DEEP BOREHOLE TENSOR STRAIN MONITORING, SOUTHERN CALIFORNIA

03-HQ-GR-0089

FINAL TECHNICAL REPORT
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TECHNICAL ABSTRACT

Maintenance programs have continued at both sites. Anomalous strain rate change reported at the San Gabriel site (Coldbrook) in the previous report has been confirmed at other sites in the local array. In depth analysis of on-going degradation of the Pinon Flat instrument indicates that it has reached the end of its useful lifetime. It is intended to continue maintenance and data archiving of the remaining channels at this site, while processes to reduce the site to a single channel instrument are investigated.

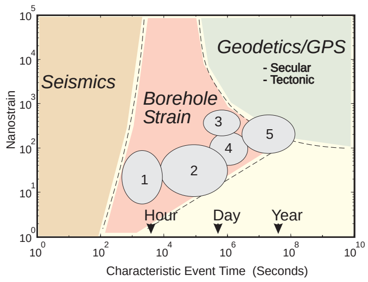


***Figure 1**.*
Effective detection capabilities of seismic,borehole strain, and geodetic instrumentation. The vertical axis is in units of strain, whilst the horizontal axis covers the period band from 1 second to 10^{10} seconds (100 years). GPS instrumentation will lower the boundary of the geodetic domain, but not significantly. For precise monitoring of short term strain rate fluctuations, there is a clear necessity for borehole strain instruments with nanostrain resolution in the minutes - months time scales. Data observed over the past 18 years have included identifiable episodes in each of the domains numbered 1 to 5

Objectives

This project continues a program of maintenance and analysis of deep borehole Gladwin Tensor Strain instrumentation (GTS) in southern California, with one site (Pinon Flat) installed in late 1983, and a second site (Coldbrook) in the San Gabriel mountains instrumented in late 1997. These instruments consist of a three component plane strain module operating at strain sensitivity of 10^{-10} and support data logging systems. They provide data sampling at 30 minute intervals for transmission via satellite for permanent archive purposes. Data are made available in near real time in the USGS Menlo Park computer system. These data supplement long baseline survey data, and permit real time monitoring for short term strain phenomena.

This project provides field observations critical to an understanding of fault processes associated with earthquakes along the San Andreas and Sierre Madre faults. Continuous high precision and high resolution borehole tensor strain data provide an essential complement to long baseline EDM studies (limited to sampling intervals of weeks), GPS studies, and seismic characterisation of faults.

The **immediate objectives** of the project are

- Maintenance of up-hole system integrity at the two southern Californian sites, with repair or production of replacement up-hole electronics if necessary.
- Manual preparation of raw instrument data for permanent archive.
- Analysis of continuous unique low frequency shear strain data (30 minute samples) and modeling studies based on the constraints of these data
- Near-real time alert response in the event of any major tectonic events in the vicinity of the two instruments.
- Archive of processed data for access by the earthquake studies community, and provision of near-real time automatically processed data for inclusion in publicly accessible web pages linked to the USGS web datasets.
- Surveillance of other relevant observation programs and integration of associated datasets from dilatometers, creepmeters, water wells, rainfall, atmospheric pressure, laser strainmeter and 2 colour interferometer studies
- Active participation in provision of instruments and expertise for the implementation of the Plate Boundary Observatory program

