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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.

During the pre-digital 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. The calibration of legacy data from the LBSN is still ongoing. To date, we have digitized tapes from 592 separate UGTs. As a proof-of-concept, we calibrated data from the BOXCAR event.

Introduction

The Leo Brady Seismic Network (LBSN) was established in 1960 by Sandia National Laboratories (SNL) primarily for monitoring underground nuclear explosions at the Nevada Test Site (NTS)—known since 2010 as the Nevada National Security Site (NNSS). The LBSN was originally comprised of four stations in California and Nevada, and it expanded to Utah shortly thereafter. The station locations were chosen to be at regional distances from the NTS and approximately evenly-spaced in azimuth (Figure 1). To minimize seismic noise, instruments were installed on poured-concrete seismic piers in abandoned mines (Figure 2).

The configuration of the LBSN has changed throughout time, both in terms of instrumentation and station location. The original four stations were operational by 1962 and located in: (1) Darwin, CA; (2) Boulder City, NV; (3) Pioche, NV; and (4) Silver Peak, NV. Between 1962 and 1963, the Boulder City, Pioche, and Silver City stations were replaced with new installations at Leeds, UT (alternately referred to as St. George); Nelson, NV; and Tonopah, NV. In the latter half of 1967, two additional stations were added in Battle Mountain and Ely, NV. The Ely station was later decommissioned in early 1973, and Nelson remained until it was moved to Marysvale, UT in 1998. Today's network configuration is thus composed of five stations in three states: (1) Darwin, CA; (2) Tonopah, NV; (3) Battle Mountain, NV; (4) Leeds, UT; and (5) Marysvale, UT.

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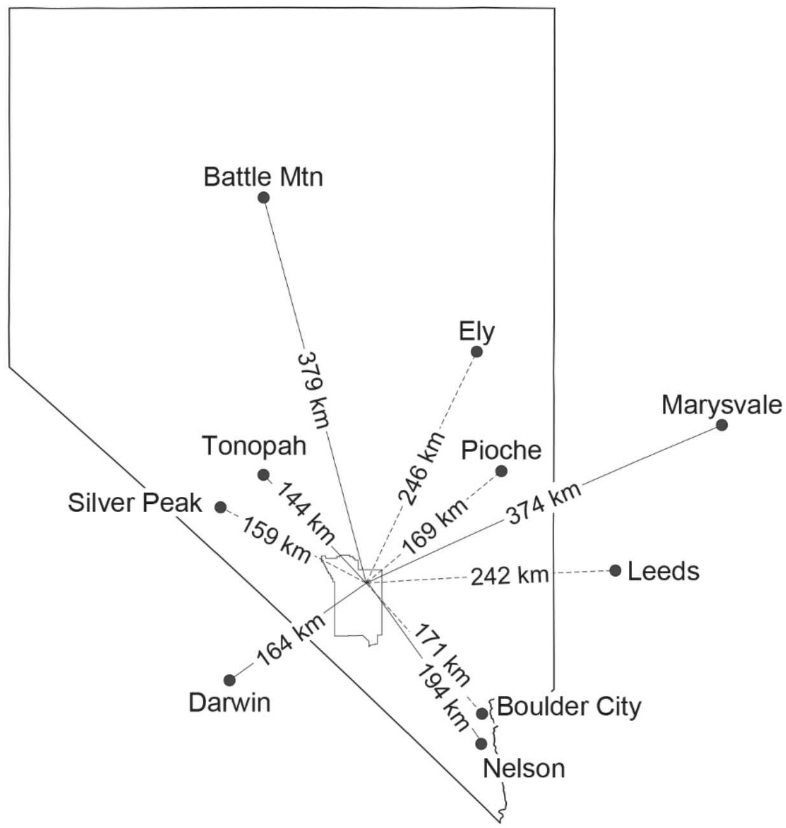

Figure 1. Map of the Leo Brady Seismic Network relative to Nevada and the historic reference coordinates of the Nevada National Security Site. Solid lines indicate stations currently in operation. Dashed lines indicate retired stations.

The instruments at each site also varied throughout time. The initial deployment consisted of three short-period Benioff seismometers (Geotech Models 1051 and 1101) and a long-period vertical Press-Ewing instrument at each site (Darwin had three Press-Ewings). The Benioff and Press-Ewing seismometers were eventually variously complimented or replaced by Geotech Models 18-300, SL-210, SL-220, GS-13, as well as National Geophysical Company Model 23. Since 1998, each site has been outfitted with Guralp CMG-3s, and the stations at Battle Mountain, Marysvale, and Tonopah additionally host Nanometrics Trillium 120s (Hankins, 1964; Brock, 1966; Brady, 1981; Garbin, 1994; IRIS, 2018).

