Technical Report to Southern California Earthquake Center:
SCEC Award — 14173

Piñon Flat Observatory:
Continuous Monitoring of Crustal Deformation

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Frank K. Wyatt (fwyatt@ucsd.edu)

Duncan Carr Agnew (dagnew@ucsd.edu)

Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, CA 92093-0225

1. Introduction

SCEC supports 18% of the costs of operating Piñon Flat Observatory (PFO), as part of monitoring strain fluctuations in southern California. PFO continues to produce the highest-quality continuous crustal deformation data available anywhere, allowing us to:

- Improve our understanding of crustal deformation over timespans from hours to years, including coseismic, postseismic, and interseismic changes. PFO's proximity to the San Andreas and San Jacinto faults gives an unmatched sensitivity for detecting slip there. The long span of the PFO records provides a unique basis for identifying and evaluating new signals.
- Provide independent high-quality data for interpreting other records from continuous GPS and borehole strain. PFO data are freely available (Section 4).
- Provide a shared facility for the development of new technologies and new measurements: in the past year new rotational seismometers and fiber strainmeters.

Consistent with these goals, our priorities remain (1) ensuring that the records from the longbase sensors are as complete and reliable as possible; (2) monitoring important auxiliary signals, such as weather and groundwater; and (3) making the data readily available. In addition, we also assist other groups collecting data at PFO; since we visit regularly, we can provide modest support at very low marginal cost. A recent notable example is the dense borehole seismometer array (BPH) installed, tested, and reworked this year, by the USArray Transportable Array program (Bob Busby) for evaluation of installation methods and for comparison with the rotational sensor already at PFO and with the LSM's.

The SCIGN and PBO GPS networks have greatly improved crustal motion measurement in southern California, but unavoidably lack the temporal depth of the PFO data. The laser strainmeter (LSM) data are unique both in the time span covered and the high quality of the measurements.

2. Financial Support of PFO

The total annual expense of running the PFO instruments (and 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. Most expense is salaries, at $74K, or 0.73 FTE. (The FTE level has shrunk over time, since we have done

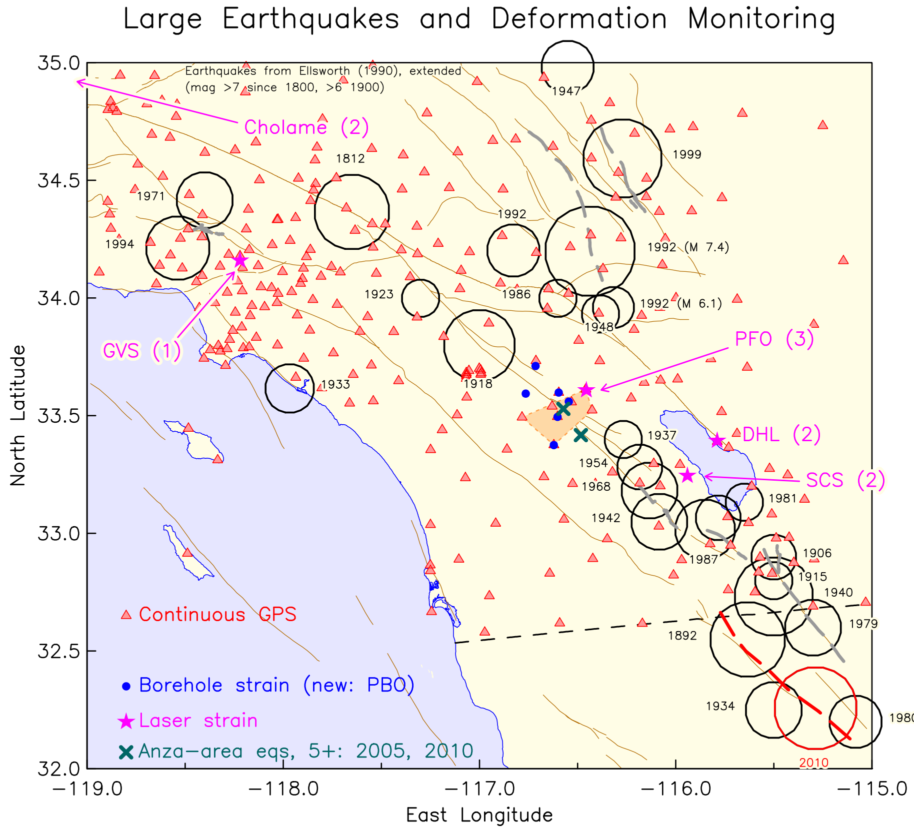

Figure 1: Map showing recent earthquakes and strainmeter locations.

all we can to keep the dollar amount fixed, and the UC benefits costs have grown.) The power bill is $15K. The annual cost for servicing/replacement of lasers, uninterruptible power supplies, and air conditioners is $17K. Travel costs (field vehicle) are $5K; and $4K covers other supplies, computer network charges, phone and other expenses. Off-campus overhead adds $30K.

