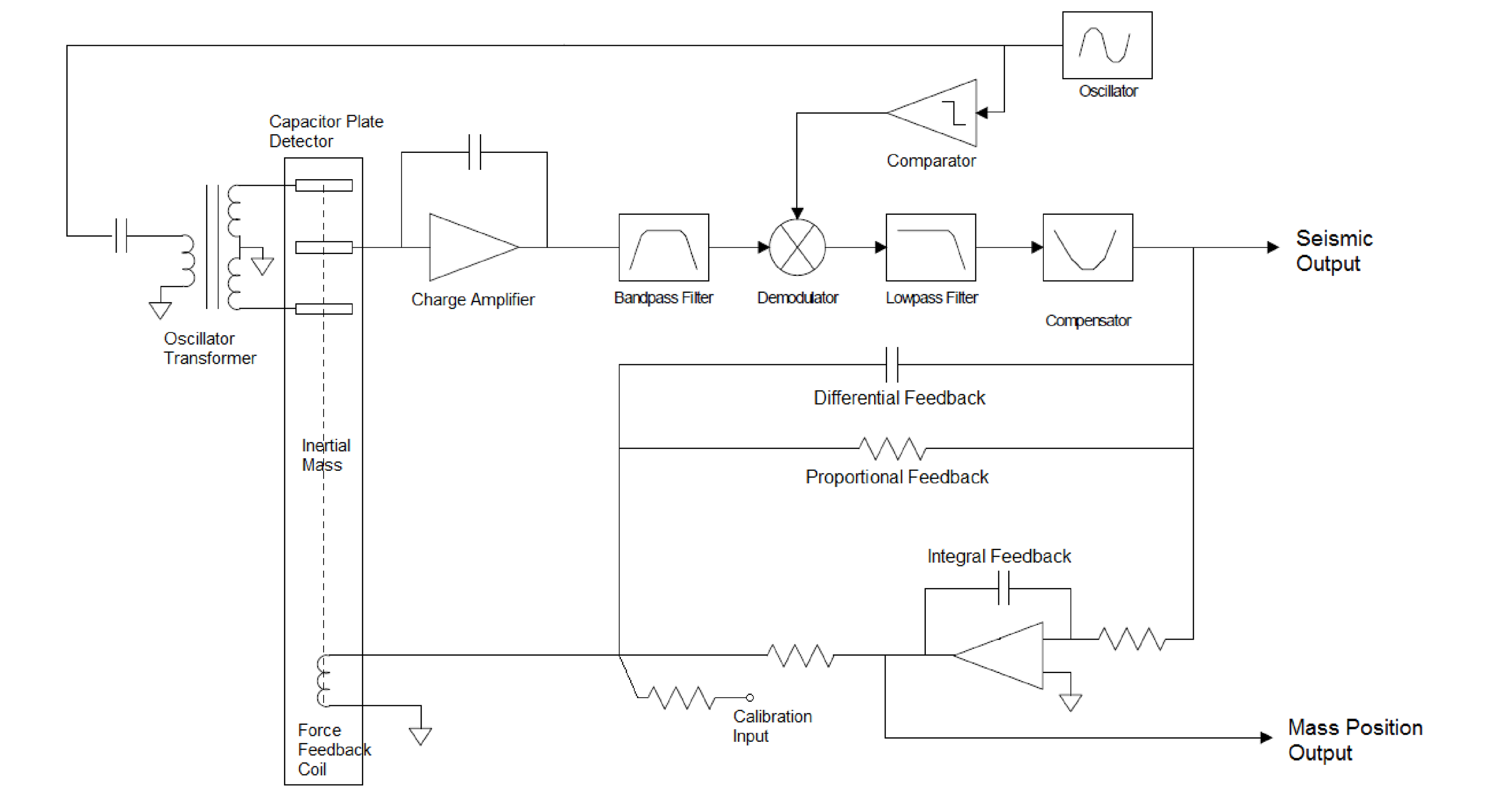
Potential Applications of an Integrated Seismic, Tilt, and Temperature Instrument