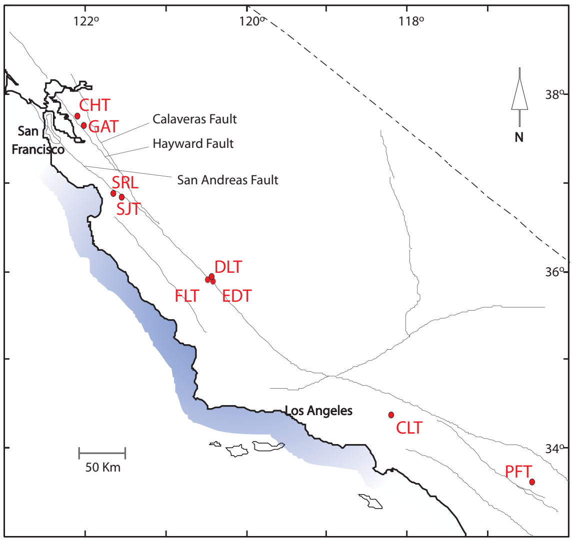


***Figure 1**. Borehole tensor strain sites in California. Sites DLT, EDT and FLT (installed in 1986) provide data for comparison with other Parkfield experiment instrumentation. Instruments at SJT (at the boundary of the northern locked section of the San Andreas fault) and PFT (colocated with the UCSD laser strainmeter at Pinon Flat observatory and with Sacks-Everton dilatometer SRL at SJT) were installed in 1983 The sites GAT and CHT on the Hayward fault were installed in 1992, and the CLT site in the Los Angeles basin was instrumented during late 1996*

Activities & Results

1) Plate Boundary Observatory.

A new activity during recent years has been to participate in the evolving Plate Boundary Observatory deliberations. We will provide our instrumentation and analysis capability as a core component for the PBO downhole strain work, and have been preparing for the production of larger numbers of instruments than have ever been produced. This has involved preparation of review documentation for the PBO Instrument sub-committee, production of higher quality documentation for design and fabrication, and attendance at the various focus meetings (eg. PBO workshops at Salt Lake City, Sept. 1999, and Palm Springs, Aug 2000, the Earthscope workshop at Salt Lake City, Oct. 2001, and various meetings of opportunity at AGU meetings). Though not funded directly by this project, these activities are a crucial project outcome because there are few qualified scientists in this area. We will continue to ensure that the technology developments of this program are available to the PBO deployment.

2) Data storage and availability.

Archived strain data from the Californian sites is stored in both raw component form, and as processed areal and shear strains. A regularly updated archive of data has been maintained in Australia with image copy in the USGS Menlo Park computer system since 1988. This data is stored in binary files with appended header information (USGS "*bottle*" format).

These data are accessible via the USGS personnel in *thecove:/home/mick/BASEDATA*. Automatically processed near-realtime data is produced and available in *thecove:/home/mick/QUICKCHECK* for USGS users with access to the *"xqp"* plotting software, and automatically uploaded to the USGS crustal deformation web pages in graphical form, managed by Stan Silverman. A fully maintained home page for download access to our source archive http://www.cat.csiro.au/dem/msg/straincal/straincal.html was established several years ago as a means to deliver quality archive support to the wider community. The raw instrument data are also forwarded to the raw data storage system which was established in 2000 on the U.C. Berkeley archive.

Scientists requiring further access to the archived data, other associated information or wishing to involve in collaborative effort in this area should contact Dr. M.T. Gladwin (+61 416 066 893 or by email *mike@gtsmtechnologies.com*.

3) Coldbrook GTS instrument

The Coldbrook tensor strainmeter was installed in the San Gabriel mountain region in late 1996, along with two USGS dilatometers at Chantry Flat and Big Dalton, to establish the initial elements of a borehole strain array spanning the previously identified high stress region between the Sierre Madre and San Andreas faults. The Coldbrook instrument is installed in competent granite at a depth of 100 m, and initial grout cure and hole readjustment processes were predominantly complete by 1998. Initial calibration is now complete. Strain data (Ea, Gam1 and Gam2) since that time are shown in ***Figure 3***. All borehole strain instruments exhibit exponential behaviour resulting from both adjustment of the instrument inclusion to the virgin stress field, as well as compression due to curing of the expansive grout used during installation. These exponentials are routinely removed from data in order to obtain the variations of the strain field of the surrounding rock.

In the thrust environment of the L.A. Basin, tilt measurements provide a critical complement to tensor strain data observations.Two component tilt modules were installed (with no Federal funding input) in the Coldbrook instrument in order to refine a borehole tilt system based on capacitive micrometry (as in the strain modules), and with pendulum suspension to provide tilt sensitivity of 10^{-9}. The data resulting from this new system are also shown in ***Figure 3***.

The gap in the data from August to December 2002 was due to a hard drive failure, repaired on the December field trip.

