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# Recovery and Calibration of Legacy Analog Data From the Leo Brady Seismic Network for the Source Physics Experiment

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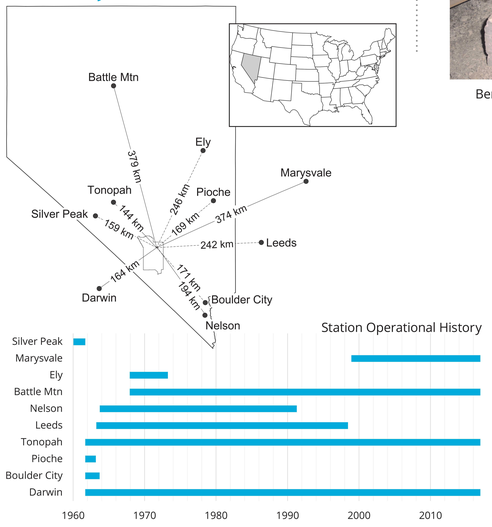
## Abstract

The Leo Brady Seismic Network (LBSN) was established in 1960 by Sandia National Laboratories for monitoring underground nuclear tests (UGTs) at the Nevada Test Site—renamed in 2010 to the Nevada National Security Site (NNSS). The LBSN has been in various configurations throughout its existence, but it has been generally comprised of four to six stations at regional distances from the NNSS with evenly spaced azimuthal coverage. Between 1962 and the early 1980s, the LBSN—and a sister network operated by Lawrence Livermore National Laboratory—were the most comprehensive U.S. source of regional seismic data of UGTs. Approximately 75% of UGTs were conducted prior to the digital era.

During the analog era, LBSN data were transmitted as frequency-modulated (FM) audio over telephone lines to the NTS and recorded in analog on hi-fi 8-track AMPEX tapes. These tapes have been stored in temperature-stable buildings or bunkers on the NNSS and Kirtland Air Force Base in Albuquerque, NM for decades and contain the sole record of this irreplaceable data from the analog era; full waveforms of UGTs during this time were never routinely converted to digital form. We have been developing a process over the past few years to recover and calibrate data from these tapes, converting them from FM audio to digital waveforms in ground motion units. To date, we have digitized tapes from 592 separate UGTs. The calibration of legacy data from the LBSN is still ongoing, and a plug-in for the Sandia-developed Telemetry Analysis and Visualization Suite (TAVS) software has been developed to rapidly calibrate these waveforms and save miniSEED + RESP files. As a demonstration, we calibrated data from the BOXCAR event. This data is now available in miniSEED + RESP format.

## Leo Brady Seismic Network

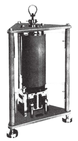


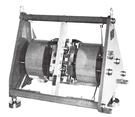




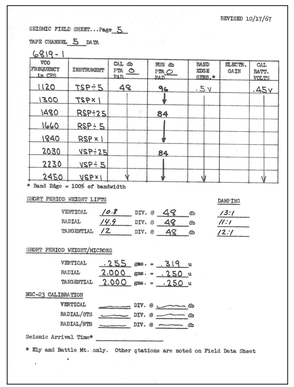
## Instrumentation & Records

Benioff 1051 | Benioff 1101 | Crown CX822





Benioff seismometers at Nelson's Landing (June 1985)



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SEISMIC FIELD SHEET...Page 5

TAPE CHANNEL 5 DATA

6919-1

| TIME (GMT) | INSTRUMENT | CAL ch. | CAL PTP cm | MIN ch. | MIN PTP cm | BAND SIDE BAND # | ELECTR. GAIN | CAL BATT. VOLTS |
|---|---|---|---|---|---|---|---|---|
| 1120 | TSP÷5 | 49 | | 94 | | 5 V | | 45V |
| 1300 | TSP×1 | | | | | | | |
| 1430 | RSP÷25 | | | 84 | | | | |
| 1440 | RSP÷5 | | | | | | | |
| 1940 | RSP×1 | | | | | | | |
| 2030 | VSP÷25 | | | 84 | | | | |
| 2230 | VSP÷5 | | | | | | | |
| 2450 | VSP×1 | | | | | | | |

* Dead Edge = 100% of bandwidth

(SHORT PERIOD WEIGHT LIFTS) DAMPING

VERTICAL 102 DIV. @ 49 cb /3:1
RADIAL 149 DIV. @ 49 cb /1:1
TRANSVERSAL 12 DIV. @ 49 cb /2:1

(SHORT PERIOD WEIGHT/MICRONS)

