Three-dimensional Seismometer Array at the Homestake Mine: Active and Passive Experiments

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Introduction (Victor to start, Vuk/Gary can add/modify afterwards)

- Motivation for the 3D array of broadband seismometers
    - Geo: weathered layer, anisotropy, surface wave propagation, noise in the underground

- Recently, the Laser Interferometer Gravitational-wave Observatory (LIGO) has announced the first direct detection of gravitational waves, generated in a merger of two black holes [REF]. This discovery marks a new direction in astrophysics, allowing the traditional electromagnetic observations of various objects and phenomena in the universe to be complemented by gravitational-wave observations. In order to fully explore the scientific potential of this new field, new and more sensitive gravitational detectors will be needed. Since these detectors are based on interferometric configurations with suspended mirrors, one of their limiting noise sources is the seismic noise. Seismic noise mechanically induces a small jitter in the position of the mirrors, hence potentially masking gravitational wave signals. Similarly, seismic noise causes the nearby rock to move, resulting in small fluctuations in the local gravitational field, which also induces a jitter in the mirror positions. Hence, understanding and potentially reducing the seismic noise limitations is critical for the future gravitational-wave detectors. And since the seismic noise is typically dominated by surface seismic waves (which are exponentially damped with depth), going underground may also provide significant benefit for gravitational-wave detectors. Being underground is also expected to reduce the local gravity fluctuations due to atmospheric perturbations and interactions at the ground-atmosphere interface.

  The Homestake Mine in Lead, SD was one of the largest and deepest gold mines in North America and has a rich history of scientific involvement. The mine officially closed in 2002, but reopened in 2007 as the Sanford Underground Research Facility (SURF) thanks to private donations and federal funding from the NSF and DOE. SURF currently features several experiments, including dark matter and neutrino experiments that benefit from the cosmic ray shielding by the rock overburden. SURF has developed significant infrastructure in the Homestake mine, including easy access to numerous underground levels, availability of power, availability of network, and safety protocols. The availability of this infrastructure underground, combined with hundreds of miles of available drifts in the mine make the Homestake mine the ideal location for development of a three-dimensional seismometer array.

- Experiences learned in executing the experiment underground important to preserve
- Expect experimental data to be used for some time so important to document the experiment
- Early analysis to demonstrate data potential but view this paper as an anchor for future work on the same data.

* Need a review of literature on applied geophysics underground measurements – this is a simple search in Geophysics. A LOT has been done for the mining industry and we need a perspective
* Basic geology review – note the rocks are schists and phyllites and high precision mapping data is preserved at Sanford lab
* Emphasize how the Homestake array is different from what was done in the past, enabling unique new studies (specify)

Seismometer Array

The Homestake seismometer array consisted of 24 seismic stations, 15 underground and 9 on the surface. The underground stations were scattered across several levels: one at the depth of 300 ft, one at 800 ft, one at 1700 ft, five at 2000 ft, three at 4100 ft, and four at 4850 ft. The locations of these stations were chosen so as to maximize the horizontal (x-y) span of the array, while still taking advantage of the available power and network underground wherever possible. In several cases, dedicated power and network cables were pulled and installed to support the stations. Attention was given to choose the stations locations relatively far from other activity in the mine and from water drainage pathways. Stations were usually placed in alcoves or blind alleys to minimize the effects of the air drifts, although several stations were installed in enlarged areas in the main drifts of the mine.

At each station, a concrete pad was poured directly onto the rock and a granite tile was glued to the pad. A seismometer was placed directly onto the granite tile, and was oriented against cardinal directions using an Octans gyrocompas. The seismometer was covered by two concentric huts constructed of 2” thick polyisocyanurate foam panels and sealed with foam sealant. The purpose of the huts was to further reduce the acoustic and air-flow induced disturbances on the seismometer. The readout electronics was placed several meters away, and included a Q330 data logger, a baler, and network and power supply electronics. Since we ensured that each of the underground locations had AC power, each station was powered by a continuously charged 12V battery. This arrangement allowed the station to continue smooth operation even in cases of up to a day-long power failures.

