Strainmeter Calibration

Duncan Agnew, Frank Wyatt, M. Gladwin

1. Introduction

In order to interpret data collected by the PBO, all the instruments used will need to be calibrated; in the context of strain measurement, this means that we will need to know what deformation in the Earth corresponds to the different instrument outputs. Usually calibration is something ‘‘done in the lab’’ but this is not really possible for borehole strain. Because the surroundings of the instrument (hole and grout) affect the response, calibrations have to be done *in situ*. It is possible, as described in more detail below, to estimate the calibration in several ways. Unfortunately the errors in these ways can be larger than desirable; in particular, these errors can be so large as to make it impossible to check the different calibration methods against each other. Long experience suggests that such checks should be part of any instrument deployment, because they often uncover effects which might otherwise be overlooked.

In the next section of this proposal we outline the issues in borehole strainmeter calibration for those unfamiliar with them; the basic ideas are quite old (Berger and Beaumont, 1976; King *et al.*, 1976) but the first full layout of them in the context of borehole strain measurement was by Hart *et al.* (1996) . In the final section we describe a pair of plans to help check calibration models: an installation of PBO borehole strainmeters at Piñon Flat Observatory (PFO), and a transportable long-base strainmeter to establish calibrations for borehole strainmeter clusters elsewhere in PBO.

2. Borehole Strainmeter Calibration: Finding the Coupling Tensor

A borehole strainmeter measures some components of the horizontal strain tensor $\mathbf{E}_I$ within the instrument casing. This internal tensor will be related to the external strain $\mathbf{E}_E$ by

$$\mathbf{E}_I = \mathbf{C}_t \mathbf{E}_E$$

where $\mathbf{C}_t$ is the fourth-order strain-strain coupling tensor. For the discussion which follows, it is useful to consider $\mathbf{C}_t$ as the product of three other coupling tensors

$$\mathbf{C}_t = \mathbf{C}_b \, \mathbf{C}_l \, \mathbf{C}_r$$

where $\mathbf{C}_r$ relates the strain on large scales (10 to 1000 km) to the strain over approximately 0.5 to 1 km, a dimension comparable to the depth of burial. $\mathbf{C}_l$ relates this local strain to that on the scale of the borehole (≈ 1 m), and $\mathbf{C}_b$ in turn relates the strain on this scale to that at the instrument envelope, including the inhomogeneity created by the instrument in a grouted hole. (We assume that relating deformations of the instrument envelope can be related to output signals through laboratory calibrations). In an ideal world $\mathbf{C}_l$ and $\mathbf{C}_r$ would both be the identity tensor $\mathbf{I}$; in actuality both will depart from $\mathbf{I}$ because of lateral heterogeneity and topography (for $\mathbf{C}_r$) and local fractures or anisotropy

($\mathbf{C}_l$, mostly).

Neither $\mathbf{C}_l$ nor $\mathbf{C}_r$ can be modelled, since we do not have adequate knowledge of the local structure. A calibration can then be done in two ways:

A. We may assume an *a priori* model for $\mathbf{C}_b$ based on instrument and hole parameters (elastic constants and sizes) and take $\mathbf{C}_l$ and $\mathbf{C}_r$ to be equal to $\mathbf{I}$. If the instrument and hole are cylindrically symmetric, then $\mathbf{C}_b$ is an isotropic tensor; by the same arguments used in elasticity theory, $\mathbf{C}_b$ can then be written using two constants, one for areal strain and one for shear, which can be found from elasticity theory (Gladwin and Hart, 1985) . If there is any departure from cylindrical symmetry, $\mathbf{C}_b$ will have 9 components (independent in the most general case), and finite-element modelling will be required to determine these.

B. We can use any known strain signal; in practice the only one available is the solid Earth tides, which have a very long wavelength, making the strain effectively homogeneous. But the accuracy of such a calibration is limited by two considerations:

    1. Modern models of the body tides, the ocean tides, and the loading Green functions have some uncertainty. They are probably accurate to a few percent in many cases, but this is not always so. Table 1 shows the calculated strain tide at San Juan Bautista, for three model ocean models and two Green functions, computed using the SPOTL programs (Agnew, 1996) and shown as the percent difference from one result.

