Strain Data from the GTSM Archive.

The strain data provided from the GTSM archive is intended to be the output of simple first pass processing. The data is not calibrated, but it is corrected for in situ gauge sensitivities inferred from the atmospheric pressure response of the four gauges. Basically it is assumed that an isotropic installation will produce identical response from imposed atmospheric loadings at all azimuths. The relative responses of the four gauges are corrected to enable better first order estimates of the shear strains.

Each gauge response is estimated using the pressure response algorithm within the GTSM processing package WinXQP using approximately three months of data in mid 2008. Many of the sites (in particular those which are either not compressing or have a strong stepping behavior) do not allow this analysis. These gauges are processed with the default gain of unity.

The general matrix form used for the calculation of gauge deformations for a given strain field is:

$$\tilde{U} = GMHT\tilde{S}$$

$$\begin{bmatrix} u_0 \\ u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} 1/g_0 & 0 & 0 & 0 \\ 0 & 1/g_1 & 0 & 0 \\ 0 & 0 & 1/g_2 & 0 \\ 0 & 0 & 0 & 1/g_3 \end{bmatrix} \begin{bmatrix} 1/2 & 1/2\cos 2q_0 & 1/2\sin 2q_0 \\ 1/2 & 1/2\cos 2q_1 & 1/2\sin 2q_1 \\ 1/2 & 1/2\cos 2q_2 & 1/2\sin 2q_2 \\ 1/2 & 1/2\cos 2q_3 & 1/2\sin 2q_3 \end{bmatrix} \begin{bmatrix} c & 0 & 0 \\ 0 & d_1 & 0 \\ 0 & 0 & d_2 \end{bmatrix} \begin{bmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{bmatrix} \begin{bmatrix} e_a \\ g_1 \\ g_2 \end{bmatrix}$$

U (one element for each gauge orientation) is the linearised or residual gauge deformation
G is the relative gain calibrations for each channel obtained from the pressure analysis
M is the measurement matrix using the gauge orientations measured counterclockwise from east.
H is the Coupling matrix allowing for the different response of the measurement system to hydrostatic and to shear deformations.
T is the topography matrix assumed here to be a unity matrix
S is the applied strain field

There are five (5) steps to the strain data: 1) Linearising, 2) Create Borehole Models, 3) Generate Residual Channels 4) Basic Channel Relative Gain Calibration, 5) Strain Calculation.

<u>1. Linearising</u>

Raw channel data is first linearised by the following process:

1. Convert all 8 digit raw channel data to a ratio (R_n)
   Ie, 55555555 = 0.55555555 (divide by 100000000)

2. Convert the arbitrary linearisation point (from the table) to a ratio (R_0)

3. For each channel data point, calculate the displacement from R_0

$$U_n = \left(\frac{R_n}{1 - R_n} - \frac{R_0}{1 - R_0} \right) \times mechgain$$

For PBO sites there are 2 different Mechanical Gains, 0.02298… and 0.0114…. The first is associated with 200 micron reference gap instruments and the second is for the 100 micron reference gap instruments. These values are listed as G in the table.

Gauge angles are obtained from the UNAVCO website. UNAVCO lists the gauge orientations in degrees azimuth *East of North*. Az is the orientation of each channel in degrees *North of East*. Go to http://pboweb.unavco.org/?pageid=89 to obtain the gauge UNAVCO orientations (East of North). The orientations used for the GTSM Strain Archive have been converted into degrees *North of East*, and are included in the table at the bottom of the document.

2. Create Borehole Models

The creation of borehole models involves a least squares fitting program for Matlab. Linearised data is opened in matlab, processed as single day averages and the long term borehole effects are determined. The most common forms of borehole models are A single exponential with a linear term, a double exponential with a linear term, or in some cases, purely a linear model is fitted to the data.

The coefficients used in the generation of the borehole models are included in the sites table and consist of:

A1	Amplitude of the 1st exponential component units in nano-strain
T1	Time constant inverse of 1st exponential, which equals 1 / (time constant in days)
A2	Amplitude of the 2nd exponential component units in nano-strain
T2	Time constant inverse of 2nd exponential, which equals 1 / (time constant in days)
Off	Model offset in nano-strain
SLOPE	slope of the linear component, in nano-strain / day
Initial	The initial value in raw counts, which is converted to Linearised Data before being applied to the model

3. Generate Residual Data

With borehole models created, the model data can be point-for-point subtracted from the linearised data to produce the “residual” data. This consists of local strain data with borehole effects removed.

Strain Data made available on the GTSM website will be generated using Residual data with borehole effects removed (where available).

