USGS Albuquerque Seismological Laboratory
Instrumentation Test Facilities and Capabilities

Charles R. Hutt and Adam T. Ringler

March 2014

Introduction

The Albuquerque Seismological Laboratory (ASL) was established in 1961 as a quiet site for testing seismometers for the World-Wide Standardized Seismograph Network (WWSSN), but quickly became the installation and maintenance depot and data collection center as well. Today, ASL occupies a 160-acre site located in a remote area of Isleta Pueblo adjacent to the south boundary of Kirtland Air Force Base, about 11 miles southeast of the Albuquerque, New Mexico, airport. The ASL's location in the Manzanito Hills is relatively isolated so that seismographic instruments can be operated and tested without major disturbance from man-made noise sources.

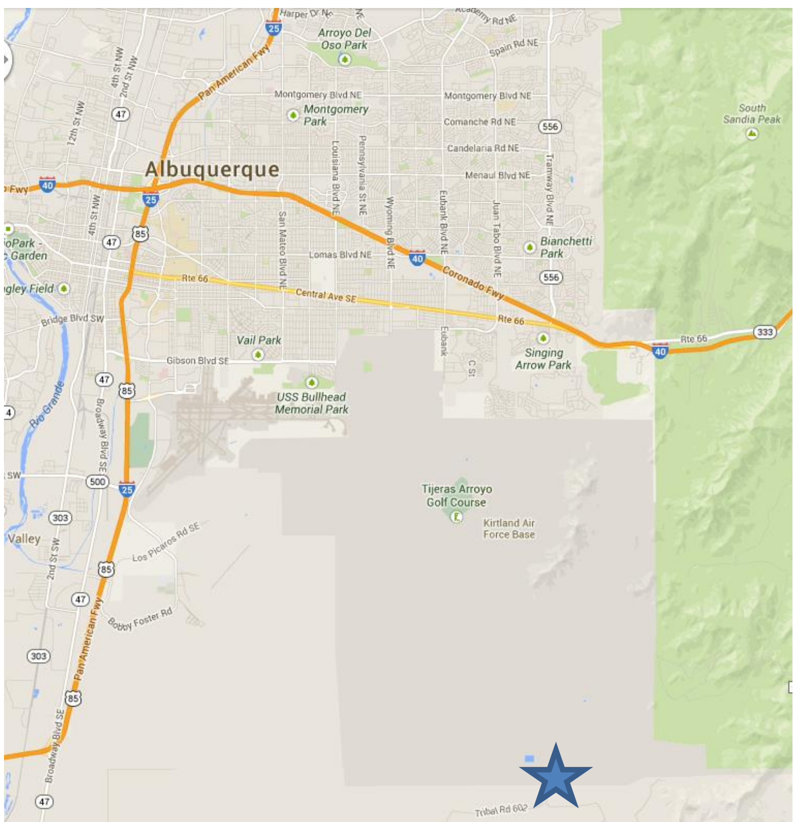


Figure 1. The blue star indicates the location of the Albuquerque Seismological Laboratory (ASL) relative to the city of Albuquerque. ASL is located just south of the south boundary of Kirtland AFB on Isleta Reservation, about 11 miles SE of the Albuquerque Sunport (airport). Map courtesy of Google Map.

The ASL consists of 15 structures, two subsurface vaults mined into a granite hill, 21 deep and shallow boreholes, and a collection of near-surface vaults. The extremely low-noise seismometer test facilities at ASL are quite important in evaluating, developing, and improving seismic instrumentation for the Global Seismographic Network (GSN), the Advanced National Seismic System (ANSS), and other regional seismic networks.