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

- The IRIS/IDA project ($22K); the IGPP infrasound group ($15K), and seismometer testing by two other sources ($8K).
- IGPP funds $5K of Wyatt's salary for PFO; IGPP's Green Foundation is providing $4K for this year; Scripps Director matching funds amount to $2.4K.

Our long-term support from the USGS as part of their NEHRP funding of geodetic networks ended March 1, 2015, as did virtually all USGS support, external and internal, for high-precision geodetic monitoring. In the view of USGS program managers such measurements have less relevance than other programs to the NEHRP-mandated goal of loss reduction. We have submitted a proposal to NSF Instruments and Facilities for funds to provide support for: operation of PFO for the duration of PBO's current phase of operations and maintenance (through fall 2018). At this time it is uncertain how the PBO measurements will continue after the present O&M period.

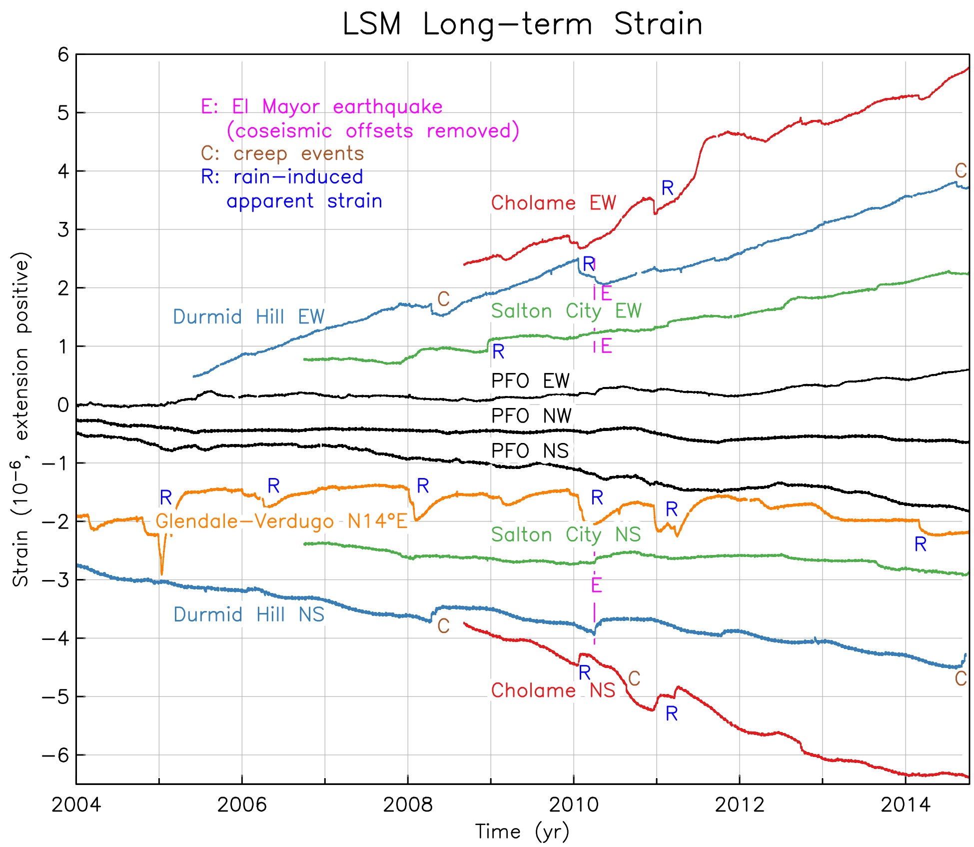

Figure 2

3. Other Laser Strainmeters

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 installed five longbase strainmeters: one at DHL, where the NEHRP-funded system has operated since 1996, two at Salton City (SCS), and two in the Cholame area. **Figure 2** shows all available long-base strainmeter data since 2004. In the strike-slip environment around the San Andreas fault the secular strains should be NS contraction and EW extension: exactly what we see, with the most rapid deformation closest to the fault. Longbase strainmeters thus record earth strain over the frequency range from seconds to many years.