Seismic equipment was mostly analog until the 1980s. At the very early stages of the LBSN, prior to each UGT, technicians would travel to each station and physically turn on the instruments. Data were recorded on rotating drums, and those records would have to be transported to the NTS or SNL for analysis. By 1966, an analog telemetry system was put in place such that instruments could be controlled, and data retrieved, in real-time from Control Point 1 (CP-1) at the NTS (Hankins, 1964; Brock, 1966). With the new system, simple tonal commands could be sent over telephone lines from CP-1 to remotely turn on/off the instrumentation at each station or perform calibration pulses and other diagnostics. The stations were equipped with audio equipment which frequency-modulated (FM) the electrical signals produced by the seismographs and sent them back to CP-1 as audio over the same telephone lines. At CP-1, these signals were split into two paths. One signal path went to de-modulation equipment and a series of rotating drum seismic recorders so that analysts could view the recordings in real-time. These drum records were the original data used for routine seismic analysis of UGTs. The other signal path went to hi-fi audio recording equipment, where the "audio" was recorded straight onto 8-track AMPEX tapes. With some exceptions, these tapes existed for posterity; it was not common to review the original seismic recordings outside of physical paper until the digital era.

Figure 2. Early 1970s photo of the installation at Nelson, NV. All the LSBN stations were installed on poured-concrete seismic piers in abandoned mines.

These original AMPEX tapes—numbering in the thousands—have been largely undisturbed over the past half-century, stored in boxes in temperature-stable bunkers on Kirtland Air Force Base. Over the past few years, we have been working on a process to recover, process, calibrate, and convert these data into a useable and standard digital form. This process is still ongoing, but a suite of calibration software is being finished, and calibrated waveforms from 18 legacy UGTs with epicenters in close proximity to the SPE series of experiments are expected to be complete by the end of 2019. When finished, these will be the only known comprehensive set of digital seismic records of UGTs from the analog era in the world.

Methods

Data Recovery

Though the AMPEX tapes are generally numbered, it takes some effort to actually go through and locate those of an arbitrary UGT of interest. Upon finding the correct tape(s), we take them back to our laboratory and bake them, literally, in an oven. Baking is necessary because of a process that many old magnetic tapes undergo called "sticky-shed" syndrome. In the manufacture of a magnetic tape, the magnetic material upon which data is stored—typically an iron oxide—is attached to the physical tape by means of a binder or glue. Some common formulations of binder attract moisture, break down, and become sticky or gummy years after manufacture. Playing back or rewinding a tape which has been affected by sticky-shed syndrome may result in the destruction of the tape and damage to the tape player. A temporary solution to this malady is to bake the tape in an electric oven (*not* gas—burning gas releases water vapor, and we're trying to dry these tapes) at 120°F to 140°F for up to 8 hours. Baking at a low temperature for many hours evaporates any accumulated moisture while minimizing potential heat damage, providing a window of opportunity to play back the tape for up to several weeks.

After baking, we play back the tape in real-time (1x speed), digitize it, and save the raw output to a computer. These raw files are a complete copy of the analog tape in digital form. Next, we use the Telemetry, Analysis, and Visualization Suite (TAVS) software to process the raw digital data and de-modulate and extract the individual waveforms stored on the tape. A brief description of the TAVS software can be found in SAND2017-5189M.

Calibration

We are developing a plugin for TAVS to measure, process, and calibrate the de-modulated waveforms and output them in the common Mini-SEED format with accompanying RESP instrument response files for converting the raw waveforms to units of ground motion (velocity). This process is specifically being done for the Benioff seismographs which were deployed in the LSBN throughout the analog era. Benioff seismographs are variable-reluctance electromagnetically-damped seismographs, generally consisting of (1) the seismometer, itself, (2) a galvanometer to amplify the output, and (3) one or more stages of amplifiers, filters, and recording equipment necessary to record the seismic data. The sensor records ground motion by way of Faraday's Law: electricity is induced in coils as a result of a magnetic material moving through them. The voltage is proportional to the velocity of the motion.