In addition to saving the data locally on a baler, the data logger was continuously transmitting data via Ethernet to a surface computer. In this way, each of the underground stations was remotely accessible, which enabled us to quickly detect and diagnose problems and failures. The stations were synchronized using a custom-designed GPS optical distribution system. The GPS signal was received by a GPS antenna mounted on the roof of the SURF administration building and piped to a Q330 in the server room of the same building. This “master” Q330 data-logger was used to convert the received high-frequency GPS signal into the separate 1PPS (1 pulse-persecond) and NMEA metadata components, which can then be used as an external timing signal for the other Q330s in underground stations. The output from this Q330's EXT GPS port was fed into an electro-optical transceiver which converts the electric into optical signals. The transceivers was custom-made for this application by Liteway, Inc. (model number GPSX-1001). An optical-fiber network of optical splitters and transceivers was installed underground to distribute this GPS timing signal to all underground stations, while maintaining its signal-to-noise ratio throughout the mine. At each station, a transceiver was used to convert the optical signals back into to electrical, which were then sent into the Q330's EXT GPS port. The timing accuracy achieved with this system was better than 1 μs. [DO WE NEED MORE INFORMATION ON THIS? MAYBE A DIAGRAM?]

Of the 9 surface stations, six were located on or near SURF property, directly above the underground stations. The remaining 3 stations were located on private land further away, roughly within 5 mile radius from the Homestake mine. At each station we placed a seismometer in an approximately 3'-deep hole, which was typically sufficient to reach the bedrock. The seismometer was placed onto a leveled concrete pad and aligned against cardinal directions with a compass (accounting for magnetic declination). The seismometer was surrounded by a "vault" featuring an inner layer of foam board insulation and an outer layer of timber in order to provide mechanical support, as well as thermal and acoustic insulation. The hole was filled back in, with additional dirt placed on top for further thermal and acoustic insulation.

The seismometer cable was brought out of the vault via a plastic conduit (for protection from the weather and animals) and into a sealed dog-house or a military-grade tote that housed the Q330 digitizer, baler, and power electronics. These enclosures provided some measure of ventilation, protection from the elements, and water drainage capabilities. All of the surface stations used GPS antennas connected to the GPS ANT port of the Q330 to provide a timing signal. The GPS antennas were attached to the top of a ~7' tall wooden post in order to provide an unobstructed view of the sky. The post also held two solar panels that were used to power the station via a 12 V, 55 A-hr battery, which was capable of supporting the station overnight and during cloudy periods. Only two of the surface stations had power interruptions due to the lack of sun exposure in short winter days.

Five of the nearby surface stations were equipped with a radio antenna (mounted on the wooden post) connected to the QNET port of the Q330. The antenna communicated with a receiver antenna mounted on the SURF administration building, providing real-time data flow from these stations to the master computer in the SURF administration building. Another nearby surface station was located near the Lead-Deadwood High School: at this station, data was transferred via a radio link to the High School, and from there further out via Ethernet. The three remaining surface stations on private property were too far for telemetry, so the data were stored locally on balers and retrieved manually.

Data from all but four surface stations were first sent to a master computer in the SURF administration building, running the Antelope real time system for acquiring and storing seismic data. This system was continuously forwarding data to another Antelope system running at the University of Minnesota, from where the data was sent further to CalTech and Indiana University, hence generating multiple copies of the data. Data from the local High School was directly sent to the University of Minnesota, and data from the three remote stations was only recorded on balers and added to the other data upon harvesting. Furthermore, data from all balers was merged with the real-time data upon retrieval of the balers, hence addressing several issues of missing data due to power or network dropouts.

