WORKING WITH STRAINMETER DATA

UNAVCO SCIENCE STRAINMETER WORKSHOP
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SCRIPPS INSTITUTION OF OCEANOGRAPHY - UC SAN DIEGO

Organizing Committee

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EXECUTIVE SUMMARY

The goals of the 2012 UNAVCO Strainmeter Science Workshop were to (1) survey current strainmeter research; (2) identify challenges related to working with strain data; (3) identify which new data products and analysis tools would best enable researchers to reach their science goals; and (4) to discuss how to continue expanding the strainmeter community. This report summarizes and makes a set of recommendations based on the workshop findings.

CURRENT STRAINMETER RESEARCH

We find that strainmeter data is being widely used in a variety of research areas, e.g., the analysis of episodic tremor and slip events, aseismic creep, coseismic deformation, seismic wave propagation, the study of the normal modes and in hydrogeodesy. We summarize these efforts in this report. The combination of seismic and strain data to study seismic wave propagation was first suggested in the 1930's but it is only in recent years, with advances in data acquisition systems and the installation of continuously operating networks such as PBO that this is now a viable research topic. Slow earthquakes and episodic tremor and slip events were relatively new phenomena when PBO was being designed and their inclusion has enabled a more detailed study of these strain transients that could be achieved with GPS or seismology. Other areas of research such as the use of strainmeter recordings of seiche signals to constrain the depth and viscosity of a magma chamber in Yellowstone are completely new.

CHALLENGES RELATED TO WORKING WITH STRAIN DATA

The critical issue facing researchers working with strainmeter data is distinguishing the signal from the noise. The very sensitivity that makes strainmeters ideal for recording small, short-term strain transients, means the data are inherently noisy. We identify several key areas that could help in the understanding and modeling of this noise. A detailed study of the site characteristics of each installation including the tectonic, geologic, topographic and borehole setting should be undertaken to develop a noise model for each site. Long-term borehole trends are not well understood and providing a detrending technique that has a physical basis would give confidence in the identification of tectonic signals. An in-depth knowledge of the down sampling routines of the borehole data loggers will be important as the high frequency data sets become more widely used. An understanding of how borehole strainmeters respond to large dynamic strains is essential for analyzing coseismic data sets.

Data products and analysis tools

As the detection envelopes of GPS, seismology, and strainmeters merge, having high rate linearized and fully processed strainmeter data in SEED format will become increasingly useful. A tool that allows easy access, manipulation and visualization of strainmeter data is essential. Not only will it be key to enabling scientific discovery, it will also be extremely useful to the educational community as a teaching aid. Strainmeter Short-courses should continue to educate the community on the basic topics of data products, data formats and data access.

Expanding the strainmeter community

The UNAVCO Strainmeter Short-courses are absolutely critical for growing the strainmeter community in an environment where strainmeters are not usually covered in geophysics undergraduate courses. Promotion of successful research using strain data will inform researchers of the contributions strainmeter data could have to their own research and key members of the current strainmeter community are encouraged to champion strain science. Strainmeter Short Courses are ideal candidates for the development of blended classes where the material is presented as a combination of on-line and face-to-face teaching. This would maximize the student's time with the instructor to discuss problems directly related to their research.

A common theme throughout every session of this workshop was the need for clear, concise and complete documentation on every aspect of working with strainmeter data. This documentation should span topics as diverse as borehole logging data, data logger down sampling routines, an assessment of the data quality of each strainmeter, references to publications, and relevant on-line tutorials. Some of this information does exist but it should be collated and presented in a fashion that makes its discovery almost intuitive. This is one of the most fundamental steps that could be taken to enable scientific discovery and expand the strain community.

1. INTRODUCTION

Strainmeters were included in the Plate Boundary Observatory (PBO) because it was recognized that they can bridge the gap between the detection envelopes of GPS and seismology (Silver *et al.,* 2000). PBO includes 75 borehole strainmeters (BSMs) and 6 Laser Strainmeters (LSMs) The strainmeters are installed in arrays along the western U.S. plate boundary: the Cascadia Subduction Zone, the Mendocino Triple Junction, along the San Andreas and San Jacinto faults, in the Eastern California Shear Zone, and around the Mount St. Helens and Yellowstone volcanic systems (Figure 1). In the years since installation the instruments have recorded multiple Episodic Tremor and Slip events in the Pacific Northwest, aseismic creep events, coseismic deformation, seiches and tsunami related strain signals.

As the 10-year anniversary of PBO draws near, it is an ideal time to assess how the strainmeter data have been used to meet Earthscope research goals, to review current strainmeter data formats and products, to identify obstacles to working with strain data, and to address the issue of growing the number of experts in the field. For this purpose UNAVCO organized a Strainmeter Science Workshop, hosted by the PBO Long Baseline Laser Strainmeter Analysis Center at U.C. San Diego, in October 2012. The goals of the workshop were to:

1. survey current strainmeter research
2. identify challenges related to working with strain data
3. identify new data products and tools that would further enable research
4. discuss how to continue expanding the strainmeter community.

2. WORKSHOP ORGANIZATION AND STRUCTURE

The Strainmeter Science Workshop was held at the Martin Johnson House at Scripps, U.C. San Diego, 10th -12th October 2012. It was felt that most would be gained from the workshop if researchers who had worked with strainmeter data would share their experiences. To accomplish this the organizers invited scientists who had given presentations at meetings or published papers using PBO strainmeter data. Emphasis was also placed on encouraging graduate students and early career scientists to attend. There were 28 participants; the group included established and early career earth scientists plus strainmeter and data engineers. The workshop was broken into four

