Workshop on Future Seismic and Geodetic Facility Needs in the Geosciences
May 4-6, 2015

Whitepapers

Global, Regional Structure, Rheology and Geodynamics

Authors: Gabi Laske, Barbara Romanowicz, Peter Shearer
Title: High-Resolution Whole-Earth Global Seismology
Keywords: Deep Earth, lithosphere-asthenosphere system, seismic tomography, seismic anisotropy, very broad-band seismometry, GABBA

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Presentations and lively discussions at a recent CSEDI workshop emphasized just how central global seismology is to the Earth sciences: seismic observations in various combinations can help distinguish between thermal and other anomalies; global tomography models are needed to constrain global convection models; seismic anisotropy validates mantle flow and texture calculations; the location and sharpness of seismic discontinuities gives insight into the state of mineral phase transformations. It may seem to some that global seismology has become so ubiquitous that it can be taken for granted, and that seismology has somehow reached its goal. Yet even today global seismic models from different working groups often vary greatly, be it as a result of the choice of data, the theory applied to interpret the data, or numerical techniques to arrive at a model. Though much progress has been made in the last 20 years, seismologists still struggle to agree on a global 3-dimensional high-resolution reference Earth model, or even on a spherical, 1-D model. Many other great questions in seismology still await answers. One challenge is to reconcile shear-wave splitting results and surface-wave azimuthal anisotropy with unifying models of anisotropy. Observations of the mantle transition zone and its bounding discontinuities under the oceans are heavily biased toward regions around oceanic islands, and constraining “normal” oceanic transition zone is still difficult.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The various flavors of seismology, in general, depend critically on the continuation of permanent and temporary seismic networks that operate broadband seismic sensors. Foremost among these are the global seismic network (GSN) and its international counterparts, but also regional permanent and temporary networks. Significant progress in the near future can be made by combining regional and global networks and adopting model parameterizations that allow for local densification. In global seismology, it would help greatly to benchmark the seismic structure around GSN stations by collocating seismic arrays around them. This is the basic idea behind the Global Array of Broadband Arrays (GABBA) initiative. These GABBA arrays will also serve other seismological projects not mentioned in the previous section, including waveform investigations on the sharpness of lateral anomalies, such as the large low-shear velocity provinces (LLSVPs), in previously unexplored regions. The seismic community heavily depends on the IRIS data management center (DMC) as a one-stop shop to retrieve all seismic waveforms in a standard format, as well as metadata from multiple networks and instrument types. As modeling techniques are refined, the community also needs access to large sets of synthetic waveforms computed with the spectral-element approach, computed for a multitude of models. In addition, the community needs easy access to high-performance computing to assemble such datasets individually.

What facility capabilities are needed to support broader impact needs post-2018 (education, outreach, training & workforce development, international)?

The importance and impact of global seismology to other disciplines in the Earth Sciences cannot be stressed enough. In return, improved feedback and dialogue with other disciplines will help seismology adjust and refocus research goals. This is best done in the form of small interdisciplinary workshops such as the CSEDI meetings. Summer school programs such as the long-standing and highly successful CIDER program, but also the Gordon conferences, have greatly helped train students and early career geoscientists, and even senior colleagues, in interdisciplinary approaches. A strong, continued presence in organizations such as Computational Infrastructure for Geodynamics (CIG) and Consortium for Material Properties Research in Earth Sciences (COMPRES) also helps nurture the synergies between seismology and neighboring fields. By nature, global seismology is an international community, and the exchange of experience and ideas on an international stage is crucial to making significant progress, as well as helping to improve access to international datasets.

Authors: William C. Hammond, Geoffrey Blewitt, Corne Kreemer
Title: GPS Imaging of Solid Earth Flex and Flow: The Future of Geodetic Networks
Keywords: Vertical rates, GPS networks

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

We will measure vertical land motion using GPS networks to constrain active crustal deformation and improve our knowledge of lithospheric geodynamics, changes in regional- to continental-scale water storage, the earthquake cycle and active tectonics. Currently our ability to parse the signals from the various processes is limited by the coverage and precision of geodetic networks. Furthermore, improving the estimates of long term trends, annual variations and deviations from secular motion is essential for separating the contributions to local sea level rise, to account for near-shore subsidence or contemporary mountain building within active tectonic plate boundaries. Observations from stable GPS networks are particularly needed to separate earthquake transients that have decades-long decay times from background tectonic deformation. We are pursuing innovative techniques for processing data from global GPS networks that are revealing new features in the patterns of vertical land motion. Our progress has been fueled by the development of new algorithms that enable processing large volumes of GPS data obtained from tens of thousands of stations, and by identifying trends in the time series using robust non-parametric estimation strategies and interpolation.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Today's frontier is tomorrow's foundation. Existing GPS networks are today's foundation that facilitates tomorrow's frontier research. Geodetic facilities currently in place are a gift to the future because continued data collection comes at a reduced cost compared to initial installation. The value of station data increases with observation duration, so shutting down stations cuts off access to the frontier of geodetic precision. At the absolute minimum the existing continuous and semi-continuous networks should be supported though regular maintenance, surveys and strategic upgrades of receivers, but greater long term value is achieved by maintaining the momentum of new station installations across North America and beyond, filling coverage gaps. Semi-continuous networks, such as the MAGNET GPS network operated by the University of Nevada, Reno, offer a precise, economical and flexible option and cast the widest possible net to best constrain background tectonic deformation and capture future earthquakes, volcanic events and other transient geophysical processes. We have shown that long-term trends in vertical motions can be measured using semi-continuous observation strategy (Figure 1), and observation schedules can always be enhanced if continuous monitoring is desired.

What facility capabilities are needed to support broader impact needs post-2018 (education, outreach, training & workforce development, international)?

GPS networks will, in conjunction with seismic networks, form a backbone of the situational awareness infrastructure needed to live on an actively deforming planet. A key broader impact of geodetic science is the improved human awareness of the movements of the solid Earth and hazards associated with earthquakes, volcanic eruptions, movement of the water, and atmosphere on the Earth. Maintaining GPS networks, telemetry, and data fidelity are essential aspects of reducing the time of arrival of important information to constituencies before, during and after time of crises, and support sound decision making to appropriately manage risk. Education helps people understand the processes at work and cope with the inherent risks of living on Earth.

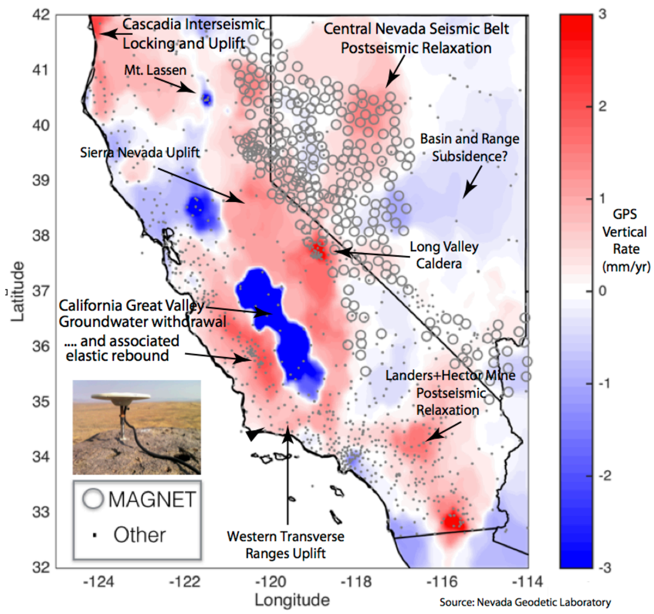


Figure 1. Vertical GPS velocity across California and Nevada from robust non-parametric estimation, with weighted median spatial filtering and interpolation applied. GPS solutions are aligned to IGS08. Continuous (gray dots) and semi-continuous GPS stations from the MAGNET GPS network (gray circles) with time series over 5 years long are used to constrain the vertical rates.

Authors: Barbara Romanowicz
Title: Large aperture arrays for deep earth structure studies at intermediate scales
Keywords: Deep mantle structure and anisotropy, D", GABBA

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

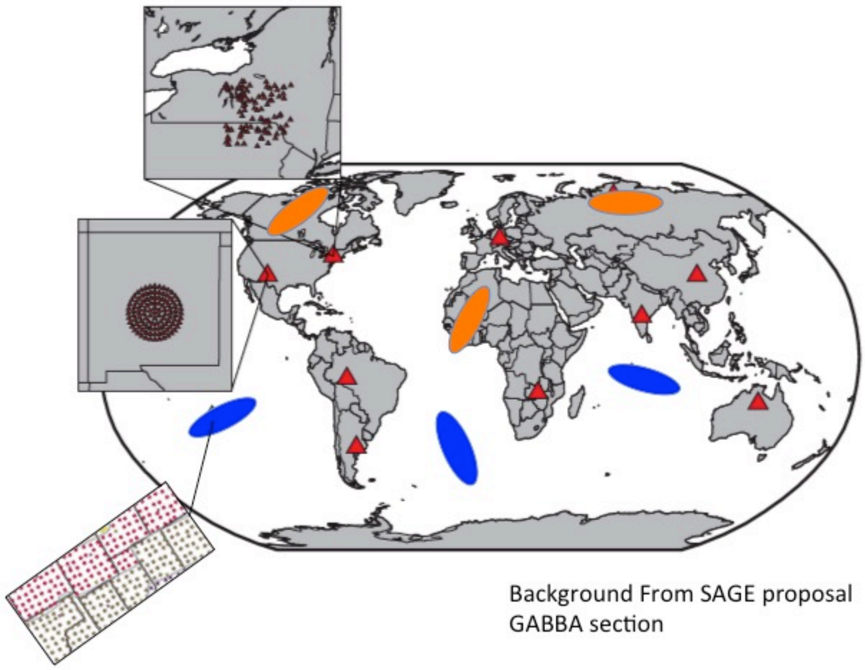
Global seismic tomography is currently reaching or exceeding 1000 km lateral resolution throughout much of the mantle. However there are smaller scale features that may be important for the understanding of mantle dynamics, and in particular, complex structure in the D" region at the base of the mantle - for example ultra low velocity zones that extend less than 50 km above the core-mantle boundary and are currently "under the radar screen" of global tomography. In order to image these smaller scale structures, it is necessary to reach into the scattered wavefield that they produce on teleseismic waves, and in particular shear waves diffracted along the core mantle boundary, in a wide enough range of azimuths and distances. This scattered wavefield is however weak in amplitude, requiring high signal to noise ratio for its capture. The wide azimuthal range is also necessary for constraining the characteristics of seismic anisotropy, which is known to be strong in D", but generally incompletely described.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Large aperture (at least 1000 km in length and 500 km in width) broadband arrays of similar station spacing as USArray (e.g. figure), and as high quality of installation, that would stay in place for at least 2 years to maximize illumination by earthquake sources in relevant locations - priority should be in the oceans, but on land, such arrays could piggy back, in some places, and at least initially, on existing regional network infrastracture. These arrays could be subsequently and progressively shifted in location, similarly to USArray.

What facility capabilities are needed to support broader impact needs post-2018 (education, outreach, training & workforce development, international)?

Training of next generation in state-of-the-art array processing techniques and 3D wavefield computations.



Caption: Sketch illustrating the concept of large aperture arrays on land and in the oceans (colored ellipses). Background from GABBA section of SAGE proposal showing potential location of dense arrays. The locations of the large aperture arrays is arbitrary - specific evaluation of optimal locations would need to be performed.

Authors: Gary Egbert, Anna Kelbert, Barbara Romanowicz
Title: Mapping lateral variations in electrical conductivity in the earth's mantle at the global scal
Keywords: global earth structure and dynamics, electrical conductivity, global mantle tomography

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

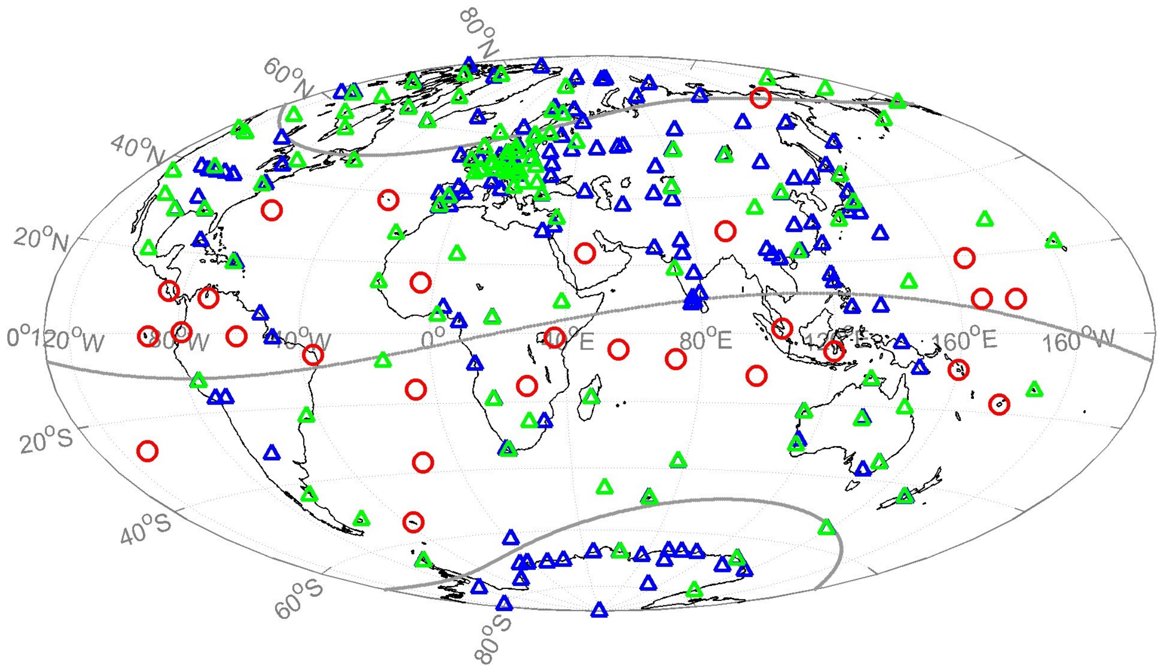
High quality seismic data from the global seismic network and large scale broadband arrays such as USArray have enabled the construction of three dimensional models of elastic structure in the Earth's mantle at increasingly higher resolution. Interpretation of these models in terms of physical parameters to inform global circulation models is ambiguous. Efforts at complementing them with attenuation tomography - a challenging problem - are under way, to help separate the effects of major element composition from contributions of lateral variations in temperature, water content and partial melting are under way. Other complementary information can be gained from mapping electrical conductivity in the deep mantle at the global scale, at least through the transition zone. This holds promise for further separating different contributions to the heterogeneity, and in particular that of lateral variations in water content. This field is still in its infancy, but will benefit, in the next few years, from theoretical progress gained from recent experience with large MT arrays at the regional scale, new satellite measurements of the magnetic field (SWARM, and ongoing efforts to improve models for external source fields. A significant limitation is the paucity of stations in the oceans (including islands, see figure).

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Installing magnetic sensors at selected existing GSN sites on ocean islands would go a long way towards filling the largest gaps in the global distribution of geomagnetic observatories at relatively low additional logistical cost of data collection and site servicing. These new installations would not have to be true observatories with absolute baseline control, and relatively low sample rates (1 hz or even lower) would be sufficient for most purposes. In addition to improved imaging of global mantle conductivity, these additional sites would be of value to the space physics community, and by improving models of ionospheric and magnetospheric current systems, to the broader geomagnetism community.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

There are still too few opportunities in the US to train graduate students in understanding the theory and practice of electromagnetic induction, and more broadly in geomagnetism. A seismic/geodetic facility that also supported research in these areas could help to maintain and build workforce capacity.



Caption: Global distribution of geomagnetic observatories and GSN sites that may be good candidates to complement this distribution. Triangles denote current or historic geomagnetic observatories as reflected in NGDC database as of 2007 (blue) and in IAGA database as of 2006 (green). The red circles indicate those seismic GSN stations that are 1000 km or more from any geomagnetic observatory, based on the 2006 database.

Authors: Gabi Laske
Title: Long-term Seismic Observations and Earth's Inner Core
Keywords: deep Earth, inner core, seismic imaging, free oscillation, very broad-band seismometry

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

After first suggestions that Earth's inner core rotates independently from the mantle, relative rotation rates inferred from seismic observations have varied greatly. While most research settled on rotation rates of 0-0.5°/year eastward, geodynamical and geodynamo modeling, and a recent body wave study, have suggested that the inner core may even shuffle back and forth. Body waves and Earth's normal modes (free oscillations) provide complementary and independent constraints, and a decade after our last normal mode study, the time is ripe to have a fresh look. In a nutshell, we evaluate how the patterns of local normal mode frequencies, the splitting functions, of inner-core sensitive modes change over time. If errors in the splitting functions are small enough, different trends for different modes - that sample the inner core in different ways - would indicate that the inner core does not even rotate as a rigid body, a revolutionary thought that has yet to be investigated. Body wave and normal mode observables depend on rather different types of seismic recordings. An ideal free-oscillation database for inner-core sensitive modes is compiled from low-noise, week-long records of great, deep earthquakes. Such events are quite rare. After the 9 June 1994 Bolivia event, it took almost 20 years to record a comparable event (24 May 2013 Sea-of-Okhotsk). Suffice it to say here that splitting functions can also be used in tomographic inversions to model inner core structure.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

This research depends critically on the continuation of permanent seismic networks that operate a very broadband seismic sensor. Foremost among these is the global seismic network (GSN) and its international counterparts, but also regional networks that have observatory-quality installations. Many of the latter are operated by IRIS-affiliates. Normal-mode research has strict demands on low self-noise of seismic sensors as well as the requirement of recording with high fidelity at very long periods between 54 min and 100 s. This research also depends on accurate long-term observations on the time scale of decades. Ideally, observatory-quality installations therefore should not change equipment nor site characteristics (e.g., relocation of sensors) and provide accurate instrument responses and other meta data. This research depends on multiple high-quality datasets, but a one-stop shop to retrieve the data is highly desirable. The corresponding data repository does not necessarily have to be one physical location, but major existing data centers are currently intricately linked to allow a user to send just one request but receive data from a large variety of centers. As data centers and data request tools have evolved in recent years, we have already experienced some degree of increased complexity. It is critical to not lose sight of a one-stop data access as being the most effective one to fully exploit a global, multi-scale dataset.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

The public often is wildly fascinated by research that appears to have rather little immediate social relevance. Discoveries in the distant universe – culminating in the Big Bang - come to mind. In the inaccessible Earth, on the other hand, the possible observation of the independent motion of Earth's inner core relative to the rest of the planet produced one of the biggest media splashes in the Earth sciences in the last 20 years. And this occurred without the involvement of a natural disaster. Ideally, Earth sciences E&O programs continue to use such poster-child discoveries to raise awareness for Earth's unique place in the solar system on one hand but also to increase efforts to leave a livable planet for generations to come. New discoveries (and theories) on the workings of Earth's interior also provide excellent opportunities to recruit the next generation of Earth scientists. To be effective, the community needs excellent state-of-the-art and frontier-level visualization tools, and not lastly experts in communication and education. By nature if its community-base governing structure, IRIS could take on a leadership role at providing these tools and services.

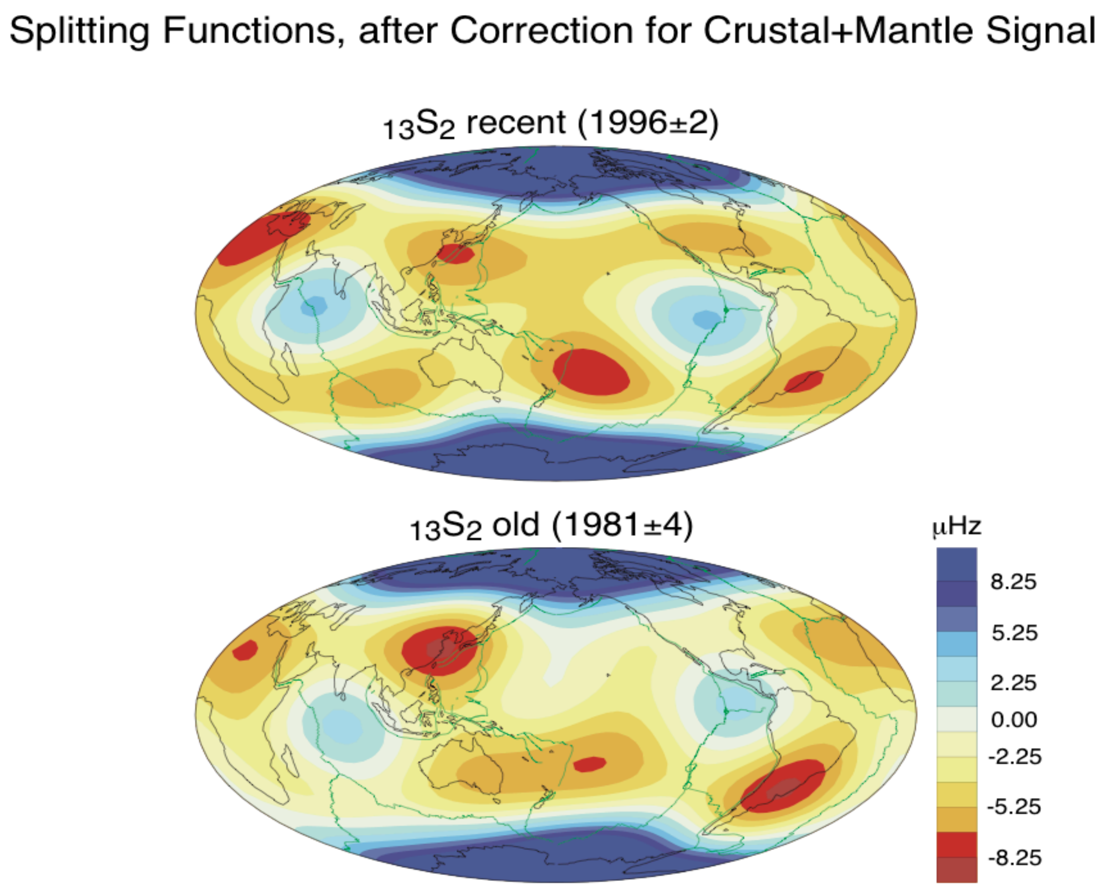


Figure 2, Gabi Laske

Caption: Splitting functions for mode 13S2. Bottom: compiled using events between 1977 and 1985. Top: using event between 1994 and 1998. Contributions from Earth's crust and mantle have been removed. Hence, anomalies shown here are solely due to inner-core structure. A westward rotation of the lower map about the vertical by 4.5° optimally aligns it with the upper map. Provided that mantle corrections were accurate, this comparison implies a westward inner-core rotation of 0.3° per year.

Authors: Barbara Romanowicz
Title: Inner core structure and anisotropy
Keywords: Deep Earth Structure and Dynamics, inner core

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Thirty years after its discovery, many questions remain about the character and distribution of seismic anisotropy in the earth's inner core, about the nature of the F layer right above the inner core boundary, and about the density contrast across the inner core boundary, all issues critical for understanding the dynamics of the earth's core. For example, there are alternative models that suggest that the strongest anomalous travel times of PKP core phases can be explained by structure in the outer core's "tangent cylinder". In order to resolve this question, it is necessary to accumulate high quality measurements for geometries where both sources and stations are at latitudes larger than 50 deg (north or south). Polar stations are also somewhat noisy, necessitating earthquakes of M>6 at the required distances (greater than 120 deg). Because M>6 earthquakes along the southern mid-ocean ridges and northern subduction zones do not occur frequently, it is important to maintain continuous recording of high quality broadband data from high latitude GSN stations for the next decades, in order to fill the gaps in coverage of polar paths of core phases. On the other hand, equatorial paths are also not sampled evenly, because of the source-station distribution imposed by the location of subduction zones and land. Long duration and large aperture ocean floor broadband arrays will help fill gaps in the illumination of the inner core and its vicinity.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

High quality GSN capabilities need to be maintained and complemented by large aperture (1000 km or more) broadband arrays at high latitude on the one hand, and in the oceans, on the other, with spacing and data quality comparable to those achieved with USArray.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Cross-disciplinary educational facilities (i.e. CIDER); training tools in full waveform modeling for the next generation of global seismologists.

Authors: Barbara Romanowicz
Title: Mantle Transition Zone Structure and the planform of global mantle circulation
Keywords: Deep earth structure and dynamics, transition zone structure

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

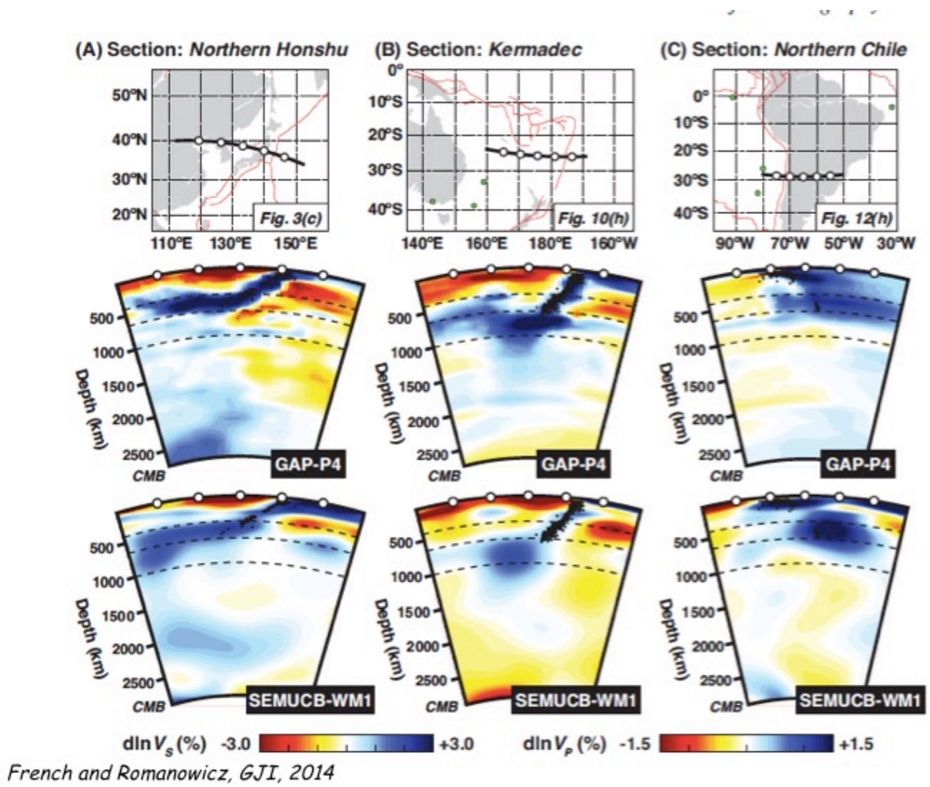
Recent tomographic models focused on subduction zones are showing evidence for horizontal slab "ponding" not only around the 660 km discontinuity, but also, in quite a few areas of the world, around 1000 km (e.g. Figure 1). Likewise, the upwelling flow from the base of mantle may be deflected and modified around 1000 km as evidenced by the morphology of wide columnar low velocity structures anchored at the base of the mantle. This until now undocumented rheological boundary needs to be studied to inform mineral physics understanding of its causes and geodynamic modelling of mantle flow at the global scale. Better resolving seismic structure and anisotropy in this extended transition zone (from 400 to 1200 km) requires very broadband waveform modelling (both forward and inverse) at the global and large regional scales, in order to access seismic phases that are generally not first arrivals (i.e. the surface wave overtone time window).

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

High quality GSN capabilities need to be maintained and complemented by large aperture (1000 km or more) broadband arrays with spacing and data quality comparable to those achieved with USArray. Access to HPC computing for large scale waveform modeling in complex structures.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Cross-disciplinary educational facilities (i.e. CIDER); training tools in full waveform modeling for the next generation of global seismologists.



Caption: Comparison of whole mantle cross sections across different subduction zones for two recent models: a P model, GAP-P4 (Fukao and Obayashi, 2013, JGR) and an S model, SEMUCB_WM1 (French and Romanowicz, 2014, GJI). The P model was obtained from travel time tomography, the S model from 3-component teleseismic full waveform inversion down to 32 s period. Broken lines are drawn at 400, 660 km and 1000 km depth. The two models agree on general slab behavior in the extended transition zone.

Authors: John LaBrecque and The Real-time Earthquake Analysis for Disaster (READI) Group
Title: Seismogeodetic Initiative for timely and accurate early warning of earthquakes and tsunamis
Keywords: Tsunamis, Earthquakes, GNSS

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

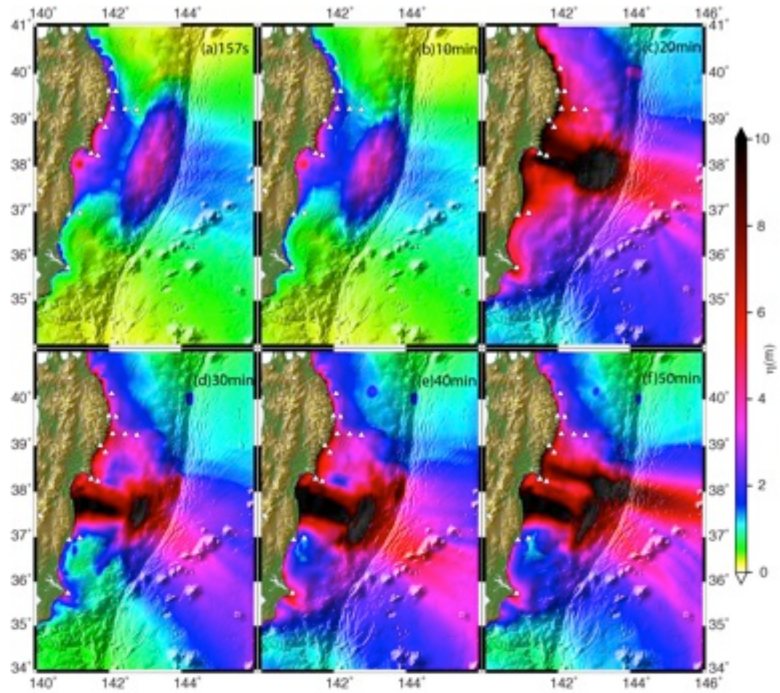
The last decade of tragic mega earthquakes revealed the strengths and weaknesses of independent seismic or geodetic systems. The large Indo-Pacific earthquakes generated tsunamis that struck the nearby coastal communities within 15-30 minutes of the initial onset of crustal failure without adequate warning, resulting in catastrophic loss of life and severe damage to infrastructure. Warning systems must be accurate, timely and provide where possible visual, graphical, and preferably quantitative depictions of an impending hazard in order to be taken seriously by the at risk populations. We recommend the Seismogeodetic Initiative to enhance national and global resilience to earthquake and tsunami hazards by providing timely and accurate warnings through a strengthening and where possible integration of existing global seismic and geodetic resources.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The Seismogeodetic Initiative recommends: • Upgrade of all existing GNSS networks with at least simple strong motion MEMS type accelerometers linked to data centers via real time communications; • Upgrade all global seismometer networks with GNSS instruments; • Deploy seismogeodetic instruments throughout tsunamigenic regions such as the Indo-Pacific, Caribbean and Mediterranean (prioritized); • Enhance research support for the development of integrated seismogeodetic algorithms and operational analysis centers with the goal of issuing earthquake and tsunami warning for earthquakes greater than Mw 7.0; • Pursue initiatives for integration with other heterogeneous systems such as near-shore wave observations and sea floor positioning.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Seek strong international cooperation in infrastructure and data sharing essential to achieving these results; Strong interaction with international operational agencies.



Caption: Progression of tsunami models in time from a rapid kinematic source model for the 2011 Mw 9.0 Tohoku-oki earthquake as Japanese seismogeodetic and wave observations become available. The process retrospectively run in real-time simulation begins with seismogeodetic displacement and velocity waveforms that are available within 3 minutes of earthquake initiation and then is supplemented by GPS buoy data and ocean bottom pressure observations as they become available [Melgar and Bock, JGR, 2015)

Authors: Jeff Freymueller
Title: Modes of Continental Deformation in the Northern Part of the North American Cordillera
Keywords: continental deformation, plate boundary zone, earthquake

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

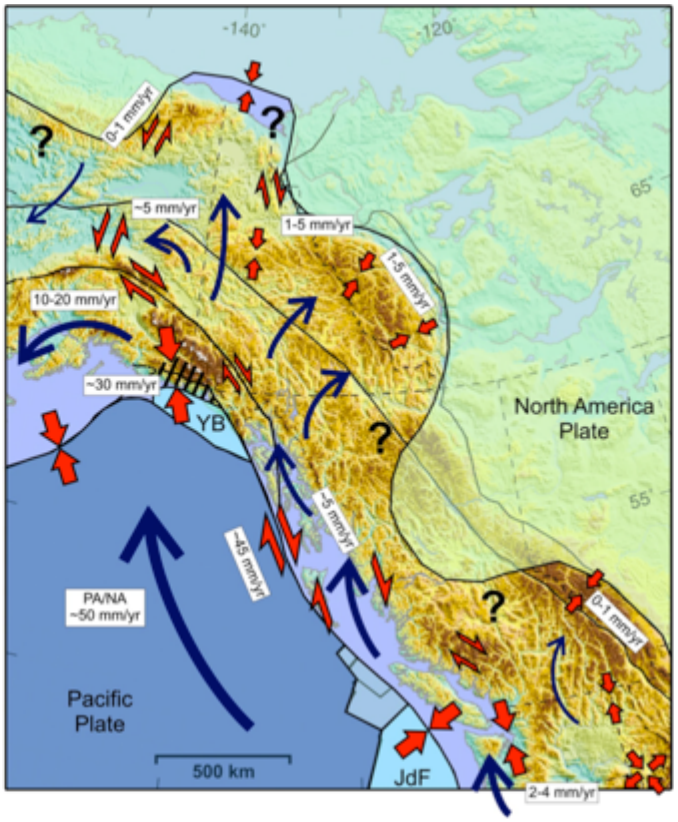
Active strike-slip deformation penetrates the continent inboard of the Queen Charlotte/Fairweather fault system, between the Cascadia and Alaska subduction zones. Compared to the San Andreas system to the south, the fraction of the deformation that is taken up inboard of the main transform system is much lower, amounting to maybe 20% of the total. Why is this different? Is it a result of the different geometric/kinematic boundary conditions, or of differences in material properties? Exactly how far inboard does the active deformation reach, and is the northern Cascadia "backstop" really fixed to North America? Farther to the north, active deformation is found in the Northern Cordillera extending all the way to the Arctic coast. It has been hypothesized that this deformation is due mainly to the collision of the Yakutat terrane in southern Alaska. Did the collision of a relatively small buoyant piece of crust (probably an oceanic plateau) really cause deformation extending almost 1000 km inboard?

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The Plate Boundary Observatory spanned the entire part of deforming North America with two major exceptions: south of the Mexican border and the northern part of the North American Cordillera. Continuous GPS sites (and seismic sites) are almost entirely absent between the Cascadia and Alaska subduction zones despite the active deformation and seismicity. This could be remedied by a PBO and TA-like deployment (the Alaska TA deployment will cover part of the region, barring further budget cuts). GPS site density should be a few 10s of km or less across the actively deforming region, instead of the current 200+ km.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Implementing this would require a cooperative US-Canada effort, which would provide opportunities for hazard mitigation work, education, outreach and workforce development on both sides of the border. New data and new work in the area would provide an opportunity to interact with rural populations and First Nations, providing an "in" for geoscience education that is not tied to resource politically polarizing extraction. The recent Craig and Haida Gwaii earthquakes offer a means to attract the attention of the population in the region, and efforts to educate people about tectonic processes and earthquakes may be more successful while the memory is fresh.



Caption: A schematic description of the active tectonic elements of the northern part of the North American Cordillera, from Mazzotti et al. (2008).

Authors: Erica Emry and Terry Wilson
Title: Antarctic POLENET and Continued Facilities for Autonomous Polar Explorations
Keywords: Seismology, Geodesy, Polar, Cryosphere

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

The Antarctic POLENET (ANET) project is a joint seismic and GPS array focused on providing vital constraints to glacial isostatic adjustment (GIA) models in order to better understand ice mass loss and future isostatic rebound throughout the region. In addition, the project is steadily recovering more information regarding 1) seismic structure and heat flux to the base of the ice sheet (including many glaciers in the region that are experiencing rapid thinning and retreat), 2) the tectonic setting of the previously poorly resolved region, 3) deformation associated with isostatic rebound and current plate motions, and 4) a wide range of seismic phenomena from glacial stick-slip motion and ice quakes to deep volcanic tremor. Data from long-running "backbone" stations are available to the global community and are being incorporated into global Earth models, providing long-needed constraints on Southern Hemisphere structure. The goals of ANET seismic research are supported through the combination of permanent and long-running (ANET backbone) sites that are supplemented by temporary (~2 years) focused array-style deployments The approach of having short-term experiments built around long-running autonomous sites provides an effective means to build robust Earth models throughout the region and also to explore a wide spectrum of seismic and geodetic signals associated with the solid Earth and cryosphere in more detail.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Central to the success of the project has been the design and development to maintain the semi-autonomous remote systems through polar winters. This capability is a pivotal improvement that allows us to create robust results despite the harsh and sometimes high-noise environment. Capabilities need to continue to improve, to develop a set of fully automated sites with low failure rates to collect continuous, high quality data while cutting back on logistical costs associated with work in polar regions. The current ANET stations use IRIDIUM satellite communications for state-of-health but have no data return capabilities. An advanced system, allowing full return of a 1 sample/s datastream for the entire year, and for selected/requested events at higher sample rate, is important, to facilitate both quicker scientific turn-around on data and enhanced station state-of-health assessment

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

The IRIS Data Management Center (DMC) and Earth Model Collaboration (EMC) provide a vital means for ANET data to be accessed. Training prior to ANET field seasons at the PASSCAL and UNAVCO facilities are important to familiarize field participants with the care of the equipment and the data recovery process, as well as expectations for field work. Workforce development and education and outreach should be handled by partnerships between universities and facilities, for example by jointly-supported undergraduate internships on POLENET-related projects.

Authors: Rob Evans, Kerry Key, Anne Pommier, Shane McGary, Emily Sarafian
Title: The Role of Electromagnetic Methods in Future Facility Planning
Keywords: Magnetotellurics, Electromagnetic Methods, Electrical Conductivity

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Electrical conductivity provides a unique constraint on processes at all depths, especially those involving fluids. These constraints are most powerful when viewed with those from other disciplines. For example, fluid released at subduction zones has been imaged at all depths with magnetotellurics (MT) and marine controlled source EM (CSEM) techniques, and similarly both MT and CSEM data have provided first order constraints on melt processes and hydrothermal circulation at mid-ocean ridges. Since constraining aqueous fluids and partial melts from measurements of bulk conductivity requires a detailed understanding of the properties of all the fluids and a petrological understanding of how these fluids interact with each other, EM data are best considered in conjunction with laboratory studies, seismic models and geochemical samples. In the asthenosphere, water dissolved in olivine is known to enhance conductivity, although there remains disagreement over the magnitude of the enhancement. Combinations of seismic and MT measurements are perfectly complementary, with differences in observed anisotropy or reductions in either velocity and/or conductivity allowing us to tease out the relative contributions of thermal structure, melt and water, and their impact on asthenosphere and lithosphere-asthenosphere boundary properties. In all cases, interpretations of field observations are advanced by parallel measurements in the laboratory.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

New EM equipment for both active and passive source studies onshore and offshore has created opportunities for significant advances in imaging pore fluids along plate boundaries and inside volcanic systems. The Earthscope program has played an important role in growing the pool of equipment available for land MT work, but we must continue to expand and update what is a relatively cheap facility. US Marine instrumentation, in contrast, leads the world, largely as a result of investment from industry, yet funds to apply this equipment to cutting edge science experiments have been frustratingly limited.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

The US EM community lags behind that of other countries in terms of numbers of scientists in tenure-track faculty positions. Over the last 20 years, the number of tenure-track appointments for new PhDs with expertise in EM methods has been limited. If the community is to grow then there must be recognition given to the value of the methods as a research endeavor, but also that practitioners of EM techniques offer teaching possibilities in a range of earth science and physics classes. The availability of Earthscope MT data has had a significant positive impact on the US EM/MT community. Data supports US PhD students supervised by several long-time MT researchers, allowing for the training of the next generation of MT experts. Furthermore, the availability of open-source modeling tools has lowered the barrier to entry for what has previously been a highly specialized field of study, allowing for new crossover MT studies where researchers and students from other fields can easily start working with MT data in their own studies. Continued support for educating and training students in EM methods is crucial for the community. Support for holding regular US EM/MT community workshops would foster community collaboration, provide an opportunity for training sessions for both students and researchers from within and outside the MT discipline, and support interactions with international groups which will continue to be important for large projects.