Plotted in ***figure 4*** with the tensor strains and NE tilt are the dilatational strains measured on the dilatometers of the San Gabriel array ***(figure 5)*** at Chantry (CN, 15km southwest of CLT), and Big Dalton (BD, 15 km southeast of CLT)and Punchbowl (PUBA, ~20km north of CLT), again with exponential signals due to hole recovery removed. Anomalies in the areal strain in March 2000 and March 2001 are correlated with rainy seasons in those years. The large offset in October 1999 is due to the Hector Mine earthquake.

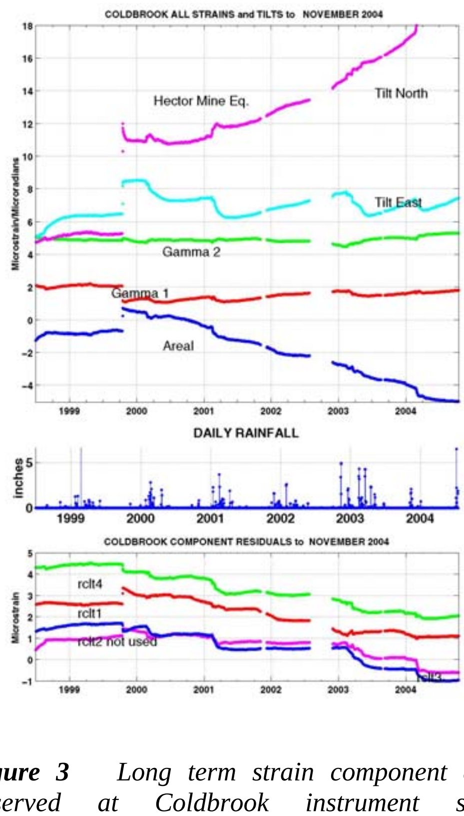


Figure 3 *Long term strain component data observed at Coldbrook instrument since installation, shown after removal of exponential hole recovery curves. Offsets in October 1999 were due to the Hector Mine earthquake, 100km to the northwest.*

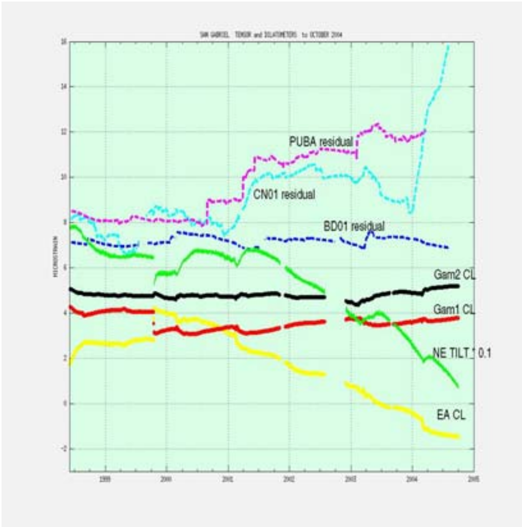


__Figure 4__ Data from Coldbrook tensor strainmeter from 1999. Changes in NE tilt, areal tensor, and dilatometers PUB, CN and BD can be seen since mid 2000.

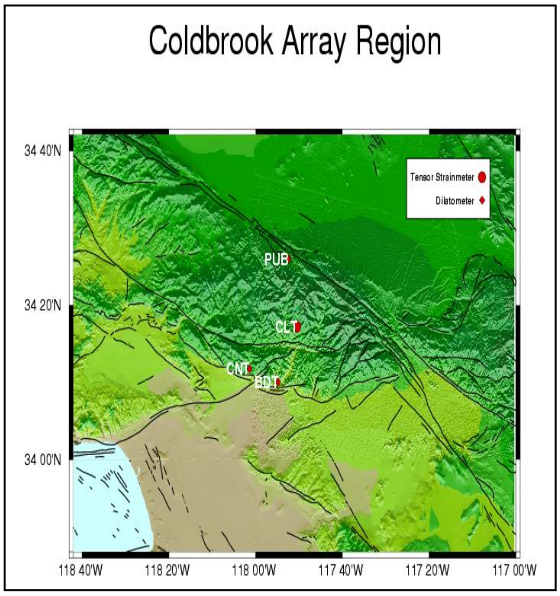


__Figure 5__ San Gabriel Array.

In the context of the three dilatometers, it is now clear that a series of anomalies occurred during 2001, evident on all sites over the interval March to June, and evident also in the NE tilt measurement. The strain trend rates established at that time have remained throughout 2004.

