year for equipment, broken down as: purchase of 3 large storage devices per year with 20Tb capacity at $25K; processing systems, 3 per year at $10K per server base price. Servers will require various add-ons depending on application ($13,000). Remaining budget will cover upgrade or replacement of the existing large tape storage device with $50K budgeted during the 5 years.

Other Costs: Other Costs include software licenses for the GNSS archive Oracle database and various developer toolkit licenses such as Adobe Flex. These licenses are budgeted at $10,610 per year. Costs for migration of some storage to cloud-based services have been estimated through service provider pricing inquiries and are budgeted at $36,386 per year.

Travel: Project personnel travel to interact with UNAVCO community members at meetings including AGU ($8500, 3 travelers annually) and 3 non-specified meetings for TLS product development over 5 years, and one international meeting per year (e.g. EGU, 2 travelers) are budgeted.

U1.2.6 Information Technology (See Part I, Section 3.2)

Definition: Information Technology represents the systems and web administration support provided to the GAGE project. System administration includes provisioning and maintaining project servers and data storage units, installing system software and maintaining connectivity. Web administration encompasses primarily the technical support of the UNAVCO web site including, web server configuration, monitoring, statistics collection and implementation of dynamic portions of the site. Web administrators also work closely with content providers to produce a well-organized, polished and easy-to-navigate web site.

Basis of Estimate - *Labor (2.35 FTE):* Staff estimates are based on server counts and resources to sustain the web administration and IT backbone of the Data Center and the entire facility. 1.35 FTE are planned for system administrators, 0.85 FTE for web administrator, and 0.15 FTE for managing the staff.

Equipment: $20,000 per year for server replacements and enhancement (2 at $10,000) are planned in addition to $4,446 for the back up data repository for PBO data.

U1.2.7 Cyberinfrastructure - (Part I, Section 3.2.4)

Definition: Cyberinfrastructure includes development, and maintenance of flexible, modular, interoperable services to expand data and metadata access and to improve the overall usability of data and ease of production of data products. Staff develop and/or operate software for web services and application programming interfaces that enable integration with capabilities at other data centers such as IRIS and SOPAC. Development to facilitate migration to cloud-based services for targeted functions is included. Synergies with development activities in data products and data archive elements will be leveraged to support cyberinfrastructure. Significant project management is required for interfacing with external data centers, EarthCube, Supersites, and COOPEUS.

Cyberinfrastructure components have been under development since 2008 when the EarthScope Portal was released, and development has proceeded under several NASA ROSES projects. These efforts guide the estimates for planned cyberinfrastructure development.

Basis of Estimate - *Labor (1.47 FTE)*: Management (0.55 FTE) primarily interfaces with the various stakeholders, database and software engineers (0.92 FTE), and perform development activities.

Travel: Costs are budgeted for interfacing on an annual basis with domestic (one trip) and international (one trip) external collaborators.

Materials and Supplies: Systems for development and testing are budgeted at $5,000 per year based on prior experience. Because this activity is mainly development-oriented, when these services become operational they are served from hardware purchased for archive and data products activities.

U1.2.8 NASA GGN Data Services - (See Part I, Section 3.2.5)

Definition: Data support to NASA GGN includes troubleshooting of data and metadata flow, identification and correction of metadata issues and metadata management for the GGN, and software support for TEQC development for application to the GGN and for support to the global GNSS community.

Data support to the International GNSS Service ("IGS") Central Bureau includes troubleshooting of data and metadata flow, identification and correction of metadata issues and metadata management, operational support for information dissemination to the IGS community, software support for metadata management and data access. Information technology support is provided for the IGS Central Bureau web site. The GDS Director is also on the executive committee of the IGS Governing Board.

***Basis of Estimate** - Labor (4.19 FTE):* GDS program director (0.35 FTE) provides interface to NASA sponsor and coordinates activities between NASA and NSF and overall project management; IT, web, and budget support is 0.60 FTE; the Data Center manager (0.2 FTE) supervises staff and coordinates sponsor needs across programs internally. Data operations are conducted by a software engineer (0.2 FTE), data engineer (0.25 FTE), and network engineer (0.50 FTE). NASA shares the cost for maintaining TEQC providing software engineers at (0.58 FTE). The staff maintains the various NASA stations and manages the data from those stations.