Authors: Lara Wagner, Thorsten Becker, Gaspar Monsalve, Anne Sheehan
Title: Mapping the Dehydration Front on Subducting Flat Slabs
Keywords: Subduction, Volatiles, Tomography, Scattered Wave Imaging, Receiver Functions

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

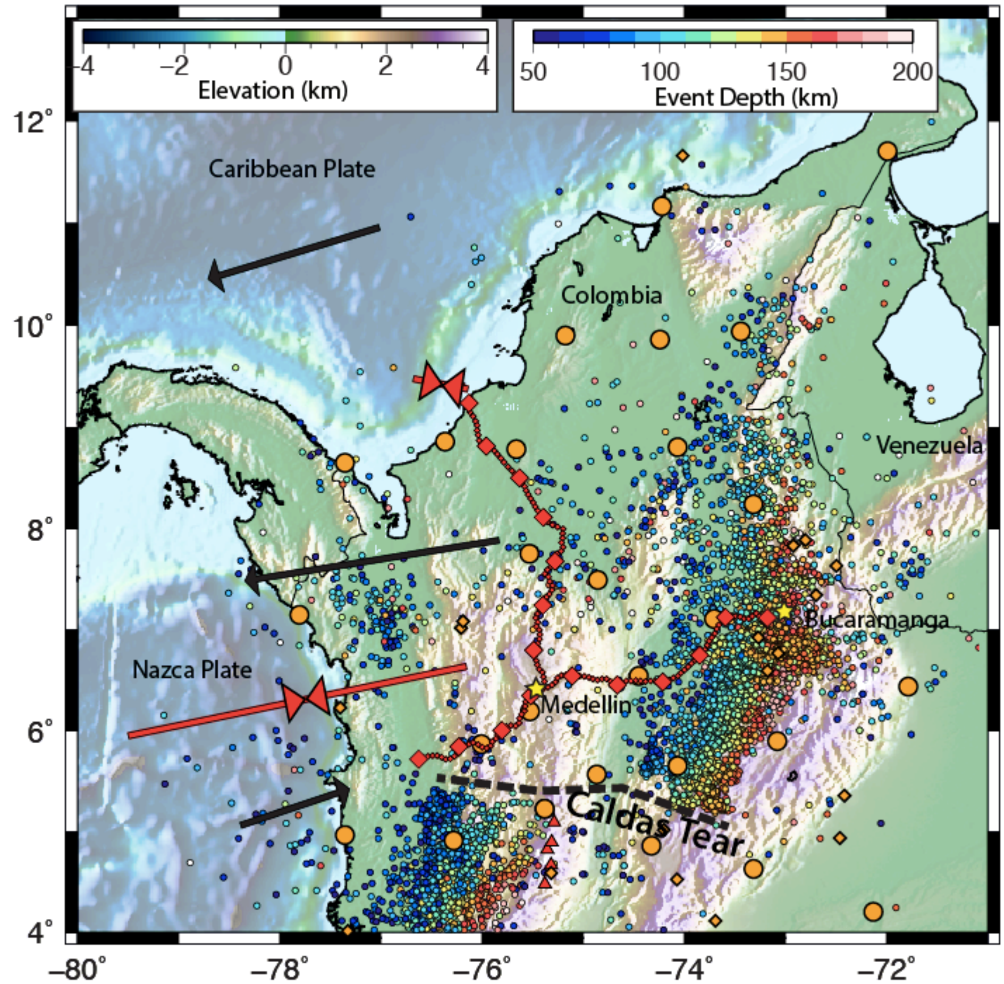
One of the enduring questions in plate tectonics is the fate of volatiles in convergent margins. We know that much (but not all) of the water subducted in oceanic plates is released in the upper mantle and contributes to continental evolution. Some water is subducted to far greater depths. Understanding this planetary water cycle is central to many earth and planetary science questions, but much of our work on this topic has been restricted to laboratory experiments and computer modeling as opposed to in-situ observations of dehydration reactions. I would like to map out the dehydration front(s) within a subducting slab seismically. In normal subduction zones, however, many of these dehydration reactions occur over short spatial scales due to a sequence of crust and mantle dehydration reactions triggered by the sharp increase in slab temperatures induced by contact of the slab with the asthenospheric wedge. These reactions can be spread out in space and time if the subducting slab reaches upper mantle depths but does not come in contact with asthenosphere for a period of time, during which slab temperature can increase gradually. This is the case in flat slab subduction zones where the slabs travel horizontally for hundreds of kilometers in the uppermost mantle. The Colombian flat slab is an ideal location to study these types of dehydration reactions as they are occurring across its 400 km x 400 km expanse at ~80 km depth before the slab bends and contacts asthenosphere.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The technical challenge to making direct observations of slab dehydration is one of resolution. We need sufficient resolution in three dimensions to image the small-scale changes in elastic properties that would result from phase changes in the subducted oceanic crust and mantle lithosphere. This is a problem that can be solved with improved seismic instrumentation that, while available for purchase, is not readily available to the scientific community. Existing IRIS broadband portable instruments are capable of recording data with the quality and bandwidth required, but they are cumbersome and expensive, limiting the number of stations that can be deployed and therefore spatial data density and resolution. New equipment with only moderately reduced bandwidth, such as the Trillium Compact, could be deployed in large numbers with simple quick-deploy systems at much greater station densities (1 - 5 km station spacing), reserving the full broadband sensors for broader (50 km) intervals at which the additional bandwidth is most valuable. Some level of telemetry or two-way communications would also be necessary to make this level of data collection feasible. In Colombia, the two proposed transects would provide a record of dehydration reactions both parallel and orthogonal to the convergence direction. Given that it is not known which plate (Nazca or Caribbean) comprises the flat slab, these data will also give clues to the evolution of this tectonically complex region.

What facility capabilities are needed to support broader impact needs post-2018 (education, outreach, training & workforce development, international)?

Our in-country collaborators often work extremely hard to help with all aspects of these deployments, from shipping, to customs, to facilities and personnel. For all of their efforts, though, they often struggle to be able to take full advantage of the data sets they make possible. They often want for computers, access to software, and money for student support and travel to conferences or to collaborator's institutions, all of which would enable a more complete integration of their research interests into these efforts. Additional resources, and the ability to use those resources to provide our collaborators with lasting infrastructure (computers, software, training, etc) that they need, would greatly improve the science done both here and abroad. Programs like the NSF PEER program need to be continued and expanded in order to fully collaborate internationally on these types of programs.



Caption: Topography, seismicity, plate motions, existing seismic stations, and our proposed seismic deployment in Colombia. Orange circles and diamonds are the broadband and short period stations of the Colombian National Network. Red triangles are Holocene volcanoes, small circles are slab seismicity colored by depth. Black vectors are absolute plate motions and red double-arrows are relative plate motions. Small and large red diamonds are our proposed intermediate and broadband stations.

Authors: Ronni Grapenthin, Susan Bilek
Title: Permanent seafloor geophysical networks
Keywords:

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Due to our lack of comprehensive geophysical networks on the seafloor, we remain with a limited understanding of megathrust earthquakes and microseismicity along convergent margins. Similarly, we do not know about interseismic strain accumulation, co-seismic deformation, post-seismic relaxation, and micro- and moderate seismicity in oceanic intra-plate environments. Our lack of high-resolution observations turns complex earthquakes like the rupture during the 2012 Indian Ocean event into a surprise. The large amount of slip at the trench in 2011 Tohoku earthquake also challenges our understanding of the shallowest part of the megathrust zone. Permanent, maybe even real-time observations of seismicity and motion of the seafloor will enhance the spatial and temporal resolution of these processes and inform about underlying mantle dynamics. These observations can be achieved with permanent geophysical networks on the ocean floor.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The Cascadia Initiative OBS deployment over a 4-year period provides a good test case of long-term seismic monitoring of a plate boundary, but the lack of geodetic monitoring limits its impact. Cost is certainly a big issue, as seafloor geophysical equipment is likely to remain expensive because of the lack of other “customers”. But the larger cost factor is ship time for deployment. Particularly, if techniques like seafloor geodesy require a ship to remain in place for an extended time (days) to repeatedly ping ocean bottom transceivers for increased precision, this effort that can only be accomplished with community facility support. While progress is being made in testing autonomous ocean vehicles (such as LiquidRobotics’s Waveglider), the ability for timely travel over long distances (e.g., along the Aleutian trench) and precise navigation in the face of strong currents is limited. Fundamentally, we need our facilities to be involved in both the seismic and geodetic instrumentation that meet the science needs. But the facility also needs to drive the development and testing of autonomous ocean vehicles that can operate at sea for extended periods of time, navigate precisely, and propel themselves rapidly. This should happen in collaboration with industry partners that include manufacturers, but also other potential consumers (such as the energy industry). The goal should be the creation of a facility that unifies the current isolated efforts in advancing our abilities.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

It is crucial for the public to be well educated and informed about the benefits that big investments into these networks will bring in terms of protecting lives and economic infrastructure (e.g., supply chain dynamics). It is ironic that the US invests heavily into perceived threats with relatively small footprint and likelihood (terrorism), while investments into natural hazard mitigation and early detection are rather sparse. Clearly, such decisions are made at high political levels. However, as the process of moving the California demonstration earthquake early warning system towards a public system shows what an impact effective communication with policy makers can have. Hence, the community that operates these facilities will need to be clear about communicating how surveying and monitoring the ocean bottoms can substantially improve our understanding of geologic hazards.

Authors: Hersh Gilbert
Title: Improved tools for integrating geologic and geophysical data
Keywords: terrane boundaries, petrology, geologic databases

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

The data collected by the EarthScope and IRIS programs, as well as other programs has yielded spectacular seismic results with unprecedented levels of detail. The expansive lateral extents of many of these images make them ideal for investigating signatures of continental evolution across North America. However, limiting studies to seismic observations leaves a great deal ambiguity while attempting to link specific features identified in images to events during the tectonic evolution of a region. This ambiguity can be further complicated in regions that possess long histories of modification. Therefore, further progress into understanding continental growth and how it has evolved temporally in North America, will need to come from combining geologic observations with the results of seismic investigations. My future efforts in the next five to ten years will be to take advantage of geologic datasets and integrate them with the results of seismic studies to improve temporal constraints on continental evolution. Observations from other areas of geoscience, including petrology, geochemistry, structural geologic, and geodesy can be better leveraged to strengthen interpretations of seismic data. Improved incorporation of additional datasets into the analysis of seismic results will help clarify the origin of seismically imaged structures, such as the polarity of ancient subduction zones or the extent of Precambrian calderas.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The IRIS facility has already created a lot of the infrastructure necessary for incorporating multiple datasets into a single framework. The tools and datasets within the Earth Model Collaboration constructed by the IRIS Data Management Center already possess a range of types of seismic models that span regional to global scales. The ability of users with a range of familiarity to seismic data to access models such as selected cross sections or even the raw model is very powerful and expands how the model can be used in a range of types of studies. Access to raw seismic models helps realize part of the EarthScope 2010 Science Plan to utilize cyber infrastructure to facilitate analyzing and comparing multiple datasets. The next step of incorporating results from geologic, and other types of investigations, into a similar format would expand the ability of researchers to incorporate temporal information into their geophysical data. The addition of geologic data will help illuminate how many of the geophysically imaged processes evolve. Achieving this research goal does not require creating a new database. Instead it can be achieved by manipulate data in a range of formats into a common format just as was achieved in the construction of the Earth Model Collaboration. IRIS Data Services can connect with efforts such as the Integrated Earth Data Applications website earthchem.org and the NAVDAT datacenter to facilitate comparing seismic and geologic data.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Strengthening the ability of researchers to incorporate multiple datasets into a single format has direct benefits to expanding the broader impact of earth science. Visualizing disparate types of data in a single format will facilitate scientific discovery and exhibit relationships that have not been previously recognized. To achieve such comparisons, it has been more and more common for researchers to import their data into commonly used formats such as GIS and Google Earth. The public has also become more familiar with data visualization in packages similar to Google Earth by seeing them used in print and television media. The scientific community can take advantage of this familiarity by sharing results and data for educational and outreach purposes in Google Earth type formats. This would lead to opportunities to convey the spatial and/or dynamic nature of geologic data in ways that may not be as easy using only static images of results.

Fault and Volcano Systems

Authors: Brandon Schmandt
Title: Opportunities for Large-N seismic arrays
Keywords: Large N, volcanoes, faults, earthquakes, environmental geophysics

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Large-N arrays here refer to seismograph networks with sufficient spatial density & aperture to measure wave field characteristics, and detect and migrate seismic sources whose energy density is too weak for detection or characterization with data from individual or widely separated seismographs. The list of geoscience questions below can be addressed with a new level of observational constraint using Large-N arrays of short-to-intermediate period seismometers. The questions are motivated by my research and augmented by community discussions at the Future Seismic and Geodetic Facilities workshop. What is the geometry of magma plumbing systems and how do they evolve through eruptions cycles? What are diagnostic signals of fluid/gas transport and stress changes in magmatic systems? What localized deformation and boundary structures exist from the brittle/ductile transition extending to Earth's core (shear zones, volatile enrichment/metasomatic fronts, mineral phase transitions, bulk compositional changes, partial melt)? How heterogeneous are high-frequency strong motions from earthquakes and what controls their spatial distribution on scales relevant to infrastructure? How do earthquake ruptures and the physical state of fault zones evolve from rupture initiation to stopping? What is the spatial and temporal distribution of mechanical work done by geomorphic processes (includes terrestrial "critical zone" and cryosphere)?

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Access to ~10,000 compact lightweight autonomous seismographs (cable free, GPS time, 3-component, 24-bit digitizer). The capability of deploying Large-N seismograph arrays would be inherently multi-use, covering current active source needs (and favoring hybrid active/passive surveys), advancing rapid response capabilities (bury a "soup can" rather than dig vault and put up solar panel), and enabling new types of pre-planned passive surveys. A new facility capability that is inseparable from Large-N arrays is a one or more order of magnitude increase in capacity of the community's data storage and distribution system. The envisioned Large-N arrays would (usually) record for shorter duration than most broadband experiments, but could generate 1-20 TB of seismic data per day of operation.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?Large-N array capabilities could provide opportunities for meaningful interactions with industry including exchange of expertise and improved identification of opportunities for mutually beneficial projects. Hybrid passive/active seismology will be a fertile area for innovation that can leverage complementary industry and academic approaches to research. A broader impact opportunity linked to Large-N array capabilities is increased involvement in geophysical field courses. Community based field programs could attract more students to geophysics as many individual institutions lack the scale of enrollment and/or equipment and human resources necessary to run modern field geophysics courses. Given that the Summer of Applied Geophysical Experience program has long had many more applicants than it can accept and it is has an uncertain future, there is a timely opportunity to step up in a similar educational role. Large-N seismographs individually require little ground disturbance and space, but do require widespread access (e.g., urban arrays or national parks containing volcanoes). This presents an opportunity to contact a greater population and advance awareness of geophysics research and informal education, and would benefit from improved community education and outreach materials that Principal Investigators can leverage, customize, and pass on improvements to future PI's through E&O experts on the community center staff.

Authors: Tobias Fischer, Diana Roman, Erick Hauri
Title: Opportunities for Large-N seismic arrays
Keywords: Network, global, volcano, spectroscopy, eruptions, forecasting

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Technological advances in instrumentation, integration of various types of data, sophisticated modeling and key observations have resulted in significant progress in our understanding of volcanic processes that lead to episodes of magmatic unrest and eruptions. The combination of seismic, geodetic and spectroscopic data provides unprecedented insights into the precursors and drivers of explosive, phreatic and effusive eruptions. Despite these advances, most volcanoes are remain poorly instrument or only monitored sporadically and one-dimensionally, i.e. with seismometers. Our goal is to expand the current seismic and geodetic network to include a spectroscopic data stream of measurements from volcanic gas plumes globally. This new data stream will provide information on the gas emissions from active volcanoes and their time-variability together with intrusive and eruptive activity, and as a function of tectonic setting (plate boundaries and intra-plate). Seamless integration with geodetic and seismic data from the IRIS/UNAVCO network will allow scientists to design real-time quantitative models of volcano-magmatic-hydrothermal systems that will lead to precise eruption forecasting and hazard mitigation. In addition to these research themes that are directly relevant to society, the proposed augmented network will provide new insights to the global emissions of volcanic CO2 and SO2 and their roles in magma generation and transport and climate forcing through time.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Current seismic and geodetic coverage needs to be expanded globally to include finer scale coverage of active volcanoes. In addition to the current capabilities, spectroscopic sensors, such as UV cameras, differential optical spectrometers, and laser-based systems need to be included in the global geophysical network. This new data stream will primarily be designed to provide information on volcanic gas emission but can also be used to measure atmospheric parameters remotely. Importantly, the proposed additional capabilities are technologically feasible and working already at several active volcanoes. In order to significantly advance our understanding of volcanic processes globally, their impact on the atmospheric CO2 budget, short-term weather phenomena and long term-climate, this network needs to be expanded to the most volcanically active regions of the world, i.e. Indonesia and Central America. Ideally, expansion of the network to cover Central American and Caribbean volcanoes should be of highest and immediate priority building on already existing infrastructure such as COCONet and the Network for Volcanic and Atmospheric Change (NOVAC) as well as efforts of the USGS via participation in VDAP.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Localized Centers of Excellence need to be established in key countries that already have investment in the global network and expertise through a national geological, seismological or volcanological observatory. Such centers of excellence need to be supported through external funds to run frequent training workshops for the regional science and engineering communities. In these workshops, the technological aspects need to be conveyed through theoretical and practical training sessions that lead to intellectual capacity building. In addition, the centers of excellence need to be supported to purchase spare parts to repair and maintain the stations in their region. Capacity needs to be established and maintained to reliably telemeter data in real-time both for monitoring and to ensure continuous operation and data recovery. As with the technological aspects, experts in data display, modeling and interpretation need to visit the centers of excellence to train the local scientists in these capacities. Close collaboration with local media, schools, colleges and universities through designated and trained individuals will ensure that local general public is involved in knowledge dissemination with regards to hazard assessment and volcano warnings.

Authors: Craig Dobson, Paul Rosen
Title: Program Scientist, Earth Surface and Interior, NASA HQ
Keywords: InSAR, NISAR, GNSS, surface deformation, sea ice, ice sheet dynamics, earthquake, volcano, flood, landslide

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

NASA is partnering with the Indian Space Research Organization (ISRO) on realization of the EarthSCOPE InSAR vision through development of the NASA ISRO SAR (NISAR) Mission. NISAR entered Phase B formulation in March 2015 with an expected launch in late 2020. NISAR will be the first dual-frequency, polarimetric free-flying SAR. NASA will provide an L-band radar, reflector/boom assembly, GPS, telecom and ground segment. ISRO will provide a S-band radar, the spacecraft, launch services and additional telecom and ground segment. NISAR will provide repeat-pass interferometry with a sun-synchronous dawn/dusk orbit at 12-day exact repeat. A SweepSAR technique will provide both high resolution (5-10m) and a broad swath yielding full coverage at the equator every 12-days. At L-band, the 80-MHz bandwidth will be split to provide ionospheric corrections. The observation plan is driven by Level-1 science requirements for dynamic Earth processes including solid earth deformation, the velocities of sea-ice and ice sheets/glaciers, and disturbance/regrowth of terrestrial ecosystems. With a 30% duty cycle at L-band, NISAR could potentially image all land and ice every pass as constrained by downlink capability to approximately 24Tb/day. The provision of science-driven, systematic InSAR data, strobed at 12-day intervals, with an open data policy will realize the EarthScope InSAR dream.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

As recognized by the initial EarthScope program, there are cross-linkages between InSAR and GNSS networks like PBO. (1) Science requires both the exquisite spatial patterns of deformation from InSAR and the continuous time series of position at GNSS stations to fully constrain and understand the processes. (2) GNSS station data provide geodetic tie points for the imagery. (3) GNSS time series can be used for characterization and removal of noise related to the wet troposphere and ionosphere. The NISAR Mission will rely upon leveraged use of existing regional/global GNSS networks to provide reference data. Cal/val activities are now in planning phases by the NISAR Project and the NISAR Science Definition Team. It is anticipated that the PBO network (or a derivative) and others will be available during the NISAR Mission timeframe and also before hand for algorithm development and calibration/validation activities that will use a combination of spaceborne data from international InSAR (PALSAR, SAOCOM, Sentinel-1, and RADARSAT) and airborne InSAR. Science will benefit most if GNSS networks: (1) have a broad global distribution including outcrops in polar regions, (2) include dense networks in some regions for verification of ionospheric corrections and use in tropospheric corrections, and (3) include stations with continuous sampling. Potential evolution of PBO to should consider the role of GNSS networks in support and utilization of geodetic imaging missions.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Given the wide-ranging application and high data rate of such a capable InSAR mission, there will be a need for workforce development and training to support the analysis and utilization of the data. In addition, the NISAR mission is expected to produce a large volume of data with free and open access, but generally processed to relatively low level data products by the project. Thus there will be broad scientific and applications need for algorithm development, computational resources and the specific workflows and processing of this data stream into high level informational products supporting broader studies of Earth surface dynamics.

Authors: Dave Chadwell, Scott Nooner, Spahr Webb, William Wilcock, Mark Zumberge
Title: Seafloor Geodetic Arrays for Monitoring Subduction and Volcanism: Need, Concept, and Demonstration
Keywords: Seafloor Geodesy, Megathrust, Subduction, Cascadia, Aleutians

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

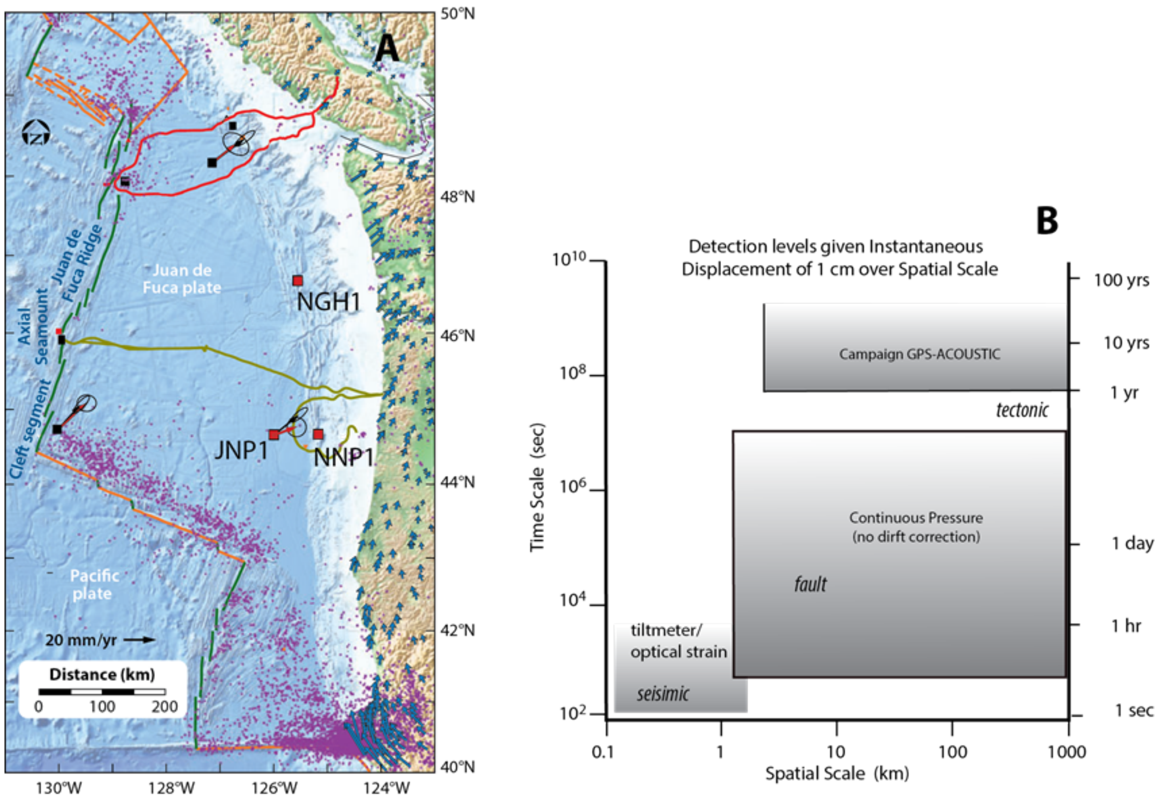
Megathrust earthquakes and their resulting tsunamis are a major geo-hazard. Seismic hazard is directly related to strain accumulation. Much of the strain buildup and release occurs offshore where land-based data have little sensitivity and therefore key questions remain about the temporal and spatial distribution of strain. Both the Cascadia and Aleutian subduction zones are high hazard and scientifically important locations to study. Recent technical developments now allow seafloor geodetic measurements to be made more routinely, at lower cost, and at an increased number of sites. Centimeter-level GPS-Acoustic measurements, have been transitioned to an autonomous ocean wave and solar powered vehicle avoiding the high costs ($50K/day) of an oceanographic vessel. Permanent seafloor benchmarks have been developed and deployed to collect long-term time series of positions. The ~10 cm/yr drift inherent in deep sea pressure sensors has been reduced to effectively ~1 cm/yr by incorporating a self-calibrating procedure. These technical developments have already been deployed at the Juan de Fuca plate in the Cascadia subduction zone. They form a nascent seafloor geodetic array upon which to build a larger offshore array. Multidisciplinary studies at the subsea Axial Volcano with prolific magma supply on very thin crust will reveal new information on the mechanics of volcanism and the impacts of subsea volcanoes on microbial life and heat flux into the world's oceans.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Seafloor geodetic observations are needed on a variety of spatial scales and with a range of displacement sensitivities. Broadly spaced coverage with GPS-Acoustic arrays is required on the incoming plate and continental slope along the deformation front to measure along strike variation in strain. Annual campaigns with ocean wave- and solar-powered autonomous vehicles can determine the centimeter-level horizontal component of motion during the inter-seismic period to map out the present day pattern of strain. In addition, by employing permanent benchmarks, eventual co-seismic and post-seismic motion following a megathrust event can be captured. Presently 3 sites are monitored in Cascadia (See Figure). Centimeter-level transient vertical motions with periods of a few seconds to days can be captured by continuously operating seafloor pressure sensors presumably collocated at the GPS-A sites. Self-calibrating pressure gauges extend centimeter-level resolution for many months and a campaign version of this instrument and possibly other techniques in development can be used to complement long-term studies. Optical interferometric strainmeters and borehole tiltmeters can be deployed to capture submillimeter-scale localized motions. Repeat high-resolution bathymetric surveys may capture co-seismic motion with broad spatial coverage and potentially meter-level or better resolution. As cabled observatories proliferate approaches to submarine geodesy can adapt.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Education of early-career scientist in the methods and operations of seafloor geodesy will be required. Workforce development will require broadening the base of engineers and technicians capable of operating in the marine environment. Commercial manufacturers are beginning to provide more of the instrumentation required for sea floor geodesy. Continuing this trend will ensure industry standard levels of quality control. International partners working seafloor geodetic methods, particularly the Japanese, exists and should be enhanced.



Caption: A) Blue arrows are the land-based GPS vectors relative to North America (NA). Black arrows are long-term geologically derived motion Juan de Fuca – NA. Red arrows are GPS-Acoustic measured JdF-NA motion. Sites JNP1, NNP1 and NGH1 are GPS-A sites presently being monitored. Black box shows locaiton of self-calbrating pressure deployment. B) The spatial and temporal resolution of seafloor geodetic methods for a nominal one centimeter displacement.

Authors: Heather Savage, James Kirkpatrick, James Mori, Emily Brodsky, William Ellsworth
Title: Scientific Exploration of Induced Seismicity (SEISM)
Keywords: fault zone drilling, induced seismicity, fault zone observatory

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

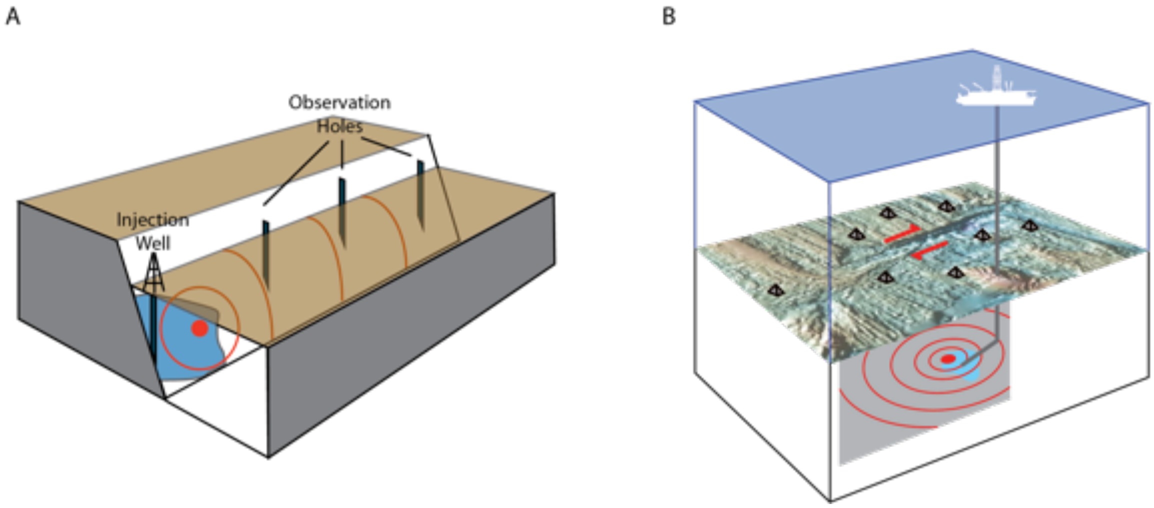
Understanding how earthquakes nucleate, propagate and arrest as well as the triggering of earthquakes by human activities is a current priority in earthquake and fault mechanics. Direct observations of the basic processes that link parameters such as stress, pore pressure, and slip on a fault are impossible without in situ measurements along a fault. These parameters could be measured by borehole and surface-based instruments during an earthquake if they were deployed near to the rupture source. Because it is difficult to predict when and where an earthquake will occur, in order to instrument a fault in advance of an earthquake, we suggest inducing an earthquake through fluid injection. An experiment like this could answer specific questions such as: 1) What is the strength of faults during earthquakes? 2) Is there an observable earthquake precursory signal? Does it scale with the size of the earthquake? 3) What is the size of the stress perturbation needed to trigger seismicity relative to the strength of the fault? 4) Does the size of the pore pressure or fluid volume perturbation correlate with the size of the triggered earthquake? 5) How does permeability vary in space and time in and around an earthquake rupture? 6) What fault structures and/or fluid pressures contribute to stopping a rupture? 7) What are the feedbacks between pore fluid pressure and fault stability? 8) Under what conditions are slow slip events triggered instead of earthquakes?

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Because of the small size of some of the signals, these measurements could never be made from the surface. Fault zone drilling is therefore the only way to answer many of these questions. We propose an active earthquake experiment to induce a moderately large earthquake on a known fault through targeted fluid injection, with extensive borehole observations. This approach has the advantage of obtaining near-field information with a network of instruments in place prior to the induced earthquake. A tectonic fault would be fully characterized before the experiment with active source seismology, borehole geophysics, surface geology, and core-based investigations. An observatory of boreholes containing strain, pore pressure, temperature sensors and down-hole seismometers constructed in advance of the experiment would collect real time data close to the source from initiation to arrest. Successfully driving a fault to failure will require injection into a fault zone well oriented for slip within a stress field where the stresses large enough for the fault to be close to failure. The size of the fault will dictate the magnitude of earthquake that follows injection. Two possible places for this work are basin and range normal faults and oceanic transform faults (Figure 1), both suitable due to their susceptibility to triggering and distance from population centers.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

In addition to learning about earthquake nucleation and propagation, such an experiment would help us understand how to mitigate the risk of unwanted anthropogenic earthquakes by more clearly articulating what conditions are necessary and sufficient for inducing earthquakes. Furthermore, our proposed measurements will elucidate important effects like permeability enhancement through strain and shaking that will be useful for efficient geothermal extraction. The project would also be a huge opportunity to engage undergraduates, grad students, and postdocs, as well as the public. As the broader impacts of this experiment are focused on advancing understanding of a widely appreciated hazard, a capability to encourage and facilitate scientists to explain that this kind of experiment could make people in areas of active oil and gas activity much safer in the long run would be valuable. Therefore public outreach would be an important facet of the broader impacts.



Caption: Figure 1. Potential target faults. A) Normal fault observatory. Fluids pumped at the injection well will trigger an earthquake that can be recorded with seismometers, temperature sensors, strainmeters, etc, at the observation holes. B) Oceanic transform fault. Fluid injected from an IODP vessel would trigger an earthquake on the fault that would be recorded by a network of ocean bottom seismometers (OBS in grey pyramids). Observation holes may also be drilled in advance of the injection.

Authors: Xiaowei Chen, Kyle Murray, Ze'ev Reches
Title: High-resolution borehole observatory for intraplate earthquakes in the mid-continent
Keywords: borehole observatory, pore pressure, GPS, stress, permeability

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

The recent increase of seismicity in the stable mid-continent has drawn significant attention to seismic hazard in the intraplate region. Intraplate seismicity is not a new phenomena, however, the cause of intraplate earthquakes is still not well understood. The high-resolution borehole network in the western United States has significantly advanced our understanding of fault slip spectrum, with the high-resolution image of non-volcanic tremor and microearthquakes. The collocated pore pressure sensor and strainmeter also enable in-situ analysis of permeability and bulk modulus of active fault zone. The high-rate GPS network coverage allows joint inversion of earthquake slip history, which helps to understand the relationship between aseismic and seismic slip. The availability of such facility will greatly enhance our understanding of the physics behind the seismic activities in the mid-continent.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The future facility needs will require collocated multiple instruments, for example, pore pressure sensor, surface and borehole seismometers, atmosphere pressure, high-rate GPS stations, etc. As the seismicity rate responds to stress perturbations, information about stress changes will lead to better understanding of earthquake occurrence, probability and forecasting. There are some possibilities of using pre-existing wells in the mid-continent, which will likely reduce the cost for drilling new boreholes.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

The increased earthquake risk poses higher demand for earthquake education in much broader regions. Therefore, it would be great to develop interactive classroom/outreach modules for broader audience. IRIS has done a great job in maintaining webpage for education and developing cross-platform softwares, such as JWEED. Suggestions for future developments: (1) maintain online open courses for some intro-level classes, where individual researchers can contribute their development to the online pool, or a dedicated education specialist can take primary responsibility. Take "intro to seismology" course as one example, series of modules can be added for interactive investigation of seismicity, location experiments, fault plane solutions and ground motion, etc. (2) Encourage portable cross-platform modules. Most legacy codes are in fortran, which will require command-line training and less interactive, MATLAB and Python modules maybe more practical for education. Earthquake hazard is an international problem, and the well-maintained educational modules will be beneficial to many other regions.

Authors: Andrew Barbour, Evelyn Roeloffs
Title: Direct Observation of Fluid-Strain Interactions Around Active Faults
Keywords: dynamic strain, pore pressure, earthquake triggering, fault-zone permeability

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Making direct colocated observations of interactions between pore-fluid pressures and static and dynamic stresses in the Earth's crust is an emerging science opportunity that we will be pursuing. Such interactions have important implications for the triggering behavior of earthquakes, and the mechanical behavior of faults. There are many questions that naturally follow from an improved understanding of fluid-stress interactions. For example: How does the earthquake cycle affect spatial patterns in response? Can there be temporal variations in response if strain rates in the crust are not constant? How do large-scale oil and gas or geothermal fields affect this response?

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Laboratory measurements of fluid-strain interactions are often made under ideal conditions, but it is a challenging task to connect them to natural settings. One way to bridge this gap is to use scientific boreholes. The Plate Boundary Observatory (PBO) project is a good example of how a dense network of diversely instrumented boreholes facilitates deeper interaction among separate disciplines. Take the recent finding that rates of tectonic strain accumulation can explain spatial variations in fluid-response, for example: colocated strainmeters and pore pressure sensors gave estimates of fluid response, while GPS stations gave estimates of strain rate via gradients in velocity profiles. Such a finding would be impossible without any of the three independent measurement systems. We argue that boreholes are, and will continue to be, fundamentally important to the advancement of geoscience research. Even though drilling and instrumenting boreholes is an expensive task, they have immense scientific value, and provide a framework for 'cutting edge' interdisciplinary studies. Furthermore, new technologies such as fiber optic strain and acceleration sensing can substantially reduce costs associated with instrumentation.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Investments should be made to ensure that high-quality observations persist, since this is just as important as the measurement itself. Stable long-term support could be allocated for the infrastructure needed to make uninterrupted high-quality data streams possible: technical support, data quality-control activities, and technological upgrades. As an example illustrating why this is important, consider the study by Elkhoury et al. (2005), who found that seismic waves trigger transient changes in permeability at the Piñon Flat Observatory. This fundamental observation about how fluid-saturated rock responds to dynamic stress has had a profound impact on the broader community; but, it would have been nearly impossible to observe without the decades of uninterrupted water well measurements and continuous seismic data made possible by long-term support of the observatory.

