# The Role of Long-Base Deformation Measurements in the PBO

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This position paper addresses what role long-base measurements of strain (and possibly of tilt) should play in the PBO; it is parallel to the discussions of creepmeters by John Langbein and of pore-pressure measurements by Evelyn Roeloffs. Certainly, the primary tool of PBO will be GPS, and the next most important borehole strain; but, for the scientific questions PBO will address, are these two techniques sufficient as well as necessary?

To state our conclusions at the outset, we do not think so: long-base strain and tilt measurements have capabilities not otherwise available, and the possible range of transient phenomena demands that we use these sensors if we are serious about studying such phenomena. The problem is, of course, the high cost of long-base sensors. We think that this means that such sensors should usually be a part of larger clusters of GPS and borehole strainmeters. If the PBO project decides that transient signals over a wide frequency range are likely in some area, and on that basis plans a major investment in borehole sensors there, then part of of this investment should go into one or two long-base instruments. If short-term fluctuations are the primary target (as at volcanoes) then long-base sensors, while potentially useful, are a luxury.

There is nothing unusual in long-base instruments having both superior capabilities and higher costs: better performance usually comes at a higher price. Given a finite budget and many goals, we do not want to overspend on high-quality sensors when other ones would do; but equally we do not want to be too economical: if what we install cannot measure the phenomenon of interest, we would have been better off spending the money somewhere else.

Given that long-base measurements have lower noise than other sensors in the period range from months to a few years, are there phenomena present which can justify their use? An unequivocal answer is not possible—after all, if it were, we would not need to build the PBO to look for transients. While it might be that all transients have time constants shorter and longer than this period range, it seems pretty unlikely. And if aseismic transient deformations have the same size-frequency relation that seismic ones do, we will see many more of them if we use instruments with lower noise.

We discuss the capabilities of long-base sensors more fully below; as an illustrative parallel, we offer the case of the 1993 deformation anomaly at Parkfield. While the first evidence of this came from borehole tensor strainmeters (Gwyther *et al.*, GRL, 1996), later studies (Langbein *et al*, GRL, 1999; Gao *et al.* JGR, 2000) put considerable weight on the data from the 2-color EDM system because of its greater long-term stability. While the borehole data was suggestive, it is not clear how convincing a case could have been made without the two-color record. We see long-base data in an array of borehole sensors and GPS being used in a similar way.

The role of long-base instruments in the PBO can best be examined by looking at 3 questions:

1. What capabilities do such sensors have that are not possessed by others?
2. What class of problems call for these capabilities?
3. How do these capabilities trade off against the costs?

**Instrument Capabilities**

All deformation measurements are of differential displacement: long-base strainmeters measure over baselines of 0.1−1 km, borehole sensors over baselines $10^{-3}$ to $10^{-4}$ times as long, and GPS (in the PBO context) over baselines 10 to $10^3$ times as long. For each system, the limits to performance come less from design details (though these are important) than from the environment in which the system operates: in a borehole, at the surface of the Earth but in a controlled setting,[1] or (for GPS and InSAR) at the surface and in the atmosphere.

What performance do these environmental differences translate into? For periods of days and less, the long-base environment is more stable than the GPS one, and the borehole one more stable yet. The two types of strainmeters thus have noise levels much lower than GPS. GPS can provide data at these frequencies, but these recordings are so noisy as to be uninteresting. There is one exception, namely at the times of large coseismic offsets (and strong shaking). At such times the borehole environment may not be very stable: not uncommonly the large dynamic strains cause readjustments in pore pressure, something which the short baselength of borehole sensors makes them very susceptible to. Long-base systems, averaging over more of the volume, are less affected (Evans and Wyatt, Tectonophys., 1983), and GPS measurements even less.

Over years and decades the stability situation is reversed, partly from the environment, and partly from instrument design. The atmospheric changes that affect GPS matter less because over long times the atmosphere is more stable: the mean air pressure, temperature, and water vapor vary less from year to year than from day to day. But at such periods a borehole is not a stable environment; hydrologic fluctuations can induce pore-pressure changes. Borehole sensors also depend on the long-term stability of materials: not just inside the instrument (which can be controlled during manufacture) but also the bonding material (less easily controlled) and the recently-drilled stressed rock nearby (not controllable at all). Long-base strainmeters, like GPS, measure electromagnetic radiation whose stability is tied to atomic standards: something far less susceptible to long-term drift.

The tie to atomic standards makes GPS the best way to measure secular deformation, though this is also possible with long-base strainmeters: the shorter baselengths are compensated for by the more-controlled environment of the end points.[2]

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[1] Much of the cost and difficulty of long-base sensors lies in keeping a vacuum between the ends and a thermally-stable environment around them.

[2] It is sometimes argued that because laser strainmeters use interferometry, they cannot monitor long-term deformation, because if the fringe count is lost there could be an unknown amount of strain (analogous to a GPS cycle slip). This is not a problem in practice; if the fringes are lost from (say) a power failure there is little

How this all works out for instrument performance is that:

A. At periods from seconds to weeks and months, strainmeters, whether long-base or borehole, have much lower noise than GPS. (Sometimes this is put in terms of ‘‘sensitivity’’, a meaningless term if the noise level varies with frequency.) The two kinds of strainmeters are roughly equivalent, though the extreme stability of boreholes at short periods makes these sensors preferable for periods of less than a month. For recording seismic waves at 1 Hz and above, borehole strainmeters do not suffer from the spatial aliasing that affects long-base instruments (though the rationale for measuring strain in seismic waves is unclear). Neither type of strainmeter measures large coseismic offsets reliably: for this, GPS is superior.