The data from most stations was available at Minnesota, Indiana, and CalTech with latency of less than 1 hour. It was immediately processed to produce diagnostic trending plots and warning flags. A rotating shift schedule was set up to monitor the diagnostic information on daily basis, which allowed us to quickly identify and diagnose problems. In most cases, it was possible to remotely address problems, for example by performing a remote mass centering of a seismometer. In a very small number of cases, addressing the problem required a physical trip to the underground station: for example, to replace a failed seismometer, or to replace a concrete pad for a station that suffered from significant glitching due to concrete cracking. Overall, the array was remarkably stable and required only two maintenance trips to Homestake after the stations were installed.

All of the underground stations were installed between December 2014 and March 2015, and remained operational until December 2016. The surface stations were installed in May 2015 and remained operational until September 2016. Nearly all of the equipment used in the experiment was provided by the Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL) instrument center, which is part of the Incorporated Research Institutions for Seismology (IRIS). Most stations used a Streckheisen STS-2 high-sensitivity broadband seismometer. The exceptions were the 300 ft deep underground station and three surface stations where due to potential moisture concerns we installed more water-resistant Guralp CMG-3T broadband seismometers.

Figure 1 shows the map of the Homestake array stations. The locations of stations are known with uncertainties on the order of 2 m. Underground station locations were obtained from maps of the mine drifts based on past mine surveys, while surface station coordinates come from GPS data.

- Brief description of when the array was operating, highlight some of the failures and fixes.
- Highlight the incredibly high data recovery rate – only loss of any significance was power problems at DEAD.   Points to importance of telemetry to identify problems early.