Authors: Greg Beroza, Jamie Steidl, and Participants in the Wavefields Earthquake Source and Seismic Hazards Online Workshop
Title: Earthquake Source and Seismic Hazards
Keywords:

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

This white paper reflects discussion during an online community workshop on Monday, April 21, 2014. The TA demonstrated the benefit of recording unaliased wavefields at long periods (10-50 s) to image the large-scale structure of the crust and upper mantle. Shorter length scales and periods are required to understand earthquake source processes and how propagation effects control seismic hazard. Recent dense observations on the scale of 100s of meters have demonstrated the ability to record complex wave propagation from local events (Fig 1). High-density deployments that combine many short-period sensors with fewer broadband instruments will help reduce uncertainty and characterize variability in ground motion prediction for future earthquakes. Recording complete three-component wavefields from a more complete range of azimuths and take-off angles – for earthquakes, the ambient field, and artificial sources – over a wide range of frequencies, with high dynamic range, and at high sampling rate are required to accelerate progress in earthquake source and engineering seismology. High-density observations enable back-projection techniques to image the earthquake source in detail – including the evolution of rupture during small events at scales of 10s of meters. Clear images of earthquake rupture over a broad range of scales are required to understand earthquake scaling, earthquake predictability, and the effects of source variability on ground motion.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Truly complete wavefields must be on-scale (unclipped). To improve the scientific basis of earthquake source and seismic hazard, a new facility needs to sample across a wide range of frequencies and amplitudes spanning 10s of seconds to many 10s of Hz, and micro-g to multiple g of ground motion. Sensor technology is improving rapidly, and emerging technology may result in three component sensors that can cover this complete range. Until a single sensor suffices for this purpose, the future facility should be prepared to use a combination of low-gain and broadband technologies, while continuing to work towards a single low-cost instrument that can cover the complete wavefield out to 10s of Hz. This requires dense 1000+ sensor deployments, which makes low cost and ease of use critical. The logistics of operating a large-N array will require low power data acquisition at high sample rates, large onboard storage, and perhaps eventually, telemetry. The data will need to be processed and supplied to users in an efficient and timely manner. The need to capture wavefields from significant earthquakes motivates technologies that allow a rapid-response, aftershock-recording capability.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

In earthquake engineering the wavefields of interest cover a range from many seconds for larger structures (bridges, tall buildings, lifelines) to many 10s of Hz for smaller structures and critical non-structural components (most buildings, control systems for nuclear facilities, power substations, etc.). Improvements in observations should lead to significantly better understanding of earthquake risk. This understanding forms the foundation needed for earthquake engineers to design structures to withstand earthquakes, and in doing so to create a more resilient society. Seismological practice is not keeping pace with the rate of data acquisition, and although seismologists work with large data sets, data-intensive computing approaches have not had much impact on the field. This motivates a workforce-training element in computational methods to accompany dense seismological data gathering if the field is to realize the full benefits of this initiative. This would have to happen at academic institutions, but centralized resources should also play an important role. High-density deployments provide an opportunity for more industry-academia cooperation.

Techniques developed by either side are applicable to this type of data set. This also has a bearing on how this type of facility might be envisioned. For example, academia could draw on the much larger industry instrument pool. It would also enhance training opportunities for students, and joint academic-industry projects.

Caption: Dense recording of the wavefield of a local microearthquake from the NodalSeismic Long Beach array.

Authors: IRIS International Development Steering Committee
Title: iRAMP: An International RAMP for Seismological Capacity-building
Keywords: Earthquake disasters

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Aftershock sequences of large earthquakes offer opportunities to learn much about the Earth: regional tectonics, active faults, and shaking amplified by local geology. But the frequency of aftershocks diminishes rapidly after a main shock so it is critical that a pool of seismometers and a well-trained group of seismologists be mobilized quickly and that travel and shipping logistics be arranged immediately. Earlier aftershocks are often the most useful for understanding rupture physics. For example, the distribution of early aftershocks in the rupture zone is related to heterogeneity of the post-seismic stress [Candela et al, 2011] and aftershock rate changes during the first day can be used to help constrain inversions for coseismic slip [Ziv, 2012]. Opportunities to record aftershocks with a rapidly mobilized seismic array arise predominantly outside of the U.S. A cursory search of NSF's Rapid Response Research awards during the past ten years with the word "earthquake" or "aftershock" in the abstract are dominated by studies related to well-known earthquake disasters in Chile, New Zealand, Japan, Haiti, and Malawi. The benefit of aftershock studies elsewhere to hazard mitigation within the U.S. is improved understanding of fundamental rupture physics, regardless of where a fault is located. Lest a specialized pool miss the best opportunities to facilitate scientific advances, any rapid mobilization capability to be designed with international deployments in mind.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Even for domestic deployments, achieving rapidity requires several important steps, including agreements with owners of leased instruments, arrangements for shipping and other logistics that are sufficiently robust to execute in a crisis, instrument technical capability to record or telemeter data with minimal set up time, advances training for staff, and employment arrangements that are conducive to infrequent but demanding "on call" service. Rapid international deployments required all of those steps and several in addition: export permission from the instrument owners, a priori import arrangements with countries where deployment is likely, staff understanding of import/export requirements, established relations with USAID and other agencies that could facilitate work, wireless data telemetry conforming to restrictions commonly found in many countries. Contributions by participants workshops in many countries could prove critical to the successful, timely acquisition of aftershock datasets. Global seismological capacity-building, recruitment of new generations of geoscientists, and fostering collaborations between individuals and institutions that engage in seismological research, monitoring, and/or education would be necessary and welcome by-products of an international RAMP.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

A RAMP for international deployments and training would provide the capabilities needed to respond to earthquakes rapidly and would serve additional purposes, including building seismological capacity around the world, recruiting young scientists to seismology, enhancing collaborations between institutions and countries, and making additional measurements that would contribute to a more complete assessment of seismic hazard than is possible with earthquakes alone. To accomplish these goals, and acquire unique data sets following large earthquakes, an international RAMP must conduct regular training and data acquisition workshops. The workshops should focus on seismic site characterization, a vital component of seismic hazard assessment, to determine the degree to which seismic waves are amplified at a site by the local geology (primarily basement geometry and sediment density, water saturation, and shear wave velocity structure). Passive-source techniques have been developed recently that provide the information at low cost, non-invasively, without disturbing the local populace, and with greatly simplified equipment needs and logistics. Data are best acquired with a combination of multi-channel seismic systems, equipped with densely-spaced vertical-component geophones, and broadband seismographs. Inexperienced but technically-savvy workers can canvass a medium-sized city in a couple of weeks by continuously recording for 1-2 hours at each site of a regular grid.

Authors: IRIS International Development Steering Committee
Title: Searching for upper plate faults that cause very destructive earthquakes along the Central America subduction zone
Keywords: Earthquake disasters

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

The Central America subduction zone, where the oceanic Cocos plate subducts, is the source of large interplate earthquakes and the locus of shallow, moderate-size but very destructive earthquakes. These destructive earthquakes occur very close to the Central America volcanic chain, where the lithosphere has been thinned by magmatic activity beneath the arc. There were the places where colonial cities were founded and evolved to become, in most cases, the most populated cities of Central America. In addition to lying on faulted crust, subjected to tectonic deformation associated with the locking and unlocking of the megathrust seismogenic zone as well as magmatic processes, building practices in Central American cities often do not conform to international building codes. Most destructive upper plate earthquakes in Central America have occurred on areas that lacked, at the time of the earthquakes, a dense seismic network that was capable of constraining earthquake locations accurately. Examples of upper plate earthquakes that destroyed Central American cities include Cartago (Costa Rica) 1910, Managua (Nicaragua) 1972, and San Salvador (El Salvador) 1985. Adding to these disadvantageous conditions, most faults that produce shallow destructive earthquakes are covered by recent volcanic deposits (or by cities), so their exact locations are unknown.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Because motion on these faults is very slow, traditional and space-based geodetic techniques (CGPS and InSAR) require many decades of monitoring to measure their motion. It is important to identify and locate active faults under cities because standard building regulations require leaving areas of at least 50 m on each side of active faults undeveloped. Urban development plans must include these areas, especially to keep essential infrastructure away from the strongest shaking and from potential surface rupture during future earthquakes. Most seismic networks in Central America currently lack the capability to locate earthquake hypocenters to accuracies better than 2-5 km. Fault spacing could be ~500 m, so it is difficult to assign each event to a particular fault. A more effective way to map active faults is through "urban seismology," employing a large number of sensors spaced tens or hundreds of meters apart. This technique consists of installing a dense array of hundreds or thousands of geophones in cities to record ground motion continuously for a period of several weeks. Although this strategy is new, it has already proved to be effective in the very noisy city of Long Beach, California (Schmandt and Clayton, 2013). We propose to deploy such a multiple-node array in the most populated cities of Central America, where destructive earthquakes have occurred in the past.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

As a pilot test experiment, we suggest starting with the city of Cartago, in central Costa Rica, which has been destroyed several times in the past. (The last destructive event occurred more than a hundred years ago.) Local institutional and popular support for such a study is strong, so deployment logistics will be relatively simple because. People in Cartago are aware of their seismic hazard are willing to allow instruments to be installed in their backyards. The results of this experiment will be useful since the Costa Rica Public Health Institution is planning to build a large hospital on the west side of Cartago, near the fault that produced the 1910 earthquake (Figure), according to several studies.

Authors: Andrea Donnellan, Ramon Arrowsmith, Yehuda Ben-Zion, Sebastien Leprince, Bernard Hallet
Title: Topographic Evolution of Land Surface Processes Through Gazing Imaging
Keywords: Topography, gazing Imaging, fault zones, landslides, volcanoes, glaciers

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

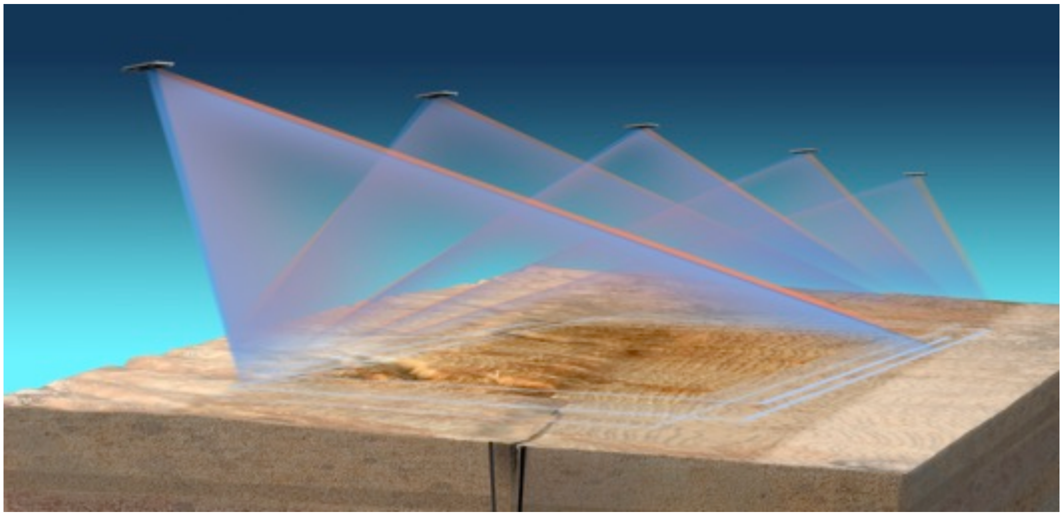
Determining the evolving 3D morphology of Earth surface and crustal processes will improve hazard assessments and mitigate losses from a variety of natural hazards. Understanding the details of these phenomena requires systematic and comprehensive observation of surface topography as they operate and evolve through time. Specific questions can be addressed with detailed measurements: 1. How do fault zones yield, rupture in earthquakes, and heal afterwards? 2. What conditions influence liquefaction and landslides? 3. How is the coastline influenced by tsunamis, hurricanes, and sea level rise, and vice-versa? 4. What are the causes and consequences of floods from large storms, rain-on-snow events, or glacial outburst? 5. How are the magnitude and frequency of sand transport and dust storms changing through time? 6. How does a volcanic eruption unfold? Natural hazard processes leave traces on the landscape and can quickly evolve in time as disasters occur. Understanding these processes requires fine scale imagery and decimeter topographic resolution that has hitherto been inaccessible in synoptic, uniform, high quality form. Such a measurement complements InSAR measurements that often decorrelate near disrupted areas, and GPS in which stations provide point measurements that are too widely separated to measure near-field details of surface processes.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Gazing imaging, in which a moving imager stares at a point on the ground from different perspectives, provides an opportunity to study numerous land surface processes, as highlighted during a recent Keck Institute for Space Studies (KISS) workshop Gazing at the Solar System: Capturing the Evolution of Dunes, Faults, Volcanoes, and Ice from Space (http://kiss.caltech.edu/study/gazing2014/20150415_Final_Report.pdf). Gazing techniques are increasingly being used on small UAV or airborne platforms to acquire structure from motion to study fault zones and other geophysical processes. Extending this capability to a spaceborne platform would provide global systematic measurement of select ground targets, and create a comprehensive dataset that can be used to study landforms and detect change during active phases of natural hazard processes. This measurement technique provides potential for observing motion over a few minutes and would add to our understanding of the process of natural hazards as disasters unfold.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Rapid data gathering and data processing must also be complemented by rapid dissemination, integration with contextual data, and the preparation of well documented higher order data products to make the observations most useful. A robust cyberinfrastructure addresses these needs as well as enables broad and open access. Investments in documentation and training are necessary to make the system as useful as possible.



Caption: A gazing instrument enables more complete 3D recovery of surface morphology by staring at and tracking targets from a range of vantage points during a single pass. For certain orbits solar illumination would vary between passes reducing the number of occlusions and improving the extraction of surface texture and structure. Dozens of images can be collected during a pass, providing the potential for 2-3 minute video of active processes. (Image credit: Chuck Carter/Keck Institute for Space Studies)

Authors: Jessica Murray and Cecily Wolfe
Title: Geodetic monitoring
Keywords: Geodetic monitoring, earthquake and volcano risk reduction

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

The USGS Earthquake Hazards Program and Volcano Hazards Program utilize a variety of geodetic data for research, hazard assessment, monitoring, and response during periods of earthquakes and volcanic unrest. USGS seeks to apply geodetic data toward the understanding of natural hazards and their underlying physical processes, and in its situational awareness products, with the goal of ultimately leading to loss reduction. USGS researchers utilize geodetic data in regions including Alaska, the Pacific Northwest, California, the Basin and Range, and the New Madrid Seismic Zone for activities such as monitoring volcanoes, assessing megathrust locking and slow slip, and conducting seismic hazard assessments. Additionally, research on the use of geodetic data for forecasting earthquake likelihoods on multiple time scales and on integrating geodetic data into the prototype US West Coast Earthquake Early Warning system are a high priority for USGS scientists. The USGS also sees great potential for seafloor geodesy in order to better understand subduction zone processes, better assess seismic hazard in coastal regions, and to improve response to tsunamigenic earthquakes in subduction zones.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The USGS either operates or funds geodetic networks in California, the Pacific Northwest, the New Madrid Seismic Zone, the Aleutians, and the Cascades. The EarthScope Plate Boundary Observatory (PBO) network is an added foundational capability for the following. Alaska: PBO sites are used for volcano monitoring, assessing megathrust locking and slow slip, and recording deformation in future earthquakes on the subduction zone or major strike slip systems. Pacific Northwest: PBO sites provide data for monitoring of very high threat volcanoes, the prototype Earthquake Early Warning system, seismic hazard assessment, and tracking slow slip events, which might influence short term earthquake likelihood. California: PBO sites are relevant for EEW, volcano monitoring, and potentially for forecasting earthquake likelihood. Basin and Range/Yellowstone: PBO data are used for volcano monitoring in Yellowstone and provide coverage along the Wasatch Front. As a frontier capability, there is value in seafloor geodetic measurements for fully characterizing coseismic slip in great Cascadia subduction zone earthquakes. With several years of observations, such measurements would also provide constraints on plate coupling. The PBO GPS and strainmeter observations are also critical for basic research, which provides greater insight into processes governing earthquake and volcanic hazards to guide more effective utilization of geodetic observations for operational purposes.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

The PBO facility capabilities are needed to support education, outreach, training, & workforce development in the field of geodesy. While USGS has the operational responsibility to provide information on earthquake and volcanic hazards in the U.S., other government agencies and private entities have a vested interest in geophysical observations that enable them to mitigate losses and optimize situational awareness in the event of an earthquake or volcanic eruption. In this context, PBO sites that contribute critical real-time data for EEW or near real-time observations capable of tracking volcanic unrest or rapid afterslip may be of interest to municipalities, utility operators, and first responders as well as NOAA for tsunami warning. Elsewhere, PBO data are of great value to the National Park Service to enable monitoring in locations like Yellowstone where volcanic hazard poses a threat to park visitors; these data are also of interest for weather now-casting. As the west coast EEW system moves toward a fully operational mode, sufficient spatial coverage of seismic and geodetic stations will be needed to realize a robust warning system. To maximize its contribution to the above-stated goals, needs and objectives, the PBO GPS network needs to be fully upgraded to modern GNSS instrumentation, with concomitant improvements to communications and data management infrastructure.

Authors: Paul Earle, Gavin Hayes, Cecily Wolfe
Title: Director of Operations, USGS National Earthquake Information Center
Keywords: Global earthquake monitoring, earthquake risk reduction

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

The USGS National Earthquake Information Center (NEIC) is a critical 24/7 facility that rapidly and accurately detects, locates, and characterizes all significant earthquakes that occur worldwide. The NEIC disseminates this information immediately to concerned national and international agencies, scientists, critical facilities, and the general public. Over 400,000 users have signed up to receive earthquake alerts and in 2014, the USGS earthquake web pages received over 66 million page views. Additionally, the NEIC directly coordinates with and provides situational awareness to federal emergency response centers, including Department of Homeland Security, the State Department, and the White House. The NEIC compiles and provides a comprehensive catalog of earthquake source information, which serves as a solid foundation for scientific research. The NEIC pursues an active research program to improve its ability to characterize earthquakes and understand their hazards. Our efforts are all aimed at reducing losses from earthquakes, tsunamis and associated phenomena. In the coming years, the NEIC will continue to improve the robustness, timeliness and accuracy of its core products, work to automate routine procedures, and expand our product base and its use.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The Global Seismographic Network (GSN), along with the ANSS national seismic network, form the core for NEIC's monitoring mission. The NEIC and the NOAA Tsunami Warning Centers rely on GSN data because of its unparalleled low-noise levels and broad-band response. Low-noise stations can detect smaller signals and provide more accurate timing and amplitude measurements. The GSN's low-frequency response enables the use of advanced techniques to model earthquake magnitude and source characteristics, including W-phase centroid moment tensor inversion and finite fault modeling. These source parameters improve USGS real-time products aimed at estimating ground shaking (ShakeMap) and shaking-related fatalities and economic loss (PAGER). Network improvements over the past decade have facilitated the rapid dissemination of earthquake information. In 2011, accurate information about the great size of the Tohoku-Oki earthquake was available within minutes, compared to hours-to-days after the 2004 Sumatra-Andaman earthquake. This dramatic improvement is a result of investments made in the GSN and the NEIC, and research and development into the rapid characterization of great earthquake sources. GSN stations are used significantly more often than other stations in W-phase inversions, which are helpful for rapidly characterizing potential tsunamigenic events. The fairly uniform distribution of GSN stations, as well as their overall data quality, improves their utility.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

A variety of national and international partnerships are vital to achieving GSN objectives. The GSN is itself a partnership between NSF, IRIS, and the USGS. At the operations and mission level, partnerships with NOAA and CTBTO are intimately connected to data flow and data delivery. Through the FDSN there are partnerships with global and national networks operated by other countries that are essential to achieving the GSN's worldwide coverage goals. At the individual GSN station level, the network operators have cultivated long-standing relationships with local hosts that are critical for maintaining the longevity of such sites. Beyond the GSN, the USGS has begun partnering with national networks in high-hazard foreign countries (e.g., Latin America) to explore how data and expertise exchange can aid common hazard mitigation efforts. Global earthquake observing requires state-of-the art equipment, emphasizing the need for a healthy level of research and development, including in seismometer instrumentation. To this end, the development of a long-term replacement for aging STS-1 instruments is seen as critical to maintain the quality of GSN observations. Similarly, development of cost effective technologies for obtaining long-term observations in the oceans will likely improve our ability to rapidly characterize earthquakes, including potentially tsunamigenic sources.

Authors: Diego Melgar
Title: Strong motion seismology with GPS
Keywords:

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

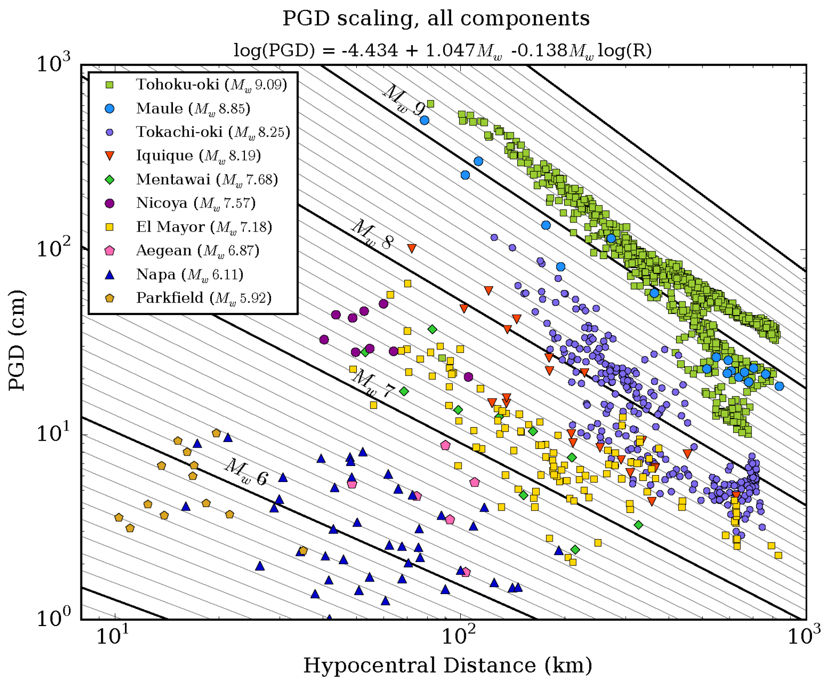
Traditional force-based design in earthquake engineering relies strictly on ground motion parameters derived from inertial sensors such as accelerometers. Intensity metrics such as peak ground velocity and acceleration (PGV and PGA) are used as inputs in the design process, thus ground-motion prediction equations (GMPEs) which relate these metrics to earthquake parameters are the subject of substantial research efforts. However, new engineering paradigms such as displacement-based design, upon which resilient buildings such as base-isolated structures are based, require broadband metrics of displacement from the lowest end of the spectrum (the static offset) to high frequency shaking. These must be synthesized through intensity metrics such as peak ground displacement (PGD) and spectral displacements. Comparison of inertial and GPS measurements of displacement for most of the large earthquakes of the last 5 years has unequivocally demonstrated that seismometer derived strong-motion displacements are biased and cannot provide actionable displacement intensity measurements across a broad frequency range. In 2018 and beyond widespread strong motion displacement recordings from high rate regional GPS stations will become increasingly important for ground motion analysis and earthquake engineering. Techniques and instruments that combine traditional inertial sensors with GPS will receive broad attention by both the seismological and engineering communities.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Continued support for existing high-rate GPS infrastructure within the plate boundary will be fundamental to continued recording of strong motion displacements. Many research groups and universities process high-rate data rom the western US and Alaska with a number of different methodologies. It will be crucial going forward that these groups be supported as the community converges, much like seismology did 20 years ago, towards a unified approach in regards to fundamental issues such as processing methodologies and data formats.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

In order for strong motion displacements derived from GPS to be useful to the ground motion and engineering communities a community effort is necessary to build a central repository of processed displacement waveforms in seismic data formats. The barrier to entry, today, for non-geodesy specialists is high. Additionally, concerted efforts to gain access to the wealth of strong motion displacements being recorded by dense networks elsewhere in the world such as Japan, Mexico, Chile, Indonesia, Peru, etc, will allow the community to build a large repository of strong motion displacement waveforms. The strong motion community has done this for many decades through initiatives like the Center for Engineering Strong Motion Data (http://www.strongmotioncenter.org/) similar initiatives, whether through UNAVCO or other agencies will do much to insure GPS data stay relevant for as many disciplines as possible.



Caption: Peak ground displacement vs magnitude scaling law determined from unfiltered high-rate GPS recordings at local to regional distances for 10 medium to large events. The plot shows no saturation and demonstrates that PGD which includes both the static offset and shaking grows as a function of magnitude at least between magnitudes 6 to 9. This is the type of data that cannot be computed from inertial seismometers that can be of widespread use in engineering and ground motion studies.

Authors: Diego Melgar
Title: Geodesy for tsunami studies and rapid response
Keywords: Tsunamis, megathrust processes, Cascadia, early warning, rapid response

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

The physical models we use to connect megathrust rupture to tsunamigenesis are too simplistic. We don't fully understand the deformation of the shallow portion of a subduction zone and how it couples into the water column. We have only just begun to consider the time-dependent processes of how a tsunami is made. This includes not just static three-dimensional deformation but the superposition of acoustic waves throughout the water column that are excited by the vibrations of the sea-floor, which, over a finite period of time, create a tsunami. In turn being able to measure these perturbations will enable us to understand shallow processes in the megathrust. Evidently, ocean bottom instruments (seismic and geodetic) will be important, but so will dense observations of tsunami propagation. These can be made not just on the seafloor with absolute pressure sensors (which are still rare) but on the surface of the ocean with moored GPS buoys. Many of these technologies require reliable geodetic instrumentation on-land (continuos GPS) as a reference backbone network. Without it, the utility of the off-shore data will suffer. In turn, widespread availability of ocean-based measurements will greatly facilitate rapid hazard response along the west coast of the United States. On-shore GPS can be used to coarsely assess the extent of a large earthquake and off-shore measurements can then provide, with great granularity, the most likely pattern of tsunami propagation and run-up.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

It is critical that there not be a significant dilution of the density of GPS stations along the west coast of the United States. Furthermore, for tsunami hazard and megathrust studies as well as for rapid response it would be desirable to see at least a slight increase in station density in Cascadia. At the very minimum continuos GPS sites need to record at 1 Hz levels and as many as possible need to be real-time telemetered. Something to consider though, is that recent large events (2012 Nicoya Mw7.6) were recorded at 10 Hz with great success. Shaketable testing has also shown that the GPS records seismic signals above its noise level at frequencies as high as 5-10 Hz. Thus, as the noise level of GPS positions is reduced through multi-constellation observation or combination with low cost MEMS accelerometers it will soon be necessary to enable all continuos sites to sample at least at the 5-10 Hz level, otherwise the improvements in position precission will be useless. This will exert great pressures on telemetry so new technologies such as on-site PPP should be considered. In this way only positions would be broadcast to the data center. In this paradigm lower sampling rate data for traditional tectonic geodesy applications can still be collected.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

It is critical that continuos GPS networks throughout the United States see a broader level of integration, both within the geodetic community as well as with seismology. The patchwork of GPS networks that cover the plate boundary often have different processing and data format paradigms and there does not exist a central repository of processed GPS waveforms. This often poses barriers for scientists who are unfamiliar with the intricacies of GPS processing, but who could otherwise make good use of displacement waveforms, to seriously consider using the data. High-rate geodesy urgently needs a unified approach. Users don't want to hear us quibble about processing and only want access to displacement seismograms in a format that is familiar to them. Furthermore, networks in Canada and Mexico are being expanded, closer international collaboration will be a boon. Finally, it's becoming increasingly obvious that GPS data is a multi-hazard instrument that can be utilized for volcano, earthquake, tsunami and atmospheric hazard warning and response, this begs the question of whether agencies in charge of hazard mitigation (USGS and NOAA) should also shoulder some of the financial responsibility of maintaining the current network and helping it to develop in the years to come. Much like the ANSS has, by mandate, to maintain a backbone seismic network, at least some of the continuos GPS sites along the western United States should be thought of in the same way.

Authors: Jeff McGuire, John Collins, Norm Farr, Mike Purcell, Jonathan Ware
Title: Long Term, Cost Effective, Seismic and Geodetic Observatories Above Subduction Zone Thrust Interfaces
Keywords: Subduction Zone Observatories, Earthquake Monitoring, Seafloor Geodesy

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

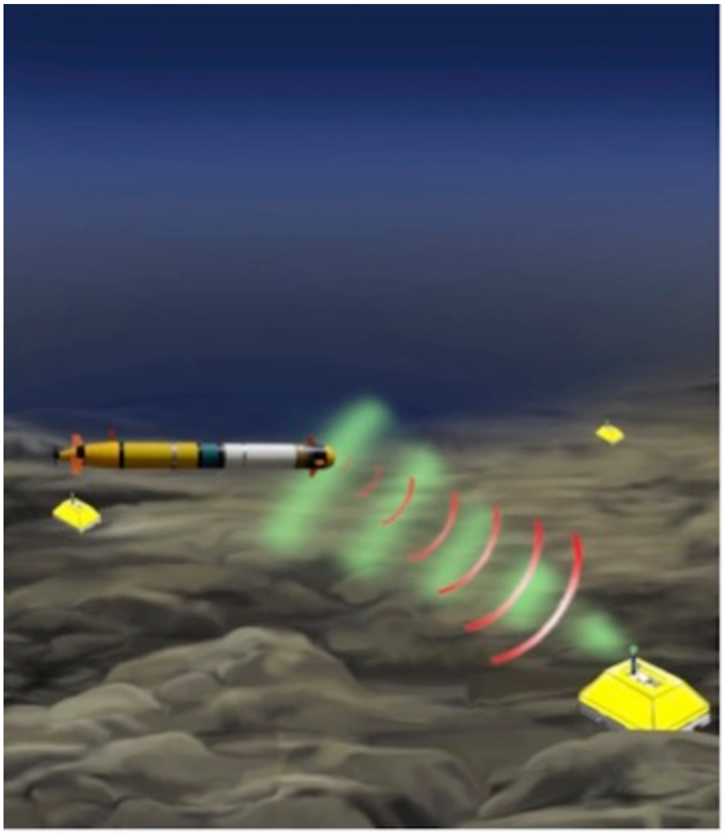
A spectacular number of great subduction earthquakes and tsunamis have occurred in recent years. Each has reminded us that the vast majority of fault motion happens offshore underneath the continental shelf. The near complete lack of modern seismic and geodetic instrumentation in the source regions of these great earthquakes has resulted in deep limitations in our understanding of the underlying processes. In the weeks before the M9 Tohoku Japan earthquake a swarm of microearthquakes migrated along the thrust interface at a speed of a few km/day. Onshore GPS data and seafloor pressure gauge data indicated that there was considerable aseismic slip in the two days before the mainshock. A large section of the plate boundary was evolving rapidly, likely as a result of coupled fluid flow and aseismic fault slip, but the motion was only barely detectable because the closest seismometers were 100 km away, onshore. Subsequently, the slip distribution of the main Tohoku rupture surprised the scientific community: not only did the rupture propagate through the nominally velocity strengthening part of the fault, but the largest slip occurred there. The physical mechanisms that allowed this slip profile probably included a combination of dynamic weakening, thermal pressurization, dynamic stress concentration, and overshoot. Yet, no instruments were deployed near the main asperity to record the wavefield and resolve the mechanical details of this extraordinary event.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Operating in campaign mode has held back the OBS community by discouraging investment in data quality, limiting data continuity, and decreasing data utilization. In contrast, Japan undertook a massive investment in large-scale networks connected to shore via fiber-optic cables. While this is a superb approach, the infrastructure and maintenance costs likely prohibit deploying such stations in sufficient numbers to adequately cover the U.S. subduction zones in the foreseeable future. A more cost-effective observatory is needed. We propose to combine new technologies to enable cost-effective, observatories. A network of long-term OBSs deployed in a subduction zone could be routinely visited by Autonomous Underwater Vehicles for data offload (via optical modem) and clock synchronization. An AUV could leave from shore, transit across the continental shelf and offload the data from each OBS. The data from ~25 OBSs could be retrieved in 2 days with a crew of 2 engineers. Compared to the two multi-week cruises with 25+ people onboard, the cost to retrieve the data would drop by roughly 2 orders of magnitude relative to the Cascadia Initiative. Long continuous time series are necessary to do the best earthquake science and this approach would eliminate data gaps for periods of years and possibly longer. By reducing the latency and continuity problems this approach would encourage greater investment in data quality. A similar argument exists for seafloor geodesy.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Understanding subduction zone earthquakes is an inherently international problem. With the notable exception of Japan, the vast majority of countries located above subduction zones are not currently able to afford major investments in offshore monitoring infrastructure. Moreover, if we want to deeply understand the 500+ year earthquake cycle in subduction zones, we need to study many of them that are currently at different stages and piece this information together into an understanding of the full cycle. While Japan can invest seemingly unlimited resources in studying its subduction zones, this is not true of many strongly affected countries in Central and South Americia. Germany has taken a strong lead in helping Chile develop offshore instrumentation and in many ways is ahead of the U.S. in this international outreach effort. The development of a cost-effective offshore monitoring system could go a long way towards helping the numerous countries along the eastern Pacific subduction zones advance their earthquake monitoring efforts to actually cover the locked zone.



Caption: Graphical illustration showing the capability under development at WHOI. A REMUS Autonomous Underwater Vehicle (AUV) ‘loiters’ above an Ocean Bottom Seismograph (OBS) as it downloads high-frequency (100 Hz) data at rates of 20 Mbits/s via an Optical Modem. The offset of the OBS clock relative to the GPS-synchronized clock carried on the AUV is measured. The improving endurance, onboard processing and satellite communication will allow AUVs to support extended data retrieval missions.

Authors: David Sandwell, David Chadwell, Dan Basset, Bruce Applegate
Title: Need for high-rate, high-accuracy ship positioning and orientation measurements
Keywords: seafloor geodesy, subduction zone processes, kinematic GPS

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

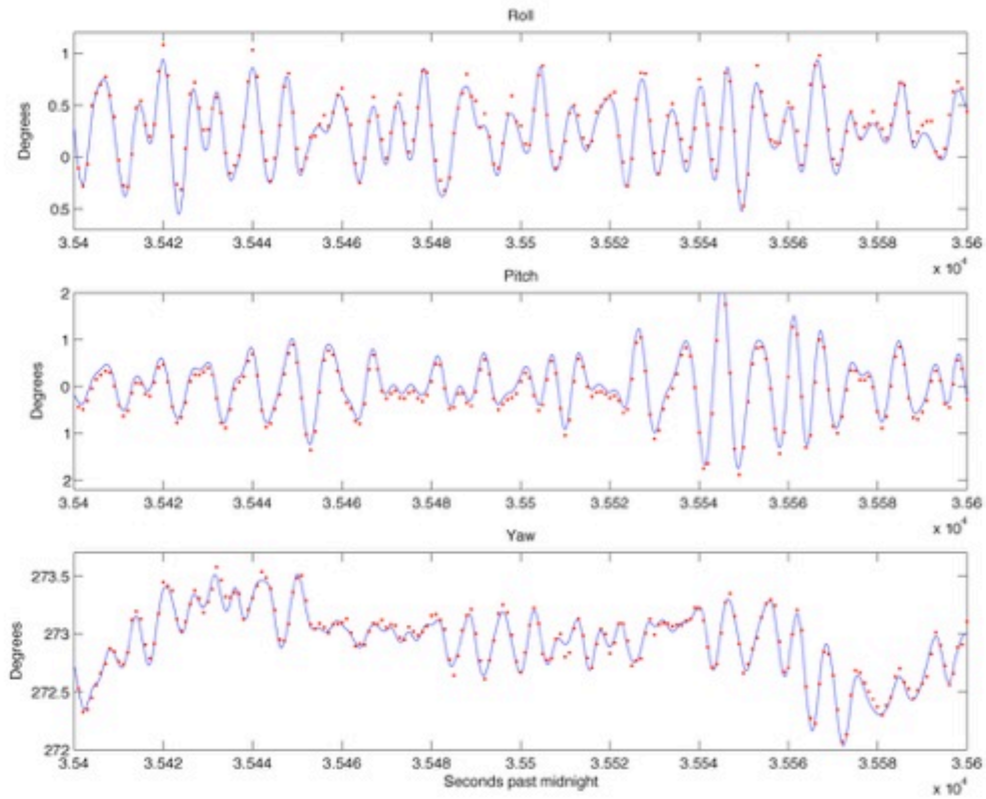
One of the eight high-level science questions posed in the recent NRC Decadal Report (NRC, 2015) was "How can risk be better characterized and the ability to forecast geohazards like mega-earthquakes, tsunamis, undersea landslides, and volcanic eruptions be improved?" The tools of GPS and InSAR are used to monitor crustal deformation onshore, but in the Cascadia Subduction Zone the locked portion of the megathrust is suggested to lie entirely offshore. The up-dip limit of the seismogenic zone, which is the most important for tsunami generation, is particularly poorly constrained by onshore observations and the ability to monitor surface deformation offshore is a key component of characterizing the likely dimensions, hazards and underlying physical properties associated with the Cascadia seismogenic zone.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

GPS-Acoustics (GPS-A) and self-calibrating pressure recorders (SCPR) offer cm-accuracy for horizontal and vertical positioning respectively, but require significant ship expenses and recurring visits for maintenance of seafloor equipment. We are investigating the possibility of decimeter-level accuracy positioning of seafloor patches using sidescan data that is routinely collected by multibeam sonars on UNOLS vessels. One of the main limitations of the archive multibeam data is that the standard GPS equipment does not achieve the centimeter accuracy needed for monitoring the ship location. Moreover the positions of the transponders and hydrophones on the hull of the ship undergo significant high frequency (10 seconds) motions associated with the roll, pitch, and yaw of the ship (Figure 1).

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

We propose that at least 3 high-accuracy GPS receivers be placed on all UNOLS vessels to support both the well-established GPS-A investigations as well as the emerging surface sonar methods. UNAVCO has the technical experience to deploy, and archive data from high-accuracy, high-rate GPS sensors in a variety of extreme environments such as the Antarctic ice and other remote locations having little infrastructure. We believe UNAVCO should develop the expertise to deploy and archive the position and orientation of all UNOLS vessels to support the emerging geodetic and seismic applications. As shown in Figure 1, the GPS sensors can augment the real-time ship orientation that is currently supplied with multibeam sonars.



Caption: Time series of the orientation of the RV Revelle acquired during a 2003 GPS-A cruise at the Juan de Fuca Ridge. High rate data (blue line) were acquired by a system consisting of geodetic GPS measurements, attitude sensed from laser-ring gyroscopes, and linear velocities from accelerometers. Lower rate orientation data (red dots) were acquired by three geodetic GPS receivers; two on the stern and one on the bridge. The GPS data capture the full 3-D ship motions to an accuracy of < 10 cm.

Authors: Michael Oskin and Greg Beroza
Title: SAGE/GAGE Rapid Scientific Response to Earthquakes
Keywords: Earthquake response, geodesy, seismology, lidar

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Major earthquakes present valuable opportunities to improve physics-based understanding of earthquake phenomena. Post-earthquake field data collection efforts must commence as quickly as possible, while aftershocks, transient motions, and surface rupture are strongest and best expressed: (1) Aftershock frequency decays quickly. Because aftershocks illuminate many aspects of fault-zone structure and its post-seismic evolution, it is critical to enhance aftershock monitoring with additional instrumentation as soon as possible. Quick instrument deployment alsoincreases the chances of capturing the nucleation process of a large aftershock. (2) Rapid geodetic measurements, especially within the near field, are needed to separate post-seismic afterslip from coseismic displacement. Where permanent station coverage is sparse, significant effort and equipment will be needed to survey campaign benchmarks around the rupture. (3) Post-seismic deformation is a natural experiment for probing the rheology of the lithosphere with tectonic geodesy. Like aftershocks, post-seismic deformation decays rapidly as well, so the sooner that the rupture trace and its endpoints are defined, and the sooner that instruments are deployed, the better the results. (4) Fault-zone imaging with terrestrial lidar and structure-from-motion techniques should commence as soon as possible, before fragile features decay or are destroyed.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

There are two realms of rapid scientific response to earthquakes for which the SAGE and GAGE facilities should be prepared: (1) managing access to data products from permanent station networks operated by the facilities, and (2) making field instrumentation available for immediate post-earthquake response. Both tasks require time and resources that need to be considered in planning for the facilities. Ideally, after a major earthquake, SAGE seismometers, and GAGE campaign geodesy and terrestrial lidar instrumentation will be in place and surveys underway within one day of the event origin time. Some ways that the SAGE and GAGE could prepare ahead of time for a rapid scientific response to a major earthquake include: (1) Develop a strategy document for post-earthquake instrument deployment, including consideration ahead of time of at what level the interruption of another ongoing experiment (moving instruments) is warranted. (2) Develop coordination plans ahead of time with partner institutions in the various states with earthquake activity, and, as appropriate, with the U.S. Geological Survey. (3) Include initial rapid response as part of the core facility funding, so that the initial, and most critical response is not delayed by funding uncertainty. (4) Consider housing some field equipment at locations along the west coast where it can be deployed as quickly as possible after an earthquake.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Rapid scientific response to strong, damaging earthquakes within the United States is essential to the missions of the SAGE and GAGE facilities. Post-earthquake rapid scientific response will be most effective if it is a team effort that spans the earthquake research community. As research consortiums, SAGE and GAGE are natural catalysts for fostering community response efforts in seismology and geodesy, respectively.

