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A FLINN Station at Piñon Flat Observatory

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1. Objectives.

1. To develop Piñon Flat Observatory (PFO) as a prototype "integrated" FLINN station: one from which many types of data are collected, combined, and made available to the DOSE program to enhance studies of local and regional strains.
2. To develop the theoretical framework and methods to integrate the various types of auxiliary data which are to be collected by NASA at space-geodetic sites of the FLINN network, with the aim of learning as much as possible about the nature of earth deformation.
3. To develop procedures for the efficient and useful storage and retrieval of such auxiliary data so that they may be efficiently utilized by DOSE investigators.
4. To investigate the stability of ground monumentation now used in space-geodetic measurements, including the field testing of existing and new monument designs.

2. Observatory Operations

Our emphasis on operations at PFO has been on providing the best quality of data, and on improving the data-handling procedures. We believe we have performed well on both of these in the past year, though on the operational side we were still resolving a few problems remaining from the massive "Palm" fire which swept through the site in 1994. While most of the instruments (and all the critical signal handling and computer installations) were only briefly affected by the fire, it did seriously damage the three laser strainmeters and much of the distributed infrastructure. The University of California provided funds for rebuilding, which were largely completed in 1996.

2.1. Data Access

We record all the long-period signals at PFO on a datalogger that is downloaded weekly; these data are assembled automatically to produce the raw time series for all sensors. To provide real-time access to the strainmeter data, we also employ a telemetry system that places data in two locations: in an anonymous *ftp* area on ramsden.ucsd.edu, and (as plots) on a Web page (http://www-pfo.ucsd.edu).

It remains the case that considerable skilled post-processing of the data is needed to produce a true measure of earth deformation from many of the instruments at PFO. In previous years we improved our software for editing these data, at the expense of being up to date. All the major series are edited through the beginning of 1996.

3. Results

The publication list (Section 4) shows what has been accomplished with support from the existing grant; we summarize these briefly here, using numbers from the publication list to indicate where there is more information on various topics.

3.1. Deformation Measurement [1, 4, 7, 9, 13, 14]:

This is the area of our greatest effort, both in collecting and interpreting data. We have, in the laser strainmeters at PFO, instruments that are unequalled in their ability to detect deformation changes at periods shorter than a few months. Assembling the long-term data series from PFO has brought out several interesting features which were not obvious earlier. **Figure 1** shows a long span of data from what we regard as the best instrument at PFO: the NW-SE longbase laser strainmeter (the only fully anchored strainmeter), together with geodetic strain estimates from the USGS single-color EDM (Geodolite) through 1991 and two-color EDM through 1992. The performance of the strainmeter was being improved over the first few years shown; from 1988 through 1992 the strainmeter record is basically smooth and shows a rate of strain accumulation that matches remarkably well the rate deduced from the EDM data (which extend back to 1973). The Landers earthquake caused a large coseismic offset, which is *not* shown: the offset in the plot at the time of this shock is actually rapid aseismic strain accumulation which began immediately after the event. This rate decreased rapidly (with a time constant of a few days); this rapid decrease was followed by a slower decrease and finally a reversal of the strain rate. This reversal in rate lasted from late 1992 to 1995; in the last year of data presented, the rate has returned to its long-term average. While it may appear that this occurred when the strain had ''recovered'', this plot omits the coseismic change (about 1 μstrain) such that the actual strain level would show a large offset, with the apparent recovery signal small in comparison. The plot does suggest however that the long-term rate resumed when the immediate post-seismic strains were recovered which is a provocative result.

Figure 2 shows the same span of data from the EW long-base tiltmeter; though this is somewhat noisier than the strainmeter, it is an extremely stable tilt record. There are several artifacts in this data series: in late 1986, when an extension was added to this instrument, a mismatch in the densities of the fluids used in the original and extension caused an apparent offset and a multi-month recovery. In late 1990 one end vault flooded, destroying the installation; this was replaced by using the extension, which was already in place for testing of end-monument anchoring using optical fibers rather than vacuum pipes. This fiber anchor is not as good as the original vacuum-path system, especially in that it creates an apparent annual cycle; the overlap in time between the original installation and the new one shows the secular results to be the same. Keeping these artifacts in mind, the series do suggest changes in tilt rate: first in mid-1986 through mid-1992 the overall tilt decreases to near zero, slower than its long-term rate (1983-87) of about -0.10 μrad/yr. (The steep slope for 1985 is a fluctuation on this long-term rate). And then after the Landers earthquake, where we see an immediate post-seismic response nearly identical to that in the strain data, which is then followed by a tilt-rate reverting to 1983-87 levels. Because of the noise in this series, we cannot yet be certain if there has been a change in 1995 paralleling the one seen on the strainmeter. Based on the relative steadiness of strainmeter record we view these tilt-rate changes with suspicion; for there to be tilts without strains would require block-like deformation, for which there is no evidence in geodetic measurements in California.