VERTICAL 255 gms. = 319 u
RADIAL 2,000 gms. = 250 u
TRANSVERSAL 1,000 gms. = 250 u

MCC-23 CALIBRATION

VERTICAL ____ DIV. @ ____ cb
RADIAL/EW ____ DIV. @ ____ cb
RADIAL/NTH ____ DIV. @ ____ cb

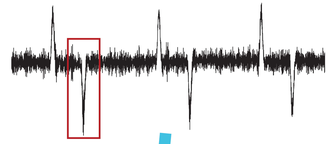
Seismic Arrival Time* _____

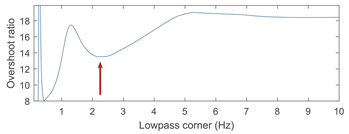
* Ely and Battle Mt. only. Other stations are noted on Field Data Sheet

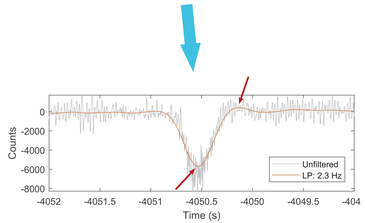
Sample seismic field notes

## Methodology

1. Digitize analog tape data
2. Demodulate signals
3. Isolate first weight lift
4. Recover weight lift
5. Determine:
   a. damped frequency
   b. overshoot ratio
6. Calculate instrument constants
7. Compute instrument sensitivity
8. Derivate instrument transfer function
9. Scale transfer function by sensitivity
10. Clean up and save waveform
11. Write RESP response file
12. Deconvolve instrument response using standard seismic software






Damped harmonic oscillator

$$\ddot{x} + 2\lambda\omega_0\dot{x} + \omega_0^2 x = 0$$

Initial conditions for weight lift:

$$x(t) = A_1 e^{i\omega_1 t} + A_2 e^{i\omega_2 t}$$

$$x(0) = x_0, \quad \dot{x}(0) = 0$$

$$\Rightarrow x(t) = x_0 \sec\phi\, e^{-\lambda\omega_0 t}\cos(\omega_d t - \phi)$$

$$\omega_d = \omega_0\sqrt{1-\lambda^2}, \quad \phi = \sin^{-1}\lambda$$

Determine deflection from Hooke's law

$$F = kx$$

$$m_w g = m_s\omega_0^2 x_0$$

$$\Rightarrow x_0 = \frac{m_w g}{m_s\omega_0^2}$$

Electromagnetic seismometer

$$V(t) = G\dot{x}(t)$$

$$\Rightarrow V(t) = -G\frac{m_w g}{m_s\omega_d}e^{-\lambda\omega_0 t}\sin\omega_d t$$

$$t_1 = \frac{\cos^{-1}\lambda}{\omega_d}, \quad t_2 = \frac{\pi + \cos^{-1}\lambda}{\omega_d}$$

Dynamic magnification

$$\ddot{x} + 2\lambda\omega_0\dot{x} + \omega_0^2 x = -\ddot{u}$$

$$\Rightarrow (-\omega^2 + i2\lambda\omega_0\omega + \omega_0^2)\hat{x} = \omega^2\hat{u}$$

$$\Rightarrow \left|\frac{\hat{u}}{\hat{x}}\right|^2 = \left(\frac{\omega_0^2}{\omega^2} - 1\right)^2 + 4\lambda^2\frac{\omega_0^2}{\omega^2}$$

The general transfer function for our Benioff seismograph is

$$\hat{T}_v(s) =$$

Seismometer $\quad K_s\dfrac{(s-z_0)(s-z_1)}{(s-p_0)(s-p_1)}$

Galvanometer $\quad \cdot K_g\dfrac{1}{(s-p_2)(s-p_3)}$

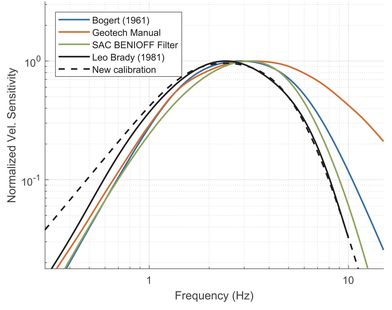
Band-pass filter 1 $\quad \cdot K_{h_0}\dfrac{(s-z_2)}{(s-p_4)}\cdot K_{\ell_0}\dfrac{1}{(s-p_5)(s-p_6)}$