Authors: Brett Carpenter, Judith Chester, Stephen Hickman, Jeff McGuire, Clifford Thurber, Hiroki Sone
Title: Capturing the Seismic Cycle: Installing a Seismic and Geodetic Observatory Directly within an Earthquake Nucleation Patch
Keywords: earthquake source, seismic hazards, seismology, scientific drilling

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

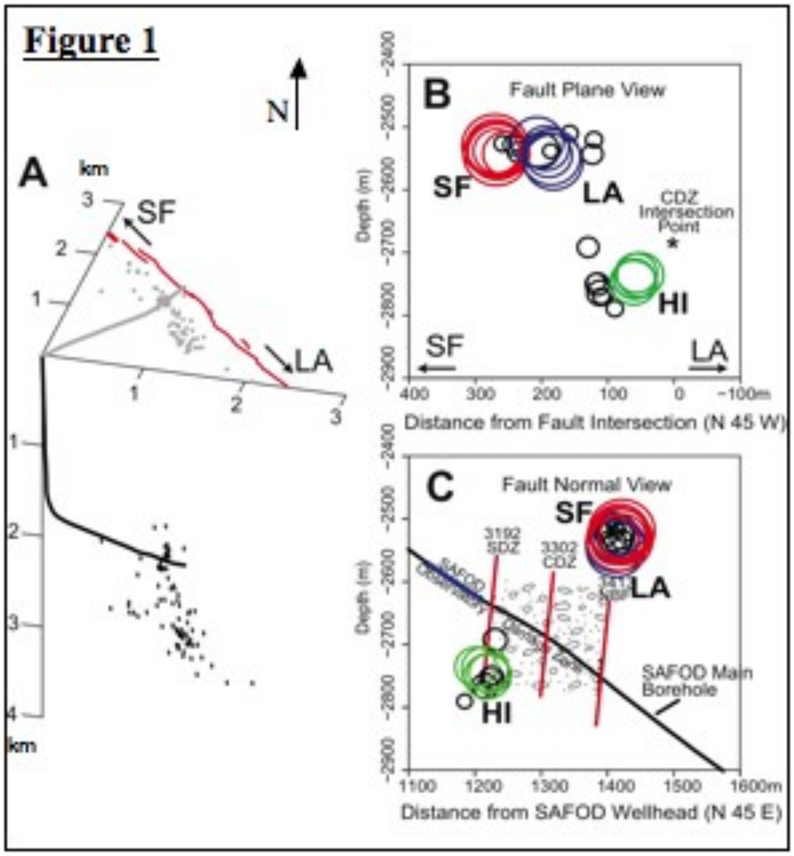
Sampling, down-hole measurements and instrumentation of active faults at seismogenic depths have produced significant advances in our understanding of fault zone evolution, structure, composition and behavior. These efforts have advanced our understanding of the physics of faulting and earthquake generation by addressing the following key questions: How do earthquakes start, propagate and arrest? How do fault zone structure and composition evolve over time, including during the seismic cycle? What is the absolute strength of faults? What are the mineralogy, deformation mechanisms and constitutive properties of fault rocks? What are the processes that lead to spatial and temporal variations in slip behavior, including the transition from creeping to locked (seismogenic) behavior? What are the physical and chemical processes that control faulting and earthquake recurrence? These questions are especially relevant for large, plate-boundary faults capable of producing damaging earthquakes. In this light, we propose targeting an accurately located, repeating seismogenic (nucleation) patch in a well-characterized fault system, where new observations from recovered material, downhole measurements and monitoring can be directly compared to previous studies. Only by studying the composition, properties and mechanical behavior of a known seismic patch through multiple earthquake cycles can we begin to tie laboratory data and rupture dynamics models to observations of fault behavior.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

It is critical that future efforts to address the above questions build off previous efforts to bridge the gaps in our understanding of fault-slip behavior over all spatial and temporal scales. The SAFOD borehole provides a unique opportunity to observe and sample a repeating earthquake rupture patch. We propose to use and expand the current SAFOD borehole by drilling an additional multilateral borehole off the main borehole to penetrate the M2 Hawaii repeating earthquake patch, located ~100m beneath the main borehole. Before such a project can be undertaken, however, a multi-level seismic array should be installed in the current SAFOD borehole to total depth. This array would allow for wide-aperture observations and accurate absolute location of the HI target earthquake, as needed to ensure that a new multilateral borehole would penetrate the seismogenic rupture patch. Sampling of fault and country rocks, downhole measurements, and monitoring long-term fluid pressure, deformation and seismicity within this new multilateral would provide unique information on the composition, physical properties, and deformational behavior of a repeating earthquake patch, for direct comparison with similar samples and observations already obtained. With the infrastructure now in place, we could then test numerous hypotheses explaining the existence of these isolated, repeating earthquakes within the SAF zone, and the processes responsible for earthquake nucleation, propagation, and arrest.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Previous phases of the SAFOD project excelled at providing education and outreach opportunities via onsite visits and offsite meetings. Additionally, a significant number of Bachelors, Masters, and PhD students assisted with both onsite and offsite activities, gaining valuable training and access to materials for their respective projects. Finally, SAFOD science has been produced by a large contingent of U.S. and international scientists. This work has defined the geophysical and geologic conditions in the SAFOD borehole and surrounding region to an unprecedented extent, and through exhaustive studies of SAFOD downhole measurements and recovered core, led to fundamental discoveries about fault zone structure and evolution, and the physical and chemical processes responsible for fault creep. The opportunity to penetrate, sample and instrument a repeating earthquake-generating patch from SAFOD would allow us to realize one of the original goals of SAFOD and EarthScope, providing an unprecedented window into the SAF and enabling us to answer fundamental questions about the physics and chemistry of earthquake generation. We envision that future work at the SAFOD site would continue to achieve broader impacts, in addition to the science outcomes, via public outreach, training of students, and international collaboration.



Caption: (A) 3-D view of the volume surrounding the SAFOD borehole, with microearthquakes shown as black dots (Zoback et al., 2011). (B) Location of repeating microearthquake clusters (SF, LA, and HI), within the plane of the SAF, showing the borehole intersection point (asterisk). The three patches produce nearly identical microearthquakes (M~2) every few years. (C) Cross-sectional view of the same micorearthquake clusters looking parallel to the SAF, with the noted fault traces (red lines).

Authors: Susan Bilek
Title: High density rapid response earthquake studies
Keywords: earthquake, rapid response, aftershocks

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

We have made significant new discoveries about the earthquake rupture process in the last decade because of fortuitous location of dense seismic arrays, including USArray, and some experiments that have managed to quickly deploy instruments within an aftershock zone. Given the earthquake hazard along the country's plate boundaries and increasingly within the interior of the country, it is very likely that the seismological community will be called up to respond to a significant earthquake in the coming years. The community should be prepared to respond with a facility that can provide high quality data so we can make the next advances in our understanding of the earthquake process. Being able to capture a more complete aftershock sequence for comparison with patterns in the main rupture, and obtaining details about how earthquakes, from large to small, rupture are important observations that will impact rupture modeling efforts, hazard analysis, and earthquake early warning efforts, among other areas.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Given the public's interest in induced seismicity and other earthquakes, it would be a shame if the US seismic community response is limited by current instrumentation, which is not the right equipment to be used in a rapid response effort, and will limit the ability to make that next leap in our understanding of earthquakes. One possible structure for a rapid response facility is the availability of a mixed-mode network of several hundred instruments, with a subset of these being easy to deploy broadband instruments (such as the "all-in-one" direct bury instruments) and the remainder being short period 1 or 3 component instruments that have even easier deployment methods such that an entire network could be deployed within a day after the mainshock. Speed of deployment is a critical issue to be able to capture the earthquakes in the aftershock sequence, which will affect options for how to structure the facility. In an ideal world, an OBS deployment would also be of interest because of the possibility of a large earthquake offshore, but I do not think the rapid component (few days) for the oceans could not be met in the near future.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Clearly this sort of facility has significant societal broader impacts as it directly relates to earthquake hazard. This facility has a broader reach, as it would provide important training for students for later employment in government agencies, private industry, and academia. As the academic landscape shifts, our community needs to increase our efforts to prepare our students for those private sector jobs, including in risk management and insurance companies. Use of this facility for earthquakes will lead to increased training in earthquake processes and hazards, preparing students for these sorts of jobs. Should the facility be used for an international response, it can aid in training and education in those countries.

Authors: Estelle Chaussard
Title: Needs for hazards monitoring
Keywords: Precursory signals of eruption, volcano-tectonic interaction, monitoring

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

The most fundamental issue still faced in volcano monitoring is the lack of a global inventory of the number of active volcanoes and their style of activity. Thus, to reach forecast of activity on longer timescales, develop a warning system for volcanoes temporarily quiescent, and monitor ongoing eruptions we need global, long term, continuous, and semi-real time monitoring based on remote sensing by satellite and aerial systems tracking surface deformation, temperature fields and gas emissions and potential for deployment of ground-based seismogram at edifices with unrest. This comprehensive global monitoring will also help elucidate coupling of related systems, including earthquake-volcano interactions, volcano-volcano interactions, and climate-volcano interactions. We additionally need to define the relationship between deformation, seismicity, intrusions, and eruptions to develop predictive models of volcanic eruptions by characterizing the physical mechanisms controlling the rates and styles of eruptions. To do so analysis of long time series of multi-method volcano monitoring records, requiring complete monitoring of a few edifices with seismic, gravity, geodesy, and gas data for long periods and development of physics-based numerical models of eruptive cycles able to reproduce the timing of each observation are necessary. Such models would be the first step towards achieving modeling capabilities with a predictive power.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

To ensure the success of volcano monitoring we need to develop an infrastructure that enables incorporating multiple datasets into a single framework. The Unavco facility host data storage for geodesy and IRIS for seismology. An integration of these resources would lead to a more efficient way to develop multidisciplinary research.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

To ensure the success of volcano monitoring we need data storage facilities (Unavco), data and result sharing platforms for across-fields datasets (WovoDat, vhub) , collaboration between these entities and Volcano Observatories. Supercomputers with free access for data processing and modeling are also a necessary resource for future geodetic and seismic science.

Authors: Stephen McNutt, Chuck Connor
Title: Integrated Geophysical Studies of Volcanoes in Central America
Keywords: volcano seismology, infrasound, deformation, volcanic lightning

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Volcanology has progressed as a science when high quality data sets become available for key eruptions. The eruptions of Mount St. Helens in 1980 and Montserrat in the 1990's are two recent examples. Thus an effective strategy is to set up the required instruments in advance so that the onset and all phases of activity can be recorded and analyzed. We envision a comprehensive network of instruments on volcanoes in Central America that will provide a rich source of scientific data to understand processes, and a fundamental improvement in the ability to forecast and assess hazards from eruptions. We intend to instrument 7 active volcanoes in Nicaragua and 5 in El Salvador. Installation will be done in stages so some data will be coming in year 1 and other data in later years. We plan for USF and collaborators to take the lead on installation and initial maintenance working with partners from Nicaragua and El Salvador. Eventually maintenance will be handed off to scientists and technicians from those countries. Data would be telemetered to USF and/or IRIS and to the relevant agencies in Nicaragua and El Salvador. Data will be immediately available for study by scientists, for demonstrations to students, and for use by other interested parties via the world wide web.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The specific instruments needed are 1) broadband, 3-component high-dynamic-range seismometers, 2) GPS receivers, 3) infrasound sensors, and 4) lightning detectors. The numbers and locations of instruments will be determined by logistics, cost, property ownership, etc. and will vary from one volcano to another. This suite of instruments will allow a broad range of modern studies to be performed, from underground processes that occur before eruptions, active processes that occur during eruptions, and atmospheric processes that occur after eruptions as the ash column moves downwind. The permanent instruments will be augmented by portable instruments for selected topical studies when conditions warrant.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

At USF a computational laboratory will be needed to properly record incoming data, perform data quality checks, perform automated analyses, display data, and store and archive databases. The project will also require a team of scientists and technicians to achieve critical mass, cover all the relevant scientific disciplines, and provide adequate coverage of ongoing eruptive activity. The project is intended to be complementary to existing efforts at USF. It builds on and extends capabilities for basic research in volcanology. It is complementary to an existing multi-purpose GPS deployment in Costa Rica and the data from the new instruments can be shared between and across disciplines for a variety of studies. The planned deployments and infrastructure will also allow additional studies of other natural events, for example large earthquakes or tropical storms. These phe nomena will produce signals on the same instruments but require separate analyses and interpretations. This is an illustration of the fact that the instruments, once in place, will have potential for growth of scientific issues beyond those that drove the original installation. The project will position USF and collaborators at the forefront of modern volcanological research with good access and potential collaborations in Central America, South America, and the Caribbean regions.

Atmosphere, Hydrosphere, Cryosphere Lithosphere Interactions

Authors: Paola Passalacqua, Patrick Belmont, Dennis Staley, Jeff Simley, J. Ramon Arrowsmith, Collin Bode, Bruce Call, Christopher Crosby, Stephen DeLong, Nancy Glenn, S.A. Kelly, Dimitri Lague, Harish Sangireddy, Kelin Schaffrath, David Taroton, Thad Wasklew
Title: Science opportunities and facility needs for analysis of high resolution topography to advance understanding of mass and energy transfer through landscapes
Keywords: High resolution topography, geomorphology, surface processes, lidar, structure from motion, radar, bathymetry

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

High resolution (>1/m^2) sampling of topography, vegetation, and the built environment enables transformative study of mass and energy transfer through landscapes. This topic has been examined recently by a 2014-2015 USGS-NSF Powell Center Working Group study (Passalacqua et al., 2015) revealing fundamental questions: How are mass and energy transported through landscapes? What patterns on the Earth's surface can inform our understanding of ecologic, hydrologic, and geomorphic processes and their interactions? How do processes in one location influence processes or rates across the landscape? Recent community efforts such as the NRC Landscapes on the Edge report highlight major questions eminently addressable with high resolution topography (HRT). HRT is a fundamental observable for many earth processes. Topographic derivatives (slope, drainage area) drive geomorphic transport laws. HRT analysis indicates different controls on landscape change over different timescales (both by direct differencing and reconstruction) and multiple spatial scales. These fine topographic observations cross fundamental accuracy and resolution scale breaks (human, earthquake, hillslope scale--10^1 - 10^0 and grain scale--10-1m). A frontier opportunity is characterizing landscape changing events spanning a broad magnitude-frequency range and quantifying landscape disturbance. Active remote sensing (lidar and radar) is essential for characterization of sensitive tropical and polar ecosystems.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Foundational: Open access to data and methods. Foundational: Support for data acquisition and analysis at multiple scales is key (e.g., UNAVCO, NCALM, OpenTopography, USGS 3D Elevation Program). This includes the need for skilled technical staff, shared resources, continued R&D, and leadership on commercial off the shelf opportunities. Foundational: Cyberinfrastructure including HPC access for large scale analysis and to enable broadest access and (re)use of the data. Must also enable seamless integration with other data types including hyperspectral imagery and radar. Frontier: Recognize the Big Data analysis opportunities: need a revolution in semi-automatic natural and anthropogenic feature extraction and topographic metric computation for large regional studies and monitoring. Frontier: Need enhanced bathymetric capability. Frontier: Integrate HRT with other remote sensing and ecological observation systems (e.g., NEON, CZO, LTER). High resolution topography and bathymetry complements critical zone studies (topographic stress, context for shallow geophysics, etc.). Reference for upper box Passalacqua, P., et al., Analyzing high resolution topography for advancing the understanding of mass and energy transfer through landscapes: A review, Earth-Science Reviews, in revision, 2015.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

The acquisition and analysis technologies and scientific applications of HRT address interdisciplinary STEM . There is great value in integrating these data into curricula at multiple levels. Their broad geographic distribution and value for numerous study types makes them well suited for place-based teaching approaches (leveraging sense of place). Social perceptions and attitudes about place can be explored virtually with HRT. 3D printing and 3D visualization environments enable tactile and immersive interaction with the data in formal and informal educational environments. Specific future facilities support for HRT broader impacts: Training at multiple levels to promote technical literacy for high resolution topographic data acquisition, processing, analysis to facilitate integration of science and engineering to meet societal needs. Formal mechanisms to develop acquisition priorities and technology development for processing and analysis HRT to achieve the full potential of the USGS http://nationalmap.gov/3DEP and related large scale governmental initiatives. Facility support has value for Earthquake, volcano, and landslide processes, hazards, and monitoring. Watershed hydrology and snow surveys Land use, land cover and surface process research enabled by multitemporal and widespread HRT data acquisition Hypotheses for dynamic landscapes to test with HRT monitoring for learning and adaptive management for geoengineering and restoration.

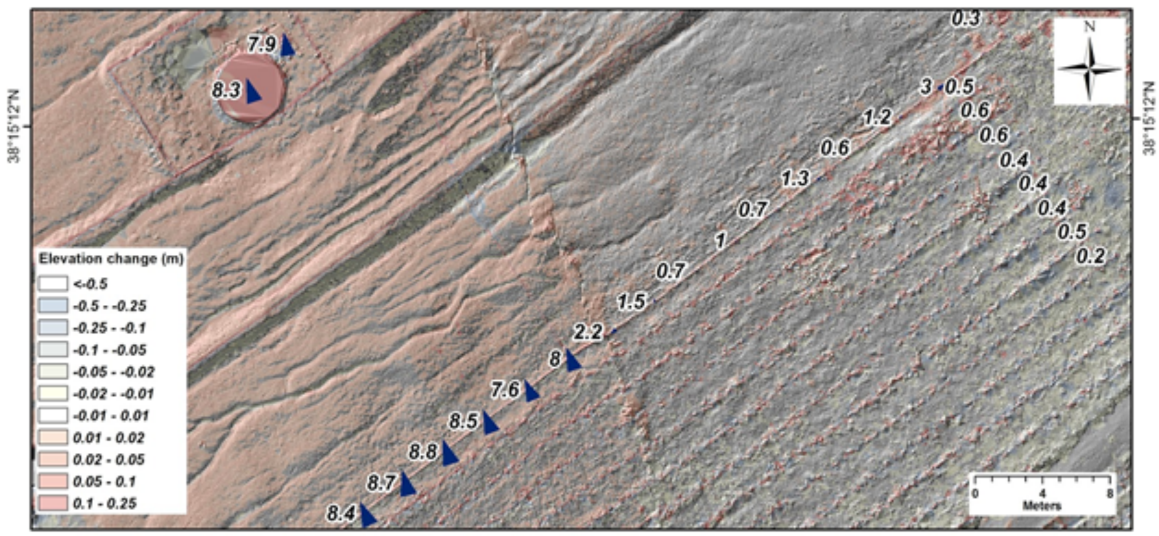


Figure Caption: Near-field geodesy: terrestrial laser scans of surface deformation after August 24, 2014 M6.0 South Napa Earthquake. Background is 2.5 cm-resolution shaded relief map of surface rupture and "bare-earth." Arrows and numbers (cm) measure post-seismic slip that occurred between 2.5 and 22 days after earthquake. Colors indicate vertical component of postseismic surface deformation. HRT data provide remarkable three-dimensional insight into solid-earth and earth-surface processes (S. DeLong, USGS).

Authors: Michael Bevis and Terry Wilson
Title: Trends, Opportunities and Emerging Requirements in Polar Geodesy
Keywords: polar, geodetic networks,

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Polar geodetic networks constructed in rock are focused on measuring viscoelastic glacial isostatic adjustment (GIA) and earth's elastic response to contemporary changes in ice mass. Constraining GIA is fundamental to GRACE and follow-on missions because the requisite 'PGR correction' is so large in some polar regions that a modest error results in major regional biases in GRACE's solutions for modern changes in ice mass. A modest investment in polar GPS networks that constrain the 'PGR correction' significantly leverages the large investment in GRACE. Existing GPS networks in Antarctica may need to be densified to constrain GIA models as well as GRACE's agenda demands. Important emerging applications include ionospheric, atmospheric and ice sheet studies. Investigations of dynamic phenomena such as scintillation and travelling ionospheric disturbances would be improved by densification of networks to make ionospheric tomography feasible. Mapping water vapor distribution in time and space ('GPS meterology') is crucial for numerical weather and climate models. Multiyear monitoring of inland ice streams and ice catchments could detect if the ice sheet is changing its displacement behavior in the deep interior as well as in marginal parts of the ice sheet presently undergoing major mass loss. These interior ice stations could support meteorology and ionospheric studies and serve as kinematic base stations for airborne LIDAR, radar, magnetic and gravity surveys.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Expansion of the GPS networks would benefit all applications. Both GPS meteorology and ionospheric applications would benefit from a better satellite geometry, which makes a switch from GPS receivers to multi-constellation GNSS receivers highly desirable. Investment in research into assimilating GPS observations into numerical weather models using techniques such as 4DVAR is needed. Collection of high rate data which is processed locally could yield low data rate products, such as scintillation indices, that could be telemetered using Iridium or the next-generation of Iridium data comms. One of the greatest challenges facing polar geodesy is reducing the logistical costs of operating polar networks. Lighter systems and reduction in the mean time between equipment failures, while supporting new applications, are required. Significant R&D efforts to mitigate failure modes and reconfigure equipment are required, at levels that exceed current facility efforts. Assignment of a larger number of field engineers to polar projects is required to mitigate the unprecedented levels of 'burnout' due to alternating Arctic and Antarctic field deployments. Enhanced training for polar field personnel should be mandated to avoid blunders that are extremely costly to repair given high-cost polar logistics. Perhaps RFPs for smaller specialized facilities that address specific functions, such as polar geodesy, or equipment R&D for polar geodesy, should be considered.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Geodetic networks in polar regions have challenges that demand international collaboration in technology development and logistical support for field deployments. Facilities have a unique mandate to provide, and benefit from, international technology transfer, data exchange and training opportunities. The demanding training requirements for field personnel working in polar environments need to be met by facility training courses.

Authors: Jeff Freymueller
Title: Post-LGM and post-LIA Glacial Isostatic Adjustment in North America
Keywords: mantle viscosity, ice loading, GIA

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Glacial isostatic adjustment (GIA) represents one of the few opportunities to probe the viscosity structure of the Earth. The response to the deglaciation following Last Glacial Maximum (LGM) features one or more uplift centers in Canada, and collapse of the forebulge causes subsidence across parts of the eastern US. GIA also results from the ongoing deglaciation of coastal Alaska and Iceland, following Little Ice Age (LIA) glacial advances. Due to the thin lithosphere and low viscosity asthenosphere, the response to these load changes is on a timescale of decades to centuries rather than millennia. 1. How does the 3D mantle viscosity structure impact the response to changing ice loads? 2. Where was the 'missing ice'? Was it in North America? Present models for the global ice load at LGM require more ice to have been lost from somewhere to account for post-LGM sea level change. Improved load and deglaciation models are required. 3. What kind of rheological model best captures the smaller but still important horizontal deformations associated with the post-LGM response across the North American continent? Are our estimates for the motion of the North American plate and for the edge of tectonic deformation being biased by GIA signals? 4. Can improved load models explain the dramatic spatial and temporal variations in uplift rate observed in coastal Alaska? How can load variations on the scale of years be merged with seasonal and interannual snow and ice loading variations?

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The most critical need is for more continuous GPS observations across the region. In both northern Canada and coastal Alaska, existing instrumentation is very sparse relative needs. Northern Canada: There are a number of sites across northern Canadafor ionospheric studies (the CHAIN network); unfortunately, many of these sites use a GPS receiver whose clock steering parameters make most of the data marginal to useless for positioning. Additional sites are needed across the poorly sampled Northwest Territories, where a substantial ice load was present at LGM. Careful site selection or re-monumentation of CORS sites across the eastern US may be required. Coastal Alaska: The spatial wavelength of the post-LIA load is much smaller than the former continental ice sheet, but the existing sites do not sample it well. Ideal site spacing would be a few tens of km or less where these coastal icefields are shrinking. Iceland: Iceland is rapidly losing ice, with uplift rates comparable to coastal Alaska. Parts of Iceland that are distant from the plate boundary and the large glacier systems may be critical in separating horizontal GIA from North American plate movement. Complementary measures of viscosity structure: Further constraints on 3D viscosity structure are needed from seismic imaging. Of particular importance are questions like, where is the edge of the thick cratonic lithosphere? What is the asthenosphere thickness beneath the cratonic part of the continent?

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

This scientific problem is pan-North American plate, and measurements from stable parts of Mexico are required to ensure that geodetic reference systems are sufficiently accurate. This opens the door for productive international collaborations including the US, Canada, Mexico, Greenland and Iceland. Post-LGM GIA causes a major enhancement of sea level rise for most of the eastern seaboard of the US. Better quantification of the vertical motions of the land will allow for more informed decisions about coastal change, which is important also in places where the land is uplifting. Any new constraints placed on the time history of ice sheet collapse in North America may provide insights into the potential for future ice sheet collapse in Antarctica. The ongoing deglaciation of coastal Alaska is a spectacular impact of ongoing climate warming. However, there is also a complex non-linear relationship between climate change and glacier response, due for example to the tidewater glacier retreat process. Further scientific knowledge of these processes is needed to better plan for future climate change. The visceral impact of the deglaciation can be a powerful antidote to the merchants of doubt who are trying to confuse the public about what we do know about climate change, although we must be careful not to mis-state the case.

Authors: Jeff McGuire, Mark Behn, and Sarah Das
Title: Monitoring Transient Ice Flow on Ice Sheets and Glaciers
Keywords: Ice sheet, transient ice deformation, basal hydrology

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

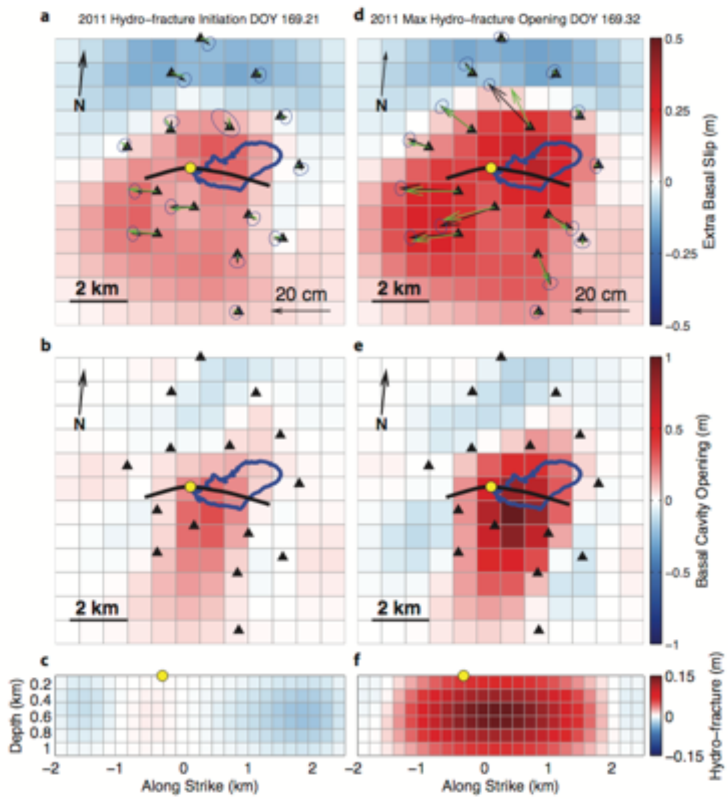
It is well established that ice sheets and glaciers experience transient periods of acceleration that are frequently linked to changes in the basal hydrology. However, the exact link between surface melting, the characteristics of the basal hydrologic system, and ice motion remains a key question in understanding how ice sheets will respond to climate change. Recent studies have shown that observations from spatially dense, high-rate GPS deployments can be used to link periods of transient surface motion with basal slip and uplift during supraglacial lake drainage events on the Greenland Ice Sheet (GrIS) using a network-inversion filter approach (see Figure). Transient deformation not associated with local lake drainages is also observed in other regions of the ablation zone of the GrIS, as well in ice streams. Understanding the linkages between these deformation events, basal hydrology, and the rheology of the ice-bed interface require additional high resolution geodetic and seismic experiments in other locations (e.g., at higher elevations near the equilibrium line elevation, across the transition from slow to fast moving ice near ice streams).

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Studying transient ice motion requires the ability to measure geodetic motions and seismic responses over a variety of spatial and temporal scales. In particular, a key need is the development of a combined high-rate (1-sec) GPS receiver and broadband seismometer package that can be rapidly deployed from a helicopter or twin otter campaign. Ideally stations could be setup in <1 hour allowing 8–12 stations to be deployed in single day. Further, these stations should be capable of surviving a minimum of 12 months before revisiting. This is particularly important in ablation areas, where the surface can be significantly altered from one melt season to the next, but also important in high accumulation regions. Power needs depend on the project goals. For example, stations investigating ice sheet response to summer melting might only require solar power from May through September, while stations focused on multi-year records would require continuous power throughout the winter months. Telemetry is desirable for stations deployed in highly crevassed regions (e.g., ice streams) where it may be impossible to recover instruments at the end of the project. Additionally, full-wavefield seismic recording at high frequencies during major deformation events, such as lake drainages, will be necessary to unravel the details of hydrofracturing within the GrIS. While a large number of short-period sensors would be required, they may only need to be deployed for a period of a few weeks i

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Continued support of field projects in Greenland provides a spectacular opportunity to engage students interested in both geophysics and climate change.



Caption: 2011 North Lake drainage, western margin of the GrIS. (a) Accumulated extra basal slip, (b) basal cavity opening, & (c) hydrofracture opening calculated from a network-inversion filter (NIF) at the time of (a–c) hydrofracture initiation & (d–f) max hydrofracture opening. Vector fields show GPS (NIF) displacement less background velocities in black (green) for (a) period between the start of the precursor and hydrofracture initiation, & (d) period between hydrofracture initiation and max opening.

Authors: W. Steven Holbrook
Title: Near-surface geophysical facilities for hydrology, geomorphology, and Critical Zone science
Keywords: near-surface geophysics, critical zone, seismic refraction, hydrology, geomorphology

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

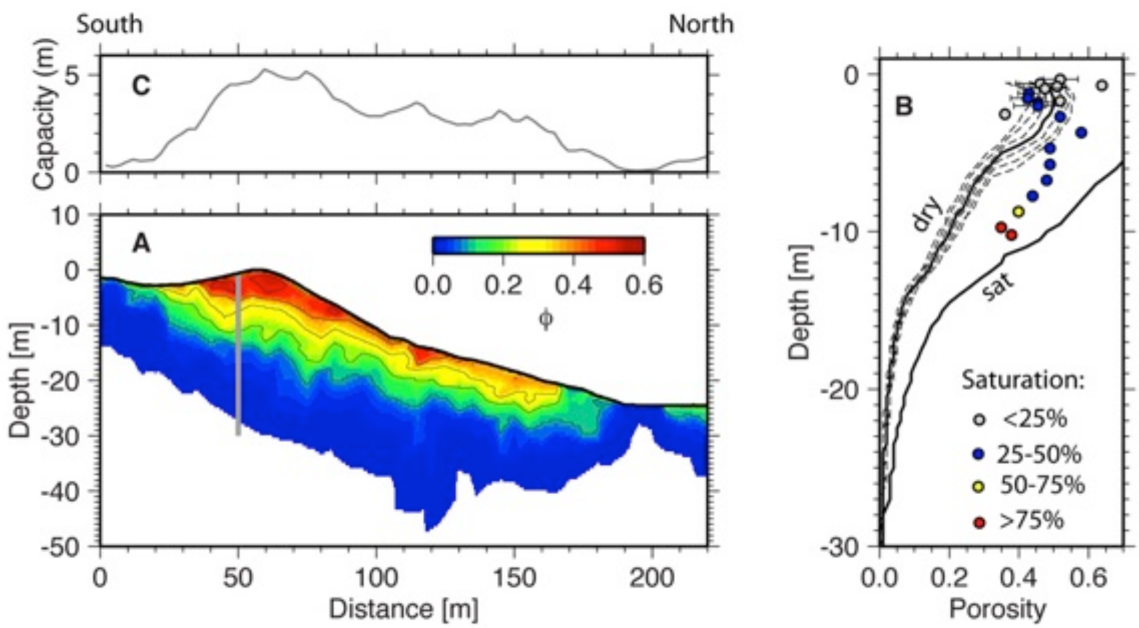
Near-surface geophysics is poised for explosive growth with increasing attention to Earth's "Critical Zone" (CZ) – the life-supporting layer that encompasses vegetation, soil, and weathered rock. In this zone ("treetop to bedrock"), a dizzying and poorly understood array of processes – hydrological, biological, geological, and chemical – combine over time to transform bedrock into soil, providing life-sustaining nutrients and water storage capacity for ecosystems. NSF has established a Critical Zone science program that focuses research in ten national Observatories (CZO's), specific sites where scientists from disciplines as diverse as biogeochemistry, soil science, geomorphology, atmospheric science, microbiology and hydrology work together to understand CZ processes. Recent results of near-surface geophysical surveys from CZO's, in combination with drilling, modeling, and theoretical advances, have provided new insights into the architecture of the deep CZ. The critical need for increased subsurface imaging of the near subsurface was a major theme emerging from another NSF-EAR planning workshop, "Future Infrastructure Needs in Surface Earth Processes," which was held in Chicago in October, 2014. Questions to be addressed include: (1) What is the architecture of the deep CZ? (2) What is the water storage capacity in the near subsurface, and what controls its variability? and (3) How does lithology control weathering thickness across landscapes?

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The challenge of understanding the architecture and processes controlling Earth's Critical Zone require more than just "geodetic and seismic" facilities – it will require a broad array of near-surface geophysical instrumentation, as well as a shallow drilling capability. The geophysical instrumentation needed includes the following: • Seismic refraction • Seismic reflection • Nodal seismic instrumentation for passive-seismic arrays • Electrical resistivity • Ground-penetrating radar • Magnetotellurics • Downhole logging tools • Magnetic gradiometry • Microgravimetry • Time-domain electromagnetics • Electromagnetic induction • RTK GPS • Magnetic resonance sounding (ground-based NMR) In addition, a community capability for shallow drilling is needed. Drilling in the near-surface (upper ~100 m) will enable collection of samples from the CZ, downhole logging and geophysical surveys, and installation of long-term groundwater monitoring. Fortunately, such a geophysical facility already exists. In 2012 the University of Wyoming received a $20 M grant from the NSF-EPSCoR program to establish the Wyoming Center for Environmental Hydrology and Geophysics (WyCEHG). A substantial portion of this funding went to build a near-surface geophysical facility that includes everything mentioned above, with the sole exception of nodal seismic instrumentation. We intend to seek long-term facility support from NSF to establish a national Near-Surface Geophysics Facility.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Near-surface geophysics offers major advantages in "Broader Impacts," especially in reaching out to college and high school students, underrepresented groups, and partners in the developing world. The instrumentation is portable, easily deployed and provides same-day data; the software is easily learned and often provides rapid views of the subsurface; and the methods are readily applied to universally important target: groundwater. The skills acquired in learning near-surface geophysical methods are directly applicable to workforce training for the environmental engineering industry. A robust program of outreach, training and education could be developed with the proper investments. Whether these efforts would be centered at the Near-surface Geophysics Instrumentation Facility or combined with other outreach efforts at IRIS/UNAVCO (or its successors) remains to be discussed. Certainly such efforts should include, at a minimum: (1) regular programs to bring underrepresented high school and college students into the field for near-surface geophysical work; (2) undergraduate field-training courses (perhaps in collaboration with the highly successful SAGE course); and (3) outreach efforts through museums, social media, and blogs. An official partnership with the “Geoscientists Without Borders” program would enhance international visibility; GWB often funds near-surface geophysical projects in developing countries, to find and develop water resources.



Caption: (A) Porosity model derived from seismic velocities in the Southern Sierra CZO. (B) Comparison of model predictions to porosity measured in auger samples on the transect. (C) Subsurface water storage capacity across the transect, computed from the porosity model. From Holbrook et al., 2014, ESPL.

Authors: Yuning Fu
Title: Using PBO GPS network to estimate water storage change in the western United States and investigate Slow Slip Events at the southcentral Alaska Subduction zone
Keywords: GPS, water storage change, Slow Slip Event

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

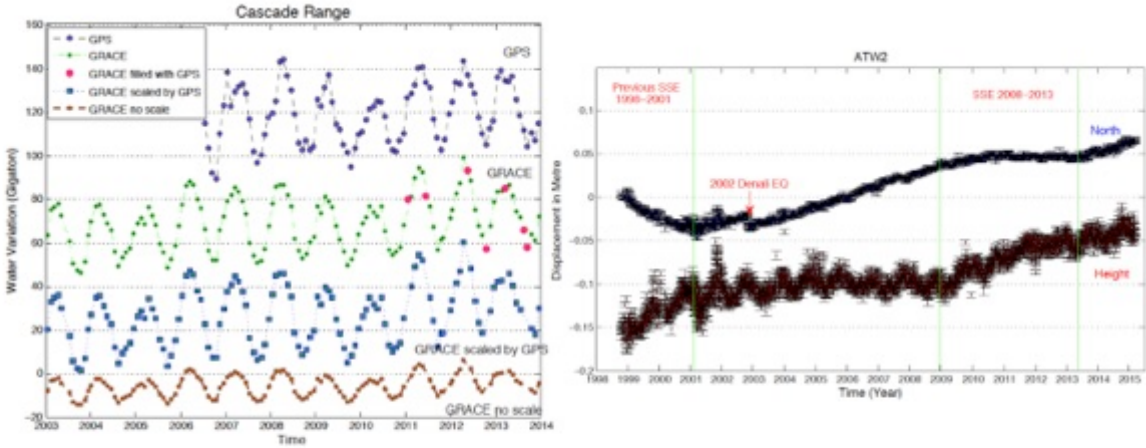
Global Positioning System (GPS) measured crustal loading deformation can be used as an independent tool to estimate and monitor terrestrial water storage change in near real-time. Fu et al. [2015] shown GPS's hydrological application in Washington and Oregon. Borsa et al. [2014] discussed GPS measured uplift in the western United States due to current drought event. GPS network has unique advantages for estimating water resource change. GPS position solution can be derived in near real time, allowing much quicker estimation of water mass change than the GRACE. Current GRACE data processing standard implies 2-3 months of data latency. In addition, for the areas with dense GPS network (e.g. western United States), GPS can provide water resource estimation with higher spatial resolution than GRACE. GPS measurement in Alaska has revealed several long-term Slow Slip Events (SSE) in the southcentral Alaska subduction zone [Ohta et al., 2006; Wei et al., 2012; Fu and Freymueller, 2013]. The SSEs here in Alaska are much longer than the SSEs of other subduction zones. Continuous GPS observation provides crucial information for scientists to quantify the slip deficit during steady interseismic period and the slip released within SSEs, therefore we can better evaluate the potential earthquake hazards in the southcentral Alaska subduction zone.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

To quantitatively monitor the terrestrial water storage variations in the western United States using GPS measured loading deformation, the continuous observation of the Plate Boundary Observatory (PBO) is essential. We need to keep PBO network running! To perform the similar hydrological study in Alaska, current PBO GPS network in Alaska is still not dense enough. In order to recover detailed water storage variation with GPS loading deformation in Alaska, a spatially densified GPS network is required. Additionally, since the Slow Slip Events in the southcentral Alaska subduction zone are long-term, more than 3-4 years [Fu and Freymueller, 2013], the time-variable slip propagation along the plate interface is important information for geoscientists to understand how the stress changes during the SSEs and during the subduction earthquake cycle. However, the current PBO GPS network in Alaska is too sparse to provide detailed data with high spatial resolution. Therefore, a densified PBO GPS network in Alaska is needed and it can benefit both our tectonic and hydrological investigations in Alaska. Borsa, et al. (2014), Science, 345, doi:10.1126/science.1260279. Fu et al. (2015), J. Geophys. Res. Solid Earth, 120, 552–566, doi:10.1002/2014JB011415. Fu and Freymueller (2013), Earth Planet. Sci. Lett., 375, 303–311, doi:10.1016/j.epsl.2013.05.049. Ohta et al. (2006), Earth Planet. Sci. Lett. 247 (1–2), 108–116. Wei et al. (2012), Geophys. Res. Lett. 39, L15309.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

International workshops about the scientific applications of PBO-GPS network are needed for the purposes of both research and education. Graduate students and earlier career professionals are encouraged and should be supported to attend.