Figure 6 shows a short segment of data illustrating the hazards of siting borehole instruments alongside water courses, especially on steep terrain**. Coldbrook** is situated beside a waterway and in steep topography. It includes non-program tiltmeters as well as strain cells. Rain in any significant amount produces both strain and tilt response, probably by thermoelastic near-surface effects. The decay time for the effect is approximately one month. Most sites on strong topographic gradients show these effects, especially in the tilt.

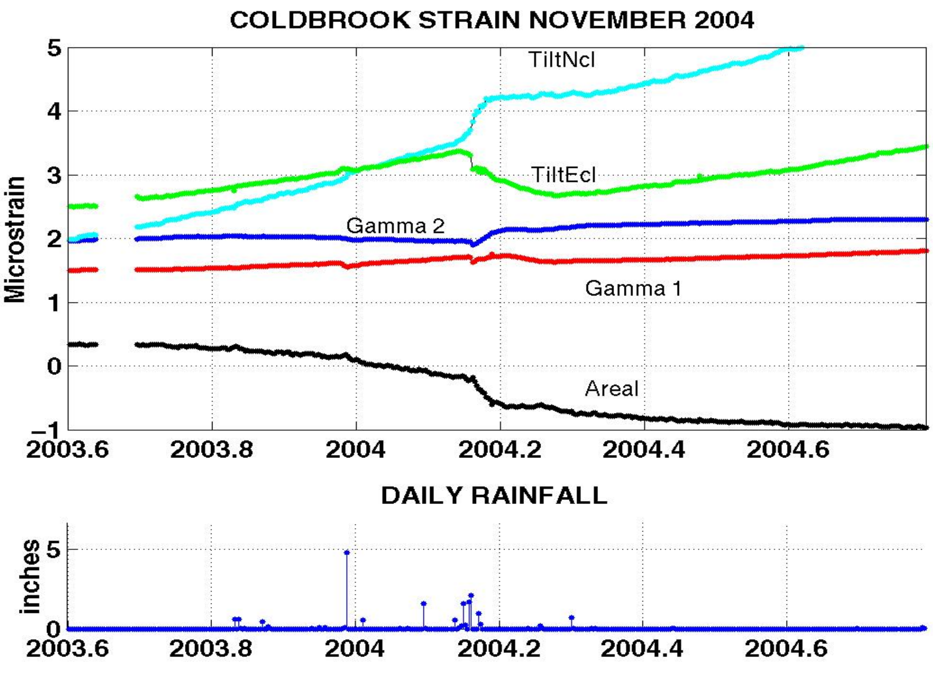


***Figure 6:** Coincidence of **flowing water** and strain and tilt signals.*

4) Pinon Flat GTS instrument.

The first Californian site instrumented was at the Pinon Flat Observatory of the University of California at San Diego. The instrument location was chosen for direct comparison of the results with both the long baseline interferometer spanning the site, and with a pair of DTM Carnegie Institution of Washington Sacks-Evertson strain meters. Installation in a stress relieved borehole at depth 151m in competent granite was completed September 16, 1983. The instrument hole was grouted to the surface to minimize thermoelastic contamination by the nearby circulation of ground water. The dominant long term change coincided with the North Palm Springs earthquake of July 8, 1986. Long term data in the period following 1986 is shown in ***Figure 6,*** with strain data shown in the upper panel, and raw component data in the lower panel**.**