Staff supporting IGS Central Bureau (1.6 FTE) includes data engineer (0.25 FTE), data technician (1.0 FTE), software engineer (0.25 FTE), web administrator (0.1 FTE).

Equipment: Costs include server replacement at 0.7 servers per year for data and metadata handling, software development servers and web servers at annual average investment of $7,000.

Travel: $22,955 is budgeted at $6,000 to support the director's travel $16,955 for other staff for trips to JPL for coordination of activities and for international (IGS meeting $9,000) and domestic meeting travel. $4,500 is budgeted for international travel for EGU and is described in the Data Management and Archiving Task.

Other Costs: A total of $124,356 includes $41,000 for the cost of hosting various NASA meetings and receptions for community members as well as the supplies, data communications charges and other expenses associated with the repair and maintenance of the network and its data archives. The estimates are based in four years of actual experience.

U1.2.9 Polar Services (OPP Arctic)

Definition: This task includes the portion of the budget dedicated to NSF-OPP. Support is data and metadata archiving and data distribution for various Arctic campaigns and polar permanent stations. This task is distributed between a data engineer and a data technician as required.

Basis of Estimate: Data support is provided by a data engineer at 0.04 FTE and a data technician at0 .04 FTE. This estimate is based on average data support provided during the previous Cooperative Agreement.

U1.2.10 Polar Services (OPP Antarctic)

Definition: This task includes the portion of the budget dedicated to NSF-OPP. Support is data and metadata archiving and data distribution for various Antarctic campaigns and polar permanent stations. This task is distributed between a data engineer and a data technician as required.

Basis of Estimate: Data support is provided by a data engineer III at 0.04 FTE and a data technician at 0.04 FTE. This estimate is based on average data support provided during the previous Cooperative Agreement.

U1.3 Education and Community Engagement - (See Part II, Section 3.3)

Definition: This is the third of three program directorates in the UNAVCO organization. It includes the following areas of responsibility: community engagement and outreach, international engagement and partnerships, community professional development, science workforce development, and outreach tools development.

UNAVCO sponsors the Geodesy Science Workshop, the biannual community national science meeting and provides partial travel and registration support for member representatives and full support for invited speakers. Scholarships for a limited number of graduate and undergraduate students are based on an application process. ECE works collaboratively within UNAVCO as well as with the broader geodesy and Earth sciences communities to provide educational materials, tools, experiences and support focused on geodetic sciences. Education support is provided through strategic communications, outreach activities and community engagement through science-focused meetings and workshops. ECE activities elevate awareness of the mission of NSF, geodesy and UNAVCO.

***Basis of Estimate** - Labor (3.97 FTE):* Director is planned at 0.90, FTE with 0.10 assumed charged to other projects and the bid & proposal account in accord with current Cooperative Agreement and charging practices. The RESESS Director is currently budgeted on a seperate award. Staffing includes:

- 1 FTE Education Specialist who designs and delivers the majority of short courses and other educational activities.
- 1 FTE media specialist who develops written, digital and audio media to promote geodesy, science education, etc.
- 0.15 FTE supporting event response communication.
- 0.15 FTE maintaining a publications database for papers using UNAVCO data.
- 0.77 administrator, budget analyst and systems administration support.

Travel: $27,300 per year includes meetings with NSF, UNAVCO Board and advisory committees of partner organizations such as IRIS and EarthScope ($8,500). Participation in science and education-related meetings and conferences (typically $14,200 per year) allows interaction with UNAVCO community members and provides outreach via exhibit displays. Staff members also travel to deliver workshops and other education experiences ($4,600).

Participant Support: $103,100 is planned per year. The bi-annual (even numbered years) Science Workshop absorbs $47,000 per year, or $94,000 per meeting. $48,000 is planned for short courses and workshops including travel expenses and travel scholarships. $8,100 is planned for ECE advisory committee annual in-person meeting (9 participants @ $900 each, based on average travel costs from member locales). $9,000 supports other participant support activities.