G. Bainbridge*, D. Easton, S. Karimi, A. McKean, T. Parker, P. Devanney
*GeoffreyBainbridge@nanometrics.ca
Ottawa, Canada

SUMMARY

Mass position represents a quasi-static acceleration applied to the inertial mass of a seismometer to keep it balanced at its operating point. This acceleration changes with tilt (due to gravity) and temperature (due to the temperature coefficient of the springs). Mass position is typically recorded with low resolution as a state of health measurement for a seismometer. However an optimized output circuit for high-resolution mass positions fed to a 24-bit digitizer would enable the derivation of simultaneous seismic, tilt, and temperature datasets from a single instrument, for applications such as volcano and reservoir monitoring.

Circuit Block Diagram



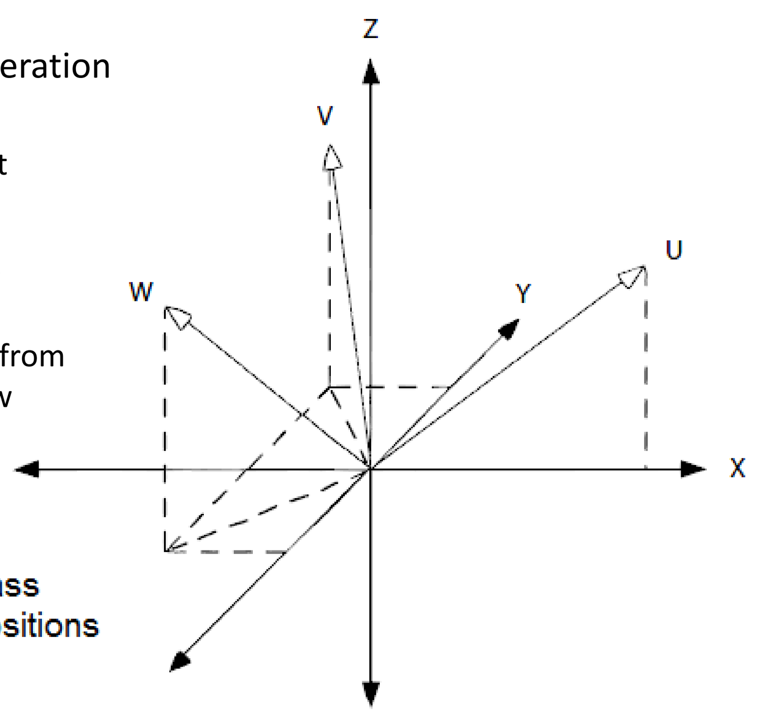
Converting Mass Positions to Tilt and Temperature

Mass "position" ⇔ Force acting on the mass ⇔ Acceleration

- Tilt = acceleration / (1 g / radian)
- Temperature = acceleration / spring temperature coefficient

In a symmetric tri-axial seismometer:

- Temperature can be calculated from the average of the mass positions, since it affects all axes equally
- Tilt in the East (X) and North (Y) directions can be calculated from differences in the mass positions based on the formula below



$$\begin{array}{l} \text{Tilt} \left\{ \begin{matrix} \\ \\ \end{matrix} \right. \\ \text{Temperature} \end{array} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \frac{1}{\sqrt{6}} \cdot \begin{bmatrix} 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \\ \sqrt{2} & \sqrt{2} & \sqrt{2} \end{bmatrix} \cdot \begin{bmatrix} u \\ v \\ w \end{bmatrix} \text{ Mass Positions}$$

Range, Resolution, and Accuracy

- We calculate that mass positions can provide a highly accurate relative measurement of tilt and temperature change from time of installation. Nanometrics Trillium seismometers also incorporate accelerometer and thermometer sensors which provide a less accurate measurement of absolute tilt and temperature.
- Trillium 120 seismometers incorporate mechanical mass re-centering, to enable higher resolution measurement in an adjustable sub-range within the total operating tilt range.

