Calibrated Plate Boundary Observatory Borehole Strainmeter Data
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Plate Boundary Observatory Borehole Strainmeters

The Plate Boundary Observatory (PBO), funded by NSF as part of the EarthScope program, includes 75 borehole strainmeters (BSMs) which makes it one of the largest strainmeter arrays in the world (Figure 1).

The purpose of strainmeters in PBO is to capture short-term strain transitions. They are fulfilling this role by measuring ET5 signals, asseismic creep events, hydrological transients and small coseismic offsets.

To incorporate the data into geophysical models the instruments need to be calibrated. Currently PBO uses the manufacturer’s lab calibrations, we propose expanding the processed data set to include in-situ calibrations. Here, we present the results of in-situ calibrations using the Earth tides.

Why is Calibration Needed?
The elastic properties of the strainmeter and grout never exactly match that of the surrounding rock. Hence, the raw instrument measurements may not be a measure of the regional strain. But, the strainmeter can be calibrated by comparing the recorded strains with a reference strain signal. We use the Earth tides as the reference strain.

We compare the amplitude and phase of the M2 and O1 Earth tides recorded by each of the 4 strain gauges (Figure 4) with predicted tidal and shear strain tides to determine a matrix of coupling coefficients that relate the gauge measurements to the regional strains. We examine the difference between calibration matrices when we assume (a) the BSM is installed in an anisotropic medium and (b) an anisotropic installation but apply physical constraints on the calibration.

Method
First we determine a calibration matrix assuming the most general case, anisotropy (see Strain Formula Box). Then, we repeated the process but apply physical constraints suggested by Gladwin and Hart (1985) and Roeloffs (2010) to produce the constrained anisotropically calibrated strain. We then compare the calibration matrices. We analyzed 2 years of data from 59 BSMs using the following steps:

1. Extract M2 and O1 tides from the strain data. Use BAYTAP-G (Tamura et al., 1991)
2. Predict the regional M2 and O1 strain signals. Use SPOTL (Agniew., 1996).
3. Calculate the general anisotropic matrix via an unconstrained least squares inversion of equation 2.
4. Perform a constrained inversion of equation 3, using 0.5 < c2 = 0.1 < 5 (Gladwin 1985, Roeloffs 2010). Use downhill simplex method to find best fitting values.
5. Compare the RMSE of the measured gauge tides to the calculated tides for each matrix.
6. Compare the matrices found in step 3 and step 4 by calculating the percentage difference of each component in the matrices.
7. Since there is trade off between the areal coupling coefficients and orientation, we examine how much the calculated orientation differs from field measurements.

Network Metrics
Every three months UNAVCO’s Borehole Strainmeter Analysis Center examines the data from each strainmeter to monitor the instruments performance and state of health (Table 1).

PBO BSM performance is assessed on four basic criteria:
1. State of Compression (Figure 2).
2. Signal to noise ratio (SNR) > 10 in the tidal band (Figure 3).
3. Recording of seismic shear
4. Absence of unexplained steps in the time series

Table 1. BSM Network Performance, 2011-07-01 to 2011-10-01

<table>
<thead>
<tr>
<th>Metric</th>
<th>% Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression</td>
<td>71%</td>
</tr>
<tr>
<td>Signal to Noise</td>
<td>95%</td>
</tr>
<tr>
<td>Seismic Shear</td>
<td>99%</td>
</tr>
<tr>
<td>Absence of Steps</td>
<td>77%</td>
</tr>
</tbody>
</table>

We expect to see a BSM fail in the M2 and O1 tidal bands. To quantify performance we compare the energy of these frequencies with those just outside the tidal band.

Results

- The RMS of the Mojave and Anza strainmeters (Figure 1) ranged from 0.67 to 0.41. Since these BSMs are free from complicated coastal loading signals we consider values within twice this range to be indicative of a reasonable fit.
- 12 BSMs had an RMS misfit > double the upper limit; 9 are near the coast.

Comparisons of the general and constrained anisotropic matrices (excluding 9 coastal BSMs)

<table>
<thead>
<tr>
<th>Comparison</th>
<th>% of BSMs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Similarity</td>
<td>80%</td>
</tr>
<tr>
<td>At least 10 of the 12 components differ by &lt; 10%</td>
<td>90%</td>
</tr>
<tr>
<td>RMS misfit degraded by &lt; 1% when using constrained anisotropic matrix</td>
<td>82%</td>
</tr>
</tbody>
</table>

Constrained Anisotropic Matrices Properties

<table>
<thead>
<tr>
<th>% of BSMs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negative areal coupling coefficients (Figure 5A)</td>
</tr>
<tr>
<td>2o/d2 ratios &lt; 2 (Figure 5B)</td>
</tr>
<tr>
<td>t value different from the measured value by &lt; 20%</td>
</tr>
</tbody>
</table>

Conclusions

- For 80% of the non-coastal BSMs there is essentially no difference between the general and constrained isotropic calibration matrix.
- The 2o/d2 ratios found in the constrained anisotropic case are large which suggests significant anisotropy around the BSM.
- Many PBO BSMs have negative areal coefficients (confirming Roeloffs, 2010).

New Level 2 BSM Data Products
In 2011 PBO added new data sets to its suite of Level 2 BSM products. In addition to the manufacturer’s calibrated data sets:

- Added areal and shear data using calibrations of Roeloffs (2010).
- Reduced latency of ASCII processed data to 24 hours
- Made simple, parsable ASCII files containing processing metadata available for download with L2 products
- Started producing a high rate processed data set (1sps) for geophysical events

In 2012 PBO proposes:

- Continuing to produce manufacturer and Roeloffs (2010) calibrated data
- Including general anisotropic calibrated data
- Expand format of ASCII data sets to include future calibration techniques
- Increase high rate processed data set to 20sps based on user requests

References
Gallowher, W. et al. (2010) Determine the GM (Global Model) strain data. The BSM model of the Earth’s surface deformation. The relative accuracies are known much larger than the errors in the GM (Global Model) strain data. The relative accuracies are known much larger than the errors in the GM (Global Model) strain data.

Figure 1: PBO Borehole Strainmeter network, December 2011.

Figure 2: Gauge 2 strain tidal signal. Table 1. BSM Network Performance, 2011-07-01 to 2011-10-01

Figure 3: BSM network designed to operate under a state of compression. We expect to see a BSM fail in the M2 and O1 tidal bands. To quantify performance we compare the energy of these frequencies with those just outside the tidal band.

Figure 4: Strain Formula

Figure 5: Constrained calibration: a) Compares coefficients from the constrained and expanded versions.

Figure 6: New Level 2 BSM data products.