4. Data Access

We process the PFO strainmeter data using software developed with PBO funds. PBO now archives its strainmeter data at the IRIS DMC; all the PFO LSM data, from 2008:058 onward, are also archived there, in the same format, and are accessible from the PBO laser strainmeter web-portal.[1]

5. Repeated Triggering of Aseismic Strain Events

A year ago we reported that PFO data had provided new evidence for aseismic strain changes and had led us to reinterpret data from the past two decades.

Figure 3 shows 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

[1] `http://www.iris.edu/pbo/processed/lsm/`.

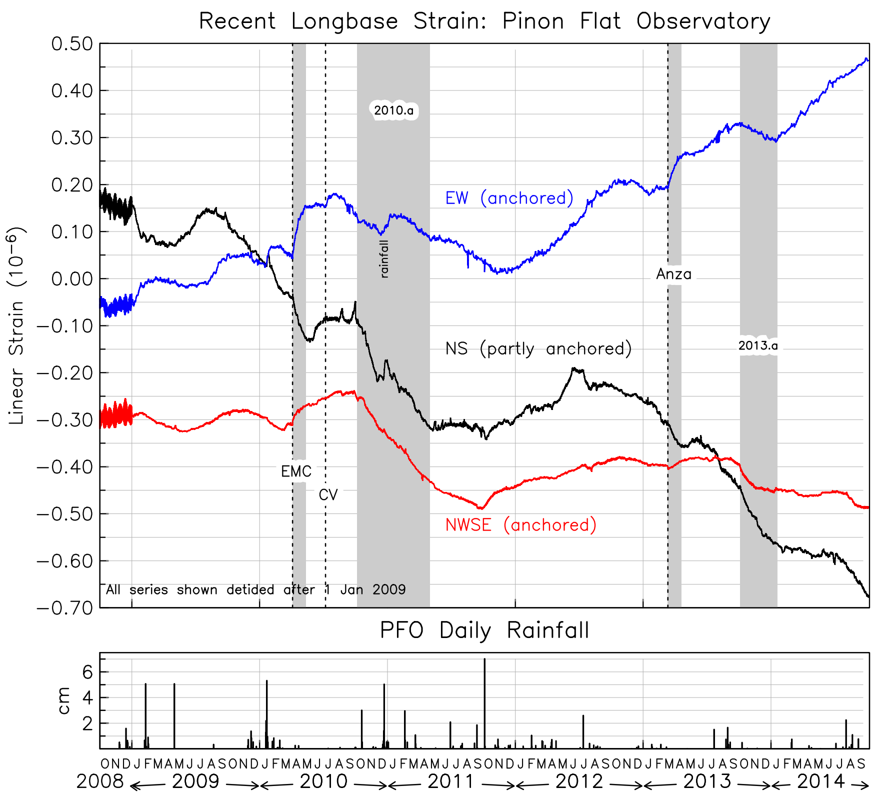

Figure 3

(2013:070). The EMC earthquake caused rapid but decaying strain changes at all the strainmeters south of Los Angeles. At PFO the initial strain rate reversed within a few hours, something not seen elsewhere, which we attribute to triggered aseismic slip closer to PFO, the San Jacinto fault being most likely.

Immediately after the March 2013 (Anza) earthquake, both the PBO-BSM's in the Anza area and the PFO LSM's showed rapid strain-rate changes. At PFO the BSM (B084) is located inside the area enclosed by the LSM's, but the systems are completely independent; both systems showed nearly identical increases in the fault-parallel shear strain ($e_{EE} - e_{NN}$) following the earthquake, with little areal strain (see **Figure 4**, top of each panel). Postseismic strain changes on the other PBO BSM's in the Anza area had significantly varied time histories.

Because the March 2013 changes did not initially appear to be decreasing, we alerted the USGS Pasadena office; after community discussion it was decided that a single and unprecedented result should not be the basis for an alert. Because we did not see a similar-sized change after the locally-strong 2010 Collins Valley (CV) event (the 'bump' in EW is actually later), we are confident that this is not some kind of purely local site response to shaking, but rather represents strains over a wider area. Computing the strains induced at PFO by slip on different parts of the San Jacinto fault suggests that the data on the LSM's could reflect aseismic slip on the fault at seismic depths and about 10-15 km NW of the 2005 Anza earthquake epicenter.

But the similarity between the 2005, 2010, and 2013 strain changes led us to review earlier data, especially from the NS and EW strainmeters; because of poorer anchoring we had given lower weight to these than to the NWSE. **Figure 4** shows that in the days to weeks after both local moderate events, and larger and more distant ones, there is a recurring pattern of strain change: an unexpected result, though also a very rewarding one because it shows how important long-term measurements are.