Every uncalibrated waveform is the result of a multi-step process—modulated, telemetering, recording, digitizing, demodulating—that renders the amplitude scale essentially meaningless. Additionally, the exact mechanical and electrical setup of the instruments, upon which instrument damping and behavior are dependent, as well as the results of any calibrations that may have been performed at the time of installation appear to be lost to history. The only method of calibration, therefore, relies upon understanding the physics of the instruments and measurements performed on the resultant data, themselves. The method we have devised involves a combination of careful measurement of "weight lift" signals at the start of each seismogram and consideration of instrument settings written on surviving field notes.

On the day of a UGT, each station underwent a series of routine diagnostics to ensure the instruments were operating nominally. One such diagnostic was called a "weight lift" test (or "ball drop," or some permutation thereof). In this test, a contraption near the instrument dropped a small weight attached to the inertial mass of the seismometer via a string. This weight drop applied tension to the string, perturbing the seismic mass and appearing as a sharp pulse of ground motion on the seismogram. After waiting a few seconds for the seismometer to stabilize, the weight was then abruptly removed, relieving tension on the string and allowing the inertial mass to return to its neutral state of equilibrium. This relaxing motion appears as a second pulse of ground motion on the seismogram (Figure 3). The shape of these pulses can be shown to be a function of the instrument damping and natural frequency. By modeling this pulse, we can deduce the response of the instrument to a real pulse of ground motion, and together with knowledge of the physics of the instrument, itself, calculate the full transfer function of the instrument to ground motion.

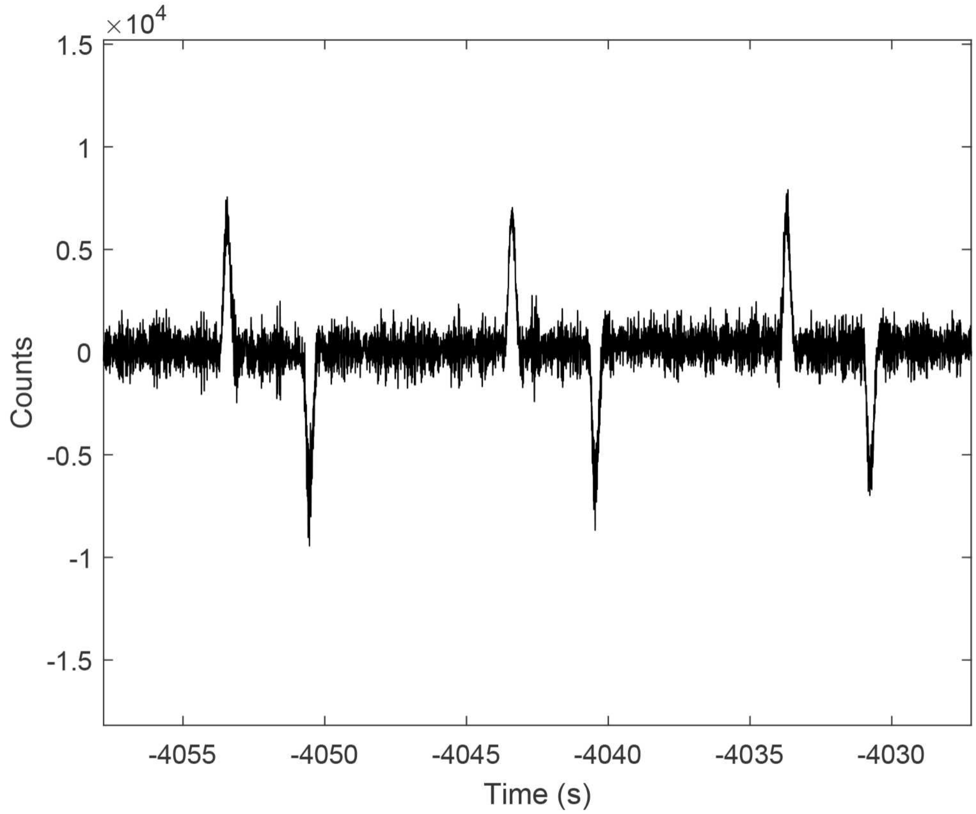

Figure 3. Weight lift test signals on the digitized vertical channel of the Geotech Benioff Model 1051. A small weight attached to the inertial mass of the seismometer is dropped, causing an upward pulse of velocity on the seismogram. The weight is then quickly removed, causing a downward pulse.