Caption: Left: Modified from Fu et al. [2015]. Demonstration that GPS-inferred water storage change can be used to fill GRACE solutions for the months when GRACE measurements are not available, and determine the scaling factor for GRACE. Right: Modified from Fu and Freymueller [2013]. Time series (north and height) of a continuous GPS station ATW2 near Anchorage. GPS data reveal two long-term Slow Slip Events in the southcentral Alaska subduction zone: the 1998-2001 event and the 2008-2013 event.

Authors: Jeanne Sauber
Title: Measurement and Modeling of Cryosphere-Geosphere Interactions
Keywords:

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

What are the temporal and spatial scales of crustal deformation due to tectonic forcing versus surface deformation due to annual and seasonal cryospheric changes in active tectonic regions? Does the load change associated with cryospheric fluctuations cause a measurable change in the background seismic rate? Are the Coulomb stress changes large enough to significantly move a region closer to failure in a tectonic earthquake; and, are there implications for earthquake hazard assessment? (1) The continued operation of permanent PBO GPS/GNSS sites in southern Alaska, along with targeted densification near glaciers, could provide an unprecedented opportunity to address the above key scientific questions. (2) NASA satellite observations will provide key input to estimate the "cryospheric signature' in GPS/GNSS time series. In addition to the broad-scale cryospheric mass change estimates from GRACE, and in the future GRACE-FO, NASA's ICESat-2 will have repeated laser altimetry tracks every 91 days that can be used to constrain interannual and seasonal cryosphere changes (launch, 2017). ICESat-2 with 6 laser beams (90 m between individual beam pairs and 2 km between pairs) will provide altimetric measurements of surface elevation along profiles that can be used to discern faults and fold structures beneath vegetation. Additionally, the precise ground elevations, averaged over 14m, can be used as ground control points for other remote sensing studies.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

To address the key questions related to interaction of the cryosphere with the geosphere requires computational capabilities to model the rheological response of the solid Earth to the complex temporal and spatial changes of the cryosphere. Support of the Computational Infrastructure for Geodynamics (CIG) Short-term Crustal Dynamics working group is essential for continued scientific advancement. The goals of this group are to provide modeling capabilities with internally consistent physics constrained by observations for the entire seismic cycle and for crustal deformation associated with surface loads. In addition to the surface deformation observations that will be provided by the NASA's NiSAR mission, a global "bare Earth" topographic map of the world at 5 meter resolution is needed (ex. the National Research Council's Earth Science Decadal Survey (2007), Tier 3 mission "LIST"). The elevation data at this spatial resolution provided by such a satellite mission is critical for understanding the interaction of tectonic and cryospheric processes especially in remote regions. Additionally, a global bare Earth DEM would provide a regional context for higher-resolution aircraft Lidar measurements.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

NASA should continue to provide training venues for their mission data to enable a broad range of researchers to fully exploit satellite data. Workshops and seminars coordinated by NASA's Mission Applications leads for each satellite mission at AGU and GSA would be helpful to broaden the user base.

Authors: Thomas Herring
Title: Ionospheric studies with GNSS receivers
Keywords: Ionospheric dynamics, traveling ionospheric disturbances, real-time warning system

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Ionospheric studies using GNSS are likely to increase in the future in order to better understand the dynamics of plasma creation, interactions between the atmosphere and the ionosphere, and traveling disturbances. GNSS receivers capable of receiving potentially 30 satellite signals simultaneously will greatly enhance the ray coverage for such studies. The ionospheric community is developing smart sensor technologies that allow them to optimize the data transmissions so that with limited total bandwidth, the data returned will maximize the science return. The methods developed here could be of great use to the geodetic community as well. Potentially with the large number of frequencies available with GNSS systems, 2nd and higher order ionospheric models could be directly tested with data.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

For ionospheric studies, GNSS receivers (as opposed to simply GPS) would be a great benefit. Also since large disturbances in the ionosphere, which can affect communications and power grids, travel at the rotation rate of the Earth, real-time monitoring can be used as a warning system to western states when large disturbances are detected on the east coast. Such a warning system would benefit greatly from international collaborations where different countries could provide warnings to those west of them. Ionospheric model developments would also benefit the L-band InSAR community as well.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Ionospheric disturbances can have a great impact on communications and power grids and better understanding of these processes will be of benefit to society. For warnings of large disturbances, real-time data transmissions will be required. There will be a need for cross-education between the ionospheric and geophysical communities.

Authors: Donald Argus, Yuning Fu, Felix Landerer, David Wiese, Mike Watkins, Tom Farr, Jay Famiglietti
Title: Evaluating changes in water resources using GPS, InSAR, and GRACE
Keywords: Snow water equivalent, soil moisture, mountain fracture groundwater, groundwater depletion, GPS, InSAR, GRACE, drought, precipitation

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Recent technical advances in GPS positioning are allowing GPS vertical displacements to be estimated to 2–4 mm. GPS has been demonstrated to be capable of weighing changes in total water mass to 0.15 m in equivalent water thickness [Argus et al. GRL 2004, Borsa et al. Science 2014], We are using GPS to determine water changes sustained during drought from 2007 to 2009, heavy precipitation from 2010 to 2011, and severe drought from 2012 to the present [Argus et al. WRR in prep.]. We are comparing water changes estimated from GPS with those estimated from GRACE. We are using InSAR measurements of land subsidence to infer the destruction of groundwater loss in Central Valley. We are furthermore placing the GPS, GRACE, and InSAR determinations of water change into complimentary measurements of snow and soil moisture. We also aim to use GPS, GRACE, and InSAR to answer outstanding questions: How are water resources throughout North America and Europe changing? Are water changes sustained during periods of drought and heavy precipitation, and if so, how? How fast are America's groundwater basins being depleted?

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

GPS sites closely spaced in areas of sustained water changes are needed. GPS sites in the existing Plate Boundary Observatory in California are nearly sufficient but must be kept active to evaluate changes in the availability of water resources, and we furthermore advocate adding 25 new GPS sites in key locations in the Sierra Nevada and Colorado Plateau to further monitor water change.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Changes in total water as a function of location across North America will be estimated from GPS and from GRACE. These water change estimates will be communicated to national, state, and local water authorities for application to the management of water resources, thereby making a strong broader impact.

Authors: Thomas Herring
Title: Hydrology signals from GPS position time series
Keywords: non-secular deformation, hydrology, loading, sediment expansion

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

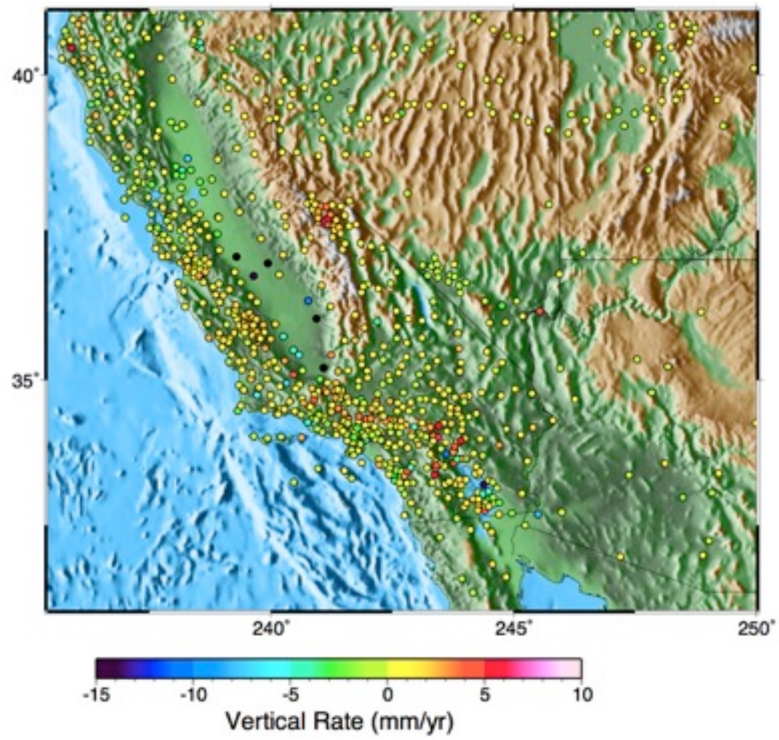
The development of geodetic methods for understanding water storage and transport in large aquifer systems is emerging as a new approach to obtaining basin wide quantitive information on water storage and depletion. Current studies have focused on secular trends (see figure) and variations in the seasonal signal in the heights of GPS sites but in the future there could be a greatly exploitation of motions on all time scales. Two phenomena affect the GPS position time series. Sites on (deep) sediments subside as aquifers are drained while surrounding sites on bedrock uplift as the weight of the water is removed and surface rebounds elastically. The potential exits to exploit more of the signal contained in the GPS time series both in terms of temporal resolution (shorter time scales than seasonal) and in understanding the relationship between the horizontal and vertical components. In regions with large snowpacks, it should be possible with the use of ancillary snowpack information to model the snow loading and ground water components by exploiting snow extent and precipitation information and the potential flow patterns of the ground water. The aims of the analyses would to understand the changes in water storage and extent.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

These studies would require the continuation of existing networks with possibly some densification in regions to better separate signals. Specifically, sites in sedimentary basins would be of interest to study the hydrology signals. These types of locations were typically avoided when tectonic studies were the prime focus of station installation. Ancillary remote sensing data will be required and on facility activity could be either to house these data or provide an interface that would support users trying to find such data.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

The use of GPS positional data to study hydrology signals and the facility could provide outreach to other disciplines and the public about the implications of the results obtained. There would also be opportunities for educational activities associated with developing and utilizing these types of methods.



Caption: Vertical rates of motions in Southern California showing subsidence in the Great Valley (black to blue colors) and uplift in the surrounding bedrock sites (yellows to reds). Only sites with rate standard deviations (computed with correlated noise model) less than 3 mm/yr are shown. Some of the vertical motions may be tectonic but temporal variations in the rates would suggest that at least some portion of the signal is hydrology induced. Data from the PBO NAM08 snapshot velocity field.

Authors: Shimon Wdowinski
Title: Sea level rise and coastal flooding hazard
Keywords: Climate change, sea level rise, land subsidence, tide gauges, GPS

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Flooding hazard due to sea level rise (SLR) is a global problem. It affects about 10% of the Earth's population, roughly 700 million people, who live in low-lying coastal areas. One of the most vulnerable areas to SLR is the US Atlantic coast due to its low elevation, large population concentrations, and economic importance. Further vulnerability arises from accelerating rates of SLR, which began in the early 2000's and caused a significant increase in flooding frequency in several coastal communities. Several studies have suggested that the accelerating rates of SLR are due to the slowing down of the northern Atlantic circulation, in particular possible weakening of the Gulf Stream. Future geodetic research should address the following issues: 1) How much of the relative rate of SLR, as measured by tide gauges, reflect land subsidence? What are the spatial scales and causes of the subsidence? 2) What are the relations between ocean current dynamics and accelerating rate of SLR along the US Atlantic coast?

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

For supporting SLR research, geodetic facilities should include: 1) Expanding continuously operating GPS networks to the Atlantic and Gulf coasts. Also co-locating GPS stations with tide-gauges (in collaboration with NOAA). 2) GPS data archive 3) InSAR data archive 4) Develop GPS-buoy systems that will provide offshore long-term, high temporal monitoring of sea surface height (SSH) observations. In other words, develop offshore tide gauge stations that will be deployed along the Gulf Stream and other currents.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Education – Prepare a land subsidence module that can be taught in natural hazard classes. Outreach – There is a need to educate the public on the issue of land subsidence and its contribution to coastal flooding hazard. International – Assist other nations that suffer from coastal subsidence (e.g., Bangladesh, Indonesia) by setting up continuous GPS networks.

Authors: Shimon Wdowinski, Kristin Larson
Title: Hydro-geodesy: Space geodetic applications for hydrology
Keywords: Hydrology, water resources, GPS, InSAR

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

One of the major challenges of the 21st century is securing freshwater supply for the increasing world population as well as for preserving natural ecosystems. Geodetic techniques, which provide highly accurate measurements of the Earth's solid and aquatic surfaces and their changes over time, are very useful tools in monitoring changes of available water resources. Future hydro-geodetic research should address the following issues: 1) Separating hydrological load signal from other signals – Geodetic observations provide an accurate measure of surface displacements and gravity changes induced by hydrological and non-hydrological processes, as tectonics, atmosphere, ocean, or mantle (GIA). Separating the effects of the various loads is important for both hydrologic and tectonic usage of the observations. 2) Obtaining meaningful hydrological interpretations – Hydro-geodetic observations typically describe the Earth's surface or gravity response to hydrological processes. Full usage of the observations requires understanding and modeling of the hydrological process. 3) Subsidence hazard – Increased water demand by growing population have led to significant land subsidence in many urban areas, which often results in structural damage to buildings and infrastructure. Geodetic observations can serve as useful tools for identifying hazard zones and when combined with hydro-mechanical modeling can forecast future propagation of the hazard, which can be used by local authorities.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

For supporting hydro-geodetic research, geodetic facilities should include: 1) Network of continuously operating GPS stations 2) GPS data archive 3) InSAR data archive

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Communicating results with hydrologists – Hydro-geodetic observations provide only partial information on hydrological processes and often in "strange" non-typical hydrological data presentation. For example, InSAR wetland detects surface water level changes, whereas hydrologists need "absolute" water level values in order to derive the hydrological head that drives the surface flow. Similarly, measurements of land subsidence induced by groundwater changes, are not that useful for hydrologists. In both examples and other usage of hydro-geodetic observations, the observations should be translated to useful hydrological data or parameters that can be used by hydrologists. In order to improve (or establish) communication between hydro-geodesists and hydrologists, we suggest planning joint workshops and special sessions at meetings.

Authors: Ronni Grapenthin
Title: Real-time Capabilities for Hazard Monitoring and Early Warning
Keywords: real-time GPS, early warning, hazard monitoring

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Hazard monitoring and early warning are areas that provide opportunities for scientific and technical advances, and tremendous impact on society. Over recent years, for example, earthquake early warning in the US moved towards functional demonstration mode (ShakeAlert project). Both seismic and GPS data contribute unique observables to answer questions of event time and location, magnitude, and slip distribution necessary for early warning and rapid response. This effort pushes the development of methodologies to combine seismic and high-rate GPS/GNSS data at various stages (data acquisition, modeling, etc.); an opportunity that is still in its infancy and that requires the full range of observables from all instruments in easily digestible formats to effectively develop these methods. In addition to earthquake early warning, related opportunities lie with volcano monitoring, albeit on a different, more relaxed time scale. A more recent opportunity for contributions from geodesy to hazard monitoring is regional scale aquifer monitoring (and injection well monitoring for that matter). GPS (as well as InSAR and, of course, gravity surveys) can contribute vital information on the state of aquifers on a broader scale than observation wells. However, monitoring of both aquifers and injection wells requires GPS station placement in environments geodesits currently try to avoid: sediment filled basins with little to no stable bedrock.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

For any early warning and rapid response (~minutes after an event) application, the most pressing need is a continued and expanded real-time GNSS network, particularly along the Western US. To cut latencies and minimize dependency on a single node of the public Internet, the signals should be distributed in a redundant manner; preferably directly from the station to the consumers. It is crucial that seismic and geodetic facility operators, scientists and manufacturers keep in open communications to ensure that available equipment meets the of the scientific community. For example, the recent trend towards onboard positioning for GPS receivers and streaming of position time series concerns me. My worry stems from the slight, but imaginable possibility that commercial receivers may no longer export phase and pseudorange observables (or require additional fees). Obviously this would cripple many of the amazing non-positioning GPS applications that have been developed. Complete independence of a black-box trend might be worthwhile to contemplate and think about adding receiver manufacturing as a capability to our facilities.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Here, it is important to lobby state and federal governments to generate political support for the early warning and monitoring activities, and necessary network expansions. Associated station deployments should be multi-disciplinary, so the facilities should have the means to reach out to other disciplines potentially interested in adding sensors at the marginal cost of power and data bandwidth increases; similar to what is now being done with the GPS-MetPack co-location for TLALOCNet in Mexico. This outreach to disciplines such as hydrology, meteorology should include advertisement of the products we can already create to increase the use of both geodetic data, but also derived products (e.g., PBOH2O, derived models etc).

Authors: Samantha Hansen, Richard Aster, John Hole, Sridhar Anandakrishnan, Ralph Stephen, Jake Walter, and Zhongwen Zhan
Title: Wavefields Initiative: Polar Investigations
Keywords: Polar, Wavefields, Cryosphere, Solid Earth Structure

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

This white paper summarizes discussion from an online community workshop that was held in June 2014 as part of IRIS's Wavefields Initiative, which is focused on promoting the scientific value of recording the full seismic wavefield. This submission highlights relevance to polar investigations. Imaging of many scientific targets, at a variety of spatial scales, can be significantly advanced via dense station coverage to produce high-resolution images of sources and structures. Such targets include ice streams, icecap systems, sub- and en-glacial hydrological systems, and ice shelves. Large N arrays show great promise for improved understanding of glacial characteristics, including basal properties and internal ice structure. Key targets for these efforts include estimating ice and water flow, temperature variations, ice shelf strength, and the roles of sediments and hydraulic conditions at the glacier bed. GPS strain estimates may also be valuable to study these processes. Large N deployments would also improve studies of rupture dynamics of faulting within ice, slip along ice-rock interfaces, and processes arising from ocean-ice-atmospheric interactions. Wavefield investigations also provide new avenues to investigate solid earth structure and tectonic processes that are coupled with the cryosphere. Densification of polar instrumentation would vastly improve resolution of crustal and mantle structure and the ability to monitor volcanic/tectonic sources at all ranges.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

While technological requirements were not the focus of the Wavefields workshop, improvements in efficient deployment strategies, power, and communications are especially critical for polar investigations, where field costs may be very high. Many geographic regions of interest are either difficult to access and/or are hazardous, making easy-to-deploy (e.g., aerially or otherwise remotely-deployed) stations desirable to expand coverage. Thus, on-ground surveying and cabling needs to be minimized or eliminated. Stations must also evolve so that they can run autonomously for up to several seasons in some scenarios, which will require new, renewable (or longer-lasting) power sources as well as improved communications technology to telemeter recorded data in real-time at a sufficient data rate. Both the associated hardware and software should be shared across the international community, possibly with internationally-shared development costs. Ultimately, the goal is to identify and inspire the next generation of facilities that allow the community to pursue the most promising new science directions in the most cost- and time-effective manner.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

To facilitate large N polar deployments, international collaborations will be crucial. Many countries have a vested interest in polar investigations, particularly in Greenland and Antarctica. Partnerships between international institutions have a strong history and will continue to promote scientific and technological advancements above and beyond that possible in single-nation efforts. Future initiatives will also require education and training of the next generation of polar scientists, particularly as the associated science and technology evolves. Course content, international mini-courses, and workshops could facilitate knowledge exchange. These avenues also provide a wealth of broad outreach opportunities, including educating the public about the importance of polar investigations in climate change research, enhancing K-12 teacher training, and providing undergraduate research experiences.

Authors: Sean Gulick, Kelin Whipple, Eric Kirby, Sridhar Anandakrishnan, Julie Elliott, and Victor Tsai
Title: Emerging scientific challenges at the interface of surface and deep Earth processes: Part 1, orogenesis
Keywords: orogenesis, tectonic-climate, crust, mantle, deformation, erosion

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?
Solid earth deformation is intimately coupled to, and influenced by, changes in surface boundary conditions. At the time and length scales associated with the evolution of orogenic systems, advancing understanding of the coupling between climate, erosion, and topography requires two fundamental components where scientific facilities will play a critical role: (1) appropriate long-term observations of lithospheric structure, the distribution of seismicity, and sedimentary basin architecture in and around active mountain belts, and (2) improvements in our understanding of the fundamentals of the underlying processes of weathering, transport, erosion, and deformation. Additionally, a vibrant new transdisciplinary field is emerging that integrates structural seismology, mantle convection models, lithospheric geodynamics, surface processes, and geologic records of paleoaltimetry (paleoshorelines, erosional unconformities, accommodation space generation, paleobotany, and isotopic records). Important uncertainties remain in interpretation and integration of structural seismic images into mantle convection models (differentiating chemical and thermal effects on wave speeds and buoyancy), characterization of the Earth's viscosity structure, and magnitude of plausible dynamic topography.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?
Understanding orogenesis requires quantifying erosion, determining effects of changing climate, studying tectonic and mantle feedbacks, and calibrating integrative models of the system. Advances are needed in understanding roles of rock strength, river floods, glacial dynamics, precipitation, and sediment transport mechanisms on erosion. Multi-scale studies are needed temporally to understand influences of orbital forcing, orographic effects, changing ice and sediment loads, tectonic forcing/feedback and mantle dynamics that influence the crust and surface. Clear opportunities exist in both nested imaging of modern systems, monitoring of active surface and tectonic processes, and modeling interactions.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?
These require regional studies using seismology and geodesy and partnerships with a range of other communities and their field or laboratory measurements.

Authors: Kelin Whipple, Eric Kirby, Sean Gulick, Sridhar Anandakrishnan, Julie Elliott, and Victor Tsai
Title: Emerging scientific challenges at the interface of surface and deep Earth processes: Part 2, fluvial processes
Keywords: fluvial, ambient noise, geomorphology, erosion, orogenesis, flooding

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?
Characterizing the rates of sediment transport by near-surface processes such as landslides and as bedload in rivers is crucial for both our understanding of long-term erosion and for prevention of associated natural hazards. While other techniques exist for such monitoring, seismic monitoring is one of the few techniques that allow us to make measurements during the most extreme events, which are typically the most important both in terms of mass transport and hazards. We identify four specific research questions where high-resolution characterization of both seismic wavefields and acoustic noise in near surface environments will be critical in future studies of both local-scale process mechanics and their large-scale implications for the interactions among climate, topography, erosion, and deformation in the evolution of orogenic systems. These are: 1. Quantifying the role of rock strength, 2. Quantifying thresholds for transport and erosion in large floods, 3. Measuring the variability of alluvial covers in rivers, and 4. Understanding the controls on flood frequency.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?
The challenges associated with instrumental monitoring of floods and mass wasting events requires a large pool of inexpensive instruments. Large seismic and other arrays aimed at capturing these processes could be transformative. At the scale of characterization of rock strength, there appears to be a growing need for continued development of capabilities in exploration geophysical techniques applied in the shallow Earth. We see a need, however, for integration of these techniques with the end-user community. Efforts to quantify rock properties would benefit from a national center(s) in rock physical properties that would facilitate integration of experimental data with field-based geophysics.

What facility capabilities are needed to support broader impact needs post-2018 (education, outreach,training & workforce development, international)?
Thus there is a clear need for partnership with core science disciplines – the rock record plus modeling brings a temporal dimension beyond observational timescale. There is also a vital role for discovery-based science such as the recent breakthroughs in acoustic monitoring of sediment transport. Both avenues provide opportunities for interdisciplinary cross-training and education and cross traditional funding boundaries.

Authors: Sridhar Anandakrishnan, Julie Elliott, Sean Gulick, Eric Kirby, Victor Tsai, and Kelin Whipple
Title: Emerging scientific challenges at the interface of surface and deep Earth processes: Part 3, glacial processes
Keywords: glacial, ice-ocean, ice-quakes, erosion, orogenesis, sea level

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?
Increasingly, the community recognizes that the feedbacks among topography, climate and erosion govern the evolution of mountain belts over millennia. At much shorter timescales, the interactions among warming oceans, wave fields, glacial dynamics, and ice shelves threatens the stability of large portions of the polar ice caps. Seismological approaches hold great potential to address these, and other, aspects of how processes in the atmosphere, cryosphere and at the Earth's surface are dynamically coupled to the solid Earth. Three specific areas of need are: 1. Measuring and understanding the response of the solid earth to change in glacial loading, 2. Improving measurements spatially and temporally of critical parameters effecting glaciers sub-glacially and englacially, and 3. Monitoring change in configuration of ice-shelves and grounded ice.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?
Progress has been made in linking dynamic processes at tidewater glaciers (with and without ice shelves) to distinct seismic signals, but these linkages have not been documented across a large number of glaciers due to a lack of adequate instrumentation. Evaluating the role various factors play in ice dynamics will require a combination of denser arrays of seismometers in glaciated regions both polythermal and polar, seismic profiles and ice-penetrating radar to image glacier bed geometry and material properties, geodetic imaging and GPS data to monitor variations in ice velocity, and fjord/marine studies at the grounding line to understand timescales and rates of processes. Determining whether there are seismic or geodetic signals of specific sub-glacial or end-glacial processes could lead to breakthroughs in understanding dynamics of glacial behavior such as surges, catastrophic retreat, as well as controls on stability of ice sheets and outlet glaciers. Increased numbers of seismometers and cGPS in glaciated (or formerly glaciated regions) are needed to robustly assess the effects of past and ongoing ice load changes on the solid earth, which will also shed light on mantle properties.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?
Critical need for partnerships between programs and agencies as these scientific opportunities lie at the current boundaries in funding and facilities management structures (marine-land, remote sensing vs ground based, glacial but not polar).

Discovery Mode Science

Authors: Michael West, Roy Hyndman, Jeff Freymueller, Bernie Coakley, John Orcutt
Title: Toward meaningful geophysics in the North American Arctic
Keywords: Arctic, USArray, PBO, amphibious, cryosphere, hydrates

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

President Obama's National Strategy for the Arctic Region (2013) calls for "a well-coordinated and transparent national and international exploration and research agenda". Despite the tremendous increase in scientific and political interest in the Arctic, the region continues to hold some of the least understood tectonics on earth. Areas proximal to the U.S. and Canada are of particular interest due to resource exploration, increases in transportation, and a host of environmental considerations with both scientific and policy implications. Some of the most intriguing tectonics are evidenced by seismicity in the Beaufort Sea and the terrestrial Arctic of Alaska and the Yukon. Lateral shear zones and the Canning-Mackenzie thrust belt point toward potential slow subduction. It is unknown whether this thrust zone is capable of large megathrust earthquakes and tsunamis. Massive submarine landslides are well documented in the Chukchi and Beaufort seas—exacerbated by heavy sediment loads and the presence of gas and gas hydrates. Poor constraints on tectonic motions also hinder efforts to estimate glacial isostatic adjustment, past ice volumes and their influence on sea level forecasts. Sea ice, glaciers, storm and climate patterns are changing rapidly across the Arctic. Also the seismic hazard ground motion implications of permafrost are largely unknown. All of these issues are taking on societal significance as infrastructure and transportation projects advance in the Arctic.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

A 1991 report by the National Research Council called for “a modern, standardized network of broad-band circum-arctic seismograph stations”. A quarter century later, this charge has not been met. Improvements in power systems and communications have made geophysical facilities more feasible. Seafloor instrumentation is increasingly viable as the ice extent shrinks, long-distance underwater ROVs are becoming a reality, and cabled technologies are advancing. Denser GPS could constrain the Laurentide uplift region and the rapidly deglaciating regions of Alaska/BC/Yukon. Though facilities in the Arctic are expensive, the eight Arctic nations provide land-based observation points as well as resources to share the scientific costs. The GLISN project in Greenland is a small-scale example for carrying out collaborative Arctic geophysics. Infrastructure could be advanced by partnering with industry and the military. The North American Arctic contains a significant proportion of the world’s undiscovered oil and gas reserves. Trans-continental communication needs are driving new seafloor cables. And the 2013 Dept. of Defense Arctic Strategy document lays out a specific challenge to develop Arctic situational awareness through “cost-effective partnerships”. USArray and PBO provide an excellent opportunity to advance Arctic geophysics. The EarthScope knowledge base and infrastructure provides a footing for spreading further into the Arctic and adding a seafloor component.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Interest and societal relevance in the Arctic is rapidly increasing. Establishing seismic and geodetic facilities in the North American Arctic would allow the SAGE/GAGE community to support the numerous other research fields already active in the Arctic. The unusual facets of the Arctic location, rapid ongoing change, and the limited solid earth geophysics now available, make transformative research unavoidable. The Arctic contains a wide range of native cultures, all of which are deeply tied to the land. They are quite cognizant of rapid environmental changes and increasing development impacts. Opportunities for outreach, education and professional training are very high. Involving local people will help illustrate the relevance of science to society and to policy makers. Arctic science is inherently international which brings challenges, but it also provides strong motivation for cross-border exchanges and student training. Institutions such as the University of the Arctic and similar institutions in adjacent Canada provide mechanisms for extending these partnerships and connecting research to the local classrooms.

Authors: Michael West, Susan Bilek, Paul Bodin, Graham Kent, Keith Koper, Won-Young Kim, Natalia Ruppert, Victor Tsai, John Vidale
Title: Tracking North America: Long-term observation to build on the legacy of USArray
Keywords: Hazards, USArray, Infrastructure, ANSS, Ambient noise, Induced seismicity, Cryosphere

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

USArray has provided an unprecedented snapshot of North America. Once the Transportable Array culminates in Alaska, the nation will have a uniform base map of seismic structure. USArray briefly sampled the changing elements of the continent as well. Transients such as large earthquakes, weather, volcanic unrest, hydrology and glacial phenomena are being sampled along with anthropogenic impacts including induced seismicity, mining, an evolving cryosphere and changing climate. USArray provides a comprehensive short duration snapshot; the proposed facility would capture the evolving vital signs. The United States needs a better long-term "benchmark" seismic facility. We now understand that numerous phenomena are evolving on the scale of even a few years. Ocean waves, weather patterns, ice fields, glaciers, large-scale mining and induced seismicity are prominent examples at the moment. Even tectonic processes once thought to unfold on geologic time, in fact, have short-term manifestations. Transient fault creep, tectonic tremor and triggered earthquakes are increasingly pervasively observed. Ambient noise and interferometric techniques are demonstrating that even the structure of the earth evolves measurably on human timescales. Many of the most exciting recent discoveries, from the inner core to the active soil layers, have come from tracking subtle changes across years. This is most effectively done with "benchmark" seismic stations.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The objective of this facility is to establish a network of 500-800 long-term research-grade seismic stations spaced across the U.S. and in proximal foreign and offshore regions. At least half of these might be existing sites already shared by IRIS, regional networks and the USGS. Remaining sites would be backfilled leveraging USArray knowledge. The resulting network would preserve some of the nation's highest-performing sites for long-term operation. Changes in instrumentation and site conditions would receive the same level of scrutiny as current GSN stations. Consistency through time would be the signature of this array. The permanence of these sites would attract a spectrum of co-located geophysical or environmental monitoring such as infrasound and meteorological sensors. USArray brought significant advances in data quality, consistency and reliability. The passage of USArray left an imprint on research and seismic network operations in all parts of the country. It has improved the state-of-health and metadata of existing data. In some regions the USArray legacy is adopted equipment and high quality stations. Regions are also benefiting from an influx of research attention. The Transportable Array provided a case study for recording GSN-caliber data in nearly every corner of the U.S. The proposed initiative would extend the USArray legacy to provide a long-term facility to track the continent with uniform seismic data. In essence it would be a "GSN for the nation".

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

This facility has the potential for unusually broad impacts because of its scientific and geographic extent. This aspect is parallel in many ways to USArray. Education and outreach opportunities would be exceptional because the facility provides locally relevant content in all parts of the country. The emphasis on tracking the dynamic environment lends itself to teachable moments. The whole point of the facility is to capture transient and newsworthy environmental phenomena. Similarly, the multi-disciplinary nature of this facility would enhance training and workforce development in fields outside of traditional seismology. While great science shouldn't be designed around the interest of politicians, this project would be easier to advocate than many. The emphasis on dynamic earth systems will provide science that has high societal relevance and the potential for compelling results. Good project accountability will be given to taxpayers. Although the O&M cost, as envisioned here, is at least $5M per year, the broad agency collaborations and synergies with existing facilities constitute a cost-conscious approach. The presence of the project in nearly all U.S. states would provide a broad base of advocates and pervasive project visibility.

Authors: Keith D. Koper, Colleen A. Dalton, Jean Paul Ampuero
Title: A Global Array of Broadband Arrays
Keywords: arrays

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

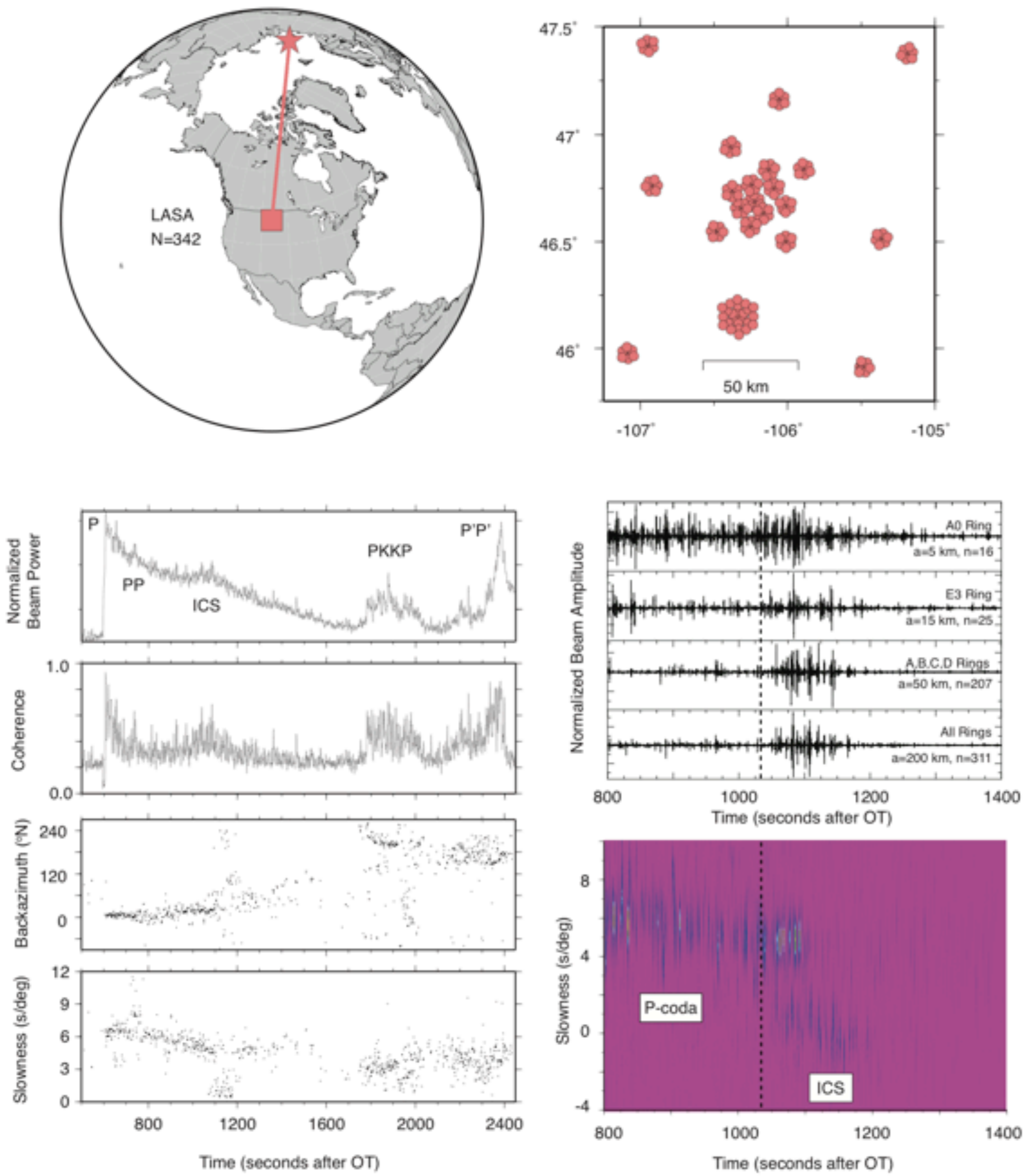
For over 30 years, the Global Seismic Network (GSN) has been essential to imaging Earth structure, from the crust to the core; to characterizing earthquake sources, for example through the systematic calculation of centroid moment tensors and, more recently, finite fault models; and to discovering new seismic sources, such as the glacial earthquakes that occur in Greenland. However, to make new, fundamental discoveries in seismology over the next 10-20 years, a significant increase in resolution is required. A global array of broadband arrays (GABBA), as described below, can provide the needed resolution. Such arrays would (1) greatly enhance the signal-to-noise ratio of subtle body waves used in imaging Earth structure, such as reflections and conversions from upper mantle discontinuities (e.g., P410P, ScS reverberations), waves that turn just below the D" discontinuity (e.g., Scd), and energy scattered from the inner core (PKiKP coda waves); (2) provide new, robust characterization of longer-period surface waves such as off great circle propagation, multi-pathing, and gradiometric properties; and (3) lead to advances in seismic source studies via detection and location of aftershocks following a large earthquake, high-resolution back-projection type imaging of earthquake ruptures, and the monitoring of sparsely instrumented regions and nuclear test sites to much lower thresholds.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

New, permanent arrays of three-component broadband seismometers are needed to address the key geophysical issues of the near future. The arrays should consist of hundreds of elements, arranged in fractal-type geometries with apertures of about 100-200 km, in order to address the next generation of scientific challenges related to imaging Earth structure, imaging earthquake rupture properties, and detecting and locating seismic sources. The Large Aperture Seismic Array (LASA) that was deployed in Montana for 1965-1973 is roughly what will be needed for future elements of a global array of arrays. This facility led to fundamental discoveries about the structure of the crust, mantle, and inner core, as well as important advances in detection, location, and characterization of seismic events. To have the greatest impact, seismic data from a future global array of arrays should be made openly available in near real time. Installing uniform equipment across each array will create efficiencies in operation and maintenance, and will simplify the data processing. It will also be important to implement modern data quality procedures as part of the routine operations and maintenance of the arrays. Initially, array installation should be focused on the southern hemisphere (especially South America, southern Africa, and Antarctica), which currently has many fewer openly available streams of high-quality seismic data compared to most of the northern hemisphere.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

At least three things will be required to support the broader impact needs associated with a future global array of broadband arrays of seismometers. (1) International partnerships will be essential to capitalizing, operating, and maintaining the arrays. In South America, for example, a coalition of nearby nations, acting in concert with the National Science Foundation, will likely be required. An array facility could serve as a regional clearinghouse and training site, helping to build scientific capacity throughout the continent. In Antarctica, a coalition of nations with existing polar science capabilities will be required. (2) Efforts should be made to expand the teaching of basic seismic array processing in graduate programs. Currently, it is uncommon in the U.S. for graduate classes in earthquake seismology to cover basic multi-channel, digital signal processing, such as computing f-k spectra. Workshops, shared lesson plans, and new textbooks will be required. (3) Connections with outside scientific communities that have more experience in array processing will be required so that the most modern, sophisticated methods can be applied to the seismic array data. Recent efforts at collaboration with active source scientists in petroleum services companies should be encouraged and amplified, and attempts to interact with scientists and engineers involved in radar and sonar technology should be initiated.