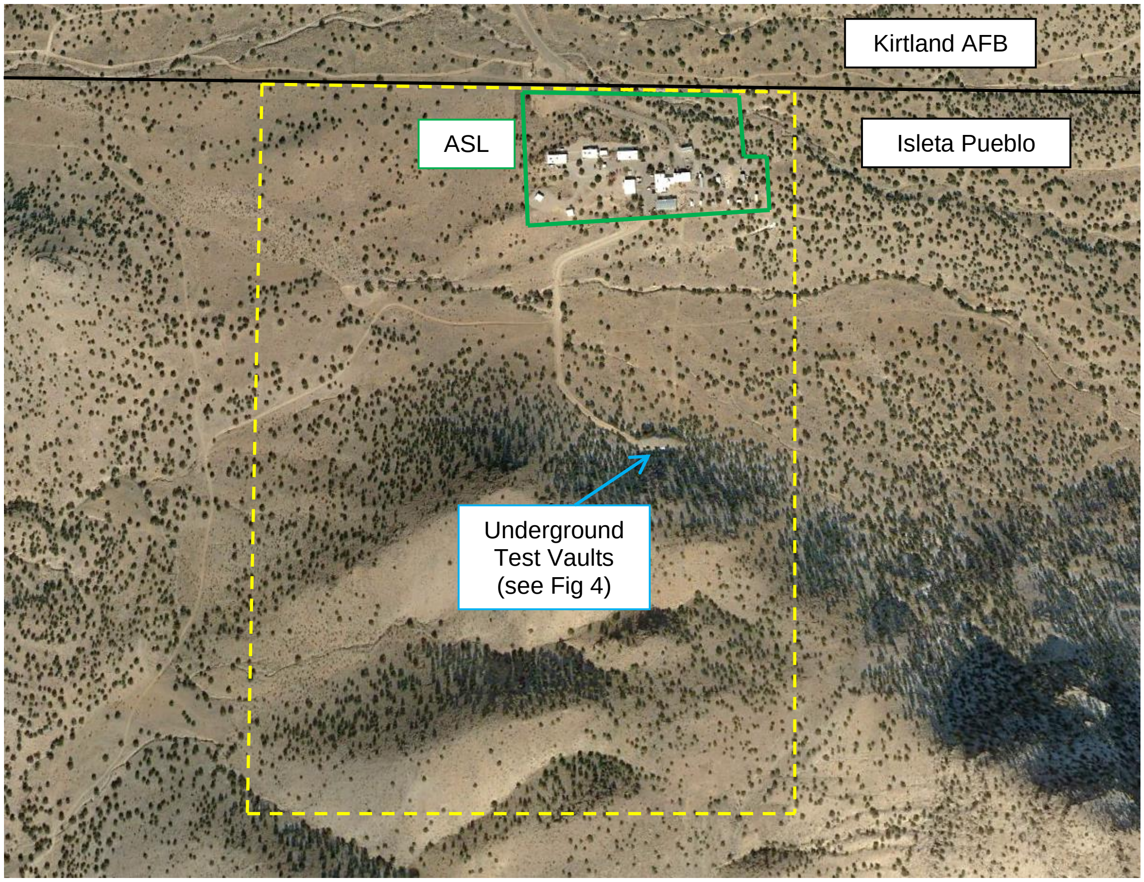


Figure 2. Google Earth view of the Albuquerque Seismological Laboratory (ASL) relative to the Isleta Reservation and Kirtland AFB (black boundary). The main facilities are inside the fenced area indicated by the green boundary while the entire leased area is inside the yellow dashed box. The area labeled "Underground Test Vaults" is the location of the two mined vaults. North is up.

The ASL test facilities are usually available for use by colleagues, collaborators, and other government agencies. Commercial entities who wish to use the facilities may be required to sign a Facility Service/Use Agreement and pay a fee (see Appendix I for an example).

Test Facility Locations and Layouts

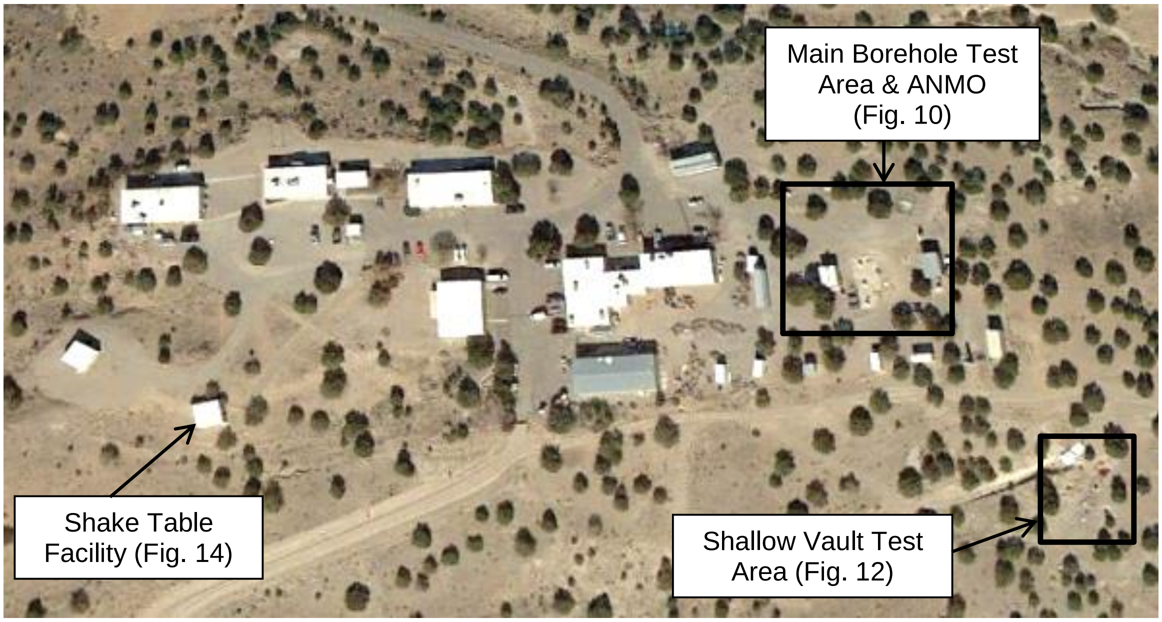


Figure 3: Satellite view of major instrument test facility locations at ASL. The Underground Vault Test area is shown in Figures 2 and 4 and not included in this figure. North is up.

Test Area Descriptions

Underground Vault Test Area

The underground vaults were mined into Pre-Cambrian granite in late 1960 and early 1961. As shown in Figure 4, there are two tunnels that extend approximately 60 feet generally southward into the north side of a hill. The entrance to each tunnel is accessed by an ordinary metal door, a ship door with rubber gaskets, and then an ordinary wooden door into a room measuring about 20 feet by 20 feet. The two rooms, known as the East Vault and West Vault, are connected by the Cross Tunnel (shown in Figure 4 as a "Controlled Pressure Area"). Each end of the Cross Tunnel is accessed via a wooden door and then a ship door with gaskets. When both ship doors into the Cross Tunnel are closed, atmospheric pressure variations are attenuated at periods less than about 20 seconds. The overburden at the south side of the East Vault and the West Vault and in the Cross Tunnel is about 37', decreasing to the North.

All floors in the underground vaults consist of high-strength concrete, about 12" thick, poured directly on the mined granite surface, which was well cleaned and washed before the concrete was poured. This means that nearly any location on the concrete floor is an excellent pier for testing both weak-motion (WM) and strong-motion (SM) seismometers.

Since the vault area is mined into granite, radioactive radon gas is present. The underground vault area is ventilated by two fans, one at each tunnel entrance. The fans blow air into the vaults via cable troughs that do double duty as air ducts. When the outer ship doors (at the tunnel entrances) are closed, and if the fans are operating, a slight overpressure is created. This overpressure, along with the circulation of air into and out of the vault area, reduces radon concentration to levels acceptable for continuous human exposure (4.0 picoCuries/liter, or pCi/l).

The fans are sometimes turned off for days or weeks at a time for seismometer noise tests. When the fans are off for extended periods, radon levels may reach as high as 100 pCi/l, a level at which exposure should be limited to no more than 2 hours per day. When the fans are turned on, the radon levels are reduced to approximately 5 pCi/l within one day.

The West Vault and Cross Tunnel are used for robust testing of both WM and SM seismic instruments. Available reference instruments include a 3-component set of Streckeisen STS-1 VBB seismometers and one Streckeisen STS-2 High Gain seismometer. Quanterra Q330 (24-bit) and Q330HR (26-bit) data loggers are used to collect data. The East Vault is used for system integration as well as operational and noise testing of instruments before shipment to the field.