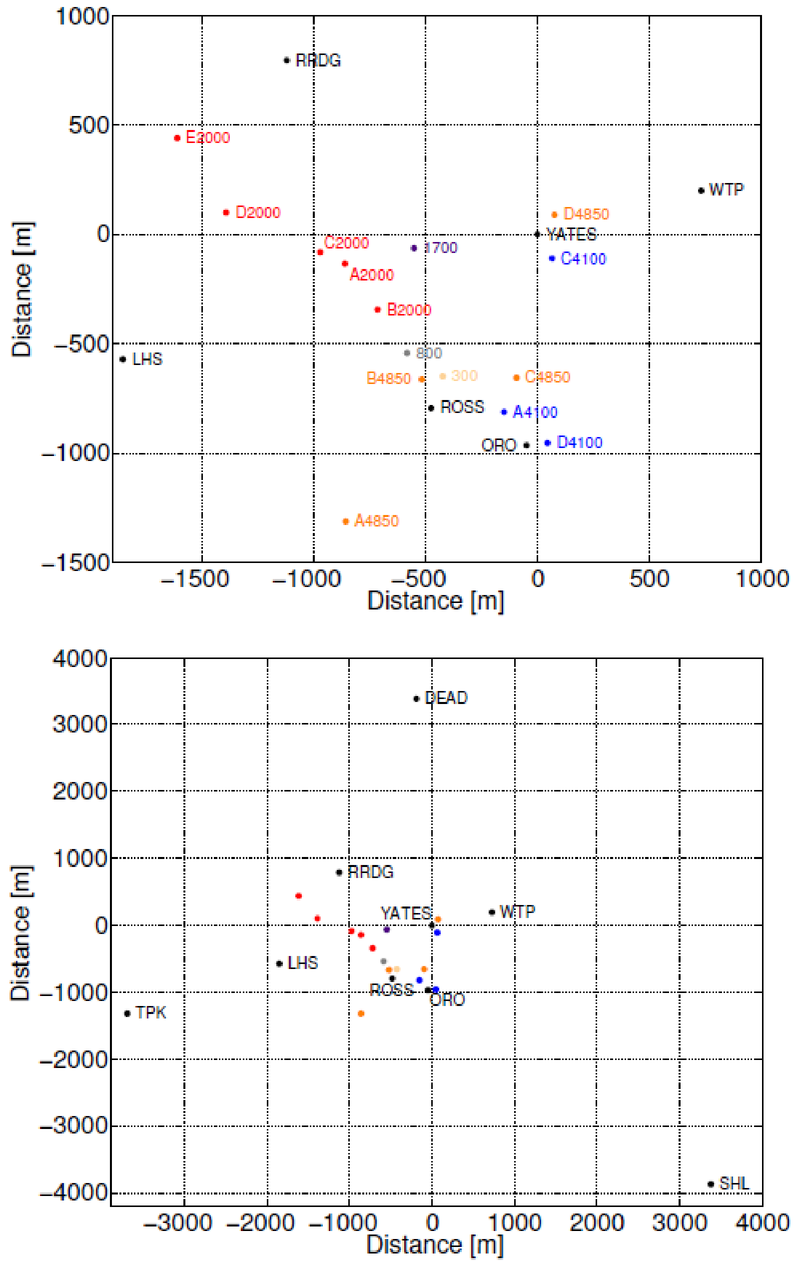

Figure 1: [PLACEHOLDER] Homestake array layout, relative to Yates shaft sation (at origin). A zoomed-in view with the underground stations labeled is shown on top (DEAD, SHL, and TPK not pictured). All stations are shown in the lower plot, but only the surface stations are labeled.

Active Experiments (Gary, with help from Victor, Boise)

- Surface Land streamer data
    - Surface recording with land streamer
    - Recorded in underground by passive array stations
    - Timing failure lead to need to estimate origin times independently (That will better be left to a different paper.)
    - Might show a record section of some of that data
    - Need a map figure of shot geometry
    - Problem – mismatch of bandwidth of broadbands and this source. Would have had better results with auxiliary geophones and/or a source that had more output at lower frequencies.
- Underground HSP experiments
    - 3 locations
    - sensor emplacement and anchoring
    - sensor orientation method
    - 9 component shooting
    - walkaway geometries
    - Need a number of maps to document this geometry.
- Underground land streamer experiment
- Critical review of approaches we used
    - Streamer collected a lot of useful data fast, but sleds were problematic in this location. Something more like a real streamer would probably have been more workable
    - Airless jackhammer was effective, but produced a very high frequency pulse when applied to bare rock. Also produced a huge airwave. Stronger source would have been helpful but there are strong safety tradeoffs. Pulse was so high frequency was nearly invisible on broadbands when only a few m away. (actually we need to look more closely at that) I know we can see spikes on the near station, but could not see it elsewhere – should confirm that.
    - Geophone coupling a huge unknown that may contaminate our data. (details later). A more effective strategy would have been to do what SDSMT people did – use a rock drill and anchor sensors to the wall with a rock bolt. Note that is the opposite approach where you aim to collect tons of data fast and beat down noise by averaging.
    - Water everywhere and always complicating things.

Preliminary Results

We compute the amplitude spectral density (ASD) of seismic noise over long periods, for different stations and different seismic channels (east, north, vertical). These are shown in Figure 2 in comparison to the low- and high-noise models by Peterson [REF]. We use one year of data (from June 1, 2015–May 31, 2016), split into 400 second intervals. For four of the surface stations, we use only 3 months of data (the rest is not yet available).
All spectra show the median amplitudes in each frequency bin for the vertical seismic channel.

The top-left panel compares the ASDs for stations at several different depths. All of the stations are in close agreement in the middle range of frequencies, which corresponds to the microseismic peak. At higher frequencies, there is significantly less noise with depth: above 0.5 Hz, the stations at 4100 ft and 4850 ft depths are nearly an order of magnitude quieter than other stations. At the lowest frequencies there is also a good agreement between the stations, although a slight trend of decreasing noise with depth is apparent; this may be due to larger temperature variations closer to the surface inducing tilts in the concrete pads.