4. Using Pressure Response for Channel Relative Gain Calibrations

GTSM uses relative gain calibrations obtained by estimation of each gauge response to the atmospheric pressure. The data bottle and the pressure bottle are High-pass filtered at 9 days, then low pass filtered at 27 hours to expose any common, 1 – 9 day low frequency signals.

Since the channel data are sampled at 600sec intervals and the diagnostics bottles are sampled at 1800sec intervals, the Pressure data are interpolated to provide equal sample rates.

The pressure response is estimated by a least-squares calculation performed in the following way:

Assuming the data is of the form, Data = offset + Coefficient x Pressure

$$\begin{bmatrix} Data_0 \\ \ldots \\ Data_n \end{bmatrix} = \begin{bmatrix} 1 & pressure_0 \\ \ldots & \ldots \\ 1 & pressure_n \end{bmatrix} \begin{bmatrix} A \\ B \end{bmatrix}$$

$$D = PC$$

$$P^T D = P^T PC$$

$$(P^T P)^{-1} P^T D = C$$

The 'B' term is the pressure coefficient and is determined in nanostrain/KPa. Constant admittance is assumed over the band except where the data evidently violates this assumption. The actual pressure calibrations obtained (where available) are in the table at the bottom of this document. In most cases, the data selected for the calculations was the three month period 10th June 2008 to the 10th September 2008. Pressure coefficients were calculated using the "Pressure Reduction" tool in the GTSM WinXQP Software Package.

The value for the gauge gain (shown as g in the calculations below) is then calculated relative to the average response of each instrument, as g_i = (Average Response) / (gauge i Response).

5. Final Strain Calculation

GTSM combines the gain, measurement and coupling matrices in the WinXQP processing package to form a matrix, 'O'. O includes the 0.5 multiplier before the transpose and inverse operations.

$$\begin{bmatrix} u_0 \\ u_1 \\ u_2 \\ u_3 \end{bmatrix} = 0.5 \times \begin{bmatrix} c/g_0 & d_1/g_0 \cos 2q_0 & d_2/g_0 \sin 2q_0 \\ c/g_1 & d_1/g_1 \cos 2q_2 & d_2/g_1 \sin 2q_1 \\ c/g_2 & d_1/g_2 \cos 2q_3 & d_2/g_2 \sin 2q_2 \\ c/g_3 & d_1/g_3 \cos 2q_4 & d_2/g_3 \sin 2q_3 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e_a \\ g_1 \\ g_2 \end{bmatrix}$$

Here, for this relative channel response estimate, 'c', 'd_1' and 'd_2' are taken as the same for all gauges. Values of c= 1.5 and $d_1 = d_2 = 2.7$, which are typical in hard rock are used for GTSM Strain Archive. The actual values at a site need to be identified by more extensive calibration procedures. c = 1.5 indicates that observed hydrostatic strains are enhanced by 1.5, and d = 2.7 indicates that observed shears are enhanced by 2.7 i.e., the instrument inclusion is softer in shear than in hydrostatic response. The topographic/geological matrix which can be used to allow for known variations at the site is processed in this case with a default value of unity.

Note that in a full calibration, different values for c, d_1 and d_2 for each channel are also allowed, indexing the variation of rock properties from top to bottom of the stack. The more general form of the gauge deformation calculation available in the GTSM Technologies processing package WinXQP is:

$$\begin{bmatrix} u_0 \\ u_1 \\ u_2 \\ u_3 \end{bmatrix} = 0.5 \times \begin{bmatrix} c_0/g_0 & d_{10}/g_0 \cos 2q_0 & d_{20}/g_0 \sin 2q_0 \\ c_1/g_1 & d_{11}/g_1 \cos 2q_2 & d_{21}/g_1 \sin 2q_1 \\ c_2/g_2 & d_{12}/g_2 \cos 2q_3 & d_{22}/g_2 \sin 2q_2 \\ c_3/g_3 & d_{13}/g_3 \cos 2q_4 & d_{23}/g_3 \sin 2q_3 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e_a \\ g_1 \\ g_2 \end{bmatrix}$$

Full calibration requires use of a priori models of, for example, the expected earth tidal strain fields for various tidal components at the site. These models are at best indicative and need to be used with great caution. The simple relative channel calibration from the pressure response in the raw strain data is model independent.

The calculation of the strain field, $\tilde{S}$, from the measured deformations is performed using the following calculation.:

$$\tilde{U} = OT\tilde{S}$$

$$O^T\tilde{U} = O^T OT\tilde{S}$$

$$(O^T O)^{-1} O^T \tilde{U} = T\tilde{S}$$

$$T^{-1}(O^T O)^{-1} O^T \tilde{U} = \tilde{S}$$

$$\tilde{S} = \begin{bmatrix} e_a \\ g_1 \\ g_2 \end{bmatrix}$$