Figures 5a through 5h are photos of the underground test areas in the West Vault and the Cross Tunnel. Figures 6 through 9 are typical power spectral densities (PSDs) of background seismic noise in the Cross Tunnel in both quiet and noisy conditions.

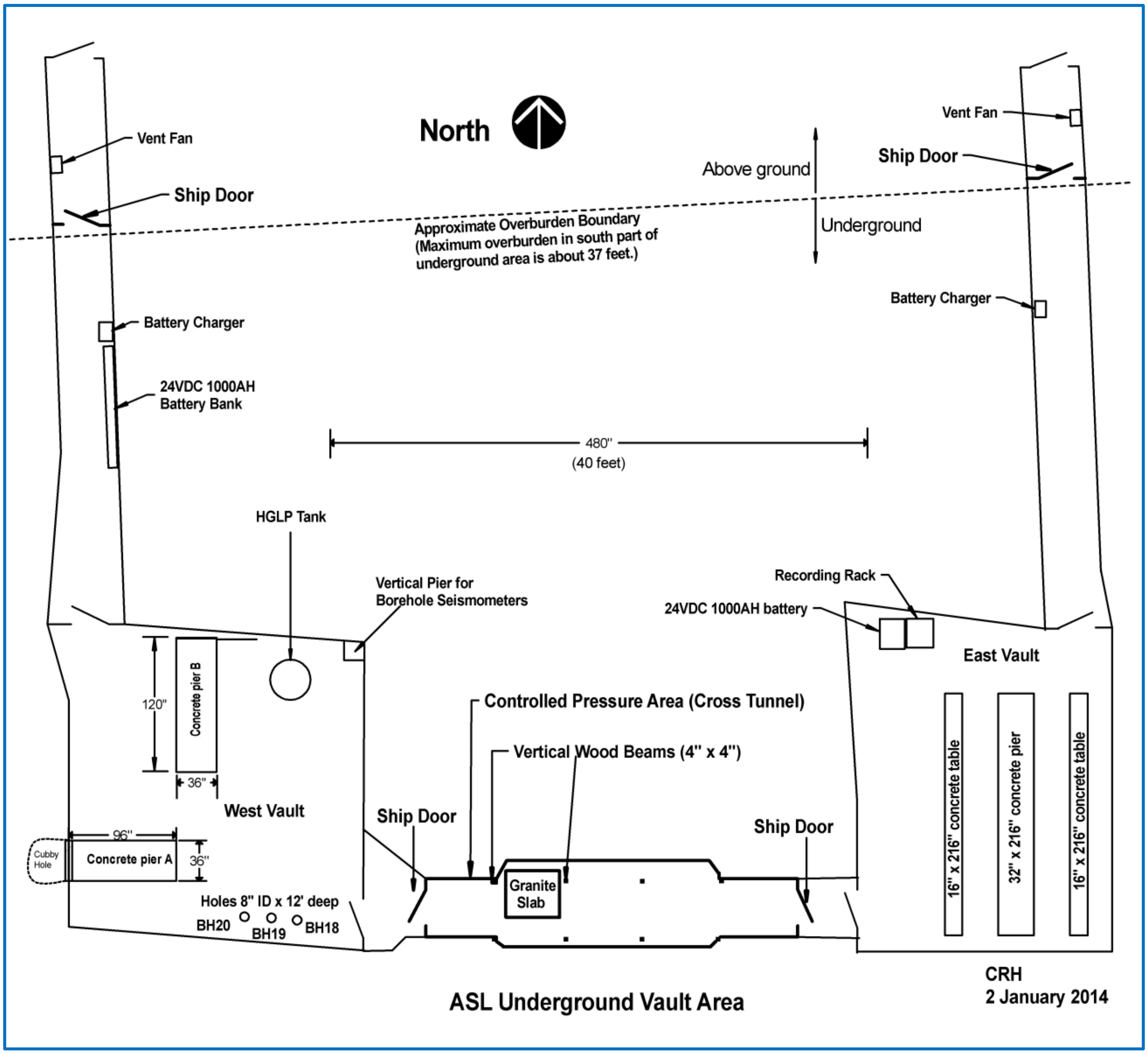


Figure 4: Underground vault test area. The "Controlled Pressure Area," also known as the Cross Tunnel, has reduced atmospheric pressure variations at periods shorter than about 20 seconds and very low temperature variations when the ship doors at both ends are closed. The shallow boreholes indicated as BH18, BH19, and BH20 are described in Table 1. 24VDC battery power is available with capacity sufficient to operate sensors and data loggers for several days with AC power turned off.

Figure 5a: West underground vault entrance.

Figure 5b: Entrance hallway to west underground vault.

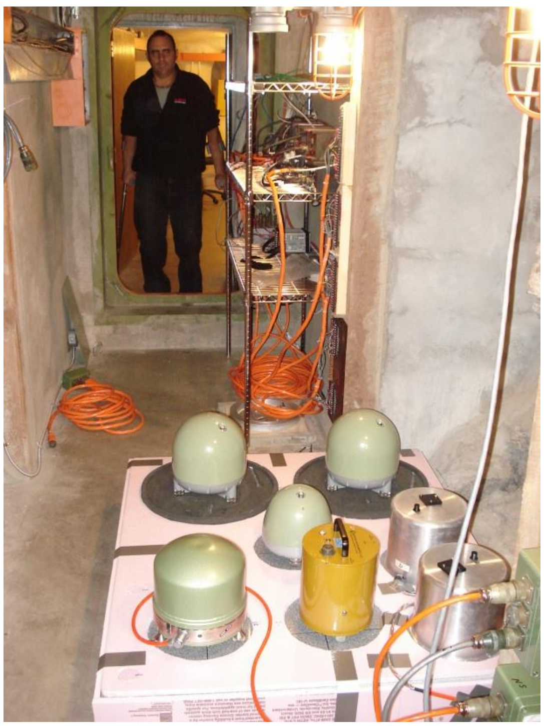


Figure 5c: View from center of cross tunnel toward west ship door, showing Leo Sandoval preparing to perform a “huddle test” of several instruments on the granite slab.