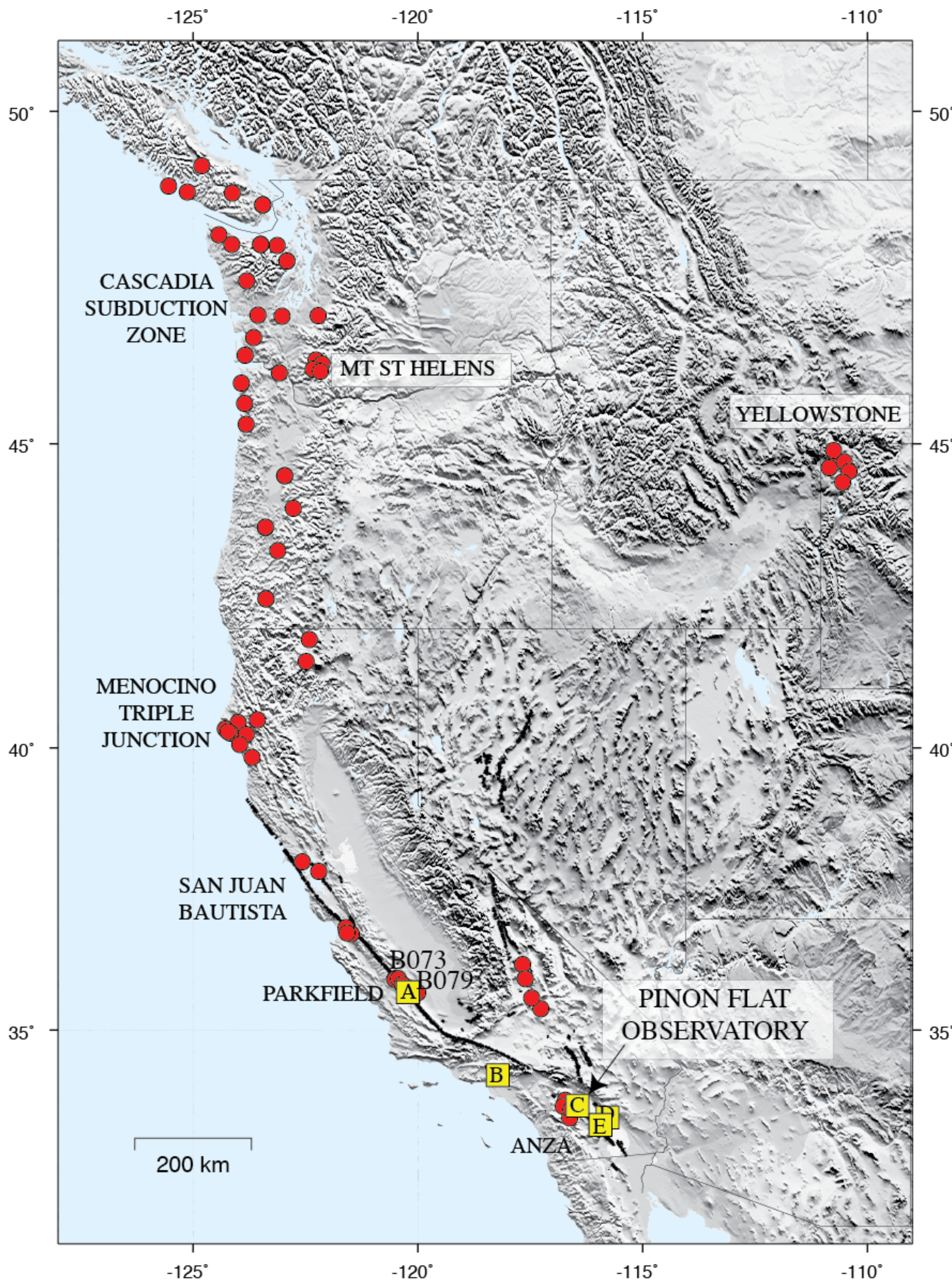

Figure 1. PBO borehole (red dots) and laser strainmeter (yellow squares) locations in the Western United States and British Columbia. Laser strainmeters: A) CHL1 and CHL2 at Cholame, B) GVS Glendale, C) PFO, Piñon Flat Observatory (non-PBO LSM), D) DHL at Durmid Hill, E) SCS1 and SCS2 at the Salton Sea.

sessions, each introduced by talks from keynote speakers and then followed by a 45-minute long discussion. Keynote speakers described their methods to extract signals and model strainmeter data. They were encouraged to share problems encountered and discuss what they would find helpful in future work. A poster session on Wednesday and Thursday afternoon gave all attendees an opportunity to present their work. The third day was spent at the UC San Diego Piñon Flat Observatory (PFO), where Frank Wyatt and Duncan Agnew (UCSD) led a tour of the long-baseline laser strainmeter, and Mark Zumberge and Scott DeWolf (UCSD) described the new optical fiber strainmeter recently installed at PFO.

Workshop Keynote Presentations

A. Outstanding Research Questions	
Outstanding Research Questions	E. Roeloffs
Laser Strainmeters: Performance, Results	D.C Agnew & F. Wyatt
Seismic Signals in BSM Data	C. Langston & B. Grant
B. Identification Of Signals In Strain Data	
Tectonic and Non-Tectonic Signals in BSM Data	H. Dragert
Strainmeters in Yellowstone	D. Mencin
Strainmeters in the Caribbean	G. Mattioli
Optical Fiber Strainmeters	M. Zumberge
C. Data Products And Tools	
PBO BSM and LSM Data Products	K. Hodgkinson
Strainmeters in the seismic frequency range	D.C. Agnew
D. Expanding The Strainmeter Community	
Education and Community Engagement discussion	D. Charlevoix

3. WORKSHOP SESSIONS

3.1 CURRENT STRAINMETER RESEARCH

While many of the benefits of strainmeter measurements were recognized in the 1930's, for example the ability to record the normal modes, and to provide estimates of site phase velocities, many of these research areas have only become viable in recent years with improved sensor technology, advances in data acquisition systems and the installation of continuously operating networks. Slow earthquakes and episodic tremor and slip (ETS) events were relatively newly-discovered phenomena when PBO was being designed, and it was hoped the inclusion of strainmeters in PBO would enable a more detailed study of these strain transients beyond what could be achieved with GPS or seismology. Other areas of research such as the use of strainmeter recordings of seiches to constrain the depth and viscosity of the magma chamber in Yellowstone National Park are completely new. The following is a brief overview of some of the research being conducted using strainmeter data based on the talks, discussion periods and poster sessions during the workshop.

3.1.1 ETS EVENTS

During the planning stage of PBO but it was recognized that strainmeters could provide a resolution of ETS events unattainable with GPS and seismology. Some of the current research on ETS event that use PBO strainmeter data include identification of Nankai-type slow slip events in Cascadia (Wang et al., 2008), examination of the tidal modulation of slow slip (Hawthorne and Rubin, 2010) and slip models that include of the migration of the slip surface (Dragert and Wang, 2011). It is expected that the data will become increasingly useful to those modeling slow slip events as the Pacific Northwest BSM network reaches maturity and the catalogue of recorded events grows.