To calibrate an arbitrary waveform, we follow the process delineated in Figure 4. The full derivations of the process will be discussed in detail in a forthcoming paper to be submitted to the Bulletin of the Seismological Society of America, but a brief step-by-step summary is given below:

1. Locate the first weight lift test (the results of the first test should be more reliable than subsequent tests)
2. Recover the original weight lift signal through progressive low-pass filters
3. Measure the overshoot ratio and period of the weight lift signal
4. Solve for the instrument constants by modeling the weight lift
5. Calculate the dynamic magnification to relate motion of the inertial mass of the seismometer to motion of the ground
6. Note the voltage divider and attenuator settings recorded on the seismic field notes
7. Calculate the total instrument sensitivity—a conversion factor between digital counts and units of ground motion (velocity)

8. Calculate the full transfer function, which relates ground velocity to seismograph output as a function of frequency
9. Scale the transfer function according to the total sensitivity
10. Write out the seismic waveform and full instrument response and metadata to Mini-SEED and RESP files

It is additionally necessary for this process to be repeated for each instrument and prior to each event because we have observed from weight lift tests that not only does each instrument deviate from the nominal Geotech Model 1051/1101 response, but the responses for a single instrument also change slightly over time (perhaps due to aging of components).

Results

We will use the BOXCAR event, as recorded by the LBSN station in Leeds, UT, as a proof-of-concept for calibration. The BOXCAR event occurred on April 26, 1968 with a yield of 1.3 Mt (NV–209). This event is ideal for testing our calibration method because there exist substantial independent data in the seismic literature. Murphy and Lahoud (1969) derived empirical equations for peak ground motion of UGTs as a function of yield and distance in several emplacement geologies, and they specifically use measurements from the BOXCAR event as an example. Their paper provides the opportunity to directly compare our newly-calculated peak ground velocities (PGV) with those observed at numerous regional stations in operation in 1968.

We examine the VSP÷5 channel (÷5 indicates a voltage divider of 5 was used to prevent data clipping), isolate the first weight lift (Figure 4a), and find the minimum overshoot ratio, which occurs at a low-pass corner frequency of 2.3 Hz (Figure 4b). With this low-pass filter, we measure the overshoot ratio to be 13.58 (Figure 4c). This compares favorably with the seismic field notes, which report a damping ratio of 13:1. Next, we calculate the damped period as 0.84 s (Figure 4c) and solve for the generator constant (Figure 4d), which is calculated to be $G = 4.9327 \times 10^9$ counts/(m/s). The dynamic magnification, evaluated at the damped frequency, is 1.7985. Next, we measure the PGV to be 14233 counts (Figure 4f). Finally, we note the field notes state attenuator settings of 84 dB for the weight lift and 48 dB for the UGT. Calculating the total sensitivity, we get a peak ground velocity of 0.1637 cm/s. Following Table 4 of Murphy & Lahoud (1969), with a yield of 1.3 Mt (NV–209) and a source–receiver distance of 276 km, we get a theoretical PGV of 0.1620 cm/s—these values match within 1%. In Figure 4, we compare this value to a plot of observations from BOXCAR in Murphy and Lahoud (1969), and we see that our calibrated value is well within the error bounds, consistent with other observational data, and very close to the predicted value. This result gives confidence in our calibration methodology.