In understanding these results we are aided by our recording of environmental series. **Figure 3** shows the water heights recorded in four boreholes at PFO (spaced 100-300 m apart, and drilled in 1982-83 for borehole strainmeters). All four show tidal responses, though of differing amounts—a reminder that in this environment (massive fractured granodiorite) such wells are better thought of as sampling the response of local fractures than as being in a uniform porous medium. This difference also holds for the long-term water-level changes: though all four show a decline followed by a relatively abrupt increase in 1993, it is clear that CIC has the shortest time constant, CIA the longest, and that UQA has a more complicated response. The increase can easily be explained in terms of rainfall: the winter of 1992-93 broke a several-year drought, with extremely high seasonal rainfall. Of more importance for interpreting the data in **Figure 1** and **Figure 2** is the lack of correlation between these groundwater changes and the deformation records: since the water-level rise in 1993 does not show on the strain or tilt records, we can be fairly secure in supposing that the fluctuations we do see in deformation are not the result of hydrological effects.

We can also rule out internal instrumental problems as explanations of the changes in strain and tilt. Over long times there is often concern that strainmeters drift; for the long-base strainmeters at PFO, whose length standard is a laser frequency tied to an atomic reference, the main sources of drift are the uncertainty in tying together data segments across loss-of-lock (which the instrument modifications mentioned above greatly reduce), and physical instability of the end-points. For the tiltmeter, which measures heights of a level fluid surface, only the last problem exists. We think that our anchoring is good enough not to be responsible for the variations we see (again, the lack of correlation with weather is telling), though perhaps deeper anchoring of the tiltmeter would reduce the longer-period noise.

These results re-emphasize that to get a complete picture of ground deformation, any large-scale GPS measurements need to be supplemented by other kinds of data such as the high accuracy records available from PFO. These results are particularly useful in corroborating (or not) models of deformation proposed from other types of recordings. For example (choosing from among three models proposed this year for southern-California strain-rate changes occurring over the past decade), data from the SCIGN network has been interpreted as showing a change in deformation rates between mid-1992 (Landers) until early-1994 (Northridge), relative to earlier and later data. The PFO data strongly support this notion, but with the indication that the resumption of long-term deformation, in this area at any rate, occurred nearly one-year later than suggested. As we in geodesy attempt to model these changes in terms of (for example) slip-rate variations on nearby faults, we will be best served by having the complete complement of recordings available.

Paper 1 shows another comparison for the nucleation phase of the Landers earthquake, illustrating that a strainmeter at even a moderate distance can provide more information about immediate preseismic deformation than a GPS system right at the epicenter.

3.2. Geodetic Network Design [5, 6, 8]:

Our initial efforts in this area were designed to determine how best to make campaign GPS measurements to determine fault parameters. The results showed the importance of minimizing monument motion (modeled as a random walk). This led us to extend these results (paper 8) to a continuous GPS network, with the finding that such motion must be minimized if the full benefits of continuous GPS are to be obtained. While the degree of random-walk motion has been disputed, it now seems to be generally agreed that minimizing it is crucial to network design, something being taken into account in the construction of the NASA-funded SCIGN project.

3.3. Geodetic Monumentation [8, 12]:

In concert with these theoretical studies, we have been developing designs for monuments which would have less motion than the conventional designs; several of these have been installed at continuous GPS stations in southern California, and have been adopted as the standard design for SCIGN. Paper 12 reports some results from our design, showing that it does provide substantially increased stability.

3.4. Tidal Loading [2, 15]:

We had compared ocean-load tides with previous funding under the Crustal Dynamics Program; further work in this area was not anticipated, but was restarted because of the appearance of new Topex/Poseidon-based tidal models.

4. Publications

We list here all the publications that have been supported, by the existing NASA grant. Most of these were supported directly, through the involvement of our group in the research; a few (such as numbers 10 and 11) reflect the general support of the PFO facility, without which the research would not have been possible.