Tilt	Range	RMS Noise 30s sample rate	Offset Drift	Drift due to Gain Change	Absolute Accuracy
Trillium Compact + Centaur	±2.5°	2e-9 rad	±2e-7 rad/year	±5e-6 rad/year	±0.1° (±0.0017 rad)
T120 Posthole + Centaur	±5.0° from vertical; ±0.1° change without re-centering	1e-10 rad	±8e-9 rad/year	±2e-7 rad/year	±0.1° (±0.0017 rad)

Temperature	Range	RMS Noise 30s sample rate	Offset Drift	Drift due to Gain Change	Absolute Accuracy
Trillium Compact + Centaur	-20 to +60 °C	7e-6 °C	±7e-4 °C/year	±0.02 °C/year	±0.1°C
T120 Posthole + Centaur	-20 to +60 °C	3e-6 °C	±3e-4 °C/year	±0.007 °C/year	±0.1°C

Resolution and accuracy in the presence of noise

Tilt and temperature change very slowly, so data can be averaged and down-sampled to reduce random noise. Accuracy is limited by drift, meaning noise which increases over time. For both the sensor and the digitizer we can express drift as

$$\mathrm{Drift}(t) \cong \int_{1/t}^{f_{Nyquist}} N(f)\,df + \Delta\mathrm{Offset}(t) + \frac{\Delta G(t)}{G} \times \mathrm{DC\_Signal}$$

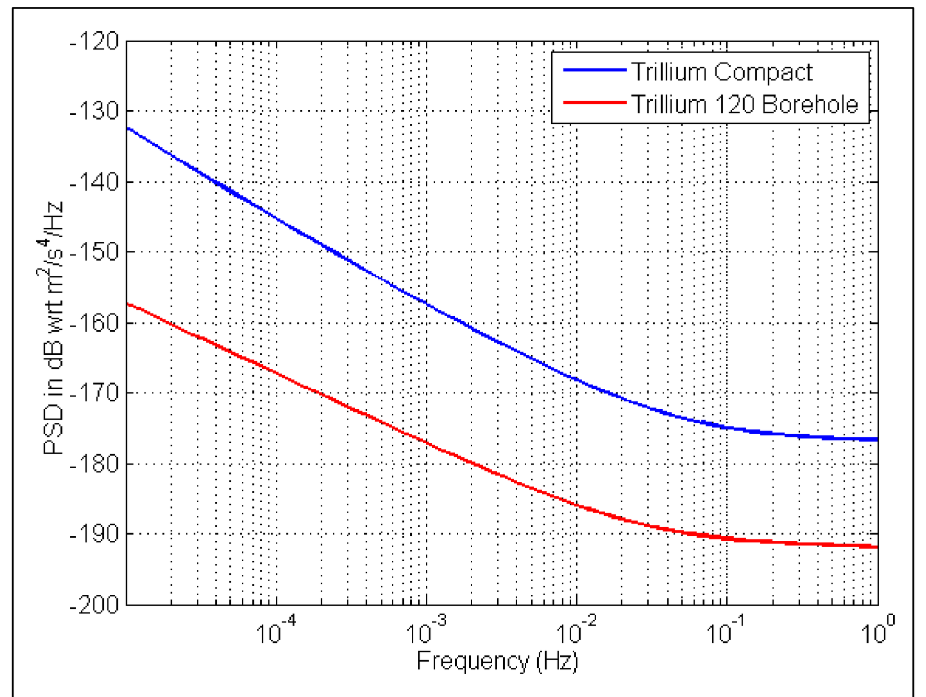
where $N(f)$ = Random noise, predominantly 1/f (flicker) noise at long periods
$\Delta\mathrm{Offset}(t)$ = Offset drift due to temperature change and aging
G = Nominal value of closed-loop gain
$\Delta G(t)$ = Gain variation due to temperature change and aging
DC_Signal = mean value of mass position signal (assumed approx. constant over measurement interval)

Because mass positions have large DC offset, **gain variation predominates over other noise**.