For the surface stations (top-right panel) there is a wide range of variability; this is due to differences in the local environment in terms of thermal insulation and proximity to human activity. Differences in the microseismic peak (0.1–0.2 Hz) are likely due to differences in the amount of data used in this analysis; the microseism experiences seasonal variations and appears differently for stations which do not include the full year of data (DEAD, SHL, TPK, and YATES).

The middle-left panel shows spectra for stations at 300 ft, 800 ft, and 1700 ft depth. The noise levels are reduced with depth at higher and lower frequencies; the higher level of low frequency noise at the 800 station is likely due to its proximity to one of the mine shafts. The middle-right panel shows spectra for the stations at 2000 ft depth. There is generally good agreement between the stations across all frequencies. B2000 experiences increased noise, especially at high frequencies, likely due to its location near a lunch room and a mine shaft.

Spectra for the stations at 4100 ft depth are shown in the bottom-left panel. The C4100 station appears to have the least noise at low frequencies, while the D4100 station experiences the most high-frequency noise. These variations are not well-understood based on station locations and expected proximity to human activity. Finally, spectra for the stations at 4850 ft depth are shown in the bottom-right panel. Here, the B4850 station experiences significantly increased high-frequency noise due to its location near a large fan and ongoing construction. Above 1 Hz, the other stations are in fairly good agreement, although each station seems to have its own individual noise peaks in the spectrum. This is likely due to the unique environment surrounding each station:
C4850 is in a storage room and very close to a rail line, and D4850 is very close to other experiments in the mina, ventilation equipment, and human activity. The A4850 station seems to have more overall high-frequency noise than these two stations, which is not well-understood since it is one of the most isolated stations in the entire array.

Figure 3 shows ASD histograms for the RRDG surface station (left column) and for the A4850 underground station (right column) as examples of a relatively good surface station and our deepest and most isolated underground station. Here, we show histograms of ASDs calculated from the 400-second data intervals over 1 year in each frequency bin, revealing the overall variability of the seismic noise at each station. The white curve represents the median ASD (identical to those shown in Figure 2), the black curves represent the 95% confidence intervals in each frequency bin, and the color scale shows the overall distribution. The Peterson low- and high-noise models are shown in dashed gray.

The histograms display about two orders of magnitude of variation across all frequencies for both the RRDG station and the A4850 station. The A4850 station measures less noise in general and appears to have less overall variation than RRDG. There also appears to be significantly more high-frequency noise in the RRDG station; this is likely due to anthropogenic surface waves that are suppressed with depth. Both stations stay within the low- and high-noise Peterson models most of the time; in the 0.3–0.9 Hz range, the A4850 station is actually below the low-noise model a significant fraction of the time. There is also a considerable difference between the vertical channel and the horizontal channels at low frequencies: at 0.01 Hz and below for both stations, the vertical channel has almost an order of magnitude lower noise than the horizontals.