1. Abercrombie, R. E., D. C. Agnew, and F. K. Wyatt (1995). Testing a model of earthquake nucleation, *Bull. Seism. Soc. Am.*, **85**, 1873-1878.
2. Agnew, D. C. (1995). Ocean-load tides at the South Pole: a validation of recent ocean-tide models, *Geophys. Res. Lett.*, **22**, 3063-3066.
3. Agnew, D.C., H. Johnson, F. Wyatt, and J. Langbein (1992). Comparison of GPS and two-color EDM measurements, *EOS Trans. Amer. Geophys. Union (Fall Suppl.)*, 121.
4. Bock, Y., Agnew, D.C., Fang, P., Genrich, J. F., Hager, B.H., Herring, T.A., King, R.W., Larsen, S., Minster, J.B., Stark, K., Wdowinski, S., Wyatt, F.K., (1993). Detection of coseismic deformation in southern California using continuous Global Positioning System measurements, *Nature*, **361**, 337-340.
5. Johnson, H., and F. Wyatt (1994). Geodetic network design for fault-mechanics studies, *Manuscr. Geodet.*, **19**, 309-323.
6. Johnson, H., D. Agnew, and K. Hudnut (1994). Extremal bounds on earthquake moment from geodetic data: application to the Landers earthquake, *Bull. Seism. Soc. Am.*, **84**, 660-667.
7. Johnson, H., D. Agnew, and F. Wyatt (1994). Present-day deformation in Southern California, *J. Geophys. Res.*, **99**, 23951-23974.
8. Johnson, H., and D. C. Agnew (1995). Monument motion and measurements of crustal velocities, *Geophys. Res. Lett.*, **22**, 2905-2908.
9. Johnston, M. J. S., A. T. Linde, and D.C. Agnew (1994). Continuous borehole strain in the San Andreas fault zone before, during, and after the 28 June 1992, *Mw* 7.3 1992 Landers, California, earthquake, *Bull. Seism. Soc. Am.*, **84**, 799-805.

10. Kohl, M. E., and J. Levine (1993). Measuring low-frequency tilts, *J. Res. N.I.S.T.*, **98**, 191-202.

11. Kohl, M.L., and J. Levine (1995). Measurement and interpretation of tidal tilts in a small array. *J. Geophys. Res.* **100**, 3929-3941.

12. Langbein, J., F. Wyatt, H. Johnson, D. Hamann, and P. Zimmer (1995). Improved stability of a deeply anchored geodetic monument for deformation monitoring, *Geophys. Res. Lett.*, **22**, 3533-3536.

13. Wyatt, F. K., D.C. Agnew, and M. Gladwin (1994). Continuous measurements of crustal deformation for the 1992 Landers earthquake sequence, *Bull. Seism. Soc. Am.*, **84**, 768-779.

14. Hart, R.H., M.T. Gladwin, R. L. Gwyther, D.C. Agnew, and F.K. Wyatt (1996) Tidal calibration of borehole strain meters - removing the effects of small-scale inhomogeneity, *J. Geophys. Res.*, **101**, 25553-25571.

