Technical Report to Southern California Earthquake Center:

Piñon Flat Observatory:
Continuous Monitoring of Crustal Deformation

Report for SCEC Award — 15007

Submitted March 14, 2016

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Project Overview

A. Abstract
Crustal deformation measurements at Pinon Flat Observatory (PFO), and at other sites not supported by SCEC, provide data on otherwise unobservable deformation changes and the fault processes that produce them. In particular, we have identified a repeated pattern of rapid aseismic strain following large local earthquakes in 2001, 2005, and 2013 in the Anza area, as well as after the 1992 Joshua Tree, 1999 Hector Mine, and 2010 El-Mayor/Cucapah earthquakes - though not after the 1987 Superstition Hills or 1992 Landers earthquakes. We attribute this to triggered aseismic slip on the San Jacinto fault at seismo-genic depths. We have also observed longer-term strain changes, in particular from October 2010 through October 2011, that can be explained by aseismic slip equivalent to a magnitude 5.8 event at the location of the 2005 earthquake. Recently we have also (with others) using the longbase laser strainmeters at PFO to elucidate seismic wavefields, by comparing seismic data on them with theoretical models, with a local array of seismometers, and with shorter laser strainmeters using optical fibers. Results so far show a number of departures from the usual models of plane wavefronts, and near-uniform strain, suggesting local site effects even at this location of uniform geology.

B. SCEC Annual Science Highlights
Tectonic Geodesy, Aseismic Transient Detection, Seismology

C. Exemplary Figure
Right Panel of Figure 3 of Technical Report. Caption (from report text):
Two comparisons between the directly measured strain rates and and velocities estimated from a local seismic array (by Chen-Ji Lin of TU München), for two earthquakes with similar directions of arrival. The records show good agreement for the largest surface waves, with some attenuation of the highest frequencies on the LSM’s – but also, significant disagreements in the longer-period surface waves, whether in the early part of the wave train, for the closer event, or the G-wave pulse for the more distant one.

D. SCEC Science Priorities
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E. Intellectual Merit
This project continues the operation of the three longbase laser strainmeters (LSM’s) and one fully-anchored long fluid tiltmeter (LFT) at PFO. These systems have provided data that are unique in quality, completeness, and length, and give an unequalled view of aseismic and seismic deformations throughout the earthquake cycle.

F. Broader Impacts
This effort provides (I) paradigmatic datasets of strain and tilt used for training researchers in this field, or for new areas of research; (II) information on the design and construction of long-base and other sensors for future replication or improvement; and (III) a readily accessible field site that can be used as a training ground for undergraduate and graduate students in a variety of solid-earth studies.

G. Project Publications
1. Introduction

SCEC supports 18% of the costs of operating Piñon Flat Observatory (PFO), as part of monitoring strain fluctuations in southern California by producing high-quality strain data from longbase laser strainmeters (LSM’s). for monitoring strain fluctuations in southern California. All contributions are critical to continued operation – especially given the loss of all support for PFO from the U.S. Geological Survey (Section 2).

Continuous GPS networks in southern California provide broad coverage of the larger deformations: secular, coseismic, and postseismic. But these lack the temporal depth and high resolution of the complement of PFO recordings, which are the highest-quality continuous crustal deformation data available anywhere. These unmatched observations:

- Improve our understanding of crustal deformation over time spans from seconds to years, with high sensitivity to slip on the San Jacinto and San Andreas faults.
- Help fulfill SCEC science objective 5b, detecting transients (see Section 5).
- Provide independent measurements for comparison with continuous GPS, borehole strainmeters (BSM’s) and other methods of sensing strain (Section 4).

We have continued to focus on (1) making our deformation data as complete and reliable as possible; (2) monitoring pertinent auxiliary signals such as weather and groundwater; (3) making the data readily available; and (4) helping other researchers to use the site, which because of its established infrastructure can be done at very low marginal cost. A recent example of (4) is the installation of the dense seismometer array (PY network) installed for comparison with the rotational sensor already at PFO and with the LSM’s; Section 4 presents some results.