Figure 5d: View looking east into cross tunnel. STS-1V/VBB seismometer is in evacuated chamber under a large amount of sand for excellent temperature stability.

Figure 5e: Seismometers under test on granite slab in Cross Tunnel. The slab is supported by three lead pads for coherent tilt across the entire surface, allowing better determination of horizontal instrument self-noise in the long period band. When noise test data are being collected, the slab and instruments are shielded against stray air currents and thermal fluctuations with a 2-inch thick insulating foam box.

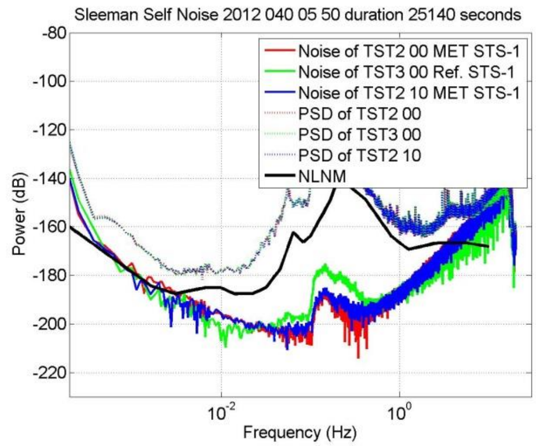


Figure 5f: Example of determination of self-noise of two vertical VBB instruments under test (00 MET STS-1 and 10 MET STS-1) by comparison with the reference STS-1V buried under sand. The ship doors on both ends of the cross tunnel must remain closed for extended periods (several days) in order to achieve good test results in the low frequency band (0.001 Hz to 0.05 Hz).

Figure 5g: Pier in West Vault typically used for testing strong motion sensors (accelerometers).

Figure 5h: Three 8” diameter, 12’ deep un-cased holes in floor of West Vault used for testing posthole and borehole sensors.

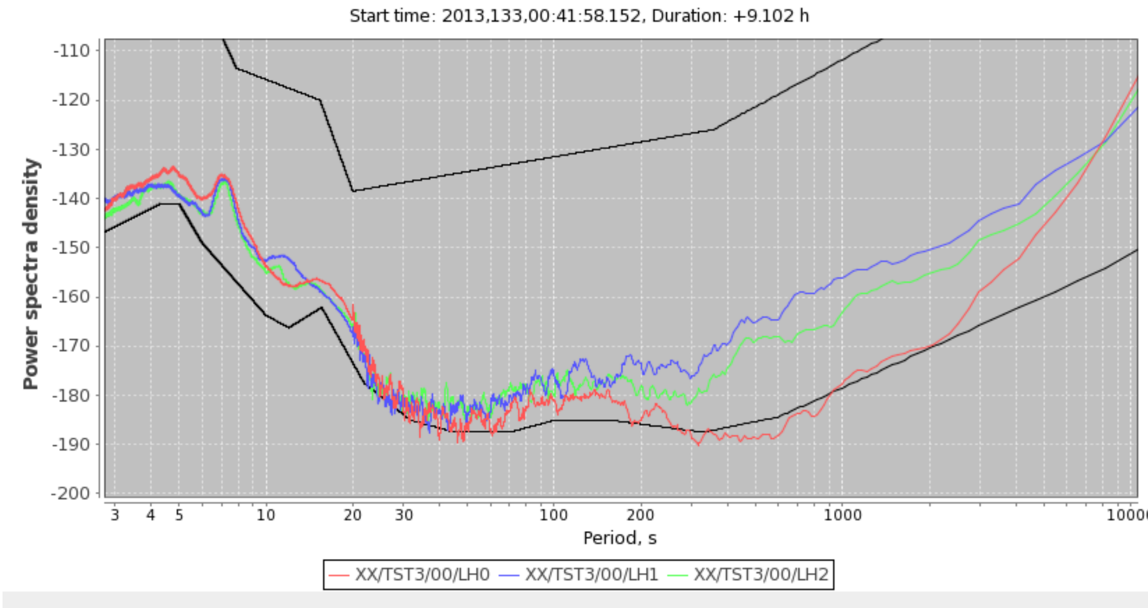


Figure 6: Typical long-period noise levels from STS-1 reference seismometers in cross tunnel during quiet conditions (little or no wind). Red = Z, Blue = NS, Green = EW. Upper and lower black lines are Peterson's (1993) New High Noise Model (NHNM) and New Low Noise Model (NLNM), respectively.