Green function	Ocean Model	% difference from reference result		
		EW	NS	Shear
Continental	CSR3.0	0.0	0.0	0.0
Continental	FES95.2	8.0	1.1	2.1
Continental	TPXO.2	6.3	0.7	1.3
Average	CSR3.0	15.5	1.1	5.2
Average	FES95.2	10.9	1.2	3.7
Average	TPXO.2	22.2	1.8	5.6

    For one of the components at this site the variations are about 1%, because the ocean load and body tide happen to be in phase; for the other two the variations are much larger. Such differences will limit the accuracy of determining $\mathbf{C}_t$ from the tides.

    2. Beyond any problems with the tidal models, there will also be an unknown error if the strain of interest—say, strain from a fault slip event—does not have the same spatial wavelength as the tides, which provide nearly homogeneous strain on scales of 10^2 km and more. If the strain of interest is not homogeneous on this scale, the tidal calibration will be more or less inapplicable.

Method B will perhaps be adequate as a calibration, but the number of assumptions in both methods means that we will not be in a good position to verify our understanding of the instrument response by comparing them with each other. If the results from A and B differ, it could suggest either that $\mathbf{C}_l\mathbf{C}_r$ is not close to the identity tensor or that $\mathbf{C}_b$ is not what we thought it was. Besides inadequate models, possible reasons why $\mathbf{C}_b$ might be different from a theoretical value include a noncircular borehole, an instrument not centered in the hole, and voids in the grout: all examples of things we would want to know about.

3. Improving Calibrations with Long-base strain Records

Any way in which we can reduce the uncertainty of empirical calibrations, by knowing the strains exactly, will make the interpretation of borehole strainmeter data less ambiguous, and allow us to do a better job of testing the adequacy of our modeling of $\mathbf{C}_b$. We can accomplish this if we calibrate borehole strainmeters not against the theoretical tides, but against the tides measured by a long-base strainmeter located on the surface at the same site. This eliminates uncertainties from the tidal models, and also reduces the problem of calibrating against strains that are more homogeneous than what we expect from nearby faults: on a 1-km scale any likely source strains will be nearly homogeneous.

All we need for this is to know the tidal strains on a 1-km scale—and this is what long-base instruments are very good at determining. Their length scale is right for the problem, and their own calibration, being based on the wavelength of light, is good at the 0.1% level. Since they operate on the surface they are not affected by the cavity effects which trouble both borehole strain measurements and those in caves or tunnels.

3.1. A Comparison at PFO

One place where we have very good measurements of the tides on this scale is at PFO, not just in strain but in tilt as well. There is no other location at which this is true. We therefore propose that one of each type of borehole instrument be emplaced there—especially for any new design being considered—as a calibration test, comparing methods A and B.

One concern is of course that we cannot really test $\mathbf{C}_b$ alone, but only $\mathbf{C}_b\mathbf{C}_l$—though this is true everywhere. We have some reason to suppose that $\mathbf{C}_l$ might not depart too far from $\mathbf{I}$ at PFO. The material at 100 m depth is unweathered granite, with a relatively low level of fracturing (Fletcher *et al.*, 1990) so that we would not expect major perturbations from that source. Anisotropy is no doubt present, but can be at least bounded using the many seismic measurements made at the site with three-component arrays. We can also get an idea of the possible departure of $\mathbf{C}_l$ from $\mathbf{I}$ using the estimates in Hart *et al.* (1996); assuming $\mathbf{C}_b$ to have been correctly modelled, and using their estimate of $\mathbf{C}_b\mathbf{C}_l$, we find, for the strain parameterized as $(e_A, \gamma_1, \gamma_2)$

$$\mathbf{C}_l - \mathbf{I} = \begin{pmatrix} -0.012 & -0.088 & 0.149 \\ -0.012 & 0.034 & -0.281 \\ 0.056 & -0.231 & -0.055 \end{pmatrix}$$

which indicates that the effects are generally not large.