Materials and Supplies: Design and printing of publications, whitepapers and workshop notebooks, other strategic documents are budgeted as well as promotional items, materials, services ($30,000) and conference registration ($25,000) shipping costs ($3,000) associated with exhibit booths at national conferences.

U1.3.8

ECE program is allocated to NASA at 6% of cost, which is consistent with NASA's share of total GAGE budget.

U1.3.9

ECE program is allocated to Arctic at 4% of cost, which is consistent with OPP-Arctic program share of total GAGE budget.

U1.3.10

ECE program is allocated to Antarctic at 4% of cost, which is consistent with OPP-Antarctic program share of total GAGE budget.

After the above allocations, NSF-EAR retains 86% of ECE program cost.

Crosscutting Elements

U1.C1 Development and Testing (See Part II, Section 3.1.3)

A number of new and continuing initiatives cut across numerous elements of the Work Breakdown Structure, across the organizational structure of the GAGE Facility, or across the interests of more than one sponsor. Salient examples include development of TLS field support, data analysis, data products, and archiving; expansion of real-time GPS observations, data flow and archiving, and data products; multi-sponsor interests served by development and testing efforts and activities; and development of the planned enGAGE Web Space. Here we develop one example of how initiatives that crosscut the elements will be managed within the WBS.

Development and Testing (D&T) creates implementation strategies and plans for new technologies based on testing and analysis of GNSS-enabled receivers and antennas, power systems, data communications devices, monumentation, and other technologies among many other activities. In addition, continuing development of TEQC and other software to integrate new GNSS constellations and observations, relies on testing next generation hardware and firmware. Staff members test hardware capabilities and work with GNSS manufacturers to ensure that science user requirements are met.

D&T focuses on projects of interest to specific stakeholders (e.g. Polar Services requires ultra-low-power, cold-hardened systems) as well as those that are of wider benefit for science infrastructure (NASA interest has driven early evaluation of GNSS capable systems; but this issue is now paramount for PBO renewal and thus of interest to EAR). Effort will most typically be charged to the sponsor and WBS element that drives the priority for each D&T task. In some cases, however, management may determine that it is more appropriate to charge a task with broad benefits or several aspects to more than one sponsor program.

Similar practices will be developed for other cross-cutting initiatives such as full integration of TLS, RT-GPS implementation, and enhancement of UNAVCO's web functionality through enGAGE.

2013 - 2018

UNAVCO COMMUNITY PROPOSAL

GEODESY ADVANCING GEOSCIENCES AND EARTHSCOPE:

THE GAGE FACILITY

Supported Personnel

Table 8. Supported Personnel.