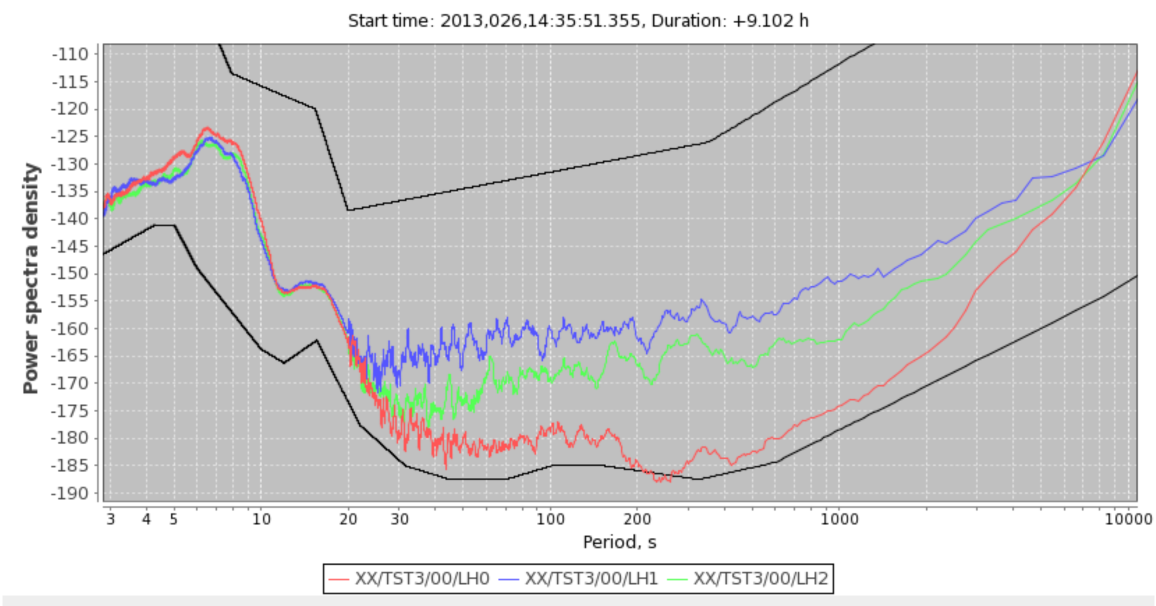


Figure 7: Typical long-period noise levels from STS-1 reference seismometers in cross tunnel during noisy conditions (wind blowing). Red = Z, Blue = NS, Green = EW. Upper and lower black lines are NHNM and NLNM, respectively. The long-period noise level in the N-S direction (blue) is nearly always higher than in the E-W direction, most likely due to the geometry and orientation of the cross tunnel.

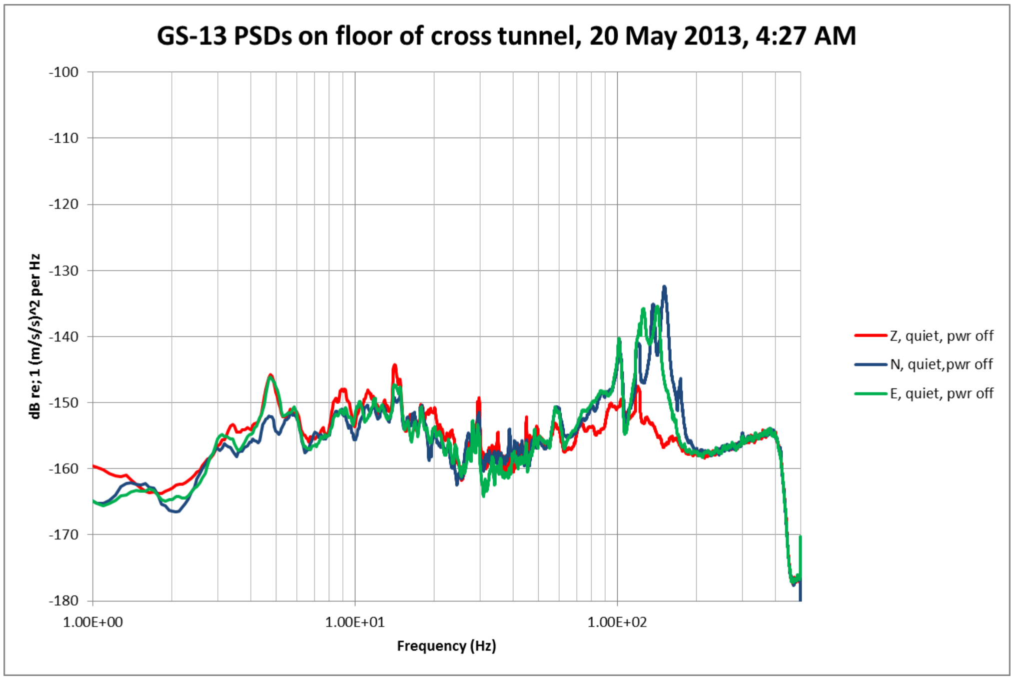


Figure 8: Typical high-frequency noise levels from Geotech GS-13 seismometers in cross tunnel during quiet conditions (little or no wind, vault power off, ventilation fans off, early morning). These data were taken with a Q330S+ data logger at 1000 samples per second and with the preamplifier gain set to X64. Window length is 66 seconds. Red = Z, Blue = NS, Green = EW. Peterson's (1993) NLNM is at -168 dB from 1 Hz to 10 Hz. A level of -160 dB on this plot roughly corresponds to 1 nano-g per root Hz. Peaks above 100 Hz in horizontal components are instrumental in origin (internal resonances in the GS-13 seismometers).

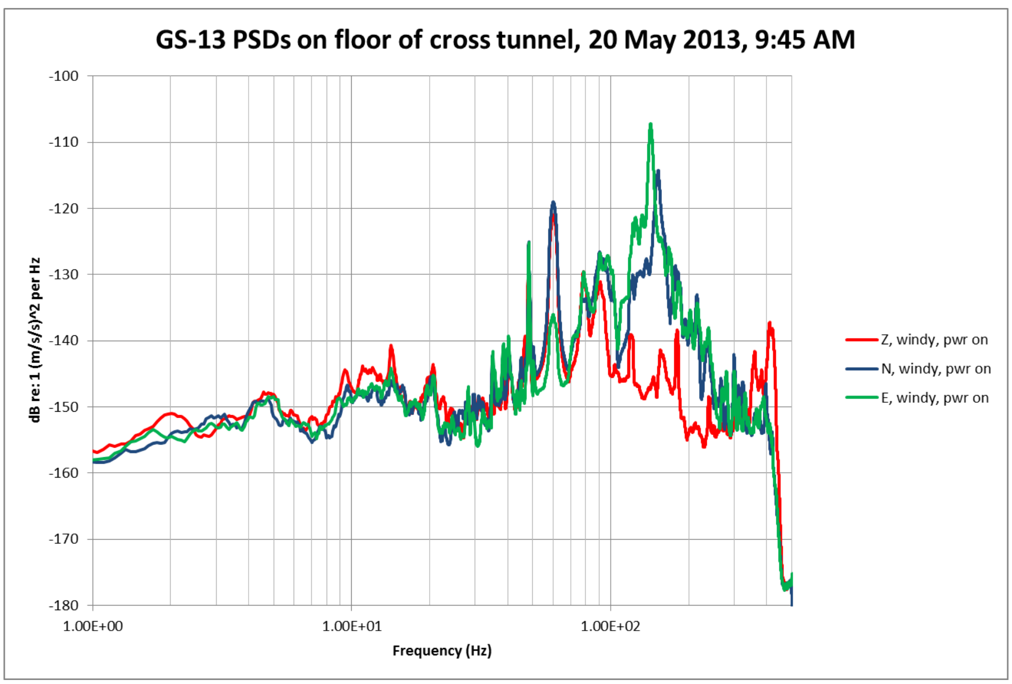


Figure 9: Typical high-frequency noise levels from Geotech GS-13 seismometers in cross tunnel during noise conditions (windy, vault power on, ventilation fans on, daylight hours), window length 66 seconds. Red = Z, Blue = NS, Green = EW. Peterson's (1993) NLNM is at -168 dB from 1 Hz to 10 Hz. A level of -160 dB on this plot roughly corresponds to 1 nano-g per root Hz. Peaks above 100 Hz in horizontal components are instrumental in origin (internal resonances in the GS-13 seismometers).