Caption: A LASA recording of a 1971 Soviet nuclear test. These data led to the discovery of energy backscattered from Earth's inner core (ICS), which in turn led to a new understanding of the structure, growth, and dynamics of the inner core. The aperture and station density of LASA are roughly what are required for elements of a global array of arrays; however, with the advances in instrumentation and data processing that have occurred since the 1970's, even more stunning discoveries can be expected.

Authors: Becky Flowers, John Hole, Terry Pavlis, Lara Wagner, Steve Whitmeyer, Mike Williams
Title: 4D-Earth Initiative: A Community Geologic Model and New Scientific Initiative for the 4D Evolution of the North American Continent
Keywords: Community Geologic Model, Cyberinfrastructure, continental evolution, geochronology

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

We envision a new interdisciplinary 4D-Earth Initiative as a natural successor to the EarthScope program, aimed at (1) expanding the primarily 3-D geophysical focus that captured a snapshot of present day North America into the 4th dimension of time, and (2) illuminating the crustal component that was below the resolution of much of the USArray image. This initiative will integrate new infrastructure and new science within an overarching scientific motivation to develop a Community Geologic Model for the 4-D Evolution of the North American continent. The goal is to unravel how and why the continent evolved to the current state and to firmly answer long-standing questions of how the time-integrated processes of plate tectonics and surface processes produce the crustal structures we see today. This effort will bring to fruition one of the original goals of the EarthScope program, to build a 4-dimensional image of the continent, and will also usher in a new way of conducting Earth science research. 21st century geologic data is as inherently sharable and quantifiable as the geophysical data that were the center of EarthScope. What is currently lacking is a mechanism that can merge geoscience data into a common framework and focus data and researchers toward achieving fundamental new advances. Our vision for the 4-D Earth Initiative will include improved access to a network of geochronologic and analytical facilities and a new cyberinfrastructure for data and model integration.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Community Geologic Model We envision development of an open source multidimensional model of North American continental evolution. As a starting point, we picture a set of time slices such as those published by Whitmeyer and Karlstrom (2007), but each time slice would be a digital model in itself, incorporating data sets, hypotheses, simulations, models of structure, stratigraphy, geochronology, geomorphology, petrology, lithospheric and crustal dynamics, and high resolution geophysics and environmental sensing enabled by observational networks such as those built by EarthScope. These digital time slices will function as a platform for discussion and collaboration, through which they will undergo iterative development and improvement as new data and models are added. The project will have important linkages with Earth Cube and related cyberinfrastructure initiatives. It will require extensive new computing infrastructure with enough flexibility to integrate geologic data, images, and models at all scales and interact with other existing databases. The model will succeed only if it provides immediate “added value” for processing new and existing geologic data. As such, it must implement open sources tools for collecting, processing, integrating, and plotting diverse datasets, including map- and field-based data, and it must have visualization tools that allow for production of both 2D and 3D images in a variety of user-defined formats at different snapshots through time.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

The 4D-Earth Initiative, almost by definition, will have huge broader impact, education, and outreach components. It, like EarthScope, has something for nearly everyone and every place. It embodies place-based-education and teaching and facilitates investigations of specific places through time. Through the new cyberinfrastructure that will underpin the community geologic model, there is great potential for the seamless integration of scientific publications and other forms of dissemination into the model framework, with relevance to organizations such as the Geological Society of America and the American Geophysical Union as they move toward entirely open access content. The model infrastructure will incorporate significant student training components in database tools and also in tools for collecting, processing, and exporting geologic and geochronologic data. We envision that outreach activities will increasingly move toward a coordinated community approach that capitalizes on the inherent but incompletely tapped public interest in Earth history. This will be an excellent opportunity to demonstrate to the broader community how the geosciences can unravel both deep and shallow time and the 4D evolution of our continent.

Supporting Image: *No image*

Caption: (No image, but it is important to highlight that the text in the fields above is a subset of a larger 4-page white paper that will serve as the focal point of a pre-meeting workshop at the Vermont ESNM meeting. We would prefer to submit the full white paper for discussion at this IRIS Future Needs workshop instead of the shorter, edited version encapsulated by this web form.)

New Technologies

Authors: Mark Zumberge, Jonathan Berger
Title: Development of an Integrated Borehole Seismic and Geodetic Sensor
Keywords: Seafloor, Seismometer, Tiltmeter, Gravimeter, Strainmeter

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

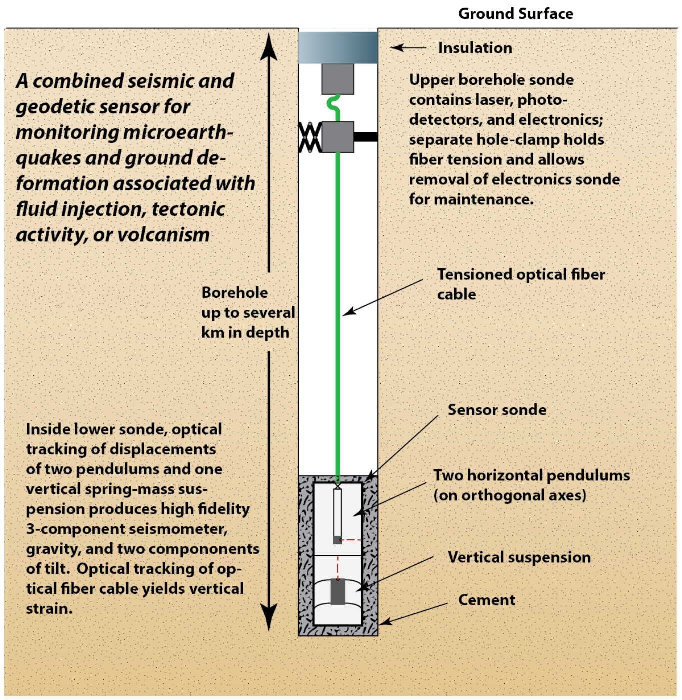
We have designed a borehole system that utilizes optical-fiber interferometry to provide in one package: (a) a broadband vertical seismometer/gravimeter, (b) a broadband two-component horizontal seismometer/tiltmeter, and (c) a low-noise vertical long baseline strainmeter. The combined system will be able to measure vertical and horizontal ground velocities, gravity, tilt, and strain with sensitivities that compare favorably with any existing system over time scales from 10 Hz to many days; the downhole components are entirely passive, giving long instrument lifetime. In the marine environment there is a distinct advantage to gaining multiple observables from a single instrument. The instrument will be ideally suited to study the distribution of episodic tremor and slip offshore.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Broad coverage in the ocean basins will be critical to mapping seafloor deformation associated with tectonics and volcanism. Installing geodetic sensors and coupling them adequately to material below will, in some cases, require shallow drilling. The capability to drill to relatively shallow depths (e.g., 10 to100 m) with assets available to the academic community will be needed.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Education of early-career scientist in the methods of seafloor geodesy and seismology will be required. The academic community must continue to develop instrumentation needed for highly precise geodetic measurements in the marine environment and be ready to train and support those interested in creating new sensing capabilities in the geosciences.



Caption: The instrument shown schematically here is currently under development. The components have been tested individually — a significant portion of the development task will be to integrate them into a single system, called an Integrated Borehole Interferometric Sensor System (IBISS&#41

Authors: Mark Zumberge, Glenn Sasagawa
Title: Seafloor Pressure Measurements for Vertical Geodesy
Keywords: Seafloor geodesy, Pressure, Vertical deformation, Sealevel

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

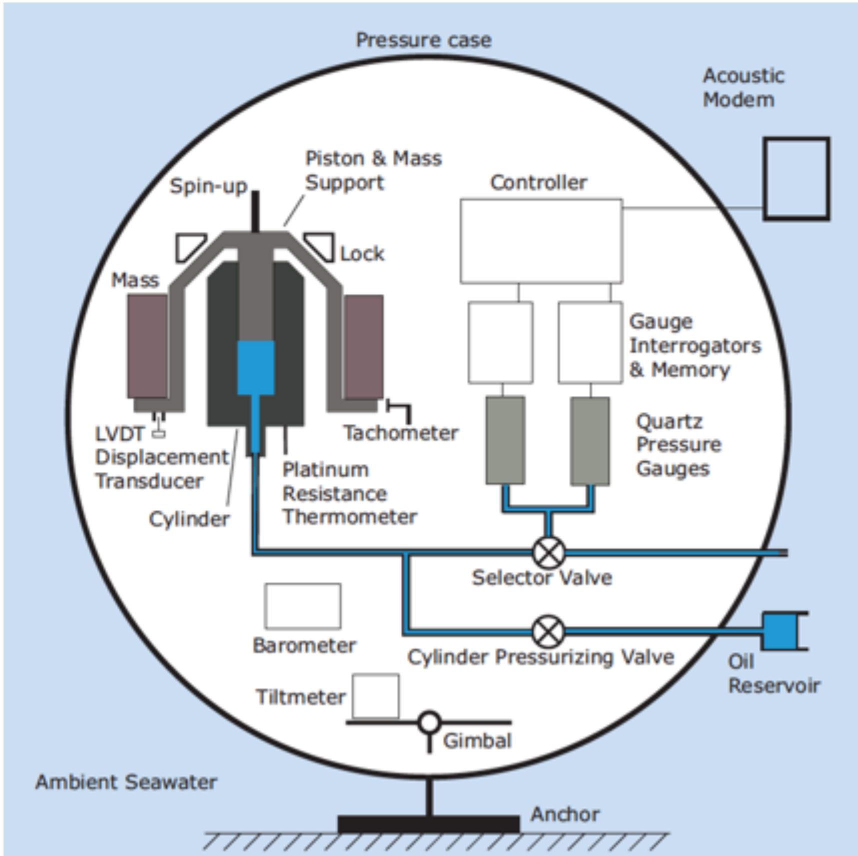
One method to detect vertical crustal deformation of the seafloor, where GPS surveys are not possible, is to monitor changes in the ambient seawater pressure, whose value is governed primarily by depth. Modern pressure sensors based on quartz strain gauge technology can detect the pressure shift associated with subsidence or uplift of the seafloor by as little as 1 cm. Such signals can be caused by tectonic or volcanic activity. However, most gauges undergo a slow drift having unpredictable sign and magnitude, which can be misinterpreted as real seafloor height change. To circumvent this problem, we have developed an instrument that calibrates the pressure gauges in place on the seafloor. In this autonomous system, a pair of quartz pressure gauges recording ambient seawater pressure are periodically tested in situ with a piston gauge calibrator. Key questions that can be addressed with this technology include the identification of the vertical components of deformation associated with subduction zone motion and volcanic inflation and deflation. For motions that occur over time scales of years, drift removal is critical. By calibrating the sensors in place, it is also possible to make pressure measurements traceable to NIST force and length standards, enabling absolute pressure measurements to be made in campaign mode at benchmarks in the abyssal hills. Such measurements can ultimately reveal the bottom pressure increase resulting from sea level rise.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Where power and data links are provided by subsea cables, deployment geometries and methodologies can be adjusted to take advantage of the connection to shore. As cabled observatories proliferate, as they likely will eventually, approaches to submarine geodesy can adapt accordingly.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Education of early-career scientist in the methods of precision metrology applied to the seafloor environment will be required. The academic community must continue to develop instrumentation needed for highly precise geodetic measurements on the seafloor and be ready to train and support those interested in creating new sensing capabilities in the geosciences.



Caption: A schematic diagram of a Self Calibrating Pressure Recorder

Authors: Vera Schulte-Pelkum
Title: Modular software for large data mining and processing in seismology, geodesy, geology
Keywords: seismological software, geological and geochemical database

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Major drivers for advances in seismology will be 1. the ability to handle large data sets efficiently, and 2. the ability to tie into geological, petrological, geochemical, and other interdisciplinary data sets efficiently.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Seismology is moving towards larger and denser data sets. While data archiving and access are already being done very well and are steadily improving, the processing on the researchers' side still largely rests on patchworks of legacy code held together by duct tape. Gary Pavlis called this the "balkanization of seismological processing" in his keynote address at the IRIS workshop in 2014. Professionally written, modular code that allows efficient manipulation of large data sets and easy modification and expansion to apply new techniques will lower the threshold for new discoveries. Non-seismological data (geology, etc.) are very important to seismological research, but are mostly scattered through the literature. Integration of those data into a central repository will boost interdisciplinary research.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Countless human-years are being spent by graduate students learning inefficient and dated code, re-inventing the wheel, and combing through papers for non-seismological data. The new capabilities above will positively impact education and training.

Authors: David Schmidt, Emily Roland, William Wilcock, Paul bodin, John Vidale, Brendan Crowell
Title: The Need for Amphibious Networks for Subduction Science and Real-Time Monitoring for Earthquake Hazards in Cascadia
Keywords: Cascadia Subduction Zone, hazard monitoring, earthquakes and slow slip, amphibious geophysical networks, earthquake early warning

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Recent devastating megathrust earthquakes off Sumatra, Chile and Japan have illustrated the hazards posed by subduction zones and raised awareness for a comparable earthquake along the coast of the Pacific Northwest. Because subduction zones span the coastline and continental shelf, geophysical investigations of subduction zone processes are optimally supported by both terrestrial and seafloor observational networks. Sustained offshore seismic networks are needed to monitor the microseismicity of the plate boundary and help to identify active structures in the accretionary prism. The paucity of seafloor geodetic instrumentation has so far limited our ability to characterize the size and tsunamigenic potential of a future megathrust earthquake. Currently, there is inadequate instrumentation offshore Cascadia to detect aseismic slip transients, let alone characterize their behavior, recurrence, and magnitude. Enhanced seafloor geodetic instrumentation capable of resolving interseismic deformation (campaign observations repeatable to one-to-a-few centimeters per year in both the vertical and horizontal) would allow us to better characterize the spatial and temporal variability in plate boundary slip behavior. Just as important, developing systems that provide these data in near-real-time could greatly enhance our ability to incorporate seafloor deformation behavior (seismically and geodetically detected) into early-warning and monitoring efforts.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

It is critical that high-rate terrestrial geodetic and seismic networks be maintained in Cascadia, as they provide the backbone for future research. To complement these terrestrial networks, a new sustained offshore network is required. Recent efforts, such as NEPTUNE Canada, OOI, and the Cascadia Initiative provide a foundation for future development. In order to characterize the locked zone and its variation along strike, multiple geodetic profiles must be occupied in Cascadia. Offshore geodesy will be challenging with the expected signals hovering near the noise level of many techniques. Field campaigns should be accompanied by continued efforts to develop new technologies, including those with significant power requirements, which are best supported by cabled deployments. Presently, there are several nascent efforts in Cascadia to initiate offshore geodetic observations. Future seismic and geodetic facilities should include resources for further developing unified horizontal and vertical displacement seafloor geodetic technology. In going forward, community objectives should be set for the spatial extent of seismic and seafloor geodetic networks, process-guided goals for observational capabilities (i.e., resolution of vertical deformation), and plans for integrating geodesy into monitoring and early warning efforts using existing cabled infrastructure.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

As earthquake early warning is implemented on the west coast, our ability to quickly detect and characterize offshore events is diminished by the lack of real-time seismic and geodetic data seaward of the coast. Additionally, an offshore data stream would bolster our ability to more fully characterize temporal changes in slip behavior, as well as transient behavior that may indicate elevated risk. Developing the infrastructure to provide these data, or some portion of it, in real- or near-real-time would greatly enhance our early-warning capabilities, as well as supplement our monitoring efforts. Cabled systems off Cascadia provide the power and bandwidth to support seismic data streams, while also providing the development platform for new geodetic techniques. An amphibious monitoring system with early-warning capabilities for Cascadia will require greater international collaboration with Canada, given that the seismic source region extends across the border.

Authors: Christopher Crosby, Ramon Arrowsmith, Viswanath Nandigam
Title: Opportunities for Advancing Research and Broader Impacts with High Resolution Topography
Keywords: high resolution topography, lidar, cyberinfrastructure,

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

High-resolution topography (HiRT) from lidar (light distance and ranging) and other imaging techniques has been revolutionary for earth science, environmental, and engineering applications. These data area a powerful tool for studying the earth's surface, its vegetation, and the built environment. Typical surface processes act at fine spatial scales (<1m) to produce intricate landforms, and HiRT measures the three-dimensional geometry of the earth's surface and overlying anthropogenic features and vegetation at resolutions appropriate to document these processes. In addition, surface changes due to erosion, transport and sedimentation, as well as earthquakes, landslides, volcanoes can be quantified with HiRT. The Earth's surface is imaged at increasing resolutions from spaceborne, airborne, and ground based sensors, making repeat and ubiquitous HiRT possible. Temporal comparisons of HiRT data will enable us to quantify change in unprecedented ways to inform our understanding of surface, volcanic, and tectonic processes. Repeat HiRT data will be sufficiently accurate and detailed to be valuable in earthquakes where coseismic (plus afterslip) displacements are larger than decimeters along the rupture trace. In addition, permanent ground deformation associated with earthquake shaking including subsidence, mass movements, etc. may be documented with these data. Finally, the ability to interpret the landscape record of prior earthquake displacements requires HiRT.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

To achieve the vision of repeat and ubiquitous HiRT for quantification of surface changes due to erosion, transport and sedimentation, as well as earthquakes, landslides, and volcanoes, continued investment in data capture as well as cyberinfrastructure will be necessary. Easy, online access to HiRT data as well as tools to process and extract information from these data will be fundamental. NSF's investment in OpenTopography (http://opentopography.org/) has already dramatically streamlined access to research grade lidar topography data collected within the academic earth science community (e.g., by NCALM); continued effort will be necessary to centralize online access to new datasets, and to coordinate with critical partners such as the USGS and their new 3D Elevation Program. As HiRT from terrestrial and mobile laser scanning platforms, as well as photogrammetric techniques such as Structure from Motion, become common, integrating these data alongside "traditional" airborne laser scanning datasets will also be important. As HiRT data become increasingly ubiquitous, a critical cyberinfrastructure challenge will be to provide processing and analysis solutions that enable rapid extraction of information from these datasets. For example, the ability to rapidly ingest post-event HiRT data and enable temporal analysis with a series of other OpenTopography-hosted HiRT datasets will make it possible to quickly extract 3D displacements following a ground rupturing earthquake.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

HiRT data are self evident to novice through expert users in their capability to depict surface features. Their high spatial resolution provides both synoptic and fine scale perspective that show the 3D structure of topography, vegetation, and the built environment. Open access and interactive processing such as that made possible by OpenTopography enable exploration of these data by non-experts and use in educational settings. The ubiquity of these data mean that there is increasing demand from a diverse community of users ranging from academia to commercial sector for reliable and easy access. Addressing these demands for requires a well designed and properly functioning cyberinfrastructure. Such a system should satisfy the needs of researchers as well as educators (where there can be a great reach), and commercial sector users. Dissemination of the data, visualizations, and tutorials should happen on multiple levels ranging from social media, standard online modes, to intensive hands-on training courses. Along with addressing science standards associated with technology, HiRT data address numerous earth science educational standards associated with natural hazards, climate change, anthropogenic modification of the environment, and mass and energy change and transfer through the environment. Collections such as the OpenLandformCatalog (http://www.opentopography.org/index.php/resources/lidarlandforms) begin to address some of these opportunities.

Caption: OpenTopography and the 2014 Napa earthquake. A) 2014 Napa dataset extent. Heatmap (B) and bounding boxes (C) of recent data downloads from OT. South Rd area surface rupture is not evident in the 10 cm hillshade computed from the point cloud (D) whereas the filtered ground returns (by S. Delong, USGS) show the rupture in the 10 cm hillshade (E). Inset shows the rupture zone with transparent blue polygon (Hudnut et al., USGS Open-File Report 2014-1249, http://dx.doi.org/10.3133/ofr20141249).

Authors: Matthew J. Fouch, Hongyu Yu, John. D. West, Mengbing Liang, Edward J. Garnero
Title: The Need for Next-Generation Broadband Seismic Sensors to Enable New Scientific Discovery
Keywords: Instrumentation, Microseismometer, Monitoring, Field Seismology, Solid Earth Structure

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

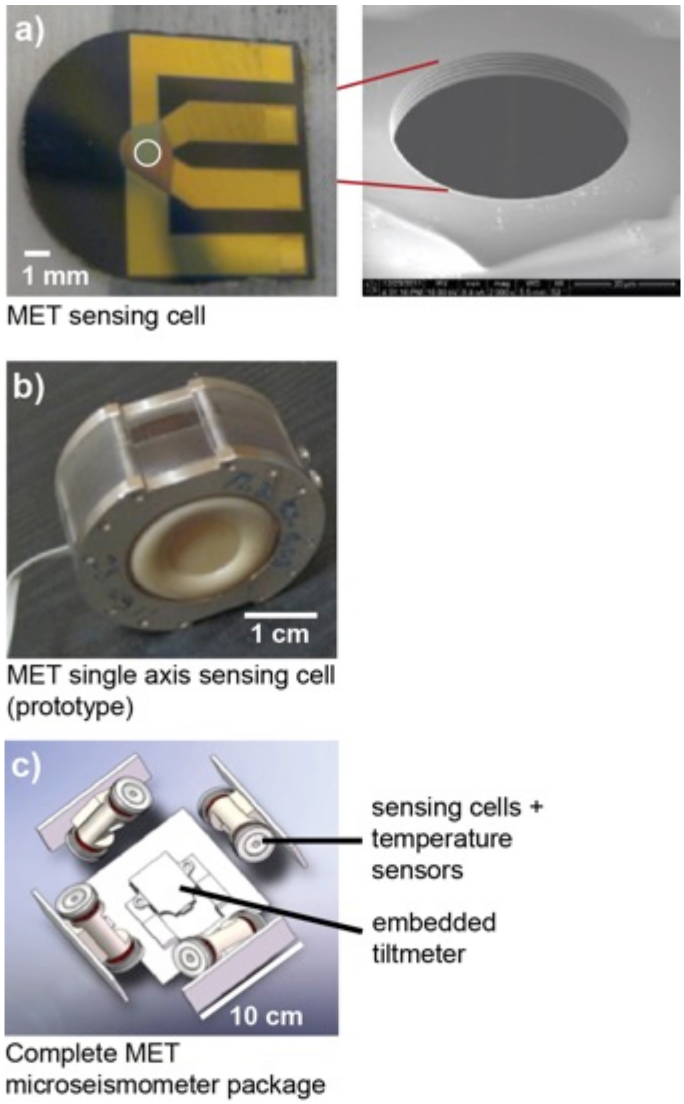
Historically, major scientific advances have been strongly coupled with key technological breakthroughs that enable previously unobtainable measurements. In solid Earth sciences, the advent of portable broadband seismometers enabled a revolution in scientific discovery via the deployment of seismic stations to record data at unprecedented resolution and scale, both spatially and temporally. While modest advances in sensor quality have been made in the past ~3 decades, broadband seismometer technology has not changed fundamentally. Substantial and successful engineering efforts have enable the deployment of these systems in environments for which they were not originally designed (e.g,. ocean bottoms, polar regions, other extreme environments, etc.). Creative community endeavors, combined with federally funded facilities such as IRIS, have pushed these systems to their limits. We submit that the next wave of rapid scientific advancement can be propelled most quickly by a next-generation seismic system. In this white paper, we describe the detailed community needs for a new microseismometer and our efforts to develop such a sensor. We note that a “Large N” white paper has been submitted to this workshop, which discusses the broad-scale needs and effort for a new system that will enable simplified deployments with denser station spacing. The justification for the system in that white paper dovetails nicely with the sensor described here.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Developing and building a next generation sensor should be a cornerstone for seismic facility capabilities. The sensor should be capable of deployment in nearly all Earth environments, including deployment by autonomous vehicles. We submit that the sensor should include the following characteristics: • Flat velocity response (frequency range of 0.02 Hz to 50 Hz or better) • Low self noise (2 x 10^-10 m/S^2/Hz^0.5 @ 1 Hz or better) • Very low power consumption (<50 mW) • High shock tolerance (100+ g; 1000+g easily achievable) • Rapid settle/equilibration time (10 s or less) • Broad operation temperature range (-55ºC to +125ºC or better) • Low mass (<1.0 kg) • Installation at any angle without sensor leveling • No moving parts A major advance in seismic sensor technology has been achieved by our group via the development of the first miniature Microelectronic Transducer (MET) sensing cell, fabricated using MEMS technology. Through sustained funding by NASA, the first prototype sensing element was fabricated and tested successfully in 2012, demonstrating the feasibility of this approach to develop a complete MET-based microseismometer. Ongoing efforts include improving and streamlining the fabrication process and assembling sensing packages. These sensors are scheduled to be tested at the IRIS PASSCAL Instrument Center (PIC) in mid-2015, with additional tests at both the PIC and the USGS Albuquerque Seismological Laboratory (ASL) at the end of 2015.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

The development of the sensor described here has inherent broad impacts across the Earth sciences. While myriad applications can be envisioned, here we highlight a few key elements. The design of the MET microseismometer will also improve the cost effectiveness of these applications. Teaching tools: The MET microseismometer will enable the deployment of scientic-grade instrumentation during a broad range of teaching, including K-12 education. Hazards monitoring: The MET microseismometer will enable substantially improved monitoring of earthquake-prone regions and a broader range of volcanic centers. Further, the technology can enable improve characterization of tsunamigenic earthquakes. International collaborations: The MET microseismometer will be particularly useful for low-income countries in need of simplified approaches to high-resolution monitoring of hazards. Other scientific communities: The MET microseismometer will enable a fundamental improvement in design of geophysical missions, including other planets, icy satellites, and near-Earth asteroids. An additional natural outcome would be improved collaboration between the planetary and terrestrial geophysical scientific communities. Workforce training: The MET microseismometer can provide necessary training for geoscientists moving into the energy sector as energy companies shift resources into passive source monitoring for both exploration and monitoring activities.



Caption: Images of the MET microseismometer. MET sensors measure fluid flow of an electrolyte through a membrane. The design increases sensor performance to enable deployment in more environments than current technology. a) MET sensing element. b) Prototype MET single axis sensing cell in housing from from original MET sensor. c) Sketch of complete sensor package. 4th element included at a separate angle for system redundancy. Dual axis inclinometer determines deployment angle.

Authors: Dave Chadwell. Scott Nooner, Spahr Webb
Title: New Platforms for GPS-Acoustic Seafloor Geodesy
Keywords: Seafloor Geodesy, GPS-Acoustic, Transponders, Benchmarks

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

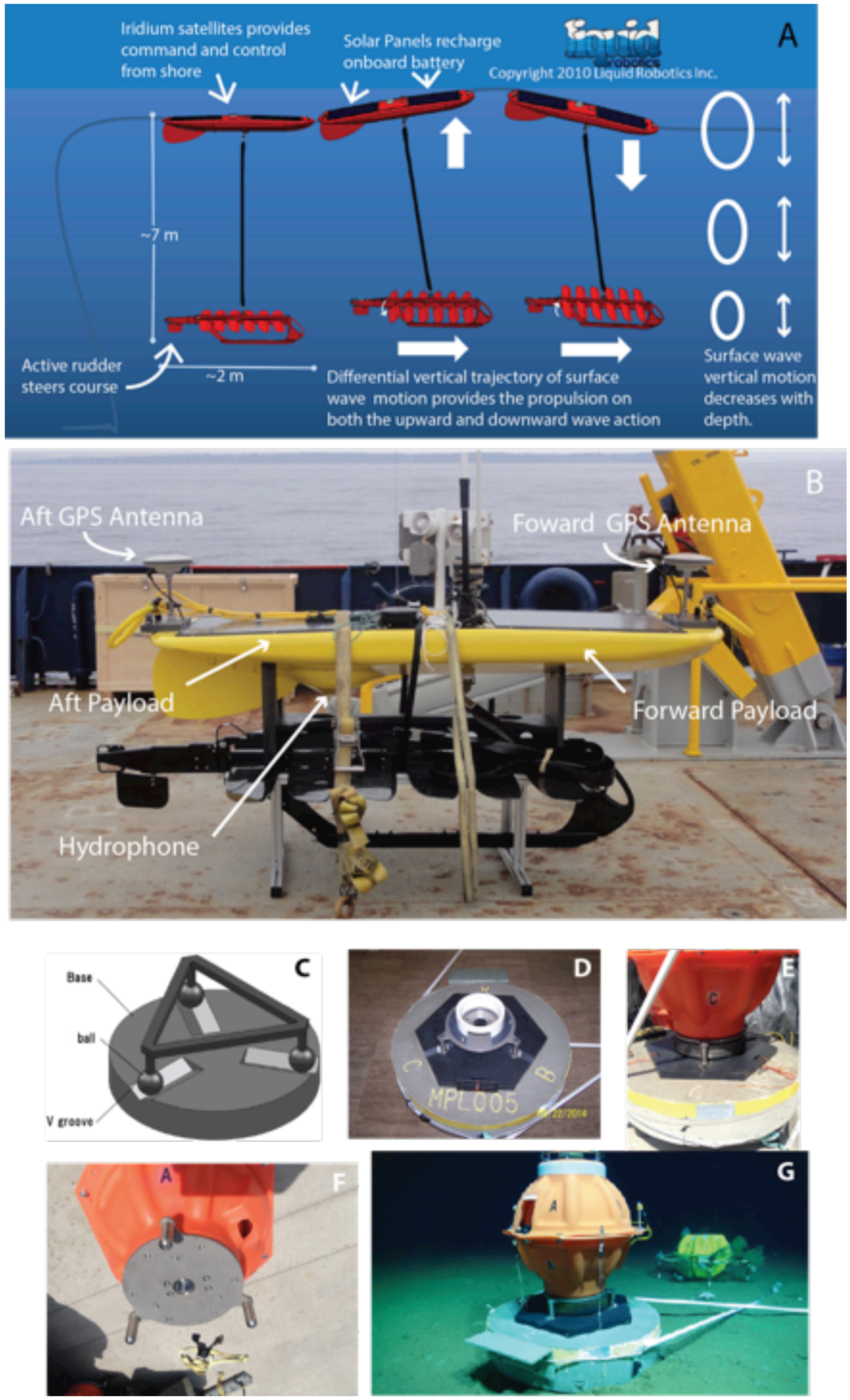
Over the past 30 years, GPS has revolutionized our understanding of subduction processes. However, GPS networks stop at the coastline while elastic strain buildup and release continues offshore. Combining GPS with precision acoustic ranging, the GPS-Acoustic technique, has proven capable of capturing seafloor motion. Seafloor displacements during inter-seismic, co-seismic and post-seismic phases of the earthquake cycle have been measured with centimeter precision. The high cost of ship time and the finite length of batteries in the seafloor packages have limited the wide-spread and long-term use of the GPS-A method. Two new technological developments address these limitations. First, the GPS-A method has been adapted to a platform, a Liquid Robotics Instruments Wave Glider, propelled by ocean surface wave motion and powered by solar panels. The system is remotely controlled from shore through periodic Iridium satellite connections. Because the system harvests renewable energy it can operate for months at a time. Costs are reduced from ~$50k per day using a large ship to ~$100 per day, a factor of 500 savings. The second development is a new permanent benchmark for the seafloor that allows sensors to removed and replaced while maintaining millimeter-level registration to the benchmark. The approach uses three balls which contact the sides of three grooved channels to control the six degrees of freedom. Transponders become pool instruments to be re-used.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

In September 2014, a GPS-A Wave Glider collected 30 hours of GPS and acoustic ranging data at a site 90 NM offshore central Oregon. Measurements are planned at two additional sites on the continental slope in Cascadia during 2016 and 2017. All three sites are using these new approaches. These two new approaches can be scaled up to provide spatial coverage to compliment the dense GPS arrays offshore. Seafloor transponders are attached to the benchmark and the entire package launched from the surface to free fall to the sea floor. As the experiment dictates, the transponders can be recalled remotely from the surface at any time over the following few years. Future updates to the time series are possible by placing a transponder in the grooved registration of the benchmark. A pool of transponders can be used with benchmarks and several Wave Gliders to establish the inter-seismic strain rates in an area. The transponders can be recovered, attached to new benchmarks, and then deployed in a new area. The transponder pool lowers infrastructure costs. The low-cost benchmarks can be reoccupied in the future after earthquakes to measure co-seismic and post-seismic motions.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Education of early-career scientist in the methods and operations of seafloor geodesy will be required. Workforce development will require broadening the base of engineers and technicians capable of operating in the marine environment. Commercial manufacturers are beginning to provide more of the instrumentation required for sea floor geodesy. Continuing this trend will ensure industry standard levels of quality control. International partners working seafloor geodetic methods, particularly the Japanese, exists and should be enhanced.



Caption: Figure 1. A) Wave Glider harvests renewable energy (wave action and solar radiation) that enables it to operate for months at sea. B) Wave Glider configured for GPS-Acoustic operations. C) Three pin and three grooved kinematic mount. D, E, and F show implementation. (G) Foreground shows new seafloor benchmark/transponder placed approximately 2 m from old (circa 2000) transponder at site offshore Oregon. ROV Jason removed and replaced the transponder with millimeter-level repeatability.

Authors: Paul Huang (NTWC) and Barry Hirshorn (PTWC)
Title: A Real-time Operational joint Seismic and GPS Tsunami Warning System
Keywords: tsunami warning, real-time, seismic, GPS

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Tsunami Warning Centers need to rapidly estimate the magnitude, and other source parameters of an earthquake to determine its tsunamigenic potential. However, for great earthquakes, initial seismic estimates of the moment magnitude tend to be too low, thus severely underestimating the danger of an ocean wide tsunami. Presently, the W–Phase method routinely determines an accurate moment magnitude and CMT in about 20- 30 minutes, which is adequate for a distant earthquake and the tsunami threat. For local and regional distance events, we need the fastest methods available to accurately determine earthquake magnitude and its tsunamigenic potential. Given sufficient sensor density in the 5 to 8 degree epicentral distance range, the W-phase can provide accurate Moment magnitudes and CMT's within 5 minutes. The GNSS networks reference real-time processing of GPS data which provides accurate earthquake magnitude estimation, three dimensional co-seismic crustal deformation and fault slip measurements within a few minutes after the earthquake initiation (Obana et al., 2000; Ikuta et al., 2008; and Hoechner et al., 2013). The sea floor deformation associated with the earthquake slip can then be used as an initial condition in a tsunami propagation and coastal inundation model for coastal warnings. The GPS networks are complementary to seismic monitoring networks and will contribute significantly to tsunami warning.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

For real time tsunami warnings using GPS data, the costal GPS stations should be complimented with direct underwater measurements. A submarine cabled real-time sea floor observatory network like Japan's DONET (Dense Oceanfloor Network System for Earthquake and Tsunami) can be used to constrain the measurements of co-seismic ocean floor deformation. The submarine observatory network will have a reliable backbone cable system, replaceable sensors and extendible interfaces. The tsunami warning system must have real-time transmission from all sensors (GPS, seismic, strong motion, tide and pressure), real-time routine automated data analysis software (inversions of all data), and a 'large earthquake trigger' alarm that alerts the TWC operators. An important aspect for the GPS system must overcome the limitation of current relative positioning that requires reference stations which may be significantly displaced during large earthquakes.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

The proposed seismic and GPS Tsunami Warning system must be able to accurately and reliably determine the permanent co-seismic deformation and fault slip distribution under all conditions including major power outage, strong shaking and wide spread earthquake damage. The system should be a turn-key system including hardware (receivers, computers, and storage systems), software (data analysis, algorithm, and alerting parameters), and messaging and communication system (satellites, radio, cell, and web pages). Education and training on how to maintain and use of the system will be provided to Tsunami Warning Center personnel. Training on Warning messages based on the GPS system will also be provided to emergency managers.

Authors: Bruce Douglas, Rick Bennet, D Sarah Stamps, Nathan Niemi, Bob Wang, Ed Nissan, Mike Oskin, Alison Duvall, Michael Hamburger
Title: Current Directions of Field Science Education with Respect to Geodetic Technologies
Keywords: static and kinematic GPS surveying and positioning, terrestrial, airborne, and mobile laser scanning; satellite interferometric radar; photogrammetry

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

There has been an ever-increasing use within the geoscience community of geodetic techniques to detail and monitor Earth surface processes and deformation. As refined and new technologies emerge there is a developing gap in the training of undergraduates and faculty responsible for teaching these undergraduates in the background and use of these new technologies (e.g. static and kinematic GPS surveying and positioning; terrestrial, airborne, and mobile laser scanning; satellite interferometric radar; photogrammetry) and interpretation of their resulting data sets. Up to the present, the emphasis has been on training at the graduate and professional level with the primary focus on academic research or professional and industrial use. Inroads are being made to incorporate geodetic techniques and data sets into introductory to advanced undergraduate courses in classroom educational settings through the incorporation of geodetic methods and data into textbooks and curricular materials, particularly through UNAVCO's education and outreach efforts. Where the community lags behind—and where exciting new opportunities abound—is in offering opportunities for undergraduate students to obtain first-hand knowledge of the instrumentation, data collection strategies, and resulting data analysis associated with geodetic imaging data. Such exposure would ensure that a high-level professional workforce moves forward with the next generation of geoscientists.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Fieldwork and field education are a long-standing tradition within the geological sciences as a means of providing critical hands-on professional experience to undergraduates. As new technologies emerged, such as the construction and use of topographic maps and stereographic aerial photos to serve as base maps for recording and displaying geologic information, these were incorporated into the basic training of geoscience undergraduates. Similarly, geophysical technologies (e.g., seismic, gravimetry, magnetometry) are frequently taught, either as components of field geology courses or field geophysics courses. We now face a similar need to provide access to geodetic tools to undergraduates, but the cost for obtaining and maintaining such instruments, the technical experience needed to operate them reliably, and availability of knowledgeable instructors limit the number of students that can receive this instruction. The root of the problem is the capital and operating cost associated with the desired suite of instruments and the institutional emphasis on instrument cost payback through research productivity. This gap is particularly vexing in that bridging it would fulfill two widely recognized needs in the training of future earth scientists: (1) familiarity with GIS and related technologies, and (2) experience in managing and working with large data sets. In a significant, but limited, number of programs this is taking place within the context of traditional field programs.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

As geodetic technology becomes more portable and cost effective (e.g., recently announced LiDAR drones), the need for students to be familiar with geodetic technology will increase dramatically. The existing UNAVCO research and E&O support facilities could serve as a platform to meet these needs. A demonstration of this ability has been taking place over the past several years through a limited number of field programs offered by several universities. What is clear from these pilot programs is that this approach can be highly effective and that demand is greater than the present capacity to respond given the current primary dedication of instruments and staff to research priorities. What is needed is a parallel system that is a shared pool of instruments, software packages, technical support, and knowledgeable faculty to effectively disseminate the application, instrument deployment, data collection and interpretation to the present undergraduate geoscience population—as well as those in allied science disciplines. Faculty must also be qualified in both field operations and expertise in the background theory and application of these instruments and their respective data sets.