NAME	TITLE	EAR	NASA	OPP	INDIRECT /NON-GAGE	TOTAL
Executive Office & Business Affairs						
Miller, Meghan	President				1.00	1.00
Rowan, Linda	Director, External Affairs				1.00	1.00
Magliocca, Jaime	Executive Assistant				1.00	1.00
Strobel, Gail	Director, Business Affairs				1.00	1.00
Myers-Wagner, Laura	Human Resources Generalist				1.00	1.00
deBourgoin, Celine	Contracts Administrator				1.00	1.00
Deitesfeld, Carol	Controller				1.00	1.00
Donato, Judy	Staff Accountant				1.00	1.00
Burkholder, Bethe	Accounting Clerk				1.00	1.00
Stephanus, Blaise	Award Monitoring Administrator	0.85	0.06	0.09		1.00
Krantz, Angela	Budget Analyst	0.85	0.06	0.09		1.00
Schissler, Megan	Budget Analyst	0.85	0.06	0.09		1.00
Reeme, Tim	Purchasing Agent				1.00	1.00
Schaub, Eric	Property & Building Coordinator				1.00	1.00
Zilling, Holly	HR Assistant/Admin Assistant				1.00	1.00
Geodetic Infrastructure						
Mattioli, Glen	Director, Geodetic Infrastructure	0.70	0.00	0.20	0.10	1.00
Feaux,Karl F	Project Manager, EarthScope & Related Projects	1.00	0.00	0.00		1.00
Luevano, Taunia	Administrative Assistant	0.65	0.04	0.06		0.76
Bohnenstiehl, Kyle R	Permitting Coordinator	0.50	0.00	0.00		0.50
Austin,Kenneth E	NW Regional Manager, GPS	1.00	0.00	0.00		1.00
Woolace,Adam C	Field Engineer	1.00	0.00	0.00		1.00
Dittmann,Stephen T	Eastern US Regional Manager, GPS	1.00	0.00	0.00		1.00
Dausz, Korey M	Field Engineer	0.80	0.00	0.20		1.00
Jenkins,Fred L	Field Engineer	1.00	0.00	0.00		1.00
Kasmer,David M	Field Engineer	1.00	0.00	0.00		1.00
Enders,Max L	Alaska Regional Manager, GPS	1.00	0.00	0.00		1.00
Boyce,Eleanor S	Field Engineer	1.00	0.00	0.00		1.00
Bierma, Ryan	Field Engineer	1.00	0.00	0.00		1.00
Willoughby, Heidi	Permitting Assistant	0.50	0.00	0.00		0.50
Walls,Christian P	SW Regional Manager, GPS	1.00	0.00	0.00		1.00
Mann,Doerte	Field Engineer	1.00	0.00	0.00		1.00
Basset,Andre J	Field Engineer	1.00	0.00	0.00		1.00
Jarvis, Chelsea	Permitting Assistant	0.85	0.00	0.00		0.85
Sklar, Jacob R	Field Engineer	1.00	0.00	0.00		1.00
Pitcher, Travis	Field Engineer	1.00	0.00	0.00		1.00
Nolting, Robert	Equipment Technician	1.00	0.00	0.00		1.00
Blume, Frederick	Project Manager, Development & Testing	0.75	0.25	0.00		1.00
Berglund, Henry	Test Engineer	0.60	0.15	0.25		1.00
Gallaher,Warren	Test Engineer	1.00	0.00	0.00		1.00
White, Seth	Test Engineer	0.00	0.00	1.00		1.00
Prantner, Andrea	Test & Field Engineer	0.00	1.00	0.00		1.00
Pettit, Joseph R.	Project Manager, Polar Projects	0.00	0.00	1.00		1.00
Hodge, Brendan	Field Engineer	0.00	0.00	1.00		1.00
Nylen, Thomas	Field Engineer	0.00	0.00	1.00		1.00
Okal, Marianne H.	Field Engineer	0.00	0.00	1.00		1.00
Miner, Jeremy	Field Engineer	0.00	0.00	1.00		1.00
Coleman, Scotty B.	Equipment Technician	0.00	0.00	1.00		1.00
Normandeau, James	Project Manager, Engineering Support	1.00	0.00	0.00		1.00
Morrison, Abraham	Field Engineer	1.00	0.00	0.00		1.00
Doelger, Sarah E.	Field Engineer	1.00	0.00	0.00		1.00
Sandru, John	Field Engineer	1.00	0.00	0.00		1.00
Williams, Keith	Field Engineer	1.00	0.00	0.00		1.00

Table 8. Supported Personnel.