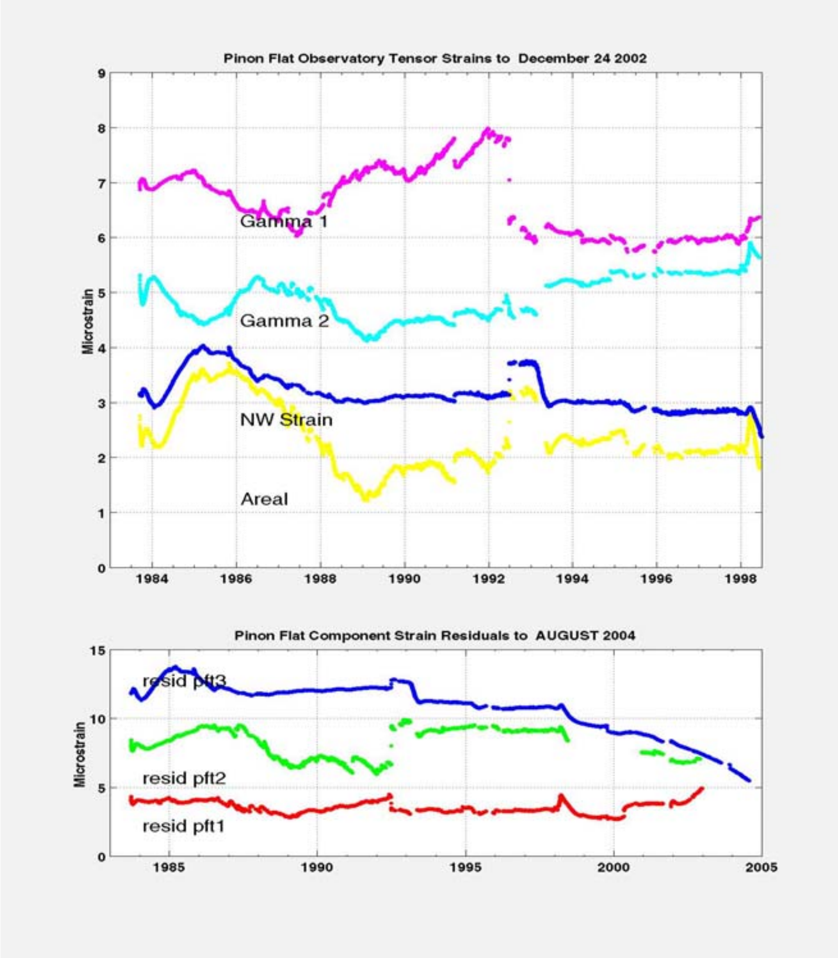
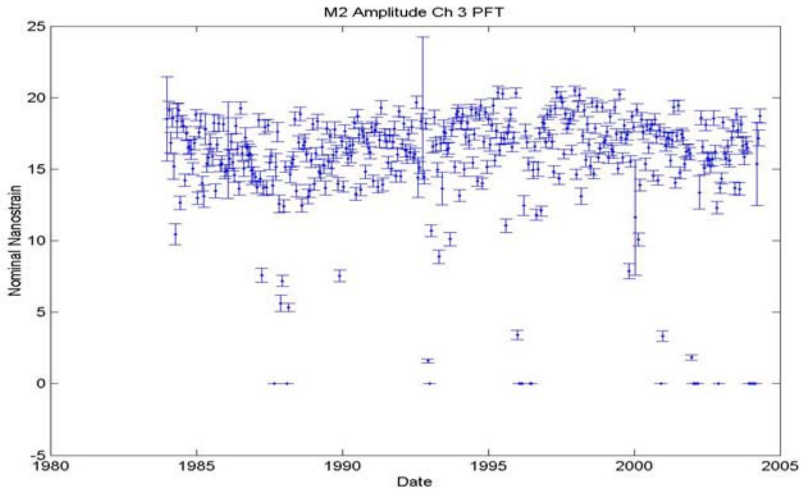


Figure 6. *Long term data observed at Pinon Flat borehole tensor strainmeter.Upper panel are tensor strains and converted NWstrain, Lower panel are residual components*

Pinon Flat BTSM instrument has suffered significant degradation **in gain** in Channel 2 from 1998 onwards, due to component failure in the downhole preamp (after 15 years of continuous operation and several lightning strikes) . The internal gain compensation system ran out of dynamic range in mid-2000. In December 2000 an uphole gain compensating circuit was installed on channel 2 in an attempt to continue normal operation to extend the 18 year dataset . September 1, 2001 produced another massive electrical storm during which all instruments at PFO were disabled. Again repairs were attempted during the December 2001 field trip, and again in late May 2002, but degradation has continued.