For a force feedback sensor, noise (or drift) of individual stages within the feedback loop can be converted to an equivalent input acceleration and combined as follows:

$$a_{Noise} = \frac{1}{S}\sqrt{\left(F_1 + \frac{F_2}{A_1} + \cdots + \frac{F_k}{A_1 A_2 \ldots A_{k-1}}\right) + \left(\begin{matrix} B_m R_m + B_m B_{m-1} R_{m-1} + \\ \ldots + B_m B_{m-1} \ldots B_1 R_1 \end{matrix}\right)}$$

where S ($V/m/s^2$) = sensitivity of mechanical plant (inertial mass, spring, and capacitor plate detector)
F_k (V^2/Hz) = noise of k'th stage of forward path
A_k = gain of k'th stage of forward path
R_m (V^2/Hz) = noise of m'th stage of feedback path
B_m = gain of m'th stage of feedback path



Random noise of sensor mass positions. Integrating over the bandwidth of interest – 1 year (3e-8 Hz) to 1 minute (0.016 Hz) – gives time-domain rms noise.

Potential Applications

Volcano Monitoring

These figures from Dzurisin, 1992 show seismic and tilt data from 10 days prior to the eruption on Oct. 22, 1986. There is a rough correlation between seismic and tilt data, however the instruments are not co-located. Dzurisin observes "offset at Raza on October 11 was caused by a local earthquake", however the earthquake does not show on the seismic intensity plots. Combined tilt and seismic instrument would enable better measurement of such an event.

Our calculations indicate the resolution of mass position tilt measurements would be sufficient to measure background signal such as the ~100 µrad diurnal variation at Station Oops. Presumably this is due to solar heating; a combined tilt and temperature instrument could better characterize and confirm this.