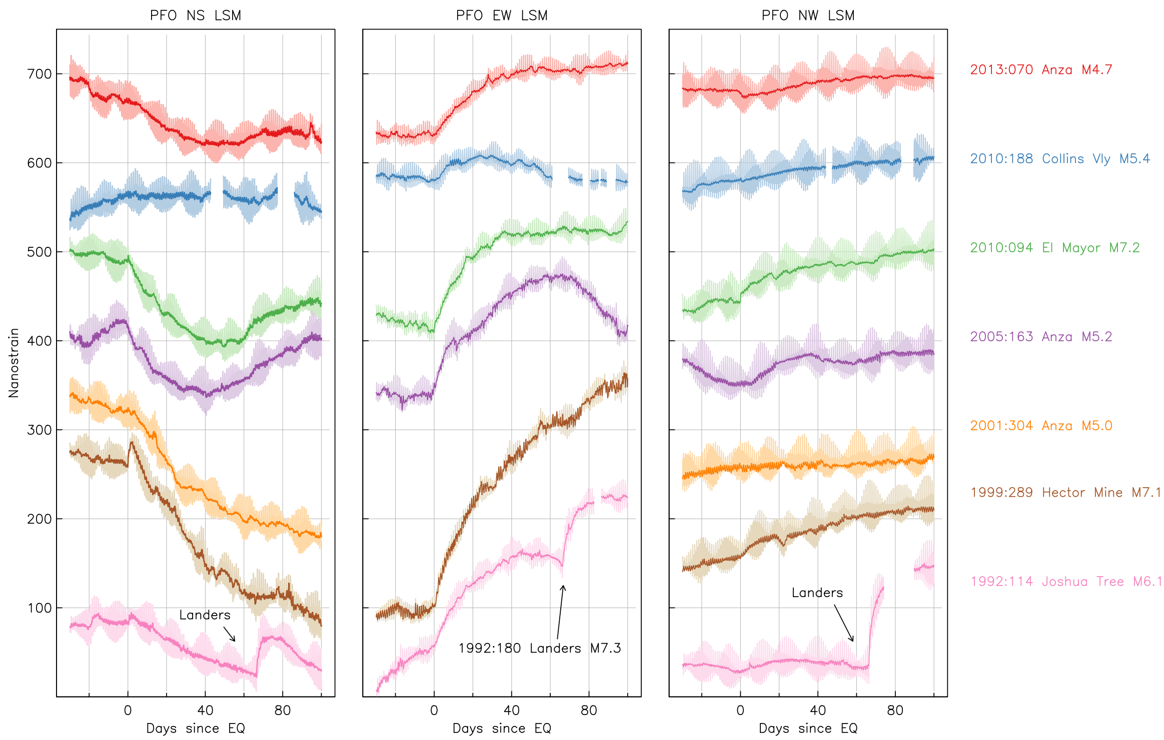

Figure 4

Within two months of the EMC event, long-term strain changes had returned to their previous behavior; but **Figure 3** 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. Variations in the NWSE record (**Figure 3**, red trace) are viewed with particular significance owing to the instrument's very low noise levels, and long-established consistent secular signal. Changes also appeared on the partially-anchored NS strainmeter and the 650-m EW long fluid tiltmeter. A source for this on the San Jacinto fault, close to the hypocenter of the 2005 Anza earthquake, would produce equal amounts of negative strain on the NWSE and EW strainmeters, but less on the NS strainmeter, with the changes seen being equivalent to a slow M_w 5.8 aseismic event: too small to be detected with the current GPS station distribution.

And this pattern of deformation repeated in late 2013 (2013.a), with all the longbase systems at the site responding similarly. In the absence of any known environmental factors (e.g., ground water variations, which are monitored), the earth at PFO registered deformation as it did in 2010. We are working with Dr. Peter Shearer to investigate the relationship of these long-term changes in the strain field, observed only through the long-term operation of PFO, to patterns of seismicity within the San Jacinto Fault system.

SCEC-Supported Publications

Agnew, D. C., and F. K. Wyatt (2014). Dynamic strains at regional and teleseismic distances, *Bull. Seismol. Soc. Am.*, **104**, 1846-1859, doi:10.1785/0120140007

Agnew, D. C. (2014). Variable star symbols for seismicity plots, *Seismol. Res. Lett.*, **85** , 775-780, doi:10.1785/0220130214