2. Financial Support of PFO

The total annual expense of running the PFO instruments, the telemetry network (over 95 devices online), and the necessary data processing, is $145K. The actual cost is somewhat higher; this amount does not include such contributions as UCSD’s support of Agnew (as faculty), and the Anza seismic network’s maintenance of communications at and to PFO.

The current and expected sources of non-SCEC funds for PFO operations total $121K These are, rounded to the nearest $1K:

- NSF support (a new grant) for the operation of the laser strainmeters at PFO ($70K); this is discussed in more detail below.
- The IRIS/IDA project, which operates a number of seismic systems at PFO ($20K); and the IGPP infrasound group, which operates infrasound arrays at PFO as part of the International Monitoring System CTBTO ($16K). Seismometer testing by two other sources is expected to provide $4K.
- IGPP funds $5K of Wyatt’s salary for PFO; IGPP’s Green Foundation is providing $4K for this year; Scripps matching funds are $2.4K (see immediately below).

Our support from the USGS, part of their NEHRP funding of geodetic networks, terminated on February 28, 2015, as part of their ending support for high-precision geodetic monitoring (strainmeters), whether inside the USGS or in the External program. This termination reflects the view of USGS program...
managers that high-precision geodetic monitoring, irrespective of its science value, is less relevant than other programs to the NEHRP-mandated goal of loss reduction. This decision terminated all USGS
support for PFO, and also for one of the two strainmeters at DHL (Figure 1); this instrument (DHL1) is now being supported by the PBO, in lieu of continued operation of the long-base strainmeter in Los Angeles (Glendale: GVS), which was turned off on May 20, 2015.

To make up the shortfall in PFO support, we submitted a proposal to NSF Instruments and Facilities to support operation of PFO for the duration of PBO’s current phase of operations and maintenance, that is through fall 2018. The argument for NSF to provide support is that the LSM data complement the GPS and BSM data that PBO will continue to collect over the next four years in the Anza area, which is – after all – seismically active, the location of a mature fault segment, and a much studied region. Our proposal was successful, and NSF will provide $70K/yr for the time requested; continuation of the PFO measurements after the fall of 2018 will become part of the larger discussion of the future of the PBO.

3. Other Laser Strainmeters and Data Access

Figure 1 shows the locations of LSM’s BSM’s, and continuous GPS in southern California, along with about 150 years of large earthquakes. PBO doubled the number of continuous GPS sites, added nine borehole strainmeters in the Anza area (based on the records from PFO) and installed five longbase strainmeters: one at DHL, two at Salton City (SCS), and two in the Cholame area. PBO currently supports operation of these five strainmeters and also the (formerly) NEHRP-funded system at DHL, which has operated since 1996,

We process the PFO strainmeter data using software developed with PBO funds; like the other PBO strainmeter data it is archived at the IRIS DMC.

4. Long-term Strain, and Strain Measurement Testing

Figure 2 shows PFO LSM data from 2008 on, with the times of the El-Mayor/Cucupah (EMC) earthquake in April 2010, and two earthquakes on the San Jacinto fault: a $M_w5.4$ shock (CV) three months after the EMC shock, and a $M_w4.7$ (Anza) beneath Toro Peak, south and very near PFO, on March 11, 2013 (2013:070). At PFO the initial strain reversed in rate within a few hours; since this was not seen elsewhere we attribute it to triggered aseismic slip closer to PFO, most likely on the San Jacinto fault. Similar rapid strain rates were observed after earthquakes in Anza in 2005 and 2001, and the 1992 Joshua Tree and 1999 Hector Mine earthquakes, a pattern found only because of the long-term measurements at PFO. Computing the strains induced at PFO by slip on different parts of the San Jacinto fault suggests that this could reflect aseismic slip on the fault at seismic depths and about 10-15 km NW of the 2005 Anza earthquake epicenter (see our earlier PFO reports to SCEC).