3.1.2 CREEP AND POSTSEISMIC DEFORMATION

The ability of strainmeters to record slow-earthquakes (Linde *et al.*, 1996) was one of the motivating factors in including them in PBO. PBO strainmeters have recorded aseismic creep events at unprecedented resolution in Parkfield where the network spans the transition zone between the creeping and locked sections of the San Andreas Fault in central California (Figure 1). Several events are recorded each year at B073; the signals typically evolve over hours, are a few tens of nanostrain in magnitude and suggest right-lateral slip. Recorded at rates of 1-sps, the complex temporal evolution of these strain signals is captured well by PBO strainmeters. PBO LSMs CHL1 and CHL2 and BSM B079, all located in the southern part of the Parkfield network, recorded aseismic creep events in August 2010 and August 2012. The August 2012 event was remarkable in that it occurred over several days and produced strain excursions of almost 100 nanostrain.

In southern California, postseismic strain transients were recorded by the SCS1, SCS2, DHL1 and PFO LSMs in the days following the April 4, 2010 El Mayor Cucapah earthquake (http://pfostrain.ucsd.edu/). The postseismic signals may have been caused by afterslip on the fault that ruptured, or by triggered slip on others. All of these aseismic events fall below the detection level of GPS. The excellent temporal resolution and high signal-to-noise ratio of the strain data may be able to constrain the depth at which slip is occurring, characterize the temporal nature of aseismic events in central California, and contribute to an understanding of the role aseismic deformation has in the accumulation and release of stress in a plate boundary zone.

3.1.3 Correlation Of Pore Pressure And Strain Observations From Earthquakes

Civilini (2011) examined the pore pressure and strain observations at PBO BSMs in Anza following the 2010 M5.7 El Mayor-Cucapah aftershock and two nearby earthquakes of M4.9 and M 5.4. The similarity of the strain records and pore pressure records suggested the observed pore pressure responses corresponded to tectonic deformation caused by the strain field associated with the earthquakes. Comparing the pore pressure response of the October 1999 Hector Mine earthquake (Mw 7.1) at the Garner Valley Downhole Array (GVDA) with the combined strain and pore measurements at the PBO sites enabled interpretation of the GVDA pore pressure measurements made during the Hector Mine event. Civilini and Steidl (2012) examined the same data set for changes in relative phase difference between the pore pressure and strain tidal signals before and after earthquakes as a way to identify changes in permeability.

3.1.4 Volcanoes

PBO maintains 4 BSMs on Mount St. Helens and 4 in the Yellowstone National Park to aid in understanding volcanic processes. Installing strainmeters with complementary instruments such as tiltmeters, seismometers and GPS allows the study of magmatic systems over a broad range of temporal and spatial scales. Combined, the data sets can be used to monitor the activity of the volcano, constrain the shape, size and location of the underlying magmatic system, and study the relation between crustal reservoirs and surface flux. The USGS has maintained strainmeter networks in Hawaii and Long Valley for decades (Hill *et al.*, 1995; Myren *et al.*, 2011) and strainmeters exist around volcanoes in Italy, Iceland and Japan. In 2003, 4 Carnegie strainmeters were installed on the

Soufriere Hills Volcano (SHV) in Montserrat as part of the multi-international CALIPSO project (Mattioli *et al.,* 2004). The network was considered a prototype for PBO volcano installations. Fully operational during the July 2003 eruption, the GPS surface deformation and borehole strainmeter data have yielded valuable constraints on the geometry, state, and evolution of the SHV system (Voight *et al.,* 2010). The strainmeters captured unique measurements of a pyroclastic-flow generated tsunami (Mattioli *et al.,* 2007) and provided constraints on the explosion source dynamics of the 2008 and 2009 vulcanian explosions (Chardot *et al.,* 2010).

3.1.5 Normal Modes

The frequency response of strainmeters can be considered flat when the signal wavelength is much longer than the baseline over which strain is measured (Barbour and Agnew, 2012) and can therefore be thought of as broadband instruments at low frequencies. They are ideal for recording long-period surface waves and the Earth's free vibrations that have frequencies below 10mHz. Normal modes of free oscillation are used to derive the radial variations of the physical quantities of the structure of the Earth, e.g., density, P and S-wave velocities. The gravest modes (periods > 1000s) are only observable after M>8 earthquakes. Where horizontal seismic records are often noisy at these periods, strainmeters have detected rarely observed normal modes (Benioff *et al*., 1961; Park *et al*., 2008). Two orthogonal laser strainmeters at the Gran Sasso observatory in Italy recorded toroidal normal modes with periods greater than 1000s following the 2004 Sumatra–Andaman earthquake (Park *et al.,* 2008). They used the normal modes in the strain data to investigate the long-period slip behavior of the event.

There have been 12 M>8.0 earthquakes since the installation of the first PBO strainmeter. The data set presents an unprecedented opportunity to study the normal modes recorded simultaneously across a network of BSM and LSMs with instrument spacing varying from a few hundred meters to 1000s of kilometers.

3.1.6 Seismic Hazard

Pollitz *et al.* (2012) showed that the significant increase in M>5.5 earthquakes around the globe in the days following the 11 April 2012 M8.6 East-Indian Ocean earthquake was concentrated in regions where the dynamic shear strains were predicted to exceed 10^{-7} for at least 100 seconds. The implication is that large earthquakes could result in a readjustment of seismic hazard around the globe. The study calculated the dynamic strains by converting synthetically generated seismograms to strain. PBO strainmeters, however, present actual measurements of the dynamic shear strains and could be used to verify such calculations.

3.1.7 Single Site Phase Velocity Measurements

In 1935 Benioff demonstrated that combining strain and seismic measurements provides information on wave characteristics that cannot be determined from either instrument alone (Benioff, 1935). More recently Blum *et al.* (2010) estimated Rayleigh wave velocities by comparing the ratio of vertical ground acceleration from a nearby seismometer with measurements from a vertical strainmeter in the SAFOD hole. By recording at 20 and 1 sps PBO strainmeters have reopened the study of combining strain and seismic data to determine properties of the Earth's crust. Installation of broadband sensors at borehole sites, a project currently underway in Anza, could reveal more site velocities that will lead to realistic models of the local Earth.