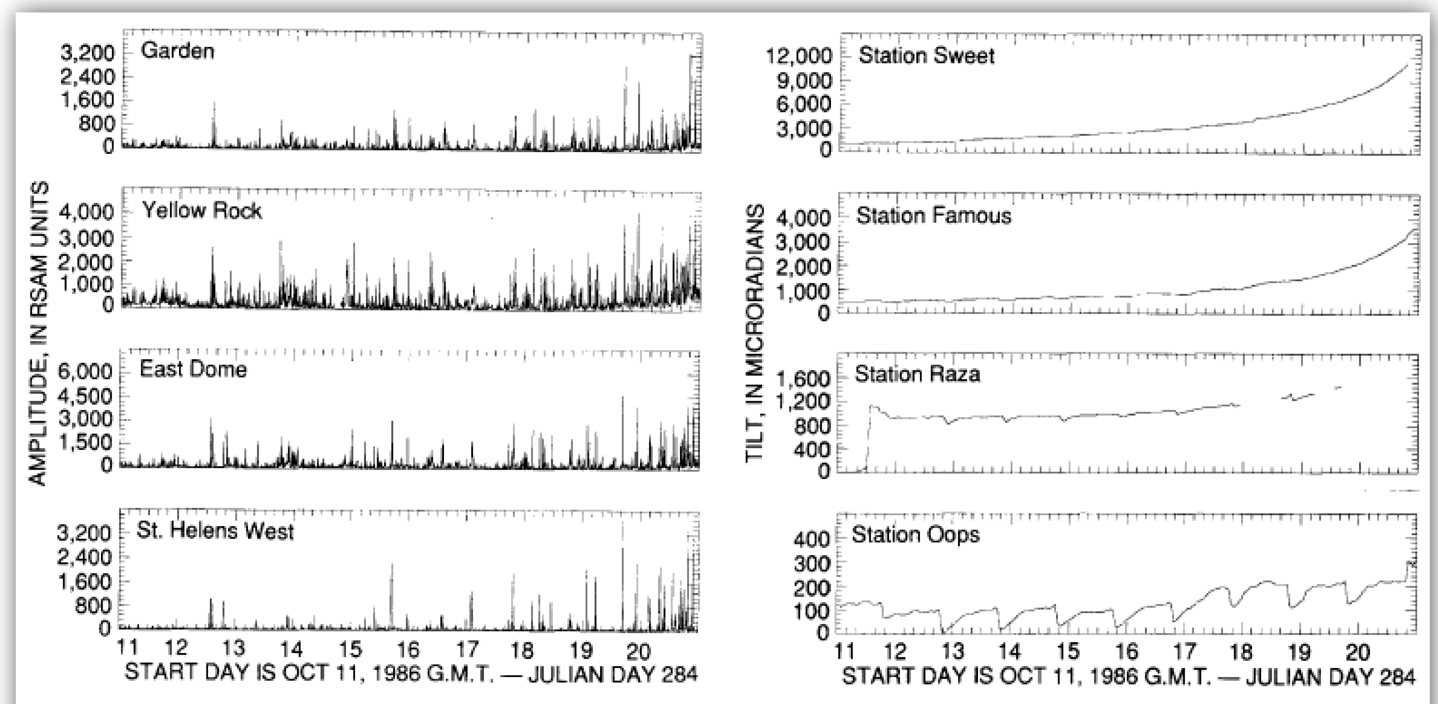


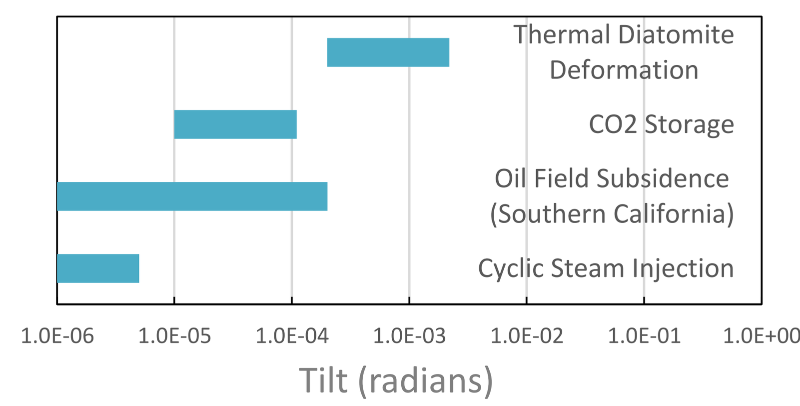
Figure 7.12. RSAM records (10-minute averages) from four seismometers at Mount St. Helens for October 11–20, 1986. Seismic activity increased steadily during this period, accompanied by inflation of the dome at an increasing rate.

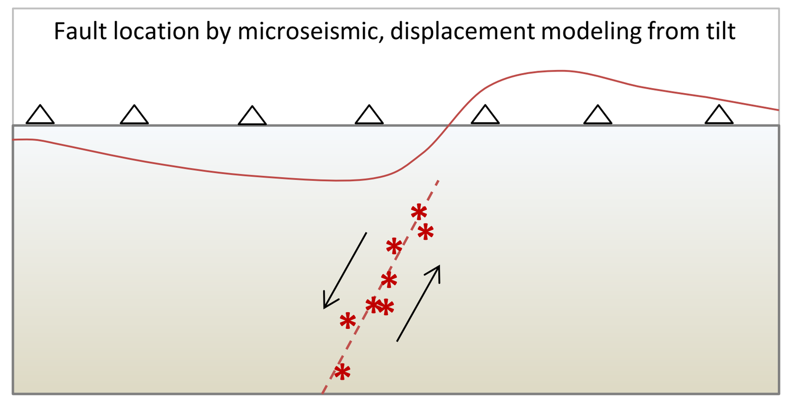
Figure 7.13. Records from four tiltmeters on the dome for October 11–20, 1986. See figure 1 for locations of tiltmeters. Note differing vertical scales. Offset at RAZA on October 11 was caused by a local earthquake during early phase of precursory activity.

Reservoir Monitoring

Davis, 2007 presented several case-study results showing deformation inferred from tilt, GPS, and microseismic data, noting "tilt provides by far the highest precision deformation measurements" and "the added constraints from the microseismic data speed the inversion process, giving a more robust solution than tilt alone".

Working back from his vertical displacement contour maps, we estimate the magnitude of tilt measured in various applications – see table below. We expect these would all be resolvable with mass position tilt data. A combined seismic, tilt, and temperature instrument would enable efficient collection and correlation of these types of data commonly used for reservoir monitoring.





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