Figure 2 also shows some later and more enigmatic changes. In late 2010 all three strainmeters showed a compressional signal (2010.a), with the rate changes on the NWSE and EW strainmeters being about $-0.20\mu\varepsilon/yr$ (allowing for rain response in EW), and lasting for at least half a year. We view changes in the NWSE record as particularly significant given this instrument’s very low noise level. This pattern of deformation repeated in late 2013, and, over a longer time scale, during the last year.

At seismic frequencies we have recently been participating in a comparison between the direct measurements of strain provided by the LSM’s and strains inferred from differential motions of a dense network of seismometers at PFO. As mentioned above, this – IRIS network code PY – is comprised of 13 broadband three-component sensors, emplaced in boreholes (initially by the USArray Transportable Array program, for field testing of their procedures and equipment; the sensors and recorders have since been replaced). As shown in the map of PFO (left panel of Figure 3), four of these form a tight array around the seismic test facility vault (STF), with the specific aim of providing a comparison for the ring-
laser rotation sensor operated in the vault by the Technical University of München (Schreiber et al. 2009). The remaining sensors are located across the site also spanned by the LSM’s, so that seismic-wave gradiometry (Langston 2007, Langston and Liang 2008, 2009) can be applied to find the time-dependent displacement-gradient tensor and, from this, the strain and rotation. Since gradiometry requires differencing nearby records, even small errors in calibrations or other site-specific effects cause much larger errors than if we are looking at single station displacements.

The right panel of Figure 3 shows two comparisons between the directly measured strains and those estimated from the seismic array; because the seismic acceleration data used was corrected to velocity, the strain rates are shown rather than the strains. These estimates were made by Chen-Ji Lin of TU München. We show a sample of the data available, which so far includes three regional and teleseismic events recorded on all three strainmeters; this sample is for the two larger earthquakes, which have similar directions of arrival though very different distances. All the records show features similar to those seen here: good agreement for the largest surface waves, with some attenuation of the highest frequencies on the LSM’s (this may be a processing issue, since cross-spectra show a smoothly varying admittance).

But the most noticeable feature is the significant disagreements that appear in the longer-period surface waves, whether in the early part of the wave train, for the closer event, or the G-wave pulse for the more distant one. Since the LSM’s have a completely flat response down to zero frequency we are suspicious of some unidentified problem with the seismic data. One possibility is inaccurate calibrations at the longer periods; another one is the contamination of the horizontal acceleration by tilts induced by the strains themselves, which would be a larger source of error at the longer periods (Suryanto et al. 2006, van Driel et al. 2012). In any case we have an anomaly that needs to be investigated (which we are doing) – but more importantly, one which could not have been found at all at any other site: PFO is the only location with high-quality strain measurements made at the surface and thus minimally affected by strain-strain coupling.

Yet another comparison that can only be made at PFO is shown in Figure 4, which compares the vacuum-path EW LSM with the Trench Optical-Fiber Strainmeter (TOFS) that was installed parallel to it this spring (purple EW line in the right panel of Figure 3). A previous installation, parallel to the NWSE
LSM, confirmed that this instrument (much less expensive to build and operate) was practicable, but also revealed a number of gain and temperature sensitivity issues that this new instrument was designed to minimize. (An earlier SCEC grant sponsored the data analysis that allowed us to make progress on this.) In particular, this new system uses two fibers with different temperature coefficients, laid in parallel. By recording the signals from both fibers we can determine both the integrated temperature along the fiber and the strain, free of temperature effects. Testing is, already leading to improvements, and Figure 4 shows very promising results: the tidal signals are clearly visible in the TOFS data, with gain identical to the EW LSM; the difference shows only longer-period variations. These are very probably caused by some combination of residual temperature effects in the system’s shallowly buried reference length (fiber on a mandrel), and unanchored end-monuments. We are working to understand and reduce these effects even further.

As these examples illustrate, the unique capabilities available at PFO allow us to improve our understanding of a wide range of measurements and phenomena; this is something we seek to continue.
References