Band-pass filter 2 $\quad \cdot K_{h_1}\dfrac{(s-z_3)}{(s-p_7)}\cdot K_{\ell_1}\dfrac{1}{(s-p_8)(s-p_9)}$

| Constant | Value |
|---|---|
| $\omega_s$ | Derived from calibration signal |
| $\lambda_s$ | Derived from calibration signal |
| $\omega_g$ | $2\pi \cdot 5$ Hz |
| $\lambda_g$ | 0.675 |
| $Q_{h_0}$ | $10^{-3/20}$ |
| $\omega_{h_0}$ | $2\pi \cdot 0.01$ Hz |
| $Q_{\ell_0}$ | $10^{-3/20}$ |
| $\omega_{\ell_0}$ | $2\pi \cdot 8$ Hz |
| $Q_{h_1}$ | $10^{-3/20}$ |
| $\omega_{h_1}$ | $2\pi \cdot 0.01$ Hz |
| $Q_{\ell_1}$ | $10^{-3/20}$ |
| $\omega_{\ell_1}$ | $2\pi \cdot 5$ Hz |

| Coefficient | Value |
|---|---|
| $z_0$ | 0 |
| $z_1$ | 0 |
| $z_2$ | 0 |
| $z_3$ | 0 |
| $p_0, p_1$ | $-\lambda_s\omega_s \pm \omega_s\sqrt{\lambda_s^2 - 1}$ |
| $p_2, p_3$ | $-\lambda_g\omega_g \pm \omega_g\sqrt{\lambda_g^2 - 1}$ |
| $p_4$ | $-\omega_{h_0}$ |
| $p_5, p_6$ | $-\left(2Q_{\ell_0}\right)^{-1}\omega_{\ell_0} \pm \omega_{\ell_0}\sqrt{\left(2Q_{\ell_0}\right)^{-2} - 1}$ |
| $p_7$ | $-\omega_{h_1}$ |
| $p_8, p_9$ | $-\left(2Q_{\ell_1}\right)^{-1}\omega_{\ell_1} \pm \omega_{\ell_1}\sqrt{\left(2Q_{\ell_1}\right)^{-2} - 1}$ |
| $K_s$ | $-1$ |
| $K_g$ | $\omega_g^2$ |
| $K_{h_0}$ | $Q_{h_0}\sqrt{2}$ |
| $K_{\ell_0}$ | $\omega_{\ell_0}^2$ |
| $K_{h_1}$ | $Q_{h_1}\sqrt{2}$ |
| $K_{\ell_1}$ | $\omega_{\ell_1}^2$ |

**Benioff Seismometer Transfer Fcn.**




## Results

Peak ground velocity for BOXCAR
- 1.3 Mt (DOE//NV-209)
- Recorded @ Leeds, UT (~275 km distant)

**Example calibration:**

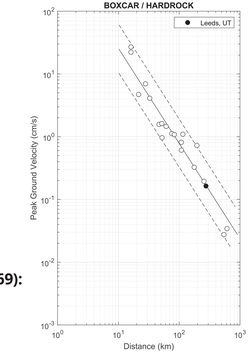
$$\text{PGV} = \frac{14233 \times 5\ [\text{cts}]}{10^{-\frac{84\ [\text{dB}]}{20}}} \times \frac{1\ [\text{m/s}]}{\left(\frac{4.9327 \times 10^9\ [\text{cts}]}{10^{-\frac{84\ [\text{dB}]}{20}}}\right)} \times \frac{1.7985\ [\text{earth movt}]}{1\ [\text{mass movt}]}$$

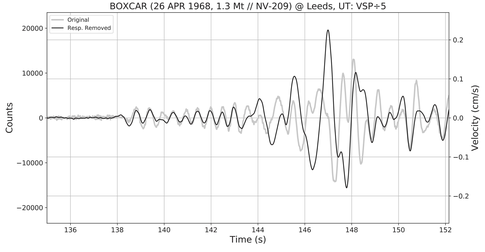
$$= 1.6372 \times 10^{-3}\ [\text{m/s}]$$

**Pre-1992 method:**
0.1472 cm/s
*(assumes constant nominal deflection, natural period)*

**New method:**
0.1637 cm/s
*(Recalculate instrument constants from recorded calibration pulses)*

**Murphy & Lahoud (BSSA, 1969):**
0.1620 cm/s
*(empirical)*

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