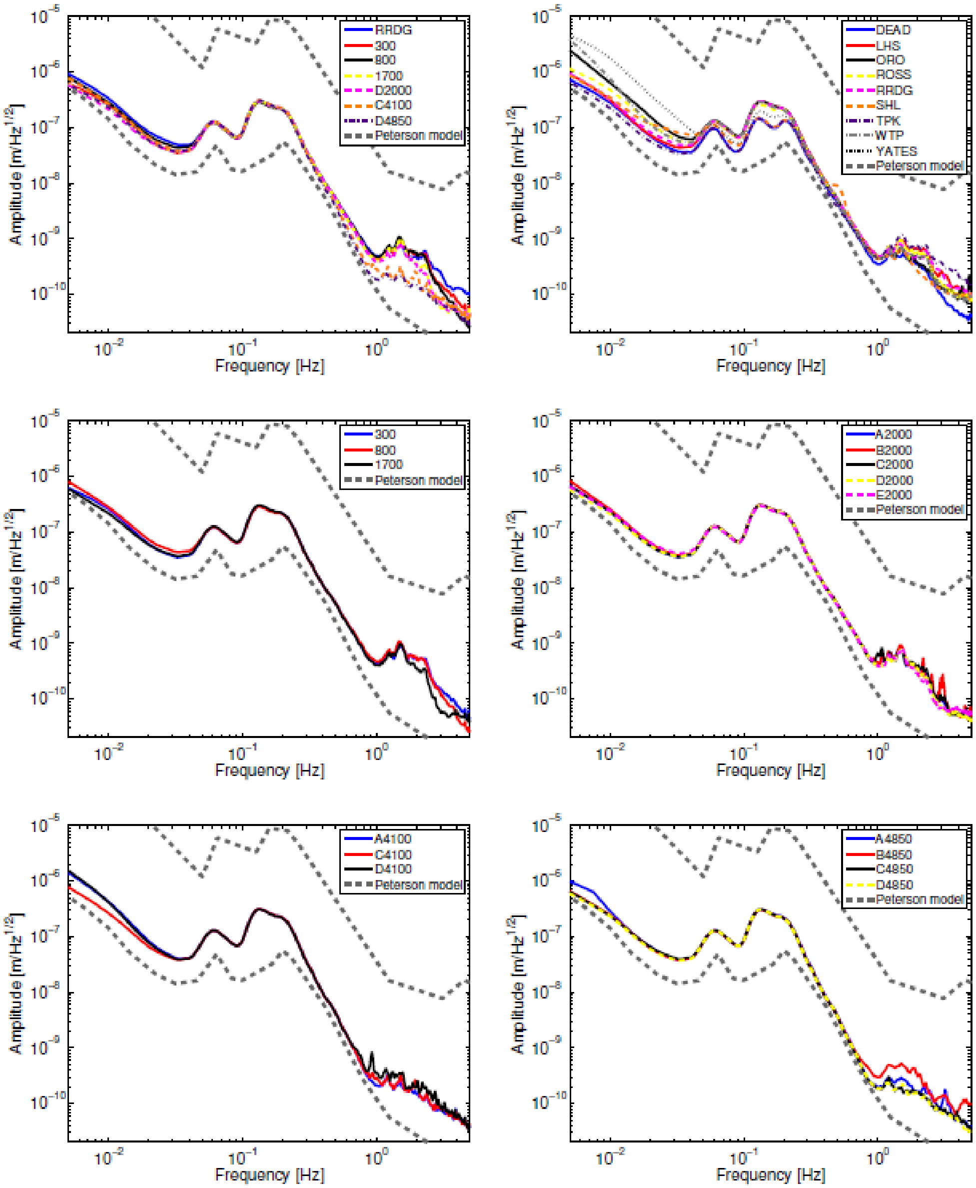

Figure 2: [PLACEHOLDER] Median amplitude spectral densities for all Homestake stations; numbers in the legend entries denote depth in feet, while numberless legend entries denote surface stations. One year of data is used except for DEAD, SHL, and TPK stations, for which only 3 months of data was used, and YATES, which is missing data due to power and communication issues. More details are provided in the text.