It is considered that this channel is now irrecoverable. Review of the field repair notes for the life of this instrument reveals that by December 1997, damage to the downhole system was suspected. Though failure of the gain compensation system occurred mid 1998, all channels post this date are suspect, because these pre-1980 instruments passively share bridge drive systems across channels downhole. Normal tidal data is still evident on channel 3, for which the amplitude and phase plots of 30day windows for M2 are shown below (**Figures 8a, 8b**).



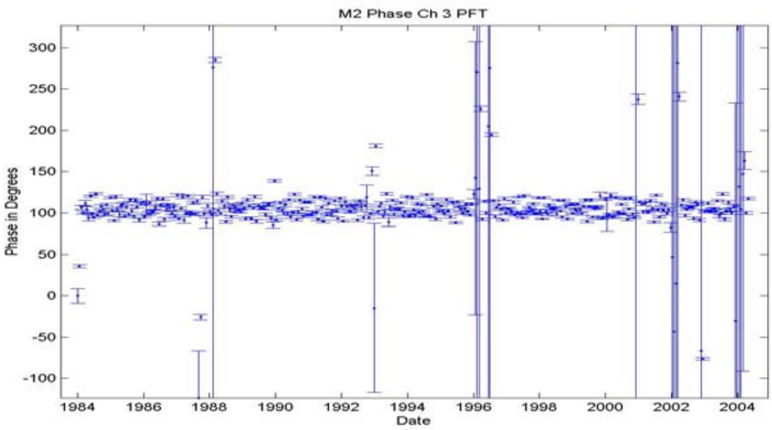


Figure 8a: *M2 amplitude for remaining channel 3 at PFT for past 15 years*
Figure 8b: *M2 phase for remaining channel 3 at PFT for past 15 years.*

The performance of Channel 3 at PFT is indicating probable failure sometime over the next 2 years. **Figure 9** shows the long term performance of a key internal verification signal since 1995 against temperature. The black trace shows the value of this parameter nominally 1000. The station has been showing a temperature associated variation and since 2000, has begun a systematic decline in gain . When the gain reading reaches 200, the compensation mechanism will no longer function, and the site will shut down.

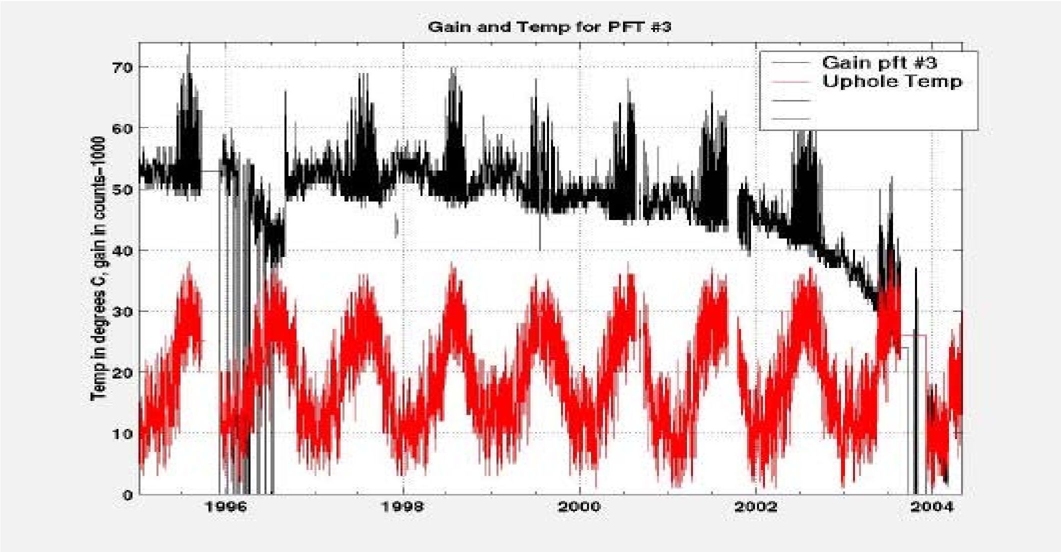


Figure 7: *Dynamic gain compensation parameter (black) for channel 3 vs temperature (red) for 10 years*

The PFT site was originally occupied in 1983 for a comparative investigation of GTSM instruments with Sacks-Everton dilatometers and the UCSD long baseline laser interferometer.