3.1.8 Seismic Wave Gradiometry

Merging strain, rotation and ground velocity measurements made at one location could provide a way of observing and understanding wave propagation in the Earth that previously could only be found from extensive arrays of seismometers. Langston and Liang (2008) demonstrate how the combination of these measurements could be used to determine direction of wave propagation, phase speeds and amplitude variations with distance and azimuth. In particular, they show that sites containing an in-situ calibrated strainmeter and a seismometer could be used to estimate wave slowness and geometrical spreading changes for the P-SV wave field. The Anza strainmeter network consisting of 9 BSMs and the PFO LSMs presents an excellent opportunity to investigate these ideas because of the proximity of broadband seismometers of the Anza Seismic network.

3.1.9 Seiche Signals

Barometrically induced seiches have been recorded at PBO borehole strainmeters installed around Lake Yellowstone in Yellowstone National Park. Finite element models of the Yellowstone Lake basin indicate good agreement between the distinct periods in the seiche signals and the fundamental modes of the system (Mencin *et al.,* 2012). The variation in amplitudes and timing of the seiche signal across the Yellowstone PBO strainmeter network was modeled by Luttrell *et al.* (2012). Using the strainmeter data, they were able to provide further evidence for the presence of a partially molten body at shallow depth, constrain that depth to be no less than 4 km and determine a Maxwell viscosity of less than 10^{11} Pa s. This novel use of strainmeter measurements is contributing to the improved understanding of the Yellowstone magmatic system and providing insight on the structure of the caldera.

3.1.10 Tsunamis

The 2009 M8.1 Samoa, 2010 M8.8 Chile and 2011 M9.0 Tohoku earthquakes generated tsunamis that were recorded by several PBO BSMs as the waves arrived along the coastline of North America. The tsunami arrival times recorded by the strainmeters were consistent with nearby tide-gauges measurements and the data were of sufficient quality to compare the frequency content of the tidal signal in the days before and after the tsunami (Hodgkinson *et al.,* 2011). Comparing strain measurements against the crustal loading signature predicted by water height changes at nearby tide gauges can yield information on the elastic modulus of the crust at the site (Mattioli *et al.,* 2007, Hodgkinson *et al.,* 2011). PBO BSMs can provide 20 Hz data in near real time; it is possible that they could provide a land-based, continuous, high-rate tsunami measurement system that complements the GPS and seismic networks currently being developed.

3.1.11 Meteo-Tsunamis

Meteo-tsunamis, atmospherically induced tsunamis, have been observed in 1 Hz PBO strainmeter data collected at coastal sites on Vancouver Island, British Columbia (Dragert *at el.,* 2012). Although these types of tsunamis are not as catastrophically destructive as those generated by large earthquakes they can cause considerable localized damage and occur more frequently. The ability of the strainmeters to record atmospherically generated tsunamis signals could be useful in tracking storm swells.

3.1.12 Optical Fiber Strainmeters

Optical fiber strainmeters are currently being developed at Scripps, U.C. San Diego. A vertical optical interferometer has been in operation at PFO since December 2011 and a horizontal instrument was installed in July 2012 (DeWolf *et al.,* 2012). Because they measure small displacements over 100 to 200 meters, the local noise effects are averaged out. The data collected at both instruments so far indicates a good signal to noise ratio in the microseism band and strong Earth tide signals. The horizontal strainmeter, installed at 1 m depth in a 180 m long trench is parallel to the NW-SE PFO LSM. Differencing the LSM and optical strainmeter data from 2012 M7.6 Costa Rica earthquake resulted in residuals of a few nanostrain. Similar residuals were observed for a coseismic offset recorded at the onset of the 2012 Brawley swarm. Comparison with the LSM data also indicates the optical fiber strainmeters are free of the calibration issues that must be dealt with for borehole strainmeters. Optical fiber strainmeters have the potential to have signal to noise ratios similar to that of the long-base line laser strainmeters but at a fraction of the cost.

3.2 CHALLENGES RELATED TO WORKING WITH STRAIN DATA

This session focused on critical questions relating to working with strainmeter data. The group identified issues related to using strainmeter data in their research as opposed to data format and products, which were addressed in subsequent sessions.

3.2.1 UNDERSTANDING THE NOISE

One of the most difficult issues researchers face when including strainmeters data in geophysical models is separating out the signal from the noise in the data. The very sensitivity that makes strainmeters ideal for studying small, short-term strain transients means they can also be very noisy in that they record non-tectonic signals such as surface loading from rainfall. Factors that contribute to the noise include: cultural setting, pumping, topography, rainfall, seasonal trends, borehole condition and proximity to bodies of water. The combination of these factors means each strainmeter will have a different noise floor. A complete characterization of the noise at each site would be useful for researchers. To do this, a detailed study for each strainmeter site is required. This would include an examination of the drilling logs to identify fractures near the strain gauges, a summary of the surrounding tectonic, geological and topographic setting, a study of rainfall response at each site, an assessment of the frequency dependence of the barometric pressure response. Once gathered this information should be collated into one central document were the user could easily relate the signal they see to possible sources of noise in the data.

In addition to the physical site characteristics a study should be made of the noise spectra at seismic frequencies. The approximately 10-second long, hourly calibration pulses performed by the BSM logger (model GTSM21) introduces null data points in the 1-sps time series and corresponding peaks in the frequency domain. The presence of these features is a significant obstacle to anyone wanting to work with that particular data set. Barbour and Agnew (2010) found that the 1-Hz data is significantly noisier than the 20-Hz data from which it is derived. Further study of the down-sampling techniques used by the PBO BSM data logger is required to understand the increased noise levels of the 1 Hz data set. Barbour and Agnew (2010) also found that several of the 8 BSM's studied had noise peaks with periods from 10-20 s that could be related to the power supply. A study of coupling of noise from the power system could also pinpoint ways to reduce noise at higher frequencies.

3.2.2 Borehole Trends

The dominant trend in BSM data is that of the rock around the instrument re-equilibrating after drilling and installation of the strainmeter. It is expected that this should be a compressional, long-term (months to years) trend. Currently UNAVCO estimates a borehole trend as part of Level 2 data products using a double exponential and a linear term. Although the method has the appeal of being transparent and is unlikely to remove short-term signals, the method lacks any physical basis. Also, while it is a sufficient for some strainmeters it is inadequate for many. A second level of detrending is always required. Other detrending methods include high-pass filtering; fitting a non-parametric function e.g., spline, and removing a trend based on a Bayesian modeling approach e.g., BAYTAP-G. Often the best method will depend on the frequency of the signal one is trying to isolate. A document summarizing the nature of long-term trends in BSM data and discussing the various methods of detrending BSM data would be beneficial.