Authors: Jonathan Berger, Gabi Laske, John Orcutt, Jeff Babcock
Title: Expansion of the Global Seismic Network into the Oceans
Keywords: Earthquake monitoring, seismic imaging, ocean bottom seismology, global seismic network

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

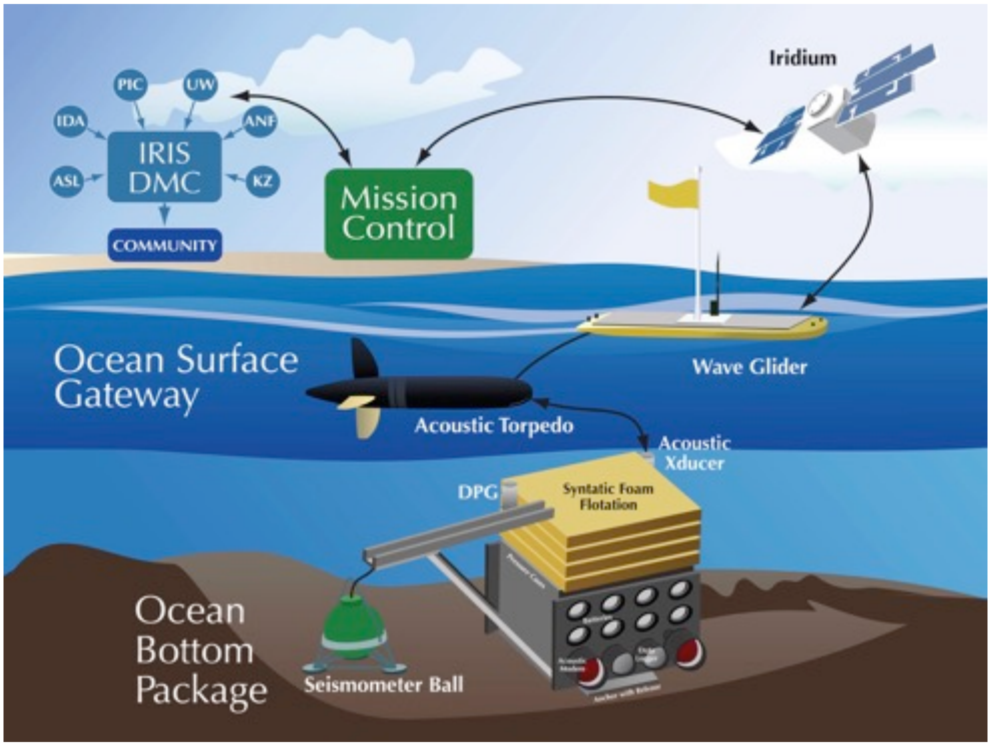
In 2004, the IRIS global seismic network (GSN) standing committee announced in an article in EOS that the GSN reached its design goal. At the time, the GSN reached the best global station coverage that can be attained by land-based observatory installations. This includes sometimes rather costly borehole installations on small ocean islands. An original goal set by GSN included that no point on the globe be farther away from a seismic station that 1000 km. While this goal was met for virtually all dry land, vast areas in the oceans remain out of reach. A multitude of consequences includes an increased detection threshold for earthquakes as well as a dramatic lack of seismic imaging fidelity in uncovered regions that affects all depth ranges from the crust to the inner core. The situation remains particularly severe in the South Pacific ocean, but parts on other oceans also still lack coverage. The next big goal for GSN therefore needs to include its expansion to the ocean floor. Broad-band ocean bottom seismometer technology has made significant progress, after advances in high-density lithium battery technology as well as low-power data acquisition systems. Year-long deployments are now standard in broadband OBS experiments, and some OBS installations reach low noise levels seen on land stations, at least on the vertical seismometer component.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

We assume that the GSN remains one the top three core facilities at IRIS. As far as current OBS deployments go, the main problem is that the data remain out of reach until the instruments are recovered a year later. For some applications, such as earthquake and tsunami monitoring, this is not acceptable. Sea cables or moorings that can provide continuous power and real-time data access are prohibitively costly, and the locations of existing sea cables may be incompatible with the expansion needs of the GSN. Wave gliders can provide an un-tethered real-time data link through a pair of acoustic modems. The wave glider link currently tested for the ADDOSS project (Autonomously Deployable Deep-Ocean Seismic System) provides continuous 1-Hz data for 4 channels (3 seismometer channels plus pressure). In addition, data at a higher sampling rate can be requested for short intervals. Power requirement by the modem currently cuts deployment times to less than a year, after which time a OBS site needs to be revisited for instrument turn-around. The next-generation wave glider are large enough to tow smaller, disposable OBS packages to a remote deployment site without the need of a ship. This provides independence from ship schedules, ship costs, and the possibility of deployments in very remote ocean locations.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

For the next years, and beyond 2018, a better integration of land and ocean going research is desirable. Currently, even amphibious seismic experiments, such as the Cascadia Initiative are not fully integrated because of persistent issues with instrumentation disparity and meta data. Many current studies therefore lack a truly amphibious seismic data analysis. While some of the current hurdles could be overcome by standardized equipment, the broader user community would benefit greatly from better awareness and training on how to deal with a diverse pool of seismic data.



Caption: Concept of Offshore GSN Station. A wave glider hovers about a ocean floor seismic station. Data is telemetered from ocean floor to ocean surface via acoustic link and then to shore via satellite link with the wave glider acting as the ocean surface gateway.

Authors: Kristine M. Larson
Title: Environmental Applications of GNSS: soil moisture, snow depth, vegetation, sea level, volcanic ash
Keywords: reflections

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

While my group has made advances in using GPS receivers to characterize environmental conditions (soil moisture, snow depth, vegetation water content, sea level, ash in plumes), I honestly think this field is just in its infancy. There are over ten thousand GPS receivers around the world which are currently tracking GPS signals; there could easily be twice that number in five years viewing signals from multiple GNSS constellations. The geodetic community has a great opportunity to engage in environmental research - and to interact with these new geoscience communities, significantly broadening the impact of our research, particularly in water management and climate monitoring. I think we are also likely to see GNSS routinely deployed at volcanos to detect ash-laden plumes.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

UNAVCO runs a state of the art GNSS archiving facility, with raw GNSS observations stored and made easily accessible. Many other archives simply store RINEX files - in many cases degrading their quality - and neglect to archive signal strength data. Most networks fail to track or do not archive new GNSS signals. We need UNAVCO to be a leader in this area - hopefully leading other archives and network operators to adopt more modern protocols. Finally, it would be extremely helpful if the UNAVCO community treated GNSS-derived environmental data products like traditional products (positions). Environmental products are science products like any other - they just don't tell you anything about faults and earthquakes. That is not a bad thing! We need to stop having science sessions called "Other Applications of GNSS," and putting everything that isn't related to faults/earthquakes in it.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

UNAVCO is a leader in outreach, training, and workforce development of GNSS geodesy. These new GNSS environmental applications also need strong support by UNAVCO, both in training researchers and helping scientists choose GNSS sites that can be used for both positioning and reflections. I think UNAVCO could also expand outreach via online tools rather than focused schools (although those are useful as well). A well-made video or animation can be a great way to reach a lot of people. And a final comment - I operate two websites, one for GPS-derived water products and the other focused on the public. I can pretty sure that I am making a greater impact via that second website.

Authors: Susan Schwartz, Geoff Abers, Ramon Arrowsmith, Rob Evans, Jeff Freymueller, Jim Gaherty, Haiying Gao, Gabi Laske, Stephen McNutt, Emily Roland, Doug Toomey, Peter van Keken, Doug Wiens
Title: The Need for a Seismic/Geodetic Facility to Support Coordinated Amphibious Science
Keywords: amphibious array, continent-ocean boundary,

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Significant and societally relevant systems in the solid earth cross continent-ocean boundaries. Their study requires amphibious projects with marine and terrestrial observation. Critical systems include: Subduction Factory and Magma-Volatiles. Crustal rocks, magmas, and other materials cycle through subduction zones. As volatiles, fluids, and melts are stored, transferred and released, these cycles control the long-term budget of H2O and CO2 and evolution of earth's crust, and regulate the planet's most explosive volcanoes. These cycles also significantly affect the rheology and dynamics of the crust and upper mantle. Passive Margins and Transform Faults. Passive margins record how rifting initiates and ocean basins form, how critical magmatism is to continental breakup, and what controls segmentation of rifts and ridges. Transform margins offer excellent opportunities to directly sample major faults that reach the surface. Seismogenic Processes at Subduction Margins. Recent great earthquakes have highlighted our ignorance of megathrust rupture processes and tsunamigenesis, such as the controls on spatial variability in rupture. The few sea-floor measurements off Tohoku, Japan have clearly shown enormous slip magnitudes, and strain transients remain intriguing features of many subduction zones. Studying these systems relies upon simultaneous onshore and offshore seismic and geodetic observations, because most interesting phenomena cross the shoreline.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Amphibious sensor arrays are a critical component to understanding these earth systems. The Amphibious Array Facilities presently deployed in Cascadia (2011-2015) offer a prototype of what could be done: 60 OBSs, 27 land seismic stations and 232 high-sample-rate GPS stations. New technologies include OBS with current and trawl shielding, atomic clocks, accelerometers and absolute pressure gauges, as well as high-sample-rate real-time GPS onshore. This project was designed and managed by open community workshops that coordinated deployment strategies and had rapid open data dissemination. An evaluation of this facility, along with recommendations for future deployments, can be found in the Amphibious Arrays Facilities Workshop Report: http://geoprisms.org/wpdemo/wp-content/uploads/2014/06/AAFW-Report-2015.pdf. Beyond the OBS and onshore facilities deployed at Cascadia, several frontier capabilities are evident. These include sea-floor geodesy for both horizontal and vertical (pressure) displacement, both passive and controlled-source electromagnetic methods onshore and offshore, complementary amphibious field geological observations, scientific drilling, and integrative geodynamical modeling. While observational needs should be tailored to specific sites, the basic principle of coordinated amphibious observation has tremendous potential. We will need to combine onshore and offshore seismic and geodetic measurements to fully address the key scientific questions.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Amphibious array deployments target coastlines of major societal risk. Great subduction zone earthquakes generate large shaking and tsunamis. Volatile-rich subduction volcanoes exhibit high explosivity, compounding the risks. To understand and manage the hazards requires an amphibious, integrative, and multi-disciplinary approach facilitated by coordinated community efforts. When data from such a deployment can be transmitted and disseminated in real time, the seismic and geodetic sensors will contribute to systems for earthquake, tsunami and volcano monitoring. This could include both traditional near real time earthquake location and truly real time earthquake early warning. Data from the Cascadia deployment have already been used for these purposes. The Cascadia deployment has demonstrated the broad impact of community-driven science. Community-planned and managed experiments can be cost-effective ways to achieve high overall scientific impact since a large PI community can be mobilized. It is not limited to primary users but brings together diverse groups to study earth processes. Open and rapid access to data likewise facilitates scientist involvement and enhances data quality control. Community science enables early-career scientists and students, lowering barriers of access to sophisticated projects. Overall, individual PI contributions hang together as part of a larger synoptic effort enabling many synergies and more sophisticated approaches to the problems.

Authors: Mike Poland, Dan Dzurisin, Mike Lisowski, Maurizio Battaglia
Title: Providing support for microgravity as a volcanology/hydrology research and monitoring tool
Keywords: gravity, volcanology, hydrology, monitoring, change detection

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Quantification of changes in subsurface mass via microgravity measurements is a key capability in volcanology and hydrology. At volcanoes, magma accumulation documented by gravity can occur without surface deformation, thus providing a new window into magma systems at depth. In hydrology, gravity measurements provide information regarding subsurface water storage—important for monitoring water resources and assessing the porosity and permeability of aquifers. While microgravity data are usually collected during episodic campaigns, continuous gravimeter deployments have also shown great promise, being used to measure such factors as the density of Kilauea's summit lava lake and the level of water in reservoirs. In the past few years, delicate spring-based gravimeters have been supplemented by a variety of more sensitive, rugged, and less-power-hungry models, including absolute instruments that are field portable and that do not require major funding initiatives to purchase (although they are still too expensive for most individual researchers). As a result, gravity is poised to become a tool that enjoys much more widespread use among geophysicists in the years to come, which should spur development of models and methods that address long-standing problems in the field—for instance, separating gravity change contributions caused by variations over time in snow/ice, groundwater, magma dynamics, and tectonic activity.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The seismology and geodesy communities have an excellent record of supporting their instrumentation needs through UNAVCO and IRIS. For example, seismic experiments can apply to IRIS to borrow instruments, and continuous GPS networks can rely on UNAVCO for equipment and installation support. There is no similar facility for gravity, which is a barrier to more widespread use of the technique. Because gravimeters are expensive and require specialized maintenance, scientists who want to experiment with the technique or use it for a single project have few avenues for obtaining reliable instruments and expert guidance. Many major universities own gravimeters suitable for microgravity measurements, but these instruments tend to be in need of maintenance and upgrading. A gravity component to a geodetic facility could solve these issues by establishing an instrument pool (through new purchases and loans of underutilized equipment) and could also develop software for data processing and analysis, test the capabilities of different instrument models, and explore the best practices for both continuous and campaign deployments. Such service would parallel the development of UNAVCO's GPS facility, which helped bring that tool to a larger user group over a shorter period of time than would otherwise have been possible had individual investigators been left on their own.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

In addition to the need for facility support for instrumentation and software, training in microgravity methods will be critical to insuring its widespread use. IRIS and UNAVCO conduct numerous workshops each year on how to analyze and interpret seismic, GPS, InSAR, and TLS data, and this approach could also be used to train new users, especially students, in the operation of gravimeters and analysis of gravity data. A gravity facility could also serve as an anchor for the community, providing a mechanism to stimulate international collaborations and exchanges (or personnel and equipment), and it could help coordinate government, industry, and academic users who now may not communicate as frequently as they could.

Authors: David Chadwell
Title: Sub-meter Accuracy Seafloor Geodesy using Multibeam Sonar: A B4 Survey for the Cascadia Subduction Zone
Keywords: seafloor geodesy, megathrust earthquake

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Active plate boundaries, especially subduction zones, pose significant hazards in the form of earthquakes and tsunamis, such as those associated with the 2011 M9.0 Tohoki-Oki earthquake. However, our ability to monitor such areas and events are severely limited because current seafloor geodetic instruments are either too inaccurate or cost-prohibitive. Multibeam sonar, despite its relatively poor resolution, holds great potential as a cheap and effective geodetic tool due to its high spatial coverage, but the limits of its accuracy are still an active area of research. In a previous experiment at very low ship speed ~1 knot we demonstrate that a patch of seafloor (~3000 m deep) can be re-positioned to an accuracy of better than 1 meter using the sidescan data from a 12 kHz multibeam sonar. In addition to the slow ship speed, the repeated surveys were performed within the critical baseline for interferometry. This displacement accuracy is at least 30 times better than has been achieved through repeated multibeam surveys at transit ship speed.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Need to perform a series of shipboard experiments to better understand how seafloor position accuracy depends on: reference-to-repeat baseline offset; the ship speed; the sonar frequency/bandwidth; and variations in upper ocean sound velocity. Also we need to instrument survey vessels with at lest 3 high rate, high precision GPS receivers in order to monitor the position and orientation of the ship to a accuracy of a few centimeters.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Need access to ship time on UNOLS vessels. Once the technique is demonstrated we need to perform a high resolution survey of the toe of the Cascade megathrust zone to serve as the reference benchmark for post-event surveys as well as provide high resolution imagery for paleoseismic analysis.

Broader Impacts

Authors: Gerald Bawden
Title: Real-time GNSS for hazard science and early warning
Keywords: RT-GNSS, early warning, real time, earthquakes, tsunamis, atmospheric rivers, landslides, hazards

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

PBO was designed to understand temporal variability in the 3D deformation field across the Pacific–North American plate boundaries and encompassed within the PBO footprint resides the greatest potential for catastrophic earthquakes and tsunamis within the US along with significant risk for volcanic unrest and large atmospheric rivers. Recent advances now make it possible for real-time GNSS (RT-GNSS) sites to routinely provide high-rate (1 Hz) point positioning with cm-scale precision and sub-sec data latencies. These advancements represent new opportunities to study a wide-range of dynamic processes in real-time and enable early warning capabilities. RT-GNSS will transform our ability to detect, measure, understand, and adapt to dynamic solid earth processes such as earthquakes, volcanic unrest, and landslides. Rapid earthquake detection and characterization of RT-GNSS data is not only providing earthquake and volcanic early warning, it is now possible to assess if a large earthquake is tsunamigenic just 3 to 5 minutes after the initial rupture begins, a significant time savings from current approaches. It is now possible to measure fluctuations in the ionosphere's total electron content (TEC) caused the tsunami and detect if a tsunami has been triggered by an earthquake, track its waves as they propagate, and provide upwards of 1 hour early warning. RT-GNSS can also be used to track glacial and ice sheet motions, nad real-time tropospheric and space weather modeling.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The future incarnation of PBO should maintain the current RT-GNSS capabilities and consider the possible addition of real-time telecommunication hardware for GNSS sites located in underrepresented regions with the goal of advancing a wide range of fundamental research science objectives, applied science goals, and society needs. The development of an adaptive RT-GNSS network that could dynamically optimize data collection strategies in real-time that maximize the scientific and societal data needs while minimizing data transmission volumes/costs, the loss of data during disasters and other unforeseen events. While not every site will need to be in fulltime RT-GNSS, there will need to be a core subset of sites designed to meet the real-time geohazard and atmospheric requirements. An adaptive network design would allow dynamic adjustments to real-time data collection strategy such that more science could be accomplished within operational constraints while balancing scientific needs, and societal benefit with earthquake, tsunami, and landslide early warning along with atmospheric modeling of atmospheric rivers and hurricanes.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

As the number of science requirements and science application needs for RT-GNSS expand with the growing global networks, there will be an increasing demand for the systematic real-time processing of the GNSS data using science specific thresholds that target dynamic adaptive RT-GNSS network collection strategies, change detection, early warning, real-time position tracking, atmospheric variability, and ionosphere dynamics. Such a facility would combine national and international RT-GNSS collection, analysis, and products with software and training.

Authors: Zhong Lu, Matt Pritchard
Title: Roles of WInSAR in 2018 and beyond
Keywords: InSAR, geodetic imaging, data archive

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Interferometric synthetic aperture radar (InSAR) provides an all-weather, day-and-night imaging capability for mapping Earth surface characteristics and measuring land surface deformation at an unprecedented precision and spatial resolution. InSAR has applications to many scientific disciplines including cryospheric, solid earth, and hydrological sciences, and free and open access to large archives to SAR data has resulted in a continued expansion of its use to new fields in the Earth Sciences. Timely observations of precise land surface topography and time-transient surface changes from InSAR will accelerate the development of models for volcanic eruptions, earthquake displacements, landslides, and land subsidence, as well as new tools for characterizing natural resources. Advanced multi-interferogram InSAR techniques will allow the monitoring of the 3-dimensional land surface deformation at fine temporal and spatial resolution, and offer the capability to image vegetation structure on a global scale for improved resource management.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The Western North America InSAR (WInSAR) Consortium was established in the 1990s by a group of practicing scientists and engineers to facilitate collaboration in, and advancement of, Earth science research using radar remote sensing. WInSAR is a community-governed organization (originally formed under the auspices of the Southern California Earthquake Center and currently reporting to UNAVCO governance). WInSAR and its members also work closely with the NASA-funded Alaska Satellite Facility that holds a large and growing collection of SAR data. WInSAR provides guidance on the acquisition and archiving of spaceborne SAR data over North America for the benefit of the membership, aiding individual investigators by simplifying interactions with data provides and with government agencies funding science. By 2020, there will be about 15 SAR satellites from 8 different space agencies – WInSAR and its members along with NASA, ASF, and other agencies will work together to maximize the scientific utility of this data for the community. Monitoring 3-dimensional land surface deformation requires a "comprehensive" InSAR data archive with contributions from domestic and foreign radar satellites. WInSAR can guide and facilitate acquisitions of past, present and future radar images, generate InSAR products for novice users, and facilitate tutorials on basic and advanced InSAR processing techniques for the broader Earth science communities.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

1. Automatic radar acquisition and archiving facilities that interact with various radar databases from foreign and domestic data providers. 2. One-stop radar "shopping" facility to ease radar data search from worldwide radar catalogues. 3. InSAR computing facilities to provide basic InSAR products along with atmospheric correction layers (from the best available method) to novice users. 4. Provide radar data in subscription-mode in which new radar data acquisitions will be automatically "pushed" into a user's desktop based on the user's geographic input/subscription. 5. Conduct both basic and advanced InSAR trainings to users of various levels. 6. Advocate funding agencies to engage foreign radar data providers for easy and affordable radar data access.

Authors: Thomas J. Johnson, Craig Dobson
Title: Global Geodetic Multi-Technique Networks for Pressing Scientific and Societal Needs
Keywords: Space Geodesy, Multi-technique Geodetic Global Networks

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Space geodetic networks provide the measurements for defining and maintaining the International Terrestrial Reference Frame (ITRF), International Celestial Reference Frame (ICRF), and the Earth Orientation (EO) and motion relative to these frames. These measurements are critical for most space-based, airborne, and ground-based systems, and enable research in a broad range of sciences, including atmospheric, oceanography, hydrology, climate, solid earth, and natural hazards. Furthermore, the modern smartphone has introduced geodetic data and some of its uses into our daily lives. As geodetic data accuracies increase and the number of users continues to grow, geodetic data is becoming more important not only for scientific application but for societal needs such as the development of early warning systems for emergency responders. The most stringent requirements come from geodynamic and sea level studies that require an ITRF with 1 mm accuracy (on a annual to decadal time scales, respectively) with stability at 0.1 mm/year (on annual time scale).

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

As these new multi-technique stations are designed, built and become operational, there are several questions that need to be investigated to improve station performance: • How can existing assets such as PBO best contribute to future global geodetic networks? • Where should new stations be deployed to best optimize the global network geometry for the ITRF? • Do network geometries exist that allow for the realization of the ITRF requirements with fewer than 30 stations? If so, what is the trade space? • While the NRC report calls for multi-technique core sites, can these different systems be better integrated to improve overall station performance? • What is the cost versus benefits of ground-based and space-based colocation of the different geodetic techniques? • How can site characterization and monitoring be used to reduce measurement errors and noise in the observations? These are just some of the questions that need to be address before science and society can realize the full benefit of these modern geodetic stations. Solutions will require careful consideration for integrating existing and future observational networks.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

To meet these requirements, it is estimated that about 30 modern integrated multi-technique observing stations are need in a global network. NRC's Precise Geodetic Infrastructure: National Requirements for a Shared Resource Report (2010) recommends the deployment of core geodetic stations with Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), 3 Global Navigation Satellite System (GNSS) receivers, terrestrial survey instruments, superconducting or preferably absolute gravimeters, meteorological sensors, and a variety of other sensors such as seismometers, tilt meters, and water vapor radiometers. The NASA Space Geodesy Program (SGP) operates and manages NASA's existing global geodetic network, analysis system, and data processing services. The SGP will also manage the construction, deployment and operation of next generation geodetic observatories in coordination with the Global Geodetic Observing System (GGOS) and our international partners.

Authors: Steven Jaume
Title: Support for the Lone Wolf Geoscientist Engaged in Research & Education
Keywords: Historical data, field equipment, real-time education

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

As the only seismologist currently residing in the high earthquake hazard zone surrounding Charleston, South Carolina, I am, and will continue to be for the foreseeable future, the chief local resource for earthquake hazard research and education in this region. For that reason alone facilities such as IRIS and UNAVCO are essential in allowing isolated geoscientists such as myself to bring the expertise and experience of the broader geoscience community to bear on pressing local needs. More specifically, I am and will be pursuing understanding of the seismic hazard in Charleston, SC. This is challenging in that the low level of background seismicity and wide coastal plain setting means that many "conventional" techniques used to quantify seismic site response cannot be used here. Thus it is critical that access to observations made in other geological similar regions (e.g., Christchurch, New Zealand) remain easily available to those such as myself in order to facilitate my work. In many other low seismicity regions, the "answer" to an important local research question may lie in data collected somewhere else.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Foundational capabilities include continued access to "historical" observations; i.e., older but still useful seismic, geodetic and other relevant data. While not currently part of any formal research database, digitized historical photographs from the 1886 Charleston earthquake are finding new life as an important dataset in characterizing both the strong ground motion and potentially the source mechanism of an important historical earthquake. While older data may not be useful in many cutting edge applications, it still retains value as future observations can be compared to historical ones to reveal important information about historical events. A frontier capability important in supporting isolated geoscientists is the continued development of easily deployed and easily maintained field equipment. Experiments requiring a significant commitment of human resources are often beyond the capabilities of an individual researcher. IRIS has already made significant advances in support of this. Any new facility would need to continue this support but also "push" instrument development to make the conduct of significant field deployments even easier. These developments will make significant deployments by an individual geoscientist with little institutional logistical support practical. I envision future facilities as being deliberately designed to be "multi-scale" and able to support the needs of a wide variety of researchers.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

As a lone seismologist at a primarily undergraduate institution in a high seismic hazard region, I am called upon to educate a wide range of audiences (students, local policy makers and the general public) on earthquake hazard issues. As I am writing this in the aftermath of the 25 April 2015 M 7.8 Nepal earthquake, I have written a press release for local news outlets, conducted one TV interview (and have more scheduled later) and reviewed initial observations of the earthquake in an introductory undergraduate course, IRIS E&O materials are crucial for educational broader impacts at all levels. A future facility would need to continue this trend of providing rapid results and information to those of us "in the field" educating a wide range of people in the science of earthquakes and other geological hazards. Perhaps the most exciting advances in made possible by the existence of IRIS and UNAVCO lies in the ability for an individual geoscientist to bring real-time observations into the classroom. Research on student experiences in STEM courses has revealed that early involvement in authentic research greatly enhances interest and retention in STEM disciplines. While the current IRIS and UNAVCO facilities already do this to a large degree, I can envision a future facility that incorporates an even broader array of geoscience data (e.g., hydrologic, oceanographic and atmospheric) that can be easily accessed and used by educators at many levels.

Caption: Similar damage to unreinforced masonry buildings occurred in the 1886 Charleston, South Carolina (top) and 2010/2011 Christchurch, New Zealand (bottom) earthquakes. Comparisons of historical data to modern observations can greatly advance seismic hazard research.

Authors: Katherine Ellins
Title: The Value of E&O Professionals at IRIS and UNAVCO
Keywords: E&O professionals are vital, new educational materials and professional development, collaboration between scientists and educators.

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

UNAVCO and IRIS educational resources are invaluable to the geoscience curriculum and teacher professional development projects that I am involved in. Minority or minority-serving teachers from these projects participate in the IRIS Seismographs in Schools program. A new project that is creating online instructional blueprints for teaching a yearlong secondary Earth Science course features IRIS and UNAVCO educational resources, including web-based mapping tools and datasets packaged for education use that promote cyberlearning. In 2016 I will be based at the University of the West Indies (UWI) in Jamaica as a Fulbright Scholar where I will teach a general Earth science university course that emphasizes geohazards related to Jamaica's seismic risk, professional development academies to secondary science educators, and organize symposia for emergency planners, industry representatives, the business community, and policy makers. In addition, I will oversee the creation of a Jamaican Educational Seismic Network (JAESN), comprising AS-1/EQ-1/TC1 seismometers installed at UWI Mona and schools across the country. JAESN will serve as the focal point to reach and motivate both university and secondary students and educators with science of immediate and direct relevance. Operators of educational seismographs may join IRIS's Seismographs in Schools Program, which serves teachers around the world.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Dedicated E&O professionals at IRIS and UNAVCO are vital to carrying out the mission of the facilities. New discoveries, cybertechnology and engineering advances will not only propel the science forward, they will create a need for new educational materials and professional development to prepare educators on how best to implement these resources.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

E&O professionals at IRIS and UNAVCO have already made important contributions to K-12, undergraduate and graduate education through successful programs that have engaged underrepresented minority students in geoscience. They have also contributed to the geoscience community through the development of teaching collections, innovative online mapping tools and visualizations, and professional development. E&O professionals who understand the science and have access to the facilities' data will be needed in the future to maintain existing teaching collections and to update them as the science is reinterpreted, as advances in learning and teaching are made, and to ensure that they are aligned with the development of new standards (e.g., NGSS). The latter, for example, require new educational resources based on authentic scientific data to effectively integrate student learning across three dimensions—Science and Engineering Practices, Crosscutting Concepts and Disciplinary Core Ideas. The expanding network of discipline-based educational researchers and geoscience education practioners creates exciting opportunities for collaboration with IRIS and UNAVCO E&O professionals, helping to support broad educational impact.

Authors: Melissa M. Moore-Driskell
Title: Facilitating Communication Between Researchers and the Classroom/Community
Keywords: outreach, education, communication, public

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

UNAVCO, IRIS, and EarthScope are vital components of the infrastructure relied upon by the geoscience community. As the need to become more interdisciplinary increases, these facilities are essential to teachers and researchers looking for resources that will strengthen their knowledge and reach into adjacent fields. In the context of teaching universities, these facilities are utilized to bridge the gap between researchers and educational specialist, each with mutual gains. The community is in need of training, workshops, and resources that cultivate the exchange of information in order to enhance communication between education, researchers, and the general population.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The most important concept of the current UNAVCO, IRIS, and EarthScope system is the ability to acquire instrumentation in a non-profit environment. This is especially important for researchers at smaller institutions who have limited access to funds for expensive geoscience experiments.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Training and education to use scientific equipment, as well as training to use research in the classroom, is invaluable. Training to communicate scientific research to a classroom or to the general public should be a priority. The general public has been cut off, in a way, from advanced scientific research. This disconnectedness breeds skepticism and misunderstanding. Part of the researcher's goal must be to appropriately communicate research to the public and show them how it benefits society. A robust education and outreach program must accompany the research program of these institutions. Appropriate communication of societal impacts to the public is necessary, and programs are needed to train researchers how to incorporate this into their work.

Authors: Aaron A. Velasco
Title: The missing link in handling big data: Engaging a diverse and interdisciplinary workforce
Keywords: For a facility to promote leading edge science, it must be accessible from a wide variety of potential users. Furthermore, academic institutions have differing research infrastructure and capabilities to ingeBig data, workforce, diversity, innovation

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

With the advance of seismic and geodetic networks, many new discoveries have been made from the analysis of this explosion of new data being collected, processed, and analyzed. However, as the amount of collected data continues to grow exponentially, new techniques, methodologies, and innovations must be developed, implemented, and shared in a broader community in order to fully exploit this data intensive environment. Key questions that can be address with this explosion of data can include: • What are the driving forces for large-scale tectonic processes (must obtain better Earth models)? • What is the link between upper mantle structure (specifically, the improved images of earth structure) to surficial geological processes? • What controls the interaction of earthquakes through seismic waves, specifically • What causes delayed dynamic triggering? • What is the role of fluids in the earthquake cycle and in induced earthquakes • What is the maximum magnitude earthquake that can be induced?

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

For a facility to promote leading edge science, it must be accessible from a wide variety of potential users. Furthermore, academic institutions have differing research infrastructure and capabilities to ingest these data, which impacts or ability to education the next generation of diverse, interdisciplinary scientists. Thus an interdisciplinary center must: • Develop effective training that reaches a broad audience of potential users • Provide an atmosphere for collaboration that includes other disciplines, such as mathematics, computational science, and computer science of cyberinfrastructre • Open access to large data sets and the tools for sharing and processing, utilizing cloud resources, semantic web technology, and distributed processing

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Despite the changing demographic in the U.S., the geosciences continues to lag far behind in diversifying its workforce. Adding to this challenge, demographics are also regionally depended, with some populations having little access to leading edge research and opportunities. A research facility must develop specific outreach and educational programs targeting faculty and students from Minority Serving Institutes (Historically Black Colleges and Universities and Hispanic Serving Institutes) and 2-year academic institutes (Tribal Colleges and Community Colleges). These programs can include research experiences for undergraduates, field based experiences for students and faculty, training for the use of the facility, and opportunities for faculty to perform research in major research groups. This programming may be expanded to include virtual training during the academic year, which may also be used training for the general geoscience community on the facility. Seismology has been the lead with open data access, which has transformed our science. It is now time that seismology again take the lead to transform the field and the national science landscape by engaging the changing face of U.S. students.

Authors: Rhonda Spidell-Whitley
Title: EarthScope's Impact on K-12 Education
Keywords: K-12, education, broader impacts, outreach

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

I'm writing in support of EarthScope's education and outreach goals and to illustrate how EarthScope has made a significant impact in the classroom. (I'm now retired, but my colleagues still use EarthScope materials.) EarthScope's data and resources engage students in the latest research and reinforce the ongoing processes of discovery through the collection and analysis of data. Students are captivated by the technology and how EarthScope's multi-disciplinary observatories are being used to understand what is taking place around the US and right under their feet. EarthScope is ideal for connecting students and providing a solid foundation for place-based and problem-solving education. Key questions that have already captivated students are listed below. What do we know about the Yellowstone Caldera? How will the Midcontinent Rift impact the continent? Is the process of fracking causing earthquakes? How will drought impact the western US? How will the Cascadia subduction zone impact the northwest? EarthScope's initiatives will search for answers and continue to find new questions and students want be on board for the journey.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Scientists will lead the way by proposing on-going research as well as new ideas for other projects sparked by analyzing data already collected. EarthScope data collected through the seismic observatories will have a lasting impact on our society. Through formal and informal education venues we can excite and motivate students to become scientifically literate and seismically aware as well as inspiring some students to select scientific careers in the geosciences.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Broader impacts will be accomplished by continuing the education and outreach components of EarthScope. EarthScope provides a wealth of educational materials, as well as the resources from the collaborating organizations such as IRIS, UNAVCO, the USGS, GeoPrisms, OpenTopography and SCEC. To continue to be effective for educators, these resources need to be maintained and updated requiring on-going technical support. UNAVCO and Iris are updating their websites to include correlations to the Next Generation Science Standards providing educators a tool to align their curriculum. Through social media and websites, educators are provided data on recent seismic events such as the most recent earthquake in Nepal. Updates as well as maps, simulations, and activities developed by EarthScope's National Office and its collaborators contribute to a dynamic opportunity to learn about the Earth. Supporting EarthScope's outreach efforts is essential as well. Numerous workshops and conference presentations have increased both formal and informal educational opportunities for educators. Educators return to the classroom excited to share their experiences with students and colleagues. In summary, educators appreciate the efforts of the EarthScope's community to share their expertise and data. Earthscope's reach is both wide and deep and broader impacts will be achievealble by continuing EarthScope's commitment to education and outreach.

Authors: Michael Blanpied, Tom Brocher, Joan Gomberg, Gavin Hayes, Peter Haeussler, Steve Hickman, Evelyn Roeloffs, Craig Weaver, Rob Witter
Title: The Future of USGS's Subduction Zone Science
Keywords: Integrated monitoring, benchmark surveys, dense seismic and geodetic arrays

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

The USGS applies science to reduce losses from natural hazards. For the nation's subduction zones, this includes providing information to responders as major events unfold, and reducing uncertainties in risk assessments and forecasts. Subduction generates Earth's most powerful earthquakes and tsunamis, and builds many of the most impactful volcanoes. To be understood these must be studied over a range of temporal and spatial scales from millennia to seconds and from tectonic plate- to grain-scale. The complexity of subduction zone processes exceeds that in other tectonic environments, demanding an integrated study approach. Retrospective studies have shown the value of integrating multiple data types of information, particularly seismic and geodetic data for earthquakes. Integrated approaches have revealed tantalizing preparatory processes preceding major subduction zone earthquakes and volcanic eruptions. Marine geodetic measurements from the 2011 M9 Tohoku-oki, Japan earthquake demonstrate that had they been available in near-real time, the enormous and devastating tsunami and ground shaking might have been anticipated. The integration of real-time geodetic data streams with seismic data adds significant reliability for earthquake early warnings, particularly for the largest earthquakes. With new real-time data streams and advances in telemetry and computing, we envision the transition to integrated seismic and geodetic approaches from research to monitoring.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

As a frontier capability, offshore measurements are required in subduction zones. Cabled systems currently operate on Cascadia's seafloor, but expanded and new offshore instrumentation is required to maximize risk reduction. No cabled systems exist in Alaska. Investments are also needed in the analysis of signals from offshore data, integration of offshore and onshore data, and in development of new sensor types. Another frontier capability is observation and interpretation of the background 'benchmark' conditions, as essential to understand the pre-, co- and post-seismic deformation of significant events. Examples include multi-beam bathymetric mapping and shallow reflection imaging of the continental shelf and near-trench, and measurement of offshore geodetic markers. Pre-event mapping has applications to earthquakes, volcanoes, landslides, coastal erosion, tsunamis and flood mapping, and other systems. A lack of observations with adequate spatial resolution and frequency bandwidth hampers the forecasting of impacts of subduction zone earthquakes on our built environment. Dense seismic arrays are needed to model source and ground motion. As significant energy may be relaxed with relatively little seismic radiation, geodetic monitoring is needed to characterize strain energy build-up and release. Results will feed into probabilistic maps of anticipated shaking, used for city planning and for simulating ground motion records used by engineers.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

The study of subduction zones needs integrated, multidisciplinary capabilities that span across the ocean-continent boundary. Enhanced partnerships also will be required, national and internationally. In accomplishing our own and supporting others' missions, USGS works closely with partners in NOAA, university-run monitoring and earthquake early warning networks, the NSF (IRIS, UNAVCO, GeoPRISMs), state geological surveys, engineering professional groups and code authorities, and emergency managers at local to federal levels. Going forward, to meet the needs described above, we envision enhancing or developing new relationships with NASA, the International Ocean Drilling Project, Ocean Networks Canada, Seafloor Earthquake Array, Oceans Observatory Initiative, integrated monitoring programs in subduction zones abroad, the private sector, and more.

Authors: Steven Semken
Title: Place-based Education: future geodetic and seismic support facilities should support broader dissemination of this powerful pedagogy
Keywords: geoscience education, place-based education, teacher professional development

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

I will continue work in geoscience education research and ethnogeology: exploring the relationships among place, culture, geoscience inquiry, and geoscience education. This research will continue to be informed by new geoscientific findings that include those from geodetic and seismic research, and I anticipate that I will remain active on the education and outreach side of this activity, as I have been with EarthScope.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

To complement active research and to help ensure it retains strong public and legislative support, geodetic and seismic facilities and programs must integrate fully robust and active programs in Education, Public Outreach, and Community Engagement, to ensure that new seismic and geodetic research findings are broadly disseminated to all stakeholders, including students, educators, the media, and the general public.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

We study and teach about the Earth in and by means of places: localities imbued with meaning by human experience. People's natural intellectual and emotional connections to places (senses of place) can motivate learning. Place-based education (PBE) leverages this by situating curriculum in local and regional landscapes and environments. PBE promotes trans-disciplinary thinking and sustainable communities. In a geoscience context, it engages students with features, processes, and history of the Earth system observed locally, and prepares them for subsequent studies at global scales. Research indicates that PBE can effectively engage and retain the interest of diverse students, especially those who have personal, cultural, or community ties to the places in which they learn. PBE draws on the pedagogical potential inherent in any place. But even though all places and regions of the United States have rich and interesting histories of geodynamic and geomorphic processes encoded in rocks and structures, many also have low relief and limited outcrop that challenge geoscience teaching focused on local crustal structure and evolution. Future seismological and geodetic research will continue to resolve details of crustal and mantle structure that can inform locally situated place-based teaching. All who operate, obtain data from, and disseminate findings from future geodetic and seismic facilities should be sure that their science is accessible locally as well as nationally.