B. For measuring strain changes over many years, especially secular strain accumulation, GPS is the tool of choice. That long-base sensors are capable of this we have demonstrated in installations at Piñon Flat and Durmid Hill (both discussed, with data plots, in our submission to the Snowbird meeting). So far as we know, reliable estimates of secular strain are not commonly made with borehole sensors.

C. Both GPS and borehole strain are quite capable of measuring signals in the period range from a month to a few years: the question is not bandwidth but noise level, since one gets noisier as the other gets quieter. Analyses of the spectra of the laser strainmeters show that these are up to 10 times quieter than the other available systems. The Landers postseismic signal observed on the NW-SE laser strainmeter at PFO (plotted in Figure 2 of the PBO paper in the IRIS newsletter) falls well below any of the signals detected with borehole sensors.

We can of course lower the noise of any sensor by combining data from more than one, as in the network filter of Segall and Mathews. However, the noise level would not decrease much more than a factor of $N^{-\frac{1}{2}}$ for $N$ independent sensors—and this level can be reached only if the candidate source is known.

One other performance issue should also be noted, namely the quality of rock required for good performance. Borehole sensors naturally work best in ‘‘good rock’’, ideally some kind of unjointed, massive rock. We have been able to operate a long-base instrument successfully in poorly-consolidated sediments, which would be difficult to impossible to emplace a borehole instrument in—though there are of course settings (alluvium, or alluvial fans) in which neither can be expected to work.

## Problems to be Studied

As noted above, it is difficult to be specific about exactly what transients we expect will be best seen with long-base sensors. As a partial guide to what can be done with these sensors, we offer the following list of what we have done with the instruments at PFO and DHL:

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ambiguity about how to interpolate across a gap. The only time geophysical information can be lost because of loss of fringe lock is from the very occasional large earthquake—but in such events GPS and InSAR record the coseismic effects quite well.

1. As noted above, we have recorded the secular strain rate, in agreement with geodetic measurements, at both PFO and DHL. Being able to do this gives us confidence in detecting any other fluctuations—as, for example, what appears to be a higher rate of secular deformation after Landers than before.
2. The same record shows the two-year-long postseismic signal from Landers, with rapid strain, slowing and then reversing before re-assuming the (higher) secular rate. Though we still do not understand this, in the sense of having a mechanism for it, it is the only observation that is, unlike the GPS and InSAR data, continuous and with a high signal to noise ratio.
3. For both the Landers and Hector earthquakes, we provided rapid-response strain-measurement capability. Because both caused seismicity close to the San Andreas, there was concern about triggering of that fault. In both cases we could say that the anomalous deformations, though present, were decaying—something that was quite reassuring to those who were deciding what warnings to issue.
4. As described in more detail in a separate proposal, we have used the instruments at DHL and PFO to measure the distortion in tidal and seismic strains due to the presence of the fault zone.
5. Finally, we believe that the long-baseline results have tended to change the view of what is likely: it seems that that deformation is not as dramatic as was sometimes thought. The design improvements that led to this result also led to our work in developing stable geodetic monuments.

**Costs**

As noted above, the high quality of data from long-base sensors comes at a price: higher capital and operations costs. We can compare these with the costs for permanent GPS, with which we are quite familiar.

The cost of a completed GPS site for SCIGN has been about $30K: $10K for the receiver and antenna, about $7K to construct a deep drilled-braced monument, and $13K for other installation costs. The operational budget for SCIGN works out at $6K for site per year; as this includes two analysis centers it may be thought high, but it does not include the replacement cost of receivers ($2K/yr if depreciated over 5 years). Note that a one-day site visit by a technician, fully burdened, is at least $500.

The capital cost of a long-base laser strainmeter, judged by our expenses for the planned instrument in Glendale, are about $450K for a single component. A large part of this is construction, especially drilling the holes needed for the optical anchors. Some of the rest is for materials, but most is for the kind of special-purpose machining, optics, and electronics needed for this type of instrument. Economies of scale are possible: a three-component system could be installed for about 2.5 times the single-component cost, and if multiple installations are made as part of PBO there will be significant economies from multiple production of components.

The operations costs of any sensor has three parts: replacement costs (depreciation), utilities costs (power and telemetry), and the labor cost of repair visits. Most parts of a long-base sensor (pipes, pumps, buildings, optics) have lifetimes measured in decades; the main items that need more frequent replacement are air conditioners, lasers, and occasionally electronics—the latter mostly when destroyed by lightning. Of course any of these replacements triggers the remaining cost, someone's labor to spend time fixing the problem. Failures requiring repair are often triggered by loss of power; our current laser strainmeter design reduces power requirements so that most of the system can run on an uninterruptible power supply. This is true of our installation at Durmid Hill (DHL), which regularly runs for several months without requiring intervention—though it must be said that when failures occur they are sometimes time-consuming to fix.

We estimate that the annual cost of maintaining/analyzing a single instrument (in isolation) to be about $30K, about the same cost as for 5-6 GPS sites, and this would be substantially lower if part of an array. We have also been making design improvements in conjunction with the instruments we are currently funded to build, and expect that these will further improve the picture.