While these methods can be used to remove the trend none are based on any physical mechanism. A detrending approach that has a physical model underlying it would give researcher more confidence in isolating tectonic signals and perhaps extend the temporal range over which strainmeter data can be used. Day-Lewis (2007) investigated the long-term poroelastic deformation following drilling and installation of a BSM and was able to provide physical models for the trends in the early data sets available. More meaningful models could also be developed using a rheology in which creep is a power-law function of time. A study investigating physical mechanisms that contribute to the long-term trends in BSM data and which recommended best practices for detrending methods could be useful for researchers. An in-depth assessment of the long-term trends of each BSM and an attempt to provide a physical model describing its behavior might help resolve this issue. Ideally a trend with a physical basis would be supplied as a Level 2 data product.

3.2.3 Seasonal Trends

Seasonal trends are evident in PBO strainmeter data. With some of the BSMs collecting data for almost 8 years it would be useful and may now be possible to model these signals. Generating a seasonal correction for each strainmeter would lower the noise level over longer time periods. Using USGS BSM data from Parkfield, Ben-Zion and Allam (2012) showed that a significant part of the seasonal signal is caused by thermo elastic strain of the Earth's crust. The method they developed could be applied used for PBO BSMs. PBO has several strainmeter clusters, 2 or 3 strainmeters installed within 100 meters of each other. These strainmeters would be particularly interesting to examine in this context, as differences between such closely-spaced sites should be minimal.

3.2.4 Coseismic Offsets

Several BSMs in the PBO network recorded offsets following the 2009 M6.9 Gulf of California and the 2010 El Mayor-Cucapah earthquakes, yet elastic half-space dislocation models predict little or no static deformation at these distances from the epicenter. The response of the strainmeters to large dynamic strains should be assessed. It is possible that there is a magnitude and distance limit beyond which the coseismic offsets cannot be trusted. One explanation of the offsets is that they are a localized site response, i.e., a combination of the site geology, tectonic setting and the borehole condition. Another could be the data logger's handling of large variations in strain over short periods. A network-wide comparison of recorded offsets, GPS displacements (if available) and offsets predicted using elastic half-space dislocation models in conjunction with the borehole logs would be useful to those interested in working with co-and postseismic BSM data.

3.2.5 Response to vertical strain

PBO installed Gladwin Borehole Tensor Strainmeters – Model 21 (GTSM21s) that are designed to record only horizontal strain. However, barometric response coefficients of several nanostrain per millibar suggests vertical strain is coupled into the horizontal strain measurements. The issue is discussed in detail by Roeloffs (2010). The result is a very noisy areal strain data set that must be interpreted with caution. The shear strains are not as affected because the common-mode noise tends to cancel in those time series. The barometric responses are significant at all PBO BSMs regardless of geologic setting or the type of grout used. The GTSM strainmeters installed by the USGS through the 1980s and 1990s are constructed slightly differently from GTSM21s in that the outside instrument casing is smooth and encloses all the gauges while the PBO GTSM21s consist of distinct units bolted together on the outside. The PBO GTSM21 external diameter varies along the instrument. An analysis of two USGS GTSM BSMs indicated barometric responses of 0.07 and 3 nanostrain per millibar (Roeloffs *et al.,* 2004). The 3 nanostrain per millibar response was considered unusually high and thought to be because of its location on a ridge. It would be worth re-examining the USGS GTSM data to estimate the response coefficients of all the USGS instruments. This would serve as a comparison of sensitivity to vertical strain for the two instrument designs.

3.2.5 Calibration

Before strainmeter data can be combined with complementary data sets or used in models it must be converted to areal and shear strain in correctly scaled units. An in-situ calibration is regarded as optimal as it incorporates the combined affect of the surrounding rock, grout, instrument casing and varying sensitivity of the gauges. Strainmeter calibration verges on a research topic in itself and papers have been published in the past two years on this topic alone (Roeloffs, 2010; Langbein, 2010; Hodgkinson *et al.*, 2013). Currently UNAVCO provides calibration matrices supplied by the instrument manufacturer, referred to as the lab calibrations, and tidal calibrations where available. While the Earth tides provide a reference signal in a frequency range that BSMs perform best in, a tidal calibration is not possible for all PBO BSMs. BSMs installed near the coastline or those with a weak tidal signal to noise ratio are poor candidates for such a technique. Grant and Langston (2009) have shown that seismic data from well-calibrated broadband array can be used to derive a reference strain against for BSM calibration. It is expected that seismic calibrations will become available in the future.

Thus, the researcher is faced with the choice of lab, Earth-tide and possibly seismically determined calibration matrices. To compound the problem the matrix can change over time when a gauge is damaged or deemed to noisy to use. This is a significant challenge in working with BSM data, which could be addressed by releasing a definitive set of calibration matrices for each strainmeter for defined epochs of time thus relieving the researcher of the task of deciding the best matrix to use.

3.2.6 Perception of Strainmeter Data Quality

The combination of the issues outlined in the sections above have the combined effect of creating an impression that strainmeter data is of poor quality. Yet as demonstrated in Section 3.1 strainmeter data are currently being used successfully in a variety of research areas. This perception could be addressed by the promotion of published work utilizing strainmeter data, including worked examples from research papers in strainmeter short courses and placing strong emphasis on the data quality assessment of each site on the UNAVCO web pages. A brief summary of data quality is currently available on the UNAVCO web pages (e.g., http://pbo.unavco.org/documentation/bsm/metrics) this should be expanded to give a full description of the noise characteristics of each strainmeter. Ideally, those interested in working with the data would be able to post questions about a strainmeter that other researchers could respond. This would enable building connections within the community, allow others to learn from problems encountered and build confidence in the data set.

3.3 DATA PRODUCTS AND TOOLS

Strainmeter data provides the most exciting research opportunities when it can be combined with other geophysical data e.g., GPS, seismology and meteorological measurements. To accomplish this the data need to be easily accessible, provided in formats compatible with the other data sets and be easily absorbed into the researchers workflow. Each one of the items above can act as an obstacle for the researcher. These issues were discussed in the Data Products and Tools session. The findings are summarized below.