Caption: Interpreters and teachers investigate and contemplate local geological evidence of rapid subsidence and flooding caused by the 1964 Great Alaska Earthquake, during an EarthScope interpretive field trip led by U.S.G.S. geologists in 2014.

Authors: Allyson Mathis
Title: Continued Need For Interpretation and Place-Based Education to Make Broader Impacts in Society
Keywords: Interpretation, informal education, place-based education, museums, parks

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

I will be involved in geology interpretation and informal education. Please see Broader Impacts Statement.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The seismic and geodetic communities will continue to need heritage interpretation and place-based education facilities. Please see Broader Impacts Statement.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Outreach to diverse parts of American society via nontraditional educational techniques such as heritage interpretation and place-based education will be a facility need of the geodetic and seismic communities after 2018. Interpretation is a type of informal education that aims to reveal meanings and relationships rather than communicate solely factual information. It usually takes place in national and state parks, museums, nature centers and similar venues. Place-based education is teaching that is situated in specific places. Seismic and geodetic facilities are located throughout our communities, towns, parks, and other shared places. It is essential that the scientific community continues to reach broader audiences that inhabit these places who are not engaged in formal educational systems. Interpretation is an especially powerful tool for public engagement with the geosciences. The geosciences aim to understand the physical nature of places, and interpretation is likewise rooted in places. The Interpretive Workshops presented by the EarthScope National Office have been a hallmark of the EarthScope Education and Outreach Program. These workshops have brought together scientists, park rangers, museum educators, naturalists and guides to learn about seismology and geodesy, and how to effectively communicate meaningful and relevant information about these complex subjects for which public understanding is essential for continued scientific advancement and public safety.

Authors: Stefany Sit
Title: IRIS internships and increasing access for undergraduates
Keywords: IRIS internships, undergraduate training

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

N/A

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The IRIS internship program is a well developed and executed program that continues to provide critical training, experiences, and support to a new generation of seismologists. As a former intern, I found that the internship program challenged me intellectually, while providing social support. Coming from a small, liberal arts college, I didn't have any exposure to seismology as an undergraduate, but the program gave me snippets of seismic techniques and broad questions I could pursue in the field. Moreover, the internship program provided an academic community of mentors and peers that I could utilize as an intern and as I continued on in academia. The IRIS facility provides a cohesive and friendly community that has fostered the development of young scientists.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

To increase the number of well-qualified and trained geoscientists, the achievements of the IRIS internship program, including computational training, field experiences, and camaraderie, can be used to broaden participation and provide more opportunities for young scientists to get involved. For instance, future facilities can help develop and distribute mini lectures and/or tutorials on seismic processing and analysis. Perhaps, the facility would host a supercomputer with basic versions of data processing and modeling available for different students to use. Additionally, the facility could act as a job/volunteer "matching site" for seismic and geodetic field experiments. A "matching site" may also be useful for researchers whose work is visually and manually intensive to find student help outside of their institution (perhaps at community college or small, liberal arts school). Students could potentially find an on-campus mentor and sign up for independent research hours once a match has been formed. These steps can ensure we will have a diverse set of students being introduced to our discipline.

Authors: Stefany Sit
Title: Educational Resources in Schools and for the Public
Keywords: K-12 education, undergraduate training, broaden participation, teaching resources

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

My current interests are in geoscience education. Key questions include, how can we effectively teach and train undergraduates in scientific analysis and what are effective pathways to introduce and support students in geoscience majors. Within the field of seismology and geodesy, there are opportunities to better evaluate and assess how our students are learning on how well they understand the disciplines' critical concepts.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Attracting the curiosity of students at an early age, while also focusing on the training of undergraduate and graduate students can provide the foundation for a more diverse and innovative workforce in seismology and geodesy. Foundationally, the facilities have provided key educational resources for students of all ages, like accessible data and easy software for K-12 teachers, IRIS and RESESS internships, professional development and student training, and support for Early Career Investigators. Continued efforts will make these resources more affordable and accessible to students from diverse and non-traditional backgrounds. The facilities also provide important means to help scientists and educators communicate and engage with the public through pamphlets, video animations, smart phone apps, and museum displays, which all help to elevate the prestige of our discipline. Along with education and outreach efforts, the facilities also have unique opportunities to facilitate the collection of education data, assessment, and research furthering our understanding of how the public and students conceptualize and learn key principles in our discipline.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Planning for our future needs, I see top priorities as a) education and training for undergraduate and graduate students and b) education and outreach for K-12 and the general public. We should capitalize on our disciplines' vast datasets and computational analysis. Therefore, I strongly believe in the development of a teaching repository and online software mini-courses. This would allow students and faculty from research universities, small liberal arts schools, community colleges, and international schools an opportunity to learn cutting edge techniques from academia and industry. Efforts to create better teaching resources can be used for all types of students and would help broaden representation in our field. An additional priority would be outreach to public communities and schools, meeting our audience through technology with an easy to use website, smart phone apps, software development of jAmaseis and InClass to help bring awareness and prestige to the seismic and geodetic fields. Especially, as more K-12 schools adopt the Next Generation Science Standards, it will be important to show how our topics intertwine crosscutting concepts and Science and engineering practices.

Authors: Derek Schutt, Christian Poppeliers
Title: Early Career Investigator Activities at IRIS
Keywords: education, early career

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

See below.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Early career investigators (ECIs), loosely defined as senior graduate students through pre-tenure faculty, are the next generation of scientists – those that will heavily rely on the next generation of large-scale, community-wide consortium, to succeed. For instance, ECIs must develop confidence as independent researchers and establish collaborations beyond their initial advisors and colleagues. Many ECIs also become classroom instructors, despite limited teacher training in graduate school. Additionally, many ECIs experience minimal mentoring and guidance, making an already difficult transitional period more stressful. In effort to lower the barriers that hinder newly-minted (or soon to be) scientists, researchers, and educators from thriving in a diverse range of career paths, the new infrastructure should include a program that supports the development of ECIs. Key aspects of this program should (1) organize practical resources and professional development opportunities for ECIs as they complete graduate school, navigate post-docs and other temporary research positions, apply to permanent jobs in and outside academia, etc., and develop as managers, administrators, or apply for tenure; (2) foster an ECI community and resources that can be virtually housed within the facility; (3) provide experience, knowledge, and funding opportunities (e.g., conferences, travel funds for individual research projects); and (4) potentially build and provide a mentoring network for ECIs.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

As described above, professional development for ECIs is essential to maximize their potential. Notably, not all ECIs have equal access to mentoring, professional connections, teaching materials, and research software, regardless of their capabilities, and a new facility could readily provide an equality of access and a commensurate equality of opportunity (especially for ECIs from smaller, financially-limited, or non-research oriented institutions) that currently is lacking. Moreover, it is imperative, particularly in the current domestic economic, government funding, and employment climate, that the next large-scale, community-wide facility (or facilities) provide(s) a broader awareness for ECIs of all potential employment options. ECIs need guidance on how to frame the skills and technical expertise acquired through a geoscience education to make them marketable for any career path. Many students are only exposed to career paths in academics or the oil/gas/energy industry – and this only at certain universities - while many employment opportunities exist outside of these arenas. The existence of an ECI-specific entity or component of an Education and Outreach Program within the new facility would expand the opportunities available to ECIs and reduce some of the barriers that have contributed to reducing the diversity of professional geophysicists and geodesists.

Authors: Jeff Ryan, Rick Bennett, Bruce Douglas, Lisa Ely, Andrew Goodwillie, Jay Cassidy, David Schmidt, Becca Walker
Title: Workforce Development can/should be supported by future research facilities
Keywords:

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

N/A

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

A key Federal objective in the support of STEM education is the training of the future STEM workforce, specifically (in the case of NSF) the future Ph.D. workforce in the sciences. IRIS and UNAVCO have played important parts in this effort through the coordination and facilitation of internship and research opportunities for undergraduate students, helping to introduce them to the fields of seismology and geodesy, and connecting them to Ph.D. professionals in these fields, first as mentors, and later as future graduate advisors. The new GeoLaunchPad project at UNAVCO seeks to reach interested students at an even earlier stage in their undergraduate careers, engaging them in geodetic/remote sensing research experiences during their first two years in college, both to "hook" them on the discipline, and to encourage their persistence in STEM fields overall.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

The coordination of sustainable internship and/or undergraduate research programs is a large job that is outside the purview and capabilities of most academic departments, so initiating and running such programs often falls to the very largest departments or institutions, or it is supported through consortium efforts (e.g., the Keck Consortium). Federally supported research facilities can fulfill this need for the disciplinary areas they support, handling the substantial logistics component of such programs, and using their network of participating investigators to ensure that students obtain rich and engaging research experiences, and that they begin developing a professional network that will support them into graduate school and (ideally) to the Ph.D. As such, any future facility supporting seismic and/or geodetic research should have as part of its portfolio of Broader Impacts activities an effort to develop and coordinate undergraduate research and/or internship programs for their communities.

Authors: Jeff Ryan, Rick Bennett, Bruce Douglas, Lisa Ely, Andrew Goodwillie, Jay Cassidy, David Schmidt, Becca Walker
Title: Diversification of the Seismic and Geodetic Workforce as a Core Broader Impact of Any Future Facility
Keywords: Diversity, RESESS

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

N/A

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

A critical benefit arising from facility support for the geodesy and seismology research communities has been the ability to foster long-term, community-scale efforts to engage students from communities and demographic groups that are under-represented in STEM fields. Effective diversity outreach activities involve extensive mentoring and support for students, who usually come from challenged circumstances and lower performing schools; provisions for extended support over time in their academic careers, to get these students past recognized hurdles on their way through degree programs; and a long-term commitment to providing such opportunities, so as to establish working relationships with other institutions and projects with similar goals and to “move the needle” in terms of numbers, given the extensive individual investments required. The RESESS program overseen by UNAVCO is a type example of a successful, long-lived diversity outreach effort that leverages the expertise of the UNAVCO facility and its PI community to provide transformative research experiences to under-represented students.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Any successor facility seeking to support the geodesy and/or seismology research communities will need to continue play a key facilitative role in fostering diversity, through outreach to students from under-represented groups to introduce them to these fields, and through the longer-term support of interested students through research experiences and efforts to mentor them into these professions. The scale of these efforts, and the time commitments required for their success, argue for a centralized, community-supported approach that a facility is uniquely able to provide. Diversity-focused activities need to be central to the broader impacts mission of any future facility supporting these disciplines, and arguably to the missions of any Federally-funded research support facility.

Authors: David Voorhees
Title: Bringing seismology to everyone
Keywords: education, science literacy

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

As our society becomes more and more technologically advanced, so does the understanding of the world around us. In this world of ubiquitous iPhones and twitter, the ability to obtain real-time information becomes easier and easier. To that end, I think that the development and promotion of real-time seismic data and seismology to any and all interested parties can be transformative to the science of seismology. It could be argued that earthquakes are as engaging to a majority of the public, as are dinosaurs to young children. Leveraging that initial interest after major seismic events or long term trends (i.e. hydraulic fracturing) into an overall improved understanding of the earth through seismology, can be a step in the right direction to increasing the overall scientific literacy of the United States, currently at an embarrassingly low level, at least in the opinion of this geoscience educator. At a recent meeting of the Advisory Committee for the Geosciences Directorate of NSF, an extended topic of discussion was ways to document a 'return on investment' of NSF Research funds. It could be argued that a well-engaged population in the science of seismology is an excellent ROI. Additionally, this well-engaged population would make inroads into elevating the low level of respect that the geosciences have been receiving of late in the media and Congress.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

To enable these real-time seismological modalities, a well designed website will be critical. If it is truly important to expose the non-seismologist to seismology, the IRIS web page needs to be user friendly to the non-seismologist, much as it is now. When an earthquake occurs, the new user of the website will need to be able to find information, data, and other resources appropriate to that event.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

There needs to be continued improvement in bringing real-time seismology to as many as possible. This includes continued development and improvement of jAmaseis and InClass. In its current version, jAmaseis is an important step in allowing real time seismic data viewable over the internet. However, there are some issues that need to be addressed, as well as providing quick and reliable technical support. To that end, there needs to be full time support dedicated solely to jAmases and SIS issues. Regional networks are a start, but there will be many entities not able to join or become part of a present or nascent Regional Seismic Network. InClass can be argued as a starting point to a fully engaged populace in seismology, as a fully functional and well promoted InClass would be able to easily support the currently flummoxed K-12 instructors trying to initiate the Next Generation Science Standards. A fully engaged K-12 teacher populace could lead to a fully engaged K-12 student population, as well as potentially identifying future seismologists. In addition to the InClass opportunities, a robust version of Seismographs in Schools (SIS) can be transformative. Witnessing a seismic event being recorded real-time IN a classroom by students can be transformative. Imagine the effect of viewing an event, and then being able to communicate with other students or a seismic expert after that event (or during it) using twitter or some other rapid communication method.

Authors: Derek Schutt
Title: Democratizing science: the interplay between broader impacts and optimizing the scientific endeavor
Keywords: broader impacts, teaching, computers, software

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Deep earth geoscience will become increasingly interdisciplinary, integrating new developments in subfields such as materials science, environmental science, mineral physics, acoustics, as well as traditional fields such as geophysics, seismology, hydrology, geochemistry, and petrology. As well, computationally intensive simulations that attempt to incorporate a larger range of physical and chemical processes, more complete explorations of model space, and a wider range of observeables, will become essential parts of a geoscientists' toolbox. However, one cannot be an expert in all things, and the ability to perform cutting edge science will be increasingly predicated upon the availability of user-friendly software, training, and educational materials that expands the ability of a scientist into regions she or he is less familiar in.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The innovative approach of the IRIS facility and its founders of creating a pool of seismic instruments that any NSF-funded PI can use, and the storage of open-access data, transformed seismology in the U.S. and has served as a model to the rest of the world. These features democratized seismology, and allow any researcher with a laptop to perform relevant seismology research in their field of expertise. Yet, it is still common that many undergraduate students are not exposed to geophysics or research at all, that graduate students use similar analysis methods to their mentors, and one's future realm of expertise is typically formed by the courses taken as an undergraduate and graduate. A new facility that supported a wide range of software, course materials, and training materials would enable a much wider range of research and a broaden the training students outside large and relatively wealthy geoscience departments receive. Consider, for instance, on-line or in-person training that would allow any motivated student, such as a physics student at a community college, to learn common seismological data analysis procedures and perform real research with a facility-provided mentor; or how much a teaching repository of quality upper level courses or course modules could enable a wider variety of geophysics being taught at small institutions; or an open-access seismology e-textbook that incorporates simulations and a full derivation and explanation of all equations.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

The potential exists for the new facility to provide a dramatically improved set of broader impacts, by expanding the diversity of the workforce and the breadth of training, through a relatively small investment. Today, students' opportunities in seismology and geodesy are largely limited by the training available where they attend college or graduate school. The means exist to vastly expand training and further democratize our science, with consequential expansion of student opportunities, workforce diversity, and scientific productivity. While in-person classes such as the USArray Short Course will remain the golden standard of training effectiveness and should be expanded, the demand for these currently is far beyond the capacity of the current facility, with current funding, to supply. To augment these, a structured series of webinars in theory and method; downloadable tutorials and primers, e-textbooks and user's guides (i.e. "A User's Guide to Aki and Richards"); and a carefully structured and populated teaching repository can all be created at relatively small expense by providing financial incentives for experts to produce these, and the necessary database, editing, and other support by the facility. An important consequence of community-created leaning resources is that it reduces class preparation time, which in turn creates a more positive work-life balance, which is one factor that has been cited in reducing diversity in the workforce.

Authors: Susan Eriksson
Title: Education and Outreach Supporting Community Science
Keywords: evaluation, strategic planning, education, using data, collaboration

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

I will support scientific research by helping plan and evaluate geoscience projects, particularly their broader impacts.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

From my experience in education and from my interest of water-related issues, any capabilities that support water-related research will be extremely important in the long term.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Facilities E&O programs: Use collective community's scientific knowledge. Example: S. Wdowinski's knowledge of geodesy and E&O staff's understanding of audience helped UNAVCO reach a broad scientific audience and influenced government decision-makers in Earth Science budgets. Hire professionals who use evidence-based practice to create programs using data and latest research. Example: R. Arrowsmith and UNAVCO staff collaborated on the first national, education short course on airborne lidar at GSA. Build programs to tap the collective expertise and human capacity of researchers, faculty, teachers, and students. Example: K. Ellins has used UNAVCO, IRIS, and ES materials for teacher professional development in Texas and will disseminate to an international audience as a Fulbright Fellow. Sustain long-term projects. Example: RESESS (2005-2015) students are in the geoscience workforce and will receive PhD degrees in 2015. Have authority associated with NSF-funded initiatives. Example: Facility and large projects have credibility in 'broader impacts' reviews of individual and community grant proposals. Measuring the impact of this work provides evidence for programs' relevance, effectiveness, efficiency, impact and sustainability. Evaluation should be integrated into planning, and activities should be monitored. The value of Education and Outreach will be then documented using the multiple lines of evidence valued in scientific research.

Caption: 2009 RESESS interns are currently working in geoscience, are in graduate school, or completing advanced degrees in 2015.

Authors: Sarah Kruse, Mitchell Craig, Rhett Herman, Rosemary Knight, Heather Lehto, George Tsoflias
Title: Increasing Field Research Opportunities for Diverse Undergraduate Populations Through a Dedicated Teaching/Research Equipment Pool
Keywords: undergraduate education, underrepresented minorities, community colleges

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

The primary objectives of this Broader Impacts whitepaper are to increase field research opportunities for large numbers of undergraduate students and to increase participation of underrepresented minorities in geophysics. We propose the acquisition of dedicated geophysics teaching/research equipment pool, and the creation of a forum for publishing results of small-scale integrated geophysical studies. Educational research targets might include, for example, subsidence associated with groundwater withdrawal or sinkholes, local hydostratigraphy, coastal morphology, or imaging of small-scale fault structures. However, the proposed geophysics equipment pool would also permit researchers to tackle problems at many scales in new ways with multiple complementary methods. In particular, seismic and geodetic studies of hydrostratigraphy, aquifer structure, and watershed processes are generally more easily interpreted and more robust when simultaneous electrical or electromagnetic are collected.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Geoscience research will require a deep and diverse workforce. The National Academy of Sciences recommends expanding support for "undergraduate … STEM programs focused on increasing the participation and success of underrepresented minority students through engaged mentoring, enriching research experiences, and opportunities to publish, present, and network" (italics added). Although the NAS report does not explicitly name field experiences, we know that field work by its nature requires 'engaged mentoring', and that any organized data acquisition forms a research experience. The education and outreach portfolios of the current programs offer great strength at two ends of the spectrum for undergraduate education: (a) intensive internship opportunities for a few; and (b) quality web-accessed teaching materials for classes that serve many. In between these end members lies a gap, and an opportunity to scale-up access to geophysical field investigations for many undergraduates at many institutions. We propose a way to fill the gap, as described in the broader impacts section.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

We propose a foundational expansion of the equipment pool to include (a) a range of instruments prioritized for use by in small-scale geophysics teaching/research equipment pool, (b) the creation of training and teaching material targeting undergraduates and their instructors, and (c) an electronic forum for publishing results of small-scale integrated geophysical studies. Equipment would be prioritized for broad access by faculty and students and faculty at institutions that currently lack cutting-edge research programs and equipment—predominantly undergraduate institutions, minority-serving institutions, and community colleges. Such studies require an instrument pool that complements and expands the existing suite. Although the inventory has grown from seismographs and GPSs to include magnetotellurics and terrestrial lidar (TLS), it is insufficient for large-scale teaching and research that involves many students. We propose to supplement existing equipment with instruments that will allow larger groups of students to gather and interpret complementary geophysical data: additional Geodes for small active seismic setups, surface wave streamers, additional TLS, resistivity and electromagnetic instruments, ground-penetrating radar, gravimeters, magnetometers, and perhaps fiber optic thermal and strain cables and a nuclear magnetic resonance (NMR) system. Staff training and support will clearly be essential for this task.

Authors: Andrew Goodwillie, Missy Holzer, Mike Passow
Title: Authentic Scientific Data in the Classroom: Improving Student Engagement, Understanding, and Retention
Keywords: student engagement, student retention, education modules, STEM, workforce,

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

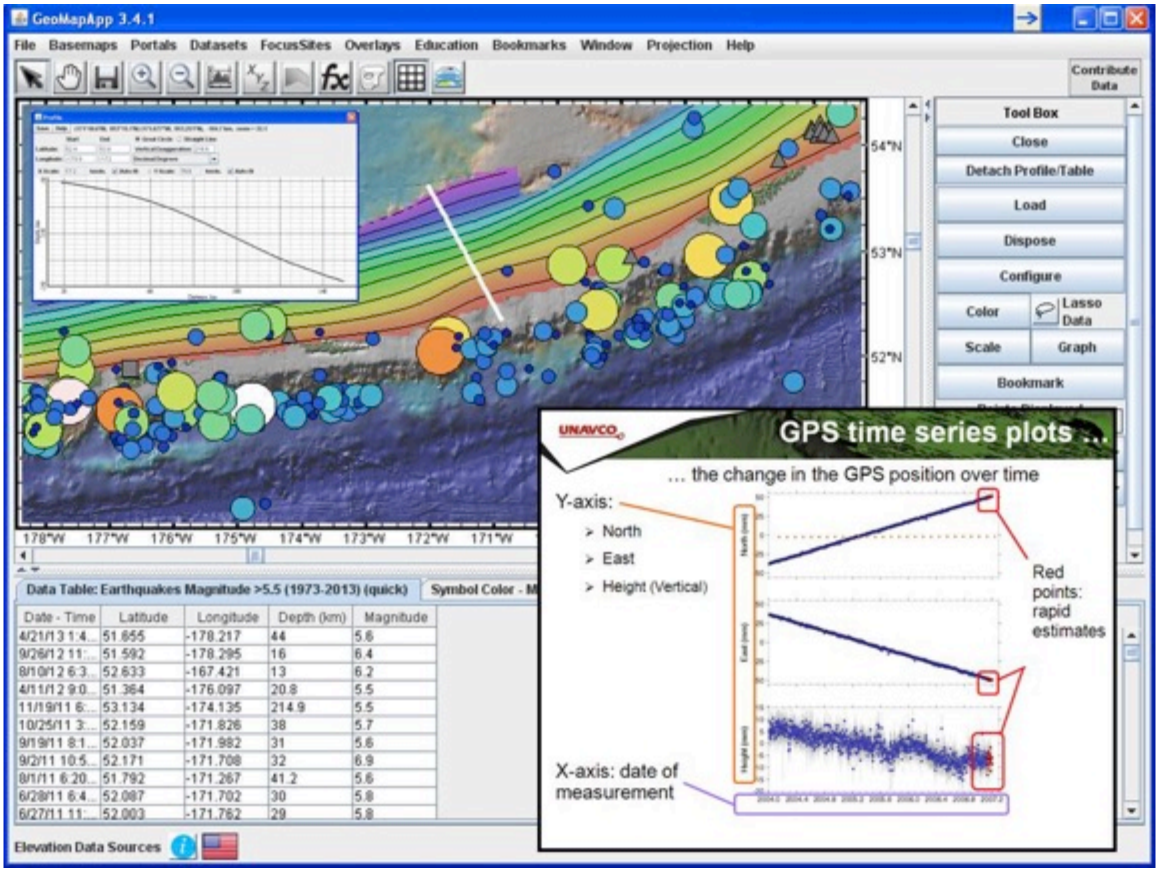
Seismic and geodetic techniques including earthquake analysis, InSAR, and terrestrial laser scanning are directly relevant to societal concerns such as earthquake propagation, volcanic flank inflation, and fault release deformation. Making data sets available in formats accessible to learners at all levels, particularly through integration in cohesive education modules, can help educators increase the broader impacts of the underlying science.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The NSTC Committee on STEM Education identifies key reasons for improving the scientific and technical skills of students and of the general public, noting the importance of a vibrant, STEM-literate population (NSTC, 2013). In addition, studies of demand and supply in the geosciences workforce indicate a gap between the increasing number of job opportunities available, which include positions in research and government institutions and in the natural resources sector, compared with the number of qualified individuals available to fill them (e.g. Gonzales and Keane, 2010). Addressing that STEM workforce pipeline is a goal of the NSF GEO Directorate (see the NSF Dynamic Earth: Geo Imperatives and Frontiers 2015-2020 report) and includes two readily identifiable components: How to attract students to geoscience courses, and how to retain their interest in the subject. Interaction with authentic scientific data in the classroom is one approach that educators can adopt to successfully boost student engagement, understanding, and retention through: • better grasp of the uses and limitations of data, • the development and promotion of critical reasoning and mathematical skills, • strengthening of spatial thinking capabilities, • improvement in an ability to make inferences based upon data, and, • enhanced familiarity with tools and techniques used by scientists.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

In addition to operating domain-specific data management centers, the next generation seismic and geodetic facilities will likely be tasked with delivery of substantial broader impacts to help address the STEM capabilities and interests of students at the school, college and graduate levels. Existing UNAVCO and IRIS learning activities are aimed at students across the K-16+ levels and provide good examples of education modules that use authentic, research-grade scientific data to enhance student interest in our field. One key aspect of increasing the value of scientific data for adoption in the classroom or lab is to ensure that data sets are made available in accessible formats, ideally as part of carefully-constructed education modules. For instance, an earthquake catalogue derived from an OBS array is more easily appropriated by educators than the underlying SEG-Y data. Taking that lead, a successor seismic-geodetic facility should feature a strong team of education and outreach specialists who, through close interaction with investigators, curriculum developers, and evaluation experts can build upon current successes and continue to bridge the gap between cutting-edge research, student engagement, and retention. References: Gonzales and Keane, 2010. Who Will Fill the Geoscience Workforce Supply Gap? DOI: 10.1021/es902234g NSTC, 2013. Federal STEM Education 5-Year Strategic Plan. National Science and Technology Council. https://www.whitehouse.gov/administration/eop/ostp



Caption: Examples of data ready for use in education. (Main image, generated with GeoMapApp) Aleutian arc seismicity: Contours show depth to the top of the subducting slab (Syracuse and Abers, 2006). White line is location of inset profile across the slab, S to N. Earthquakes (circles) are coloured by magnitude, scaled by depth. EarthScope PBO (triangles) and USArray stations (squares) are in grey. Large inset: Geodetic data explained in Groom et al.'s UNAVCO module on Cascadia Episodic Tremor and Slip.

Authors: Robert Butler
Title: Professor
Keywords: K-16 Earth Science Education

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

I hope to continue working with Jenda Johnson to develop animations that translate earthquake, tsunami, and volcanic processes for novice learners. Collaborations with IRIS EPO and UNAVCO EPE or their successor geoscience education organization(s) is essential to continuing this education research and development.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

There must be a core staff of geoscience educators within the Future Seismic and Geodetic Facility to support regional and state programs that promote earthquake and geodesy education in their areas.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

From 2008 to 2010, Teachers on the Leading Edge (TOTLE) offered one six-day workshop each summer for K-14 teachers featuring EarthScope science and Cascadia geologic hazards. Much of the earthquake science and pedagogical approaches came from IRIS EPO. Educational resources on geodesy were adaptations of activities developed by UNAVCO EPE. The Cascadia EarthScope Earthquake and Tsunami Education Program (CEETEP) is offering six four-day workshops during 2013-16 for educators in Cascadia coastal communities. CEETEP PIs work closely with IRIS EPO and UNAVCO EPE to develop earthquake, tsunami, and geodesy classroom activities and align those activities with the Next Generation Science Standards. A TOTLE innovation was developing animations to translate earthquake, tsunami, and volcanic processes for novice learners. TOTLE, IRIS EPO, UNAVCO EPE, and CEETEP have funded a growing collection of animations that are used by K-16 Earth science instructors and emergency management educators. Animations are posted on the IRIS EPO and UNAVCO EPE web sites and on YouTube where these animations have received over 2 million views and viewership is growing rapidly. With the assistance of education program(s) within the Future Seismic and Geodetic Facility, regional educational programs like TOTLE and CEETEP can seize future opportunities to feature seismology and geodesy for students and the public. Without such support, these opportunities will be severely limited.

Caption: The Astoria, Oregon team of K-12 teachers, parks and museum interpreters, and emergency management educators examine the relative earthquake hazard map for their community.

Authors: Jeffrey Ryan
Title: Broader impacts cannot be disentangled from science – a case for robust BI support in future geodetic/seismic support facilities
Keywords:

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

UNAVCO and IRIS supported science already focuses on a wide range of issues of critical societal importance: hazardous deep-Earth event prediction and analysis; climate change; global water resources; hazardous weather/atmospheric events prediction and analysis. The growing applications of TLS and related Earth imaging technologies will inevitably lead into a wider range of societally critical questions to answer, which any successor enterprise must inevitably support and facilitate.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The ability to explicitly address the societal relevance and impacts of science is becoming all the more critical in an age where the overwhelming expansion of (largely un-vetted) information leads to public confusion and doubt about the importance of science in their daily lives. As such, at every level, being able to make a compelling case to non-scientific constituencies, both in proposing new investigations and in documenting the outcomes and benefits of scientific investments is an absolute necessity.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Individual investigators will not have either the experience or resources to provide the kinds of compelling arguments needed to justify scientific investments to a skeptical public or to the policy-makers who must approve these kinds of investments. More and more, it will be the role of community-based networks and facilities to gather these data, and to make those cases based on the accumulated results of that community. Any successor enterprise to the current UNAVCO and IRIS facilities must have as a central part of its structure a robust education and community outreach enterprise that both supports individual investigators in making the case for the societal benefits of their work, and especially in gathering the results of these many PI-led efforts in terms of their societal impacts (education, insfrastructure, preparedness, sustainability, etc.) and making a coherent national-level case for the need for future investigations. This entity will require the resources to fully support PI-led Broader Impact activities, to ensure that these activities yield the intended outcomes, and to gather from all investigators information about these outcomes to make a community-level case for the importance of these scientific efforts.

Authors: Elizabeth Cochran
Keywords:
Low cost sensors, crowdsourced data, large-N networks.

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

In recent years, community-driven or crowd-sourced collection of scientific data has become a popular way for non-scientists to engage in the scientific process. Involving the public in seismic and geodetic data collection is a natural extension of our existing, more traditional sensor networks. Several efforts are underway within our community to engage the public in the collection of ground motion data, including Quake Catcher Network, Community Seismic Network, MyShake, etc. It is expected that these types of efforts will continue to grow as sensors become more and more ubiquitous in our daily lives. However, to date most of these efforts have been undertaken independently and the effort to 'close-the-loop', e.g. make the data easily available to scientists and the public, has been fragmented at best. There are enormous currently untapped opportunities to further the potential of these networks to provide seismic and geodetic data as well as and inspire the next generation of earth scientists.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Key facility needs to support geoscience research based on community-driven or crowd-sourced seismic and geodetic data can be achieved through an extension of existing data archival and distribution efforts. However, these data types present new challenges to standard metadata (e.g. SEED, etc) in order to appropriately capture the (often lower-quality) timing, location, and orientation information. And, the potential for very large volumes of often-noisy data presents new challenges for data processing and analysis. Automated quality-control metrics, improved event detection techniques, and 'smarter' waveform analysis will be required. It is likely that many researchers may prefer data that has some quality checks and processing applied rather than raw time-series data.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Community-driven and crowd-sourced networks require that data are made available to participants and the general public in the form of easy-to-digest products. A clear feedback exists between how engaged participants are and their ability to access the data or data products that they helped to collect. Participants will want to access images of seismic or geodetic waveforms, download time-series, and view a host of data products that are based on the data collected. Additionally, there is enormous potential for these types of networks to provide a platform for improving scientific literacy of the participants.

Other

Authors: Adam Schultz
Title: New Frontier Observatory for Studies of the Anthroposphere
Keywords: magnetotelluric, electromagnetic, electrical conductivity, geothermal, water resources, mineral resources, conventional energy, natural hazards, tectonics

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

The emergence of large-scale arrays for magnetotelluric investigations of the continental crust and mantle has revealed the power of such investigations in complementing seismic/geodetic data, providing an independent set of constraints on earth properties, obeying different constituent relations and equations of state. Work mainly under EarthScope support has revealed e.g. that the sensitivity of MT to bulk interconnected fluids within the rock matrix can play a pivotal role in the interpretation of other geophysical/seismic data sets in geothermal/hydrothermal/magmatic systems, helping to distinguish between thermal anomalies, partial melt and hydrothermal activity. We envision that this activity will continue past 2018, continuing the systematic mapping of North American (and beyond) mid-crust to upper mantle, in 3D. An emerging frontier is to extend such studies into the near surface (0-5 km in particular, but extending down to mid-crustal depths of 0-12 km). The need for high-resolution, 3D baseline mapping of electrical conductivity structure provides critically important information on subsurface structure, temperature, fluid content, composition and state in the region of greatest interest to society - depths that extend to the drill bit. Emerging technologies in 4D EM geophysics allow observations of temporal changes in the subsurface, related to resource extraction and waste disposal, and to the dynamics of magmatic processes and changes in stress field.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

The National Geoelectromagnetic Facility at Oregon State University operates 94 land MT systems, of which 26 are wideband capable of imaging the near surface, and the remainder are long-period, configured for mid-crustal to upper mantle studies. The long-period MT instrument pool is based on aging systems that are maintained and updated by OSU. There is a pressing need for expansion and modernization of the pool. OSU is currently developing a new generation MT receiver that will be lower cost than the existing generation of MT receiver. New technologies are required in magnetic field sensing to reduce the cost of total system ownership, and to allow expansion of the MT pool to hundreds rather than tens of instruments. Work along the continental margins reveals the importance of coordinated amphibious MT arrays. There is no national marine MT instrument pool, but SIO and WHOI have marine MT instruments. Support for these facilities and close coordination with the expanded land facility is required and under discussion. To extend into the near-surface (anthroposphere), in addition to supporting an expanded suite of wideband EM instruments and building a national capability for controlled source EM work for high-resolution studies, the use of swarms of autonomous aircraft systems equipped with magnetic field sensors, coordinated with mobil land-based transmitters, would permit efficient wide-area near surface 3D/4D mapping on a continental scale.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

There is paradox facing the US EM geophysics community. New capabilities in 3D and 4D geoelectromagnetic imaging have emerged in the past decade, leading to a proliferation of large-scale projects across a wide range of application domains (fundamental earth process studies, geothermal and natural resource investigations, etc.). This up-ramp in MT and related EM activities, particularly in the past 5-6 years, coincides with a demographic crisis. Prior to the current revolution in EM techniques and activity, the US academic community did not prioritize development of EM programs, nor did institutions with existing EM programs prioritize the replacement of existing researchers as they retired. Few graduate students were trained, and a demographic downward spiral ensued. Most academic geoscience departments in the US have little to no expertise in these areas, and the dynamics of consolidation from geophysics departments to larger, broader geoscience units has accelerated this decline in capabilities. There are fewer than five US academic institutions with robust magnetotelluric programs, and most of these will wind down within the next 5-10 years due to retirements. A coordinated national effort is required to build new EM programs within US academic institutions; use of multi-institutional web-based curricula and NSF and other funding instruments for graduate student training.

Caption: A view of part of the current inventory of the National Geoelectromagnetic Facility's land EM instruments (EM receivers, magnetic field sensors, electric field sensors)

Authors: Timothy Melbourne
Title: Facility Requirements for Real-time GPS Seismic and Geodetic Monitoring
Keywords: real-time GNSS

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

Over the past century, seismic networks have provided the primary source of rapid earthquake characterization that inform first responders. However, as earthquakes grow large and exhibit fault rupture times exceeding several seconds in duration and fault ruptures of tens of kilometers, the complexity and extended coda of local body waveforms, coupled with saturation on local networks, can make accurate magnitude estimation and finiteness of rupture difficult to ascertain without depending on teleseismic waveforms and their attendant travel-time delays of minutes. As a result, rapid and accurate magnitude estimation of the largest earthquakes based solely on local seismic measurements remains challenging.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Because near-field (static) deformation grows linearly with respect to earthquake moment, as opposed to the moment rate that controls far-field, teleseismic amplitudes, GNSS position measurements computed in real-time can, provided sufficient instrument density, be highly complementary to traditional seismometers in characterizing large earthquake sources rapidly. EarthScope's Plate Boundary Observatory now contains over 300 continuously-telemetered GPS receivers, most of which were upgraded to this capacity from supplemental ARRA funding from NSF under the Cascadia Initiative. In conjunction with other real-time networks, currently over 600 GPS blanket the San Andreas and Cascadia fault systems that define the North American plate boundary, while another ~thousand or so instruments operate throughout the Pacific Rim. These instruments can provide on-the-fly characterization of transient ground displacements highly complementary to traditional seismic strong-motion monitoring, and are proving to be incredibly useful for rapid earthquake characterization, tsunami excitation, and volcanic unrest. A myriad of different University and federal agencies are currently developing new algorithms to better employ the existing and incipient real-time streams for a wide variety of applications that depend on accurate, rapid earthquake characterization, including Earthquake Early Warning, tsunami excitation and volcanic inflation.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

Unresolved issues bearing on the integration of real-time GPS with seismic streams include: • Should high-rate GPS time series be archived alongside conventional seismic data streams? • If so, which organization will be tasked with doing so? Currently neither the IRIS DMC or UNAVCO, INC archive high-rate GPS data at full-resolution and without down-sampling. • If high-rate products are saved, should processing be specified (RTK; PPP; products used, etc). • If high-rate, real-time GPS becomes widely adopted by agencies tasked with hazards mitigation (principally USGS, NASA and NOAA), which agencies will support the continued real-time operations of these networks, given that the real-time aspect of their nature lends itself more to hazards monitoring, which is not typically the focus of NSF, rather than basic science, which is.

Authors: Fred W. Schroeder, Derek Schutt
Title: Geophysics Teaching Repository
Keywords: Training, repository, teacher, education

What key scientific questions, emerging science opportunities and technical advances will you be pursuing in 2018 and beyond?

In 2018 and beyond Fred Schroeder hopes to be contributing educational materials to such a geophysics teaching repository.

What foundational or frontier geodetic and seismic facility capabilities will be required to support geoscience research in 2018 and beyond?

Outside my area of expertise.

What facility capabilities are needed to support broader impact needs post-2018 (education,outreach,training & workforce development,international)?

A strength of the geophysics community is its members' commitment to teaching excellence. With existing communication technology, a new facility can help leverage this teaching expertise so that students around the globe can benefit. The IRIS facility's InClass and Early Career webinars are a great beginning towards this goal. Both programs should be expanded. A master plan should be developed such that a world-class geophysics teaching repository is available to science teachers for all grade levels. For K-12, age-appropriate teaching resources (videos, slides, documents, activities) would exist for common earth science topics. For high school, there would be multi-lesson units that build upon one another in a cohesive manner. Other geophysics teaching resources could be designed for undergraduate and graduate geoscience courses. A distinct feature of the current and future expanded teaching repository is that it will be filled proactively. To insure a coherent and complete set of materials, contributions would not be accepted passively, rather, the new facility's staff would develop lists of topics and then solicit volunteers from within member institutions and elsewhere. Educators would contribute materials using common templates and styles, with material curated by facility staff. The impact of this project on students K through grad school would be phenomenal, by enabling a far wider range of populations to be educated in Earth Sciences.