Borehole Test Area

The main borehole seismometer test area consists of 14 shallow and deep instrumentation boreholes, ASL's water well, and a 5 foot deep concrete pit (see Figure 10). Details are given in Table 1, where we see that all of the deep (depth > 10m) boreholes are cased with steel oil-well casing (the casing is cemented to the surrounding rock or soil over the full depth of the hole). Of the seven shallow boreholes, two are cased with steel casing and five are cased with PVC pipe. All of the shallow boreholes (depth < 10m) in this area terminate in the ~10m deep soil/conglomerate that lies on top of Pre-Cambrian granite. The deep boreholes terminate in the granite. Two of the deep boreholes are used for GSN station ANMO's operational borehole seismometers (Geotech KS54000 and Guralp CMG-3TB) – the other 12 deep boreholes and all of the shallow boreholes are used for testing. These boreholes are inside the main fenced ASL compound and are fairly close to high frequency noise sources including building HVAC systems and small amounts of vehicle traffic. The ANMO instrumentation allows this high-quality GSN station to serve as a reference platform for seismometers under test. In addition to the seismic data, the station also has weather channels and other geophysical measurements available, including continuous magnetic field and infrasound recordings. Wind speed and direction, pressure, temperature, and rainfall data are useful when interpreting background seismic noise levels, especially in shallow installations.

Figures 11a through 11d are photos of the ANMO borehole area and main borehole test area.

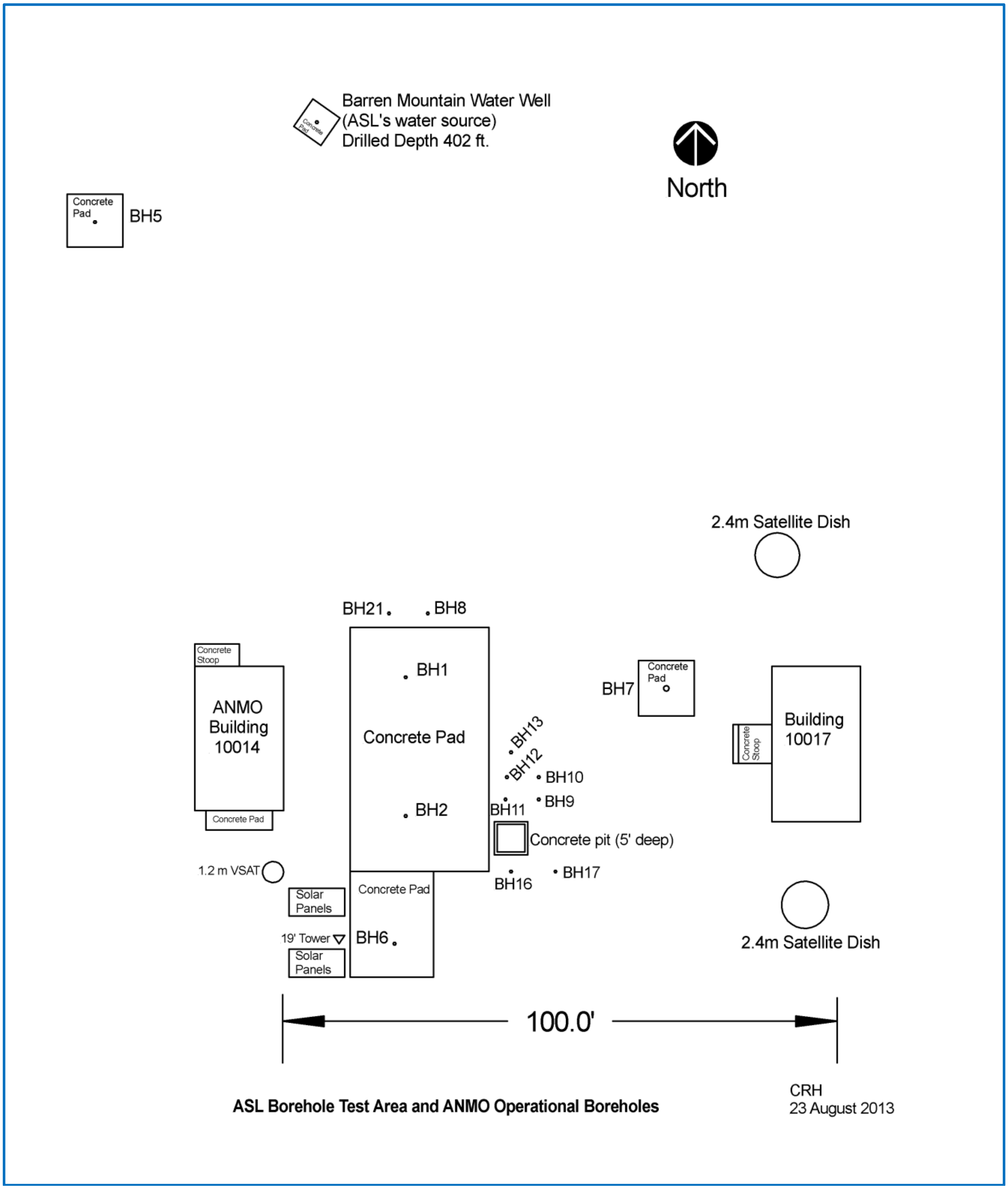


Figure 10: Main borehole test facility. Scale is approximate. Depths and diameters of boreholes are listed in Table 1. Boreholes 10 and 11 (BH10 and BH11) contain the two ANMO broadband borehole seismometers.

Figure 11a: Main ASL borehole test area. ANMO boreholes are under the two white covers.