3.3.1 ARE CURRENT DATA FORMATS ADEQUATE FOR RESEARCHERS?

UNAVCO produces strainmeter data in various formats; some specified by the PBO Data Products Working Group and others added later to address specific needs of a researcher. Table 1 compares the data formats used by attendees and the formats strainmeter data products are currently provided in. It is noted that the researchers used many different formats and it posed no problem to work in this way as long as conversion tools were available to them.

Table 1. Data Formats

Data Formats	Number of users	Strainmeter data
SEED	9	YES (raw)
SAC	8	NO
BOTTLES	6	YES (raw)
ICE-9	2	YES (raw)
Tabulated ASCII	10	YES (processed)
XML (an ASCII format)	4	YES (processed)
css	2	NO
TSOFT	1	NO

Bottle and ICE-9 format are the native formats produced by the PBO BSM and LSM loggers respectively. Although the number of people using these formats is small there was a strong demand to continue archiving the data exactly as it was collected on the logger. SEED, SAC and ASCII-formatted files were the most popular formats. Both SEED and SAC are formats widely used by the seismic community and a plethora of code has been produced by the community to handle it. UNAVCO converts all PBO strain and ancillary data to SEED format and archives it at IRIS and the NCEDC. It does not produce SAC format but since IRIS provides tools to convert SEED to SAC there seems little need to do so.

Because the strainmeter and associated data sets have grown to accommodate new instruments being added at sites, and to address user requests, the result is a mixture of data formats stored in a variety of places. It can be confusing to decide which to use. One clear and concise web page describing the data sets with the advantages and disadvantages of each data set would be of use to the researcher.

3.3.2 Linearized Strain In A Seismic Format

Although the raw gauge measurements are available as SEED, a basic processing step is required to convert that data stream, which is in digital counts, to units of strain; the data need to be linearized. There was a consensus among the group that it would be useful to have a linearized gauge strain data set in SEED format. This would reduce the workflow required to compare processed strain data with seismic and high rate GPS data in the future. Linearization of the data is straightforward, if the instrument diameter, reference gap and a fixed data point are known and could be done at the same stage as translation to miniSEED.

3.3.3 Improving The Quality Of The 1-Hz Data Stream

The calibration pulses performed by the GTSM21 logger present an obstacle to anyone wanting to work with the 1-Hz data (see). The 10-second pulses introduce null data points in the time-series and peaks in the frequency spectrum. Removing calibration pulses is a substantial issue, because how the signal is removed may influence downstream analysis of the data. Options are to omit the calibration pulse all together from the data stream, interpolate across the duration of the pulse or supply a separate correctional time-series. The first and second options both have disadvantages. Introducing breaks in the data creates problems for those requiring a continuous time series, and if interpolation is used the researcher must be made aware of that and the method used chosen carefully so as not to hamper further analysis. For these reasons the third option, a separate correctional time-series may be the best. The original measurements would remain unaltered and the decision left to the researcher as to whether to use the supplied correction or not.

3.3.4 Current Processed Data Formats

UNAVCO makes processed data available as XML files and in a simplified tab-delimited ASCII format. Both are five-minute interval data sets. The processed data files contain clean strain, borehole trends, tidal and barometric pressure correction time series. The ASCII version is simply a space-delimited columnar version of the most recent XML files. Their advantage over the XML is that they can be absorbed into most analysis packages with minimal, if any, reformatting. The XML, though, contains all the station and processing metadata, e.g., scale factors, response coefficients, which were used to process the data. The disadvantage of the XML is that the files are large, are an unknown format to most, and the XML reader provided by UNAVCO is required. The motivations behind using the XML format are still valid i.e., repeatability and transparency in the production of processed data sets. It is possible though that rather than containing the full time series within these files they should contain only the processing information. Ideally the user would be able to combine the information in the XML file with the raw data to generate a processed data set. In this way XML files would become analogous to a dataless SEED file for seismic data where the instrument responses are contained in the dataless SEED and the user applies that information to the raw seismic data stream. This is further discussed in the data tool section.

3.3.5 High Rate Processed Data in SEED format

Since 2010 UNAVCO has generated a high rate (1-sps) processed data set in the space-delimited ASCII format following earthquakes and upon user request. There is interest in generating a continuous processed data stream in SEED format. The processed time series would include: the barometric pressure, calibration pulse and tidal time-series correction for each strain gauge and for each of the tensor shear strain components. This could be accomplished in near-real time by assuming the processed data was regarded as "best effort at the time". That is the data would be processed automatically and using the current best estimates for tidal models, barometric response coefficients and calibration matrices. The rapid data set would eventually be superseded by a post-processed data set. In addition to the time-series listed above it would contain an estimation of step offsets and data quality flags. Currently, data quality information is represented in the XML and ASCII files by tagging each data point with a flag that describes it as good, missing or bad. This could be translated to a numerical code and that in turn translated to SEED as integer data.

3.3.6 Strainmeter Data Processing Tools

As described above, translating the raw strain data stream to units of strain is the first step in generating a time-series that can be incorporated into geophysical models. Long term borehole trends, ocean load and earth tide signals, barometric pressure responses need to be removed before tectonic signals can be isolated. Finally, the gauge measurements need to be combined to generate areal and shear strains. Currently UNAVCO provides the processed data in the XML and corresponding ASCII formats. But these are at a fixed five-minute interval and there are no tools, other than that which the researcher writes, to investigate the data. It would be useful for the researcher to have a tool to easily manipulate the data applying various detrending methods, excluding sections and selecting which gauges to use when generating areal and shear strain. Having such a tool would not only be useful for the research community but would be extremely helpful for teaching purposes. New tools that could be provided are MATLAB-type toolboxes or command-line-driven code. Two possible developed options are described below, at MATLAB GUI tool or a command line driven tool.

MATLAB GUI Tool: UNAVCO could expand the MATLAB GUI tools currently being developed by UNAVCO to allow the access, manipulation and visualization of strain data and utilize the Level 2 data products. The user could request gauge strain data in miniSEED format using the IRIS web services tool. Once on the client side, the data, already in MATLAB format, could be read into the MATLAB tool. The user could then download the metadata required to proceed to the next level of processing from UNAVCO. For example, the XML file, which contains the tidal information, edits, barometric response coefficients, calibration matrices, site coordinates and strainmeter orientation is already available. The user could select the gauges to create areal and shear strain.