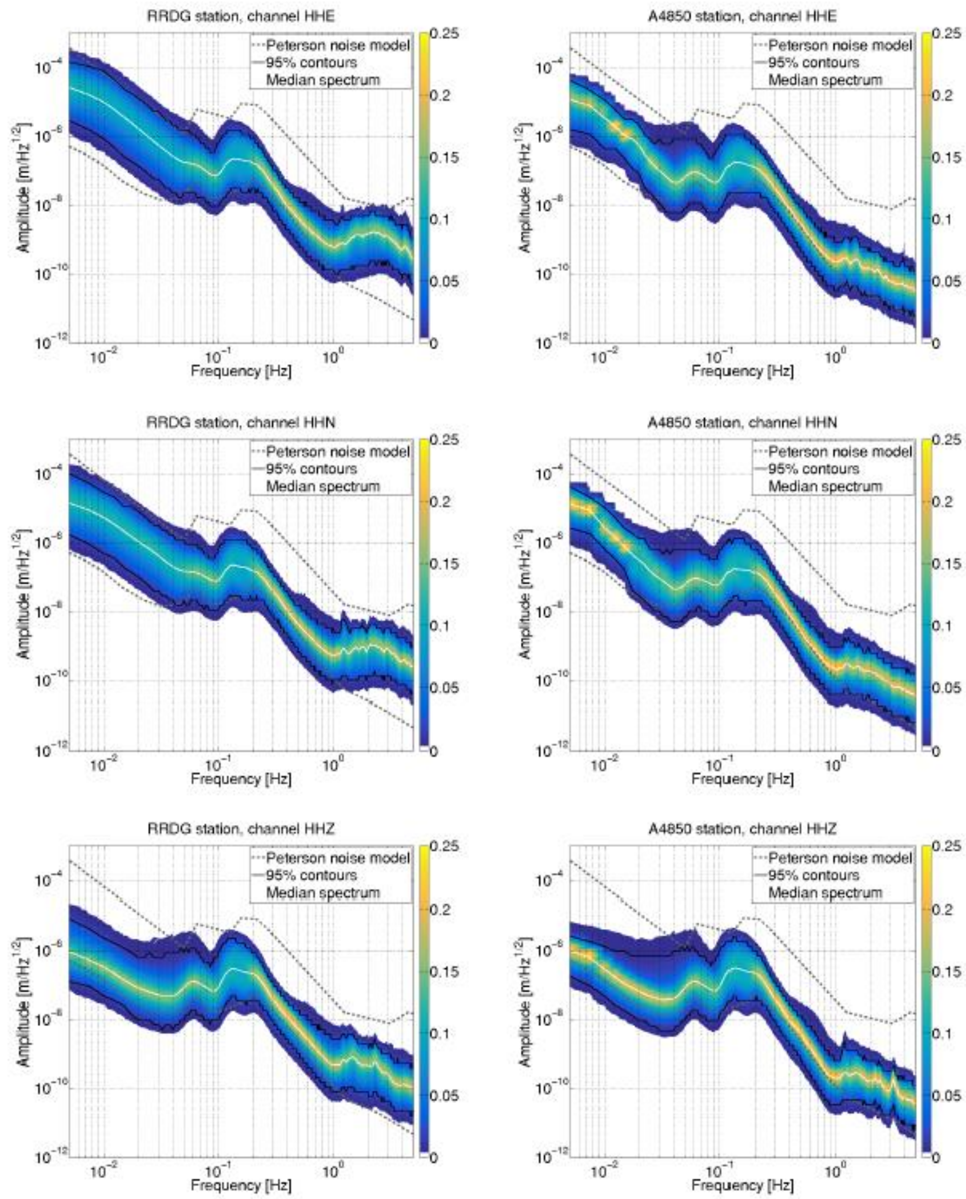

Figure 3: [PLACEHOLDER] Histograms of amplitude spectral density in each frequency bin for a surface station (left column) and for an underground station at 4850 ft depth (right column). The plots are divided into rows by channel: east (top), north (middle), and vertical (bottom). Median ASDs (solid white), 95% confidence intervals for each frequency bin (solid black), and the Peterson low- and high-noise models (dashed gray) are shown. See the text for more details.

- Passive: (Pat)
  - Example seismograms of mining explosions and teleseismic events
  - Figure of location estimates of mining events processed to date

- Active: (Gary, Ross)
    - Data examples from different shots
    - Preliminary velocity estimates?
    - Preliminary statements on reflections?

Conclusions (TBD, let's see what the paper looks like)

- Useful data with a wide range of scientific use to better understand wave propagation
- Emphasize low noise, high SNR potential – especially at very long periods
- Preliminary indications about velocity distribution etc
- S-wave speed estimates from underground land streamer (3.5 something + or – something) with small differences in the different named formations.