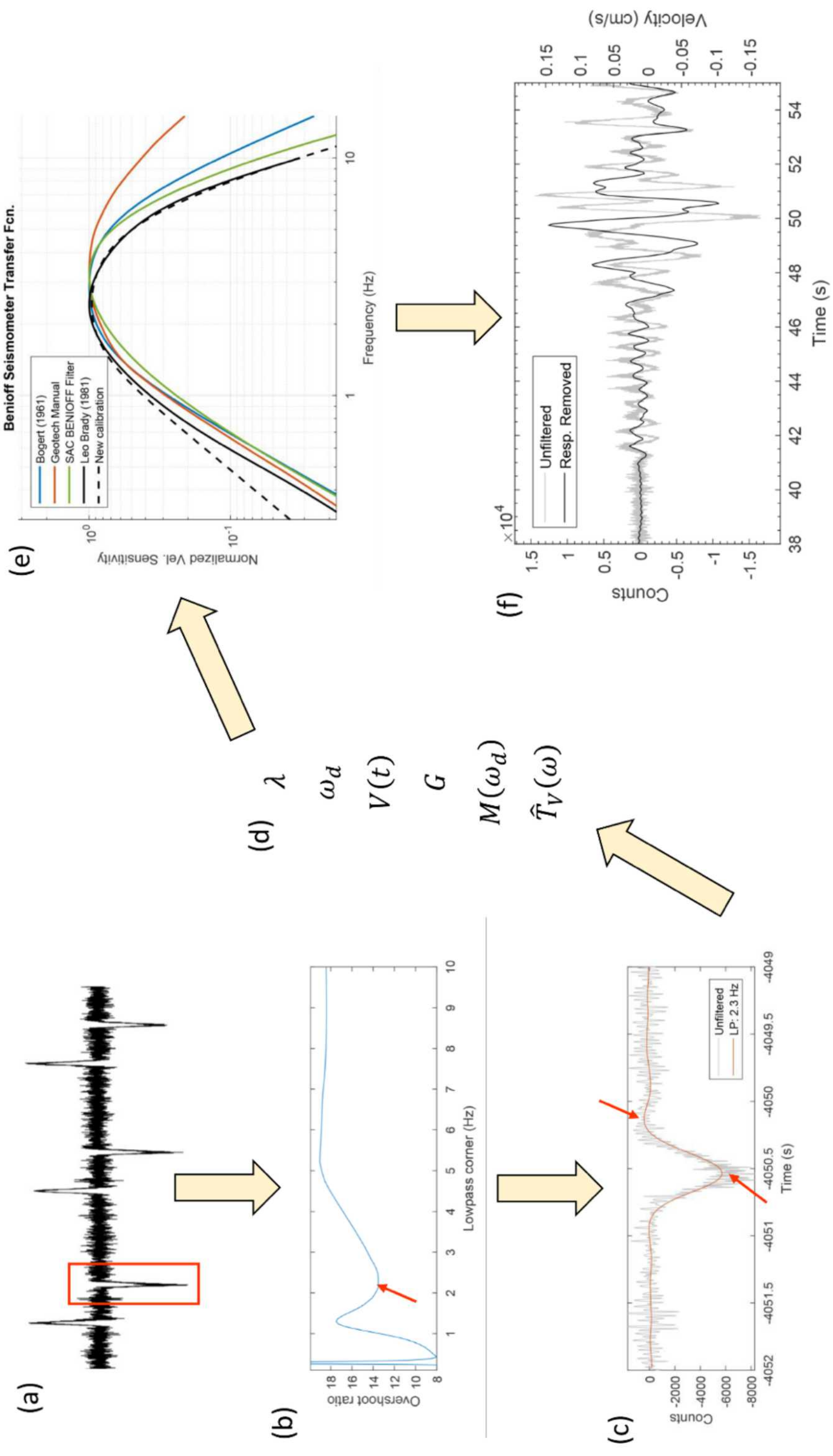

Figure 4. Generalized flow chart detailing the calibration process. The first weight lift test is isolated, recovered, and measured. The instrument sensitivity and transfer function are then calculated. The transfer function and sensitivity are finally used to deconvolve the instrument response and convert the raw data to units of ground velocity. Example data is from the vertical short-period seismograph at Leeds, UT for the BOXCAR event.

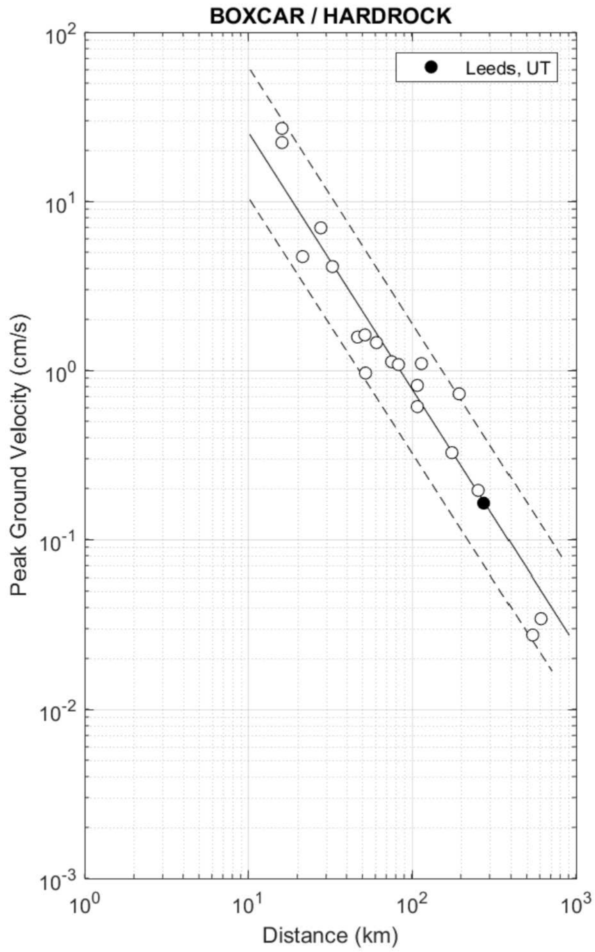

Figure 5. Peak ground velocity vs. distance digitized from Figure 7 in Murphy & Lahoud (1969). White circles are station observations, and the solid and dashed lines are the predicted PGV and uncertainty, respectively. The black circle is our calibrated value at Leeds, UT, of 0.1637 cm/s.