Figure 11b: Five shallow PVC-cased boreholes that terminate in the soil layer. Two steel-cased boreholes are in the background (with yellow bags over them).

Figure 11c: Deep (150m) steel-cased hole used for testing KS54000 and other BB and VBB borehole seismometers. Mast with pulley on top is used to support seismometer over hole when installing and retrieving the instrument.

Figure 11d: Adam Ringler preparing to lower a Trillium T120PH seismometer into 106.7m deep, 12 5/8" diameter hole for noise testing. This large diameter borehole is also known as the "Russian Borehole," as it was drilled for testing a Russian BB seismometer in 1990. This seismometer had a diameter of 9 inches, too large to fit into the standard 6.5" ID boreholes.

Table 1: ASL Borehole & Posthole List
23 August 2013 - CRH

Well Name	Where	Depth	ID or OD	Casing	Date Drilled	Comment
ASL BH1	ANMO Area	498.8’ (152.0m)	7.0” ID	Steel	01 Aug 1973	~33’ soil, then granite. ANMO KS5400 at 476’ (145m).
ASL BH2	ANMO Area	701’ (213.7m)	6.5” ID	Steel	01 Jul 1973	~33’ soil, then granite. ANMO CMG-3TB at 57m (187’). Severe tilt below about 200’ (up to 11° at bottom).
ASL BH3	Snake Pit Area	31’ (9.4m)	6.5” ID	Steel	1973(?)	~6’ soil, then granite North hole.
ASL BH4	Snake Pit Area	29’ (8.8m)	6.5” ID	Steel	1973(?)	~6’ soil, then granite South hole.
ASL BH5	ANMO Area	617.5’ (188.2m)	6.5” ID	Steel	16 Apr 1974	~33’ soil, then granite. North test hole.
ASL BH6	ANMO Area	492.6’ (150.1m)	6.5” ID	Steel	06 Nov 1984	~33’ soil, then granite. South test hole.
ASL BH7	ANMO Area	350’ (106.7m)	12 5/8” ID	Steel	27 Aug 1990	~33’ soil, then granite. Russian test hole.
ASL BH8	ANMO Area	10’ (3.0m)	6.5” ID	Steel	Aug 1973(?)	In soil, not cemented.
ASL BH9	ANMO Area	9’ (2.7m)	8.0” ID	PVC	April 2012	In soil, not cemented. Drilled by Earthscope TA project.
ASL BH10	ANMO Area	14’ (4.3m)	6.0” ID	PVC	April 2012	In soil, not cemented. Drilled by Earthscope TA project.
ASL BH11	ANMO Area	25’ (7.6m)	6.0” ID	PVC	April 2012	In soil, not cemented. Drilled by Earthscope TA project.
ASL BH12	ANMO Area	15’ (4.6m)	6.0” ID	PVC	April 2012	In soil, not cemented. Drilled by Earthscope TA project.
ASL BH13	ANMO Area	9’ (2.7m)	6.0” ID	PVC	April 2012	In soil, not cemented. Drilled by Earthscope TA project.
ASL BH14	Snake Pit Area	5’ (1.5m)	8.0” ID	None	April 2012	Cored into granite, no casing. Hole closest to snake pit. Drilled by Earthscope TA project.
ASL BH15	Snake Pit Area	4.5’ (1.4m)	6.0” ID	None	April 2012	Cored into granite, no casing. Drilled by Earthscope TA project.
ASL BH16	ANMO Area	95’ (29.0m)	6.5” ID	Steel	18 Sep to 15 Oct 2012	~33’ soil, then granite.
ASL BH17	ANMO Area	192’ (58.5m)	6.5” ID	Steel	18 Sep to 15 Oct 2012	~33’ soil, then granite.
ASL BH18	West Underground Vault	12’ (3.7m)	8.0” ID	None	Nov 2012	Cored through vault floor into granite, no casing. East hole.
ASL BH19	West Underground Vault	12’ (3.7m)	8.0” ID	None	Nov 2012	Cored through vault floor into granite, no casing. Center hole.
ASL BH20	West Underground Vault	12’ (3.7m)	8.0” ID	None	Nov 2012	Cored through vault floor into granite, no casing. West hole.
ASL BH21	ANMO Area	10’ (3.0m)	6.5” ID	Steel	25 Jun 2013	In soil, cemented. Casing is tilted 5° off vertical.

ASL PD	ANMO Area	401.6’ (122.4m)	6.5” OD	PVC	11 Jan 1990	Water well with 4” ID PVC inside outer PVC casing. Bottom part from 337’ to 401.6’ is screen PVC.

Shallow Vault Test Area

The Shallow Vault Test Area consists of a shallow vault known as the "Snakepit Vault", four shallow boreholes (Table 1, Figure 12), and four other shallow vaults (Figure 12). These vaults and boreholes are useful for evaluating seismometer and vault performance at shallow depths, including sensitivity to air temperature variations and wind noise at various depths. Figure 13a through 13f are photos of the Shallow Vault Test Area.

The Snakepit Vault (Figures 13a and 13b) has a concrete floor poured directly on Pre-Cambrian granite at about 2m below the ground surface. The walls are concrete block and the roof is of wood construction covered with waterproof foam roofing material. The roof is roughly at ground level. The walls are backfilled so that the building is partially buried.

Boreholes BH3 and BH4 (Figure 13b) are located immediately adjacent to north-east end the Snakepit Vault and are steel-cased 6.5" ID holes about 9.5m deep, the bottom of which terminates in granite. Boreholes BH14 (8.0" ID) and BH15 (6.0" ID), are uncased holes drilled about 1.5m deep directly into granite, whose surface is about 0.3m below ground surface in the bottom of the trench outside the south-west entrance to the Snakepit Vault (Figure 13a).

The McMillan Vault (McMillan, J. R., 2002, USGS Open-File Report 02-144) is a shallow vault consisting of two plastic Poly-Over Pac containers (one is 95 gallon, the other is 50 gallon, used for shipping hazardous waste material) embedded in concrete (Figure 13c). The concrete block in which these yellow barrels are mounted terminates in soil (it does not contact the granite surface below). The inside of each container has concrete on the bottom for a seismometer or accelerometer to sit on, at a depth of about 0.6m below ground level.