15. Agnew, D.C. (1997). NLOADF: A program for computing ocean-tide loading. *J. Geophys. Res.*, **102**, 5109-5110.

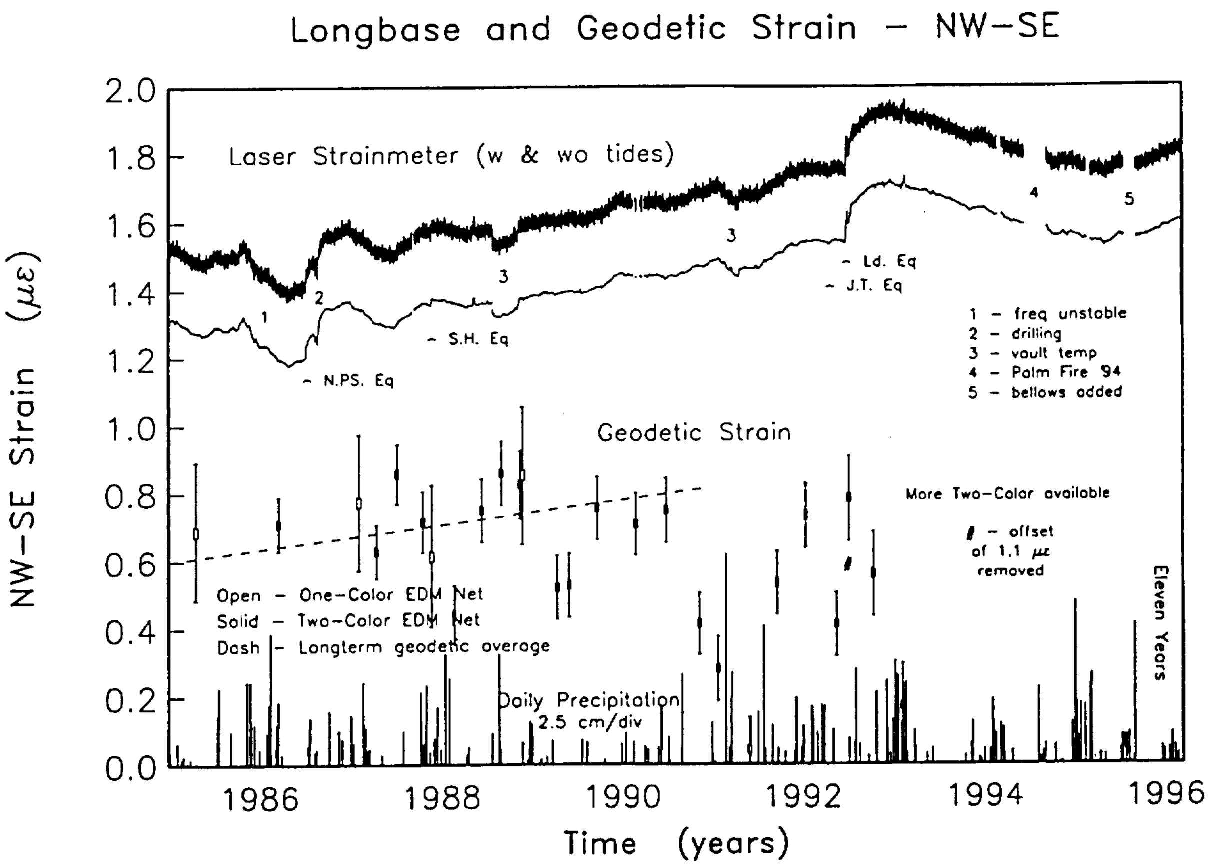
Longbase and Geodetic Strain – NW–SE
Laser Strainmeter (w & wo tides)
Geodetic Strain
NW–SE Strain (με)
Time (years)
1 – freq unstable
2 – drilling
3 – vault temp
4 – Palm Fire 94
5 – bellows added
– N.PS. Eq
– S.H. Eq
– Ld. Eq
– J.T. Eq
More Two-Color available
– offset of 1.1 με removed
Open – One-Color EDM Net
Solid – Two-Color EDM Net
Dash – Longterm geodetic average
Daily Precipitation 2.5 cm/div
Eleven Years