Finally, we calculate the full instrument response of the seismic system (seismometer, galvanometer, and two band-pass filters) and plot the amplitude response in Figure 6. The derived amplitude response compares very favorably with the shake-table measurements shown by Leo Brady in a memo (1981), and it doesn't match the responses from the BENIOFF filter in SAC, the Geotech Model 1051 User Manual, or the derived response by Bogert (1961) (which is also implemented in SAC as the "BENBOG" instrument). This demonstrates what we suspected about the LBSN, which is that the configuration of the Benioff seismometers was not standard. Our newly-calculated transfer function does not decay as steeply at low frequencies as that given by Leo Brady, but after some discussion with USGS Albuquerque Seismological Laboratory (Bob Hutt, USGS ASL, personal communication), we cannot determine a physical reason for the decay to be as steep as Leo Brady shows.

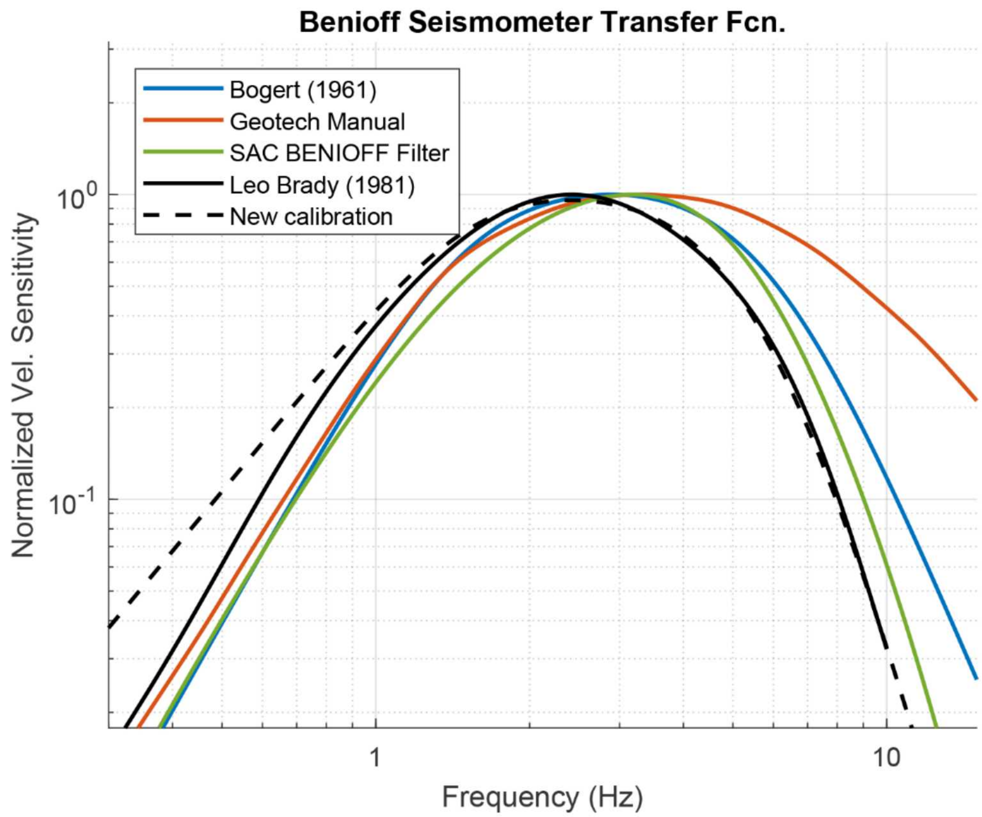

Figure 6. Normalized amplitude responses of various transfer functions for the Benioff 1051 seismograph.

Conclusions

We have demonstrated a process to take legacy analog seismic data on magnetic tapes all the way to calibrated digital waveforms. Our derivation of the instrument response and instrument sensitivity are more complete and rely on fewer assumptions than the methodology used in the analog era. With careful measurements, we believe it's possible that we can get more accurate ground motion results from these old data than was possible with paper records. The completion of the calibration software and a set of calibrated seismograms will be a major milestone, as it will be the only known digital set of calibrated UGT data from the analog era in the world.

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