The CERI Vault (Figures 13e and 13f) is a somewhat deeper shallow vault about 3m deep. It consists of a fiberglass "bottle" embedded in concrete poured directly on granite, and with a layer of concrete inside the bottom. The entry hatch (the "neck" of the "bottle") is about 3' diameter. The bottom part of the "bottle" is 6' diameter. The bottom of the "bottle" is intact. It was designed by the Center for Earthquake Research and Information (CERI), University of Memphis, for deployment in areas with wet soils and very shallow ground water. It is completely impervious to ground water penetration.

TA Vault 1 (Figure 13d) and TA Vault 2 are essentially the same design as was used in early deployments of the Earthscope Transportable Array. Each consists of a piece of 3.5' diameter black plastic corrugated sewer pipe installed vertically with the lower end embedded in concrete at the bottom. The bottom of each is about 2m below ground level and does not contact the granite below. TA Vault 2 is sealed with a piece of waterproof pond liner material to prevent water leakage. A layer of concrete was poured on top of the seal to serve as a seismometer pier. TA Vault 1 does not have this seal, so is subject to ground water intrusion through the concrete. Also, the plastic sewer pipe of TA Vault 1 is encased in concrete all the way to the surface, making it more susceptible than TA Vault 2 to tilt noise generated by wind.

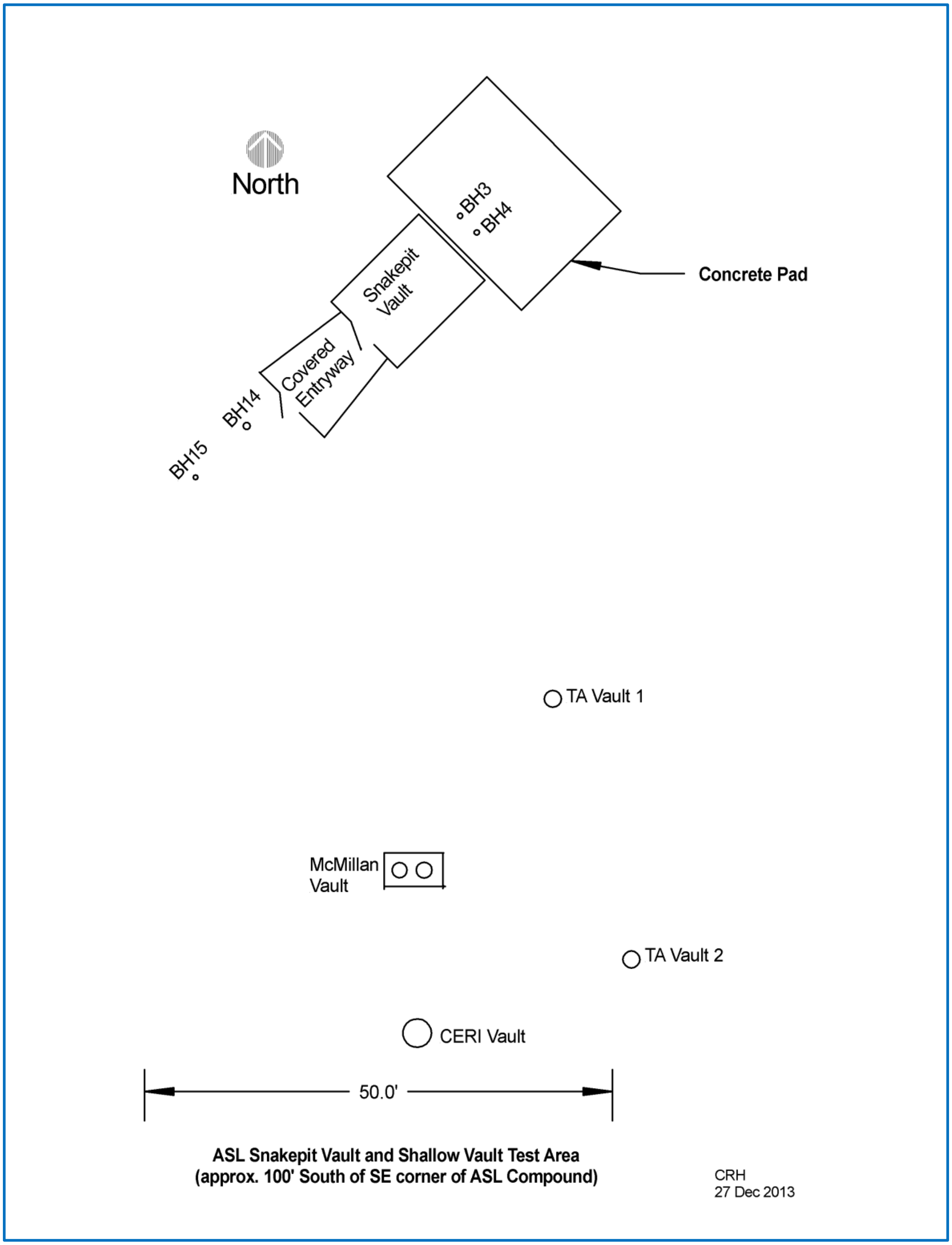


Figure 12: Shallow vault test area. The "Snakepit Vault" is a partially buried concrete block building with the roof exposed at ground level. The concrete floor is in direct contact with granite. See Table 1 for a brief description of boreholes BH3, BH4, BH14, and BH15. The other shallow vaults are described in the text. Scale is approximate.

Figure 13a: View of Snakepit Vault entrance, looking east. Shallow postholes in granite are under the black plastic covers in foreground.

Figure 13b: View of roof of Snakepit Vault and boreholes BH3 and BH4, looking southwest.

Figure 13c: McMillan Vault

Figure 13d: TA Vault 1

Figure 13e: CERI vault being installed in 2005

Figure 13f: Top of CERI vault after installation

Shake Table Facility

The Shake Table Facility is a 25’ x 25’ concrete block building located a few hundred feet away from most of the main ASL buildings (see Figure 3). It contains three large concrete piers poured directly on outcropping granite and isolated from the concrete floor of the building (Figure 14).