Figure 1

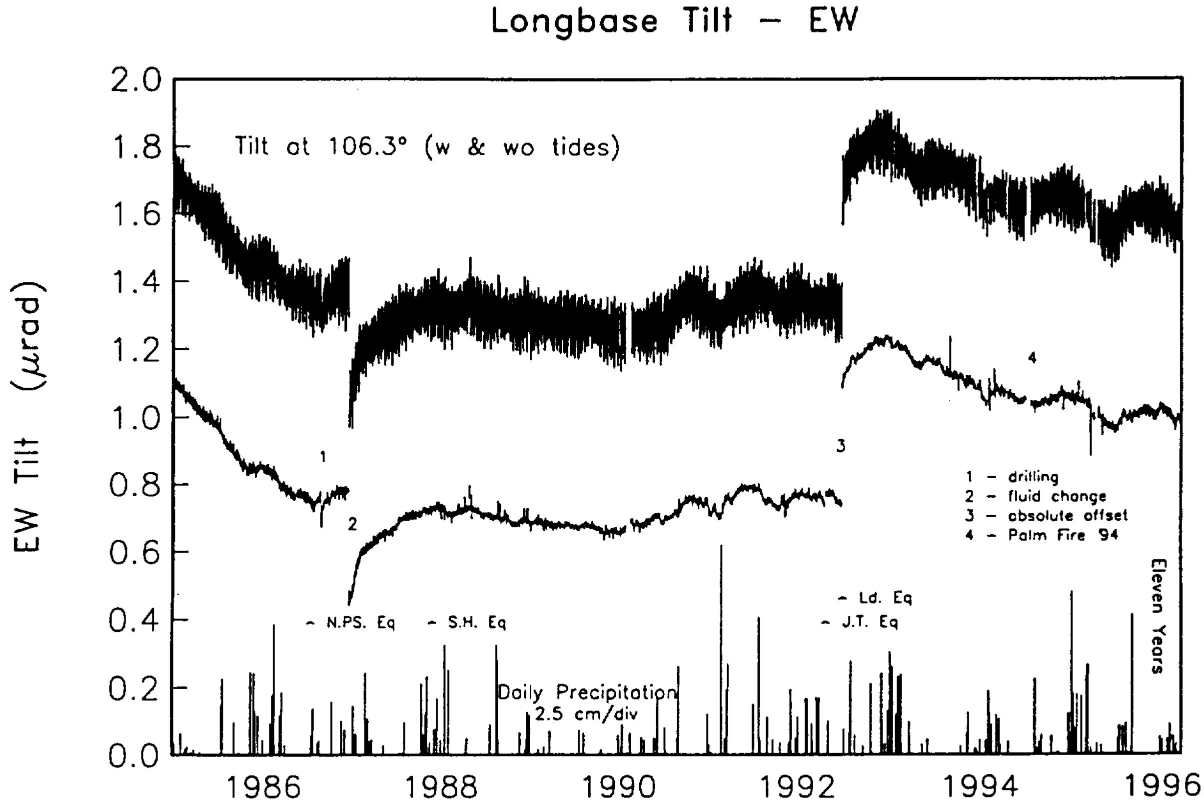

Figure 2

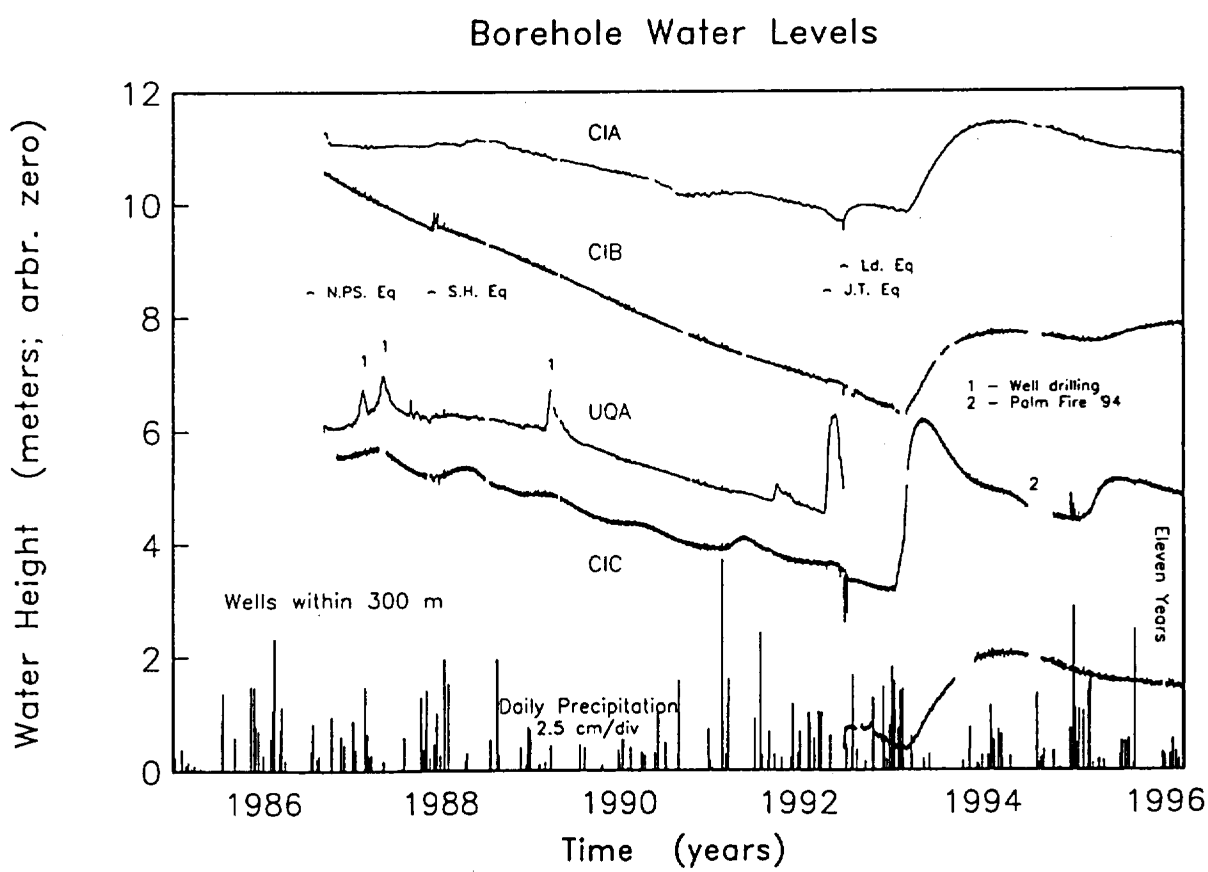

Figure 3