NAME	TITLE	EAR	NASA	OPP	INDIRECT /NON-GAGE	TOTAL
Geodetic Data Services						
Meertens, Charles	Director, Geodetic Data Services	0.55	0.35	0.00	0.10	1.00
Boler, Frances	Project Manager, Data Center & Cyberinfrastructure	0.80	0.20	0.00		1.00
Estey, Lou	Senior Software Engineer	0.80	0.20	0.00		1.00
Trochim, Eddie	Software Engineer	0.75	0.25	0.00		1.00
Wier, Stuart	Software Engineer	0.37	0.38	0.00		0.75
Maggert, David	Manager, Data Operations	0.48	0.50	0.02		1.00
Jay, Cassidy	Data Technician	0.94	0.00	0.06		1.00
Flores, Nicandro	Engineer		1.00	0.00		1.00
Braddy, Tim	Data Technician	1.00	0.00	0.00		1.00
Williamson, Hans	Data Technician		1.00	0.00		1.00
Shenefelt, Cassandra	Student Assistant	0.50	0.00	0.00		0.50
Mencin,David J	Project Manager, Borehole Geophysics Operations	1.00	0.00	0.00		1.00
Fox, Otina C	Data Engineer	1.00	0.00	0.00		1.00
Looney, Karen T	Data Technician	1.00	0.00	0.00		1.00
Sievers, Charlie	Data Engineer	1.00	0.00	0.00		1.00
Gottlieb,Michael H	Manager, Borehole Operations	1.00	0.00	0.00		1.00
Johnson,Wade C	Field Engineer	1.00	0.00	0.00		1.00
Van Boskirk, Elizabeth	Field Engineer	1.00	0.00	0.00		1.00
Pyatt, Chad	Field Engineer	1.00	0.00	0.00		1.00
Snett,Lee D	Project Manager, Software Engineering & IT	1.00	0.00	0.00		1.00
Smith, Jeremy A	Software Engineer	1.00	0.00	0.00		1.00
Blackman, Brian L	Web Administrator	1.00	0.00	0.00		1.00
Riley, Jim	Web Administrator	0.45	0.30	0.00	0.25	1.00
Jeffries, Susan	Database Analyst	0.30	0.00	0.00	0.45	0.75
Hanzel, Karl	Systems Administrator	0.84	0.08	0.08		1.00
Leeds, Roland	IT Help Desk Specialist	0.84	0.08	0.08		1.00
Duncan, Stuart	Systems Administrator	0.84	0.08	0.08		1.00
Torrez, Damian L	Software Engineer	1.00	0.00	0.00		1.00
Petzke, William	Software Engineer	1.00	0.00	0.00		1.00
Phillips, David	Project Manager, Data Products	1.00	0.00	0.00		1.00
Puskas, Christine	Data Engineer	1.00	0.00	0.00		1.00
Gross, Susanna J.	Data Engineer	0.75	0.00	0.00		0.75
Hodgkinson, Kathleen M	Data Engineer	1.00	0.00	0.00		1.00
Henderson, David B	Data Technician	1.00	0.00	0.00		1.00
Chris Crosby	Project Manager, Geodetic Imaging	0.85	0.00	0.00	0.15	1.00
Baker, Scott	Software Engineer	1.00	0.00	0.00		1.00
Education & Community Engagement						
Charlevoix, Donna	Director, Education & Community Engagement	0.77	0.06	0.07	0.10	1.00
Olds,Shelley	Education & Community Engagement Specialist	0.86	0.06	0.08		1.00
Sloan,Valerie	GeoScience Education & RESESS Specialist	0.13	0.01	0.01	0.85	1.00
Berg, Megan	Education & Community Engagement Generalist	0.86	0.06	0.08		1.00
Weber, Melissa M	Administrative Assistant	0.76	0.01	0.01	0.22	1.00
Schiffman,Celia R	Education & Community Engagement Specialist	0.13	0.01	0.01		0.15
Subaward Key Personnel						
Agnew, Duncan	Professor, Scripps Institute of Oceanography	0.05				0.05
Allen, Richard	Director, Berkeley Seismological Laboratory	0.00				0.00
Bock, Yehuda	Director, SOPAC	0.02				0.02
Dreger, Douglas	Associate Director, Berkeley Seismological Laboratory	0.00				0.00
Herring, Thomas	Professor, Dept of Earth, Atmospheric & Planetary Sciences	0.08				0.08
King, Robert	Principal Research Scientist	0.40				0.40
Melbourne, Timothy	Director, PANGA Geodesy Lab	0.19				0.19
Murray, Mark	Assoc. Research Professor	0.82				0.82
Wyatt, Frank	Geophysics Principal Development Engineer	0.29				0.29