The Sacks-Everton systems failed before any long term comparison could be made. Two of the three components of the UCSD laser strainmeter are too unstable to allow direct comparison of long and short baseline instruments for anything but tidal measurements.

This leaves only the SE/NW laser component for the comparison.

Figure 9 shows the SE/NW laser data (supplied by Wyatt and Agnew) compared with the

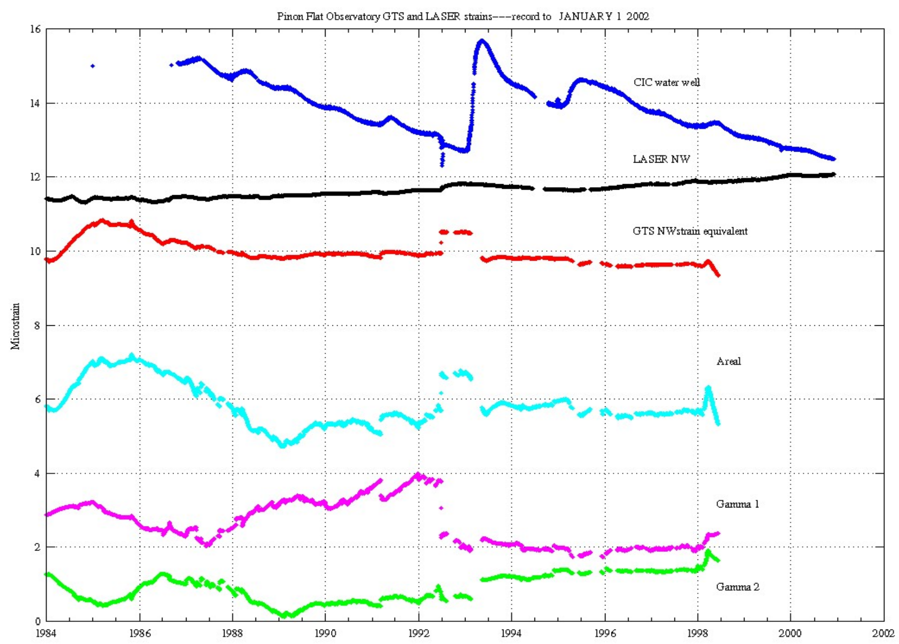


Figure 9: *GTSM areal(cyan), gamma1(magenta), and gamma2(green) are plotted together with inferred GTSM NWstrain(red),which should be compared with LSM NWstrain(black). Strain rate variations from the measured UCSD laser strainmeter over the period 1988 to 1998 are minimal.The blue trace is nearby water well CIC. Though channels 1 and 3 continue, loss of reliable channel 2 data post June 1998 eliminates tensor strains from this date.*

SE/NW strain inferred from the 3 component GTSM borehole data. For the 10 year period 1988-1998, the measured strain rate variation of the GTSM is different by less than 50ne/year from the absolute strain rate identified by the LSM. This is an important and fundamental result which confirms the long term stability of the GTSM system.

Both instruments show the influence of the CIC water level to different degrees

The GTSM data includes all major earthquake steps (Landers, HectorMine**{**see ***figure 6*** for channel 2 and 3 steps**}**) which are not included in the LSM data because of loss of line lock during the seismic wave arrivals,eg Landers.

A calibration method that incorporates cross coupling of remote areal/shear strains into instrument areal/shear strains has brought strain tides measured by the Pinon Flat GTSM (borehole diameter 200mm) into very good agreement with strain tides measured by the co-located LSM (dimensions ~1km). The cross coupled calibration has also yielded good agreement between the GTSM observations of the 1992 Landers earthquake and geodesy-based modeling, and co-located EDM measurements *(Hart,Gladwin,Gwyther,Agnew and Wyatt 1996).*

The short baseline GTSM instrument shows higher short period noise than the LSM throughout the record, as is to be expected.

It is intended to continue maintenance and data archiving of the remaining channel at this site, while processes to reduce the site to a single channel instrument are investigated.

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Acknowledgements

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