Since several open boreholes suitable for borehole strain installation already exist at PFO, and most of the signal-recording infrastructure is in place, the cost would be just that of the instruments to be installed—though it might be a good idea to drill new holes to take advantage of any advances since the existing holes were drilled (in 1981).

3.2. A Transportable Long-Base Strainmeter

To get a good local measurement of the tides, which have amplitudes of 3×10^{-8}, we need 10^{-9} resolution; as this is 0.01 mm over 10 km, geodetic techniques are not adequate. A laser long-base strainmeter is. Several years ago we therefore proposed to NSF to build a long-base instrument specifically for tidal measurements. This was done with a combination of NSF-I&F and University funds, with much recycling of old equipment (due to limited funding), and installed at Durmid Hill (DHL), close to the San Andreas fault, to look for fault-induced effects on $\mathbf{C}_r$. In designing the instrument we aimed to minimize the installation and maintenance costs; and make the instrument as ‘‘portable’’ as possible, by making sure that everything not sunk in the ground could be removed and re-installed elsewhere.

The basic design is a Michelson interferometer with one arm spanning an extended (and evacuated) path: the displacement between the two ends is measured continuously by counting interference fringes. The end-buildings are shipping containers with all electrical wiring, air conditioning, electronics and optics installed. The vacuum pipe is installed above ground: it takes about 3 days to survey in the pipe supports, install them, and place the pipe. Since we are not trying for long-term stability (but do need to be decoupled from the surface layers) the end-monuments are built using inclined and vertical rods driven to 6 m depth and isolated from the material around them to a depth of 1.5 m. Compensation for the varying length of the vacuum pipe was done using automated telescopic joints, available from several of the PFO strainmeters.

This instrument has given tidal records good at the 1% level with a few months of data, clearly showing that $\mathbf{C}_r$ is further from $\mathbf{I}$ close to the fault, at DHL, than it is at PFO. It has also been a success in requiring little attention and in being easy to set up in a new azimuth (it has been run at two azimuths at DHL).

For use in PBO, we would want to refurbish some of the older, hard-to-use parts of the instrument and make the make the system more portable. We would estimate this could be done for $120K. To make measurements in 3 azimuths at one site would take a year and cost approximately $90K (approximately $45k for the initial set-up and $22.5k for each move at a given site, operations and analysis included): about the cost of one borehole strainmeter. We therefore suggest that such a calibration exercise be part of any extensive cluster of borehole strainmeters, and be viewed as part of the deployment cost—just as calibrating an array of seismometers is part of the cost of deploying them.

References

D. C. Agnew, “SPOTL: Some Programs for Ocean-Tide Loading,” SIO Reference Series 96-8, p. 34 (1996).

J. Berger and C. Beaumont, “An analysis of tidal strains from the United States of America, II, The inhomogeneous tide,” *Bull. Seismol. Soc. Am.*, 66, p. 1821−1846 (1976).

J. Fletcher, T. Fumal, H.-P. Liu, and J. C. Carroll, "Near-surface velocities and attenuation at two boreholes near Anza, California from logging data," *Bull. Seismol. Soc. Am.*, 80, pp. 807-831 (1990).

M. T. Gladwin and R. Hart, "Design parameters for borehole strain instrumentation," *Pure Appl. Geophys.*, 123, p. 59−80 (1985).

R. H. G. Hart, M. T. Gladwin, R. L. Gwyther, D. C. Agnew, and F. K. Wyatt, "Tidal calibration of borehole strainmeters: removing the effects of local inhomogeneity," *J. Geophys. Res.*, 101, pp. 25553-25571 (1996).

G. C. P. King, W. Zürn, R. Evans, and D. Emter, "Site correction for long-period seismometers, tiltmeters, and strainmeters," *Geophys. J. R. Astron. Soc.*, 44, p. 405−411 (1976).