GMTStrain: MATLAB is not available to all. A software package could be created using widely available existing command line software, e.g., SPOTL, GMT, for those that do not have access to MATLAB or prefer the repeatability that comes from processing data via command-line scripts. In this case also, the raw data would be requested from the archives and the processing information from UNAVCO. The user would then use command-line driven software to with input parameters to select various options such as the time window and gauge combinations to use. Plots would be generated with GMT. An analogous tool exists for SAR data GMTSAR.

As described in section 3.2 there may be a suite of calibration matrices available to the user. One of the barriers to using BSM data is the difficulty in being able to generate the areal and shear strain time series using different sets of calibration matrices. This problem would be alleviated if the user could have a tool, which could absorb ready-made matrices or generate basic matrices within the processing tool. The two options listed above could easily implement this feature. Being able to do this would mean that multiple sets of processed data sets would not have to be archived. Instead only the metadata required to generate the calibration matrix need be archived along with the raw data.

3.3.7 Documentation

Documentation for PBO data formats and processing techniques does exist on the UNAVCO web page. However, attendees were generally not aware of it. The documentation pages should feature more prominently on the web site making its discovery more intuitive. Existing documentation should be reviewed and updated to give it a more consistent look and feel. PDF documents could be replaced with web pages with links cross referenced to publications, data products, processed plots, figures and strainmeter highlights. It is also critical that the Strainmeter Short Courses continue to educate the community about the data sets that are available and the data formats used, and to give instruction on how to access the data.

3.4 EXPANDING THE STRAINMETER COMMUNITY.

One of the goals of the workshop was to solicit feedback on past strainmeter short courses as well as to seek input on future training opportunities related to strainmeters and strainmeter data, as well as how to grow the size of the strainmeter community. Participants were asked to contribute to this goal through discussion focused on two areas during this session.

3.4.1 What Would Be Useful In Building The Strainmeter Community?

The first exercise asked participants to form small groups with others sitting near them and address the question: *What would be useful in building the strainmeter community?* Participant responses are categorized into four broad themes: Data accessibility, Expanding community, Documentation improvement, and Education efforts.

Data Accessibility. Consensus was that working with strainmeter data could be a challenging process with many intricacies. These challenges are currently seen as a barrier to broader use of data. Providing more data processing tools and improving the accessibility of data are recommended as approaches to improving the ease of data access and use. Providing a summary of data quality would help researchers new to working with strainmeters and strainmeter data better understand the limitations and nuances of the data. Another suggested approach was to make data and data products available in formats such as SEED at the DMC. This could enable leveraging against the much larger seismic community. Finally, data quality could be summarized in a scholarly publication or in a series of documents provided via the UNAVCO website.

Documentation Improvement. Enhancing the quantity and availability of documentation related to strainmeters and strainmeter data is considered an area of moderate effort and high impact. An emphasis on and promotion of successful research published using strain data will inform researchers of the contributions strainmeter data could have to their own research. Participants felt it was important to have clear descriptions of instrument sites and comprehensive summaries of each instrument. Key members of the current strainmeter community are encouraged to champion strain science. In addition, workshop participants stressed that changing the perception of strainmeters as having poor quality data is critical for the growth of the community.

Expanding Community. Traditionally the strainmeter community has been small with few researchers, who have focused on strainmeter instrumentation, strainmeter data and tools. The workshop participants collectively expressed the need to expand the mentor group working in strain science. One possibility put forth was to connect to the hydrology community focusing on using strain data for hydrologic studies. Another recommendation was to mobilize a specific group of expertise for a specific region or scientific goal and through these campaign efforts, broaden the awareness of strainmeters with the end goal of making strain science more visible.

Education Efforts. All workshop participants agreed that expanding the community requires reaching out to early career scientists and graduate students. Several participants urged expansion of the community by demonstrating the broader use of strainmeter data. Many of the education-related efforts can be cross-referenced with the efforts to improve documentation. Well-written documentation for researchers can also be used as a general education tool to graduate students and the scientifically literate pubic. Suggestions for increased education include a stronger presence on the UNAVCO website including an overview of strainmeters, an FAQ on instrumentation, data and tools. UNAVCO could also directly support student understanding of strain science and strainmeters by sponsoring interns during the summer, integrating strainmeter topics in the speaker program and incorporating strainmeter science into parts of the geodesy curriculum of universities. Including strain science in a curriculum would require partnering with the academic community to assist them such that the theory and practice could be taught to graduate students. Currently, there is a lack of strain expertise in teaching. Finally, more funds to support students in strain science to conduct research, publish and attend conferences could increase the exposure of the science as well as grow the community.

3.4.2 Provide Ideas For Future Strainmeter Short Courses Offered By UNAVCO

The second half of the working session focused on how to improve technical training associated with strainmeter instrumentation, strainmeter data and tools. Participants were asked to self-select into groups based on their expertise in strainmeter science: graduate students & early career, mid-career, and established scientists. The three groups discussed how to improve short courses and reported out collectively. Responses can be summarized broadly by: Levels of training, Delivery mechanism, Location and Content.

Levels of training. Workshop attendees were asked to "think outside the box" in terms of how training and education on strainmeter science should be delivered. Participants suggested workshops be targeted to specific audiences based on their expertise. Recommendations included offering courses focused on beginners, intermediate and expert or by level of complexity such as theory, preparation for analysis and problem solving. Providing an advanced workshop or discussion forum was recommended as a mechanism to engage researchers who are already working with strainmeter data but struggling to interpret data or gain confidence in results.

Delivery mechanism. There is a desire to maintain the fundamentals of the course but to present it in a more understandable way. This included having training sessions that promoted interactions between early career scientists and graduate students with established scientists. Interactions between these groups were identified as an important element of both continuing and expanding the community. Workshop participants stated it could be beneficial to explore additional or alternative methods of instruction.

Participants indicated interest in having a follow-up mechanism so that short course attendees had a way to interact with experts and course instructors after the short course concludes. Participants also expressed the desire to have the short course be as "hands on" as possible.

UNAVCO is encouraged to explore the possibility of online instruction. Online instruction could take the form of synchronous or asynchronous instruction. Additionally a blended, or hybrid, form of instruction could be considered. Blended instruction is that in which there is a combination of online and face-to-face elements. Online instruction would provide an avenue for training without participant travel. An online asynchronous component could cover basic information and a synchronous component would provide the opportunity for short course participants to discuss and cover basic questions. Blended instruction could provide efficiencies in instruction by allowing participants to conduct pre-work, such as reviewing basic theory and installing software. The face-to-face element would focus on delving into more advanced topics, processing data and recognizing good or bad signals. Online communications could continue after the conclusion of the face-to-face workshop providing avenues for interaction with instructors. Live and archived webinars on focused topics would provide a continuing resource to participants in the course and others interested in exploring strainmeters.

Location. This workshop was held in La Jolla, California at Scripps Institute of Oceanography, in part due to the proximity to the Pinyon Flat, San Jacinto Fault Zone. Workshop participants expressed that having the short courses close to strainmeter instrumentation would be a significant benefit to the participants, allowing them to visit the instrumentation and provide a more hands-on experience. Other suggestions included having short courses at AGU or other national meetings to leverage travel attendees might already be doing. Finally, having the short courses in areas of active tectonics or generally near strainmeter networks, such as at the Yellowstone Lodge in Yellowstone National Park, would provide venues with an instant connection to the larger science questions being addressed.

Content. Significant input was provided on short course content with several avenues of focus. One recommendation includes focusing on the most current strain science highlights of BSM publications and short presentations from PhD studies or reviews of the latest results and scholarly publications. Along this line of focus would be having courses devoted to case studies or general topics such as looking at challenges, problems and "low hanging fruit". A case study approach would provide a step-by-step methodology that would allow all short course attendees to go from raw data to the final result on two or three data sets. This could provide people confidence in their ability to use strain data. This methodology would focus on practice and obtaining results that can be reproduced.

There is a need to have better software tools for short courses as well as additional resources such as showcase wiki pages on stations of interest. Additionally, improved instruction materials and notes as well as a short course book and animations of data would be a learning asset to participants. Participants also stated short courses should focus more on sharing techniques and programs and less on theory and installing software.

4. RECOMMENDATIONS

CHALLENGES IN WORKING WITH STRAINMETER DATA

- A characterization of site noise should be made for each borehole strainmeter. This should include an examination of drilling logs to identify fractures near the strain gauges, a summary of the surrounding tectonic, geological and topographic setting, rainfall response and summary of cultural noise.
- An in-depth assessment of the long-term trends of each borehole strainmeter and an attempt to provide a physical model describing the trends using mechanisms such as poroelastic deformation or power law creep would improve the ability to distinguish strain transients from background noise.
- A paper summarizing the nature of long-term trends in BSM data and discussing methods of detrending and exploring physical models that underlie the trends would be beneficial to the community.
- Reduce the seasonal signal in PBO strainmeters by modeling the thermo elastic strains using the method developed by Ben-Zion and Allam (2012) for USGS BSMs.
- The response of the BSMs to large dynamic strains should be assessed. This should include a network wide comparison of recorded coseismic offsets, predicted offsets and GPS displacements in conjunction with examination of the borehole logs.
- Encourage the deployment of broadband instruments around PBO BSMs to determine a seismic calibration for each BSM.
- Release a definitive set of calibration matrices for each strainmeter for defined epochs of time thus relieving the researcher of the task of deciding the best matrix to use.
- Further study of the down-sampling techniques used by the PBO BSM data logger is recommended to understand the increased noise levels of the 1 Hz borehole strainmeter data.
- Compare the barometric response coefficients of USGS GTSM BSMs and PBO GTSM21 BSMs. This would serve as a comparison of sensitivity to vertical strain for the two instrument designs.
- A study of coupling of noise from the borehole strainmeter power system into the strain measurements could also pinpoint ways to reduce noise at higher frequencies.

DATA PRODUCTS AND TOOLS

- Provide high rate (1 Hz) processed strainmeter data in SEED format. This would reduce the workflow required to compare processed strain data with seismic data and possibly high rate GPS data.

- Provide a separate time-series in miniSEED format that removes the calibration pulse in the 1-Hz BSM strain data.
- Provide a tool that facilitates the download, processing and visualization of strainmeter data. Suggestions include developing a MATLAB toolbox and creating a package of existing command-line driven software.
- Create a web page containing a collection of data format converters and provide links to existing converter e.g., at IRIS or ORFEUS.
- Provide clear and concise web pages describing the various data sets and data products available to the researcher.
- A detailed data quality assessment of each strainmeter should be available on the UNAVCO web pages for researchers to access.
- Documentation pages should feature more prominently on the web site making it's discover more intuitive. Existing documentation should be reviewed and updated to give it a more consistent look and feel.
- Strainmeter Short Courses should continue to educate the community about the data sets that are available, data formats used and give instrumentation on how to access the data

Expanding the Strainmeter Community

- Providing more data processing tools and improving the accessibility of data are recommended as approaches to improving the ease of data access and use.
- Promotion of successful research published using strain data will inform researchers of the contributions strainmeter data could have to their own research. Key members of the current strainmeter community are encouraged to champion strain science.
- Expand the mentor group working in strain science by building connections outside the traditional strainmeter research groups and mobilize groups with specific expertise in specific regions or scientific goals with the end goal of making strain science more visible.
- Support student understanding of strain science and strainmeters by sponsoring interns at UNAVCO during the summer, integrating strainmeter topics in the speaker program and incorporating strainmeter science into parts of the geodesy curriculum of universities.
- Short courses should be tailored to focused on beginners, intermediate and expert data users or by level of complexity such as theory, preparation for analysis and problem solving.

- Short course should be as “hands on” as possible. Utilizing a case study approach, e.g., ETS events, would provide a step-by-step methodology that would educate attendees on how to go from raw data to a research-ready data set.
- Develop the use of blended instruction with a combination of online and face-to-face elements for Short Courses. An online component could cover basic information and theory while the in-class component would provide the opportunity for participants to discuss questions with instructors and other students.
- Online communications could continue after the conclusion of the face-to-face workshop providing avenues for interaction with instructors.
- Improved instruction materials and notes as well as a short course book and animations of data would be a learning asset to participants.
- Having the short courses in areas of active tectonics or generally near strainmeter networks would provide venues with an instant connection to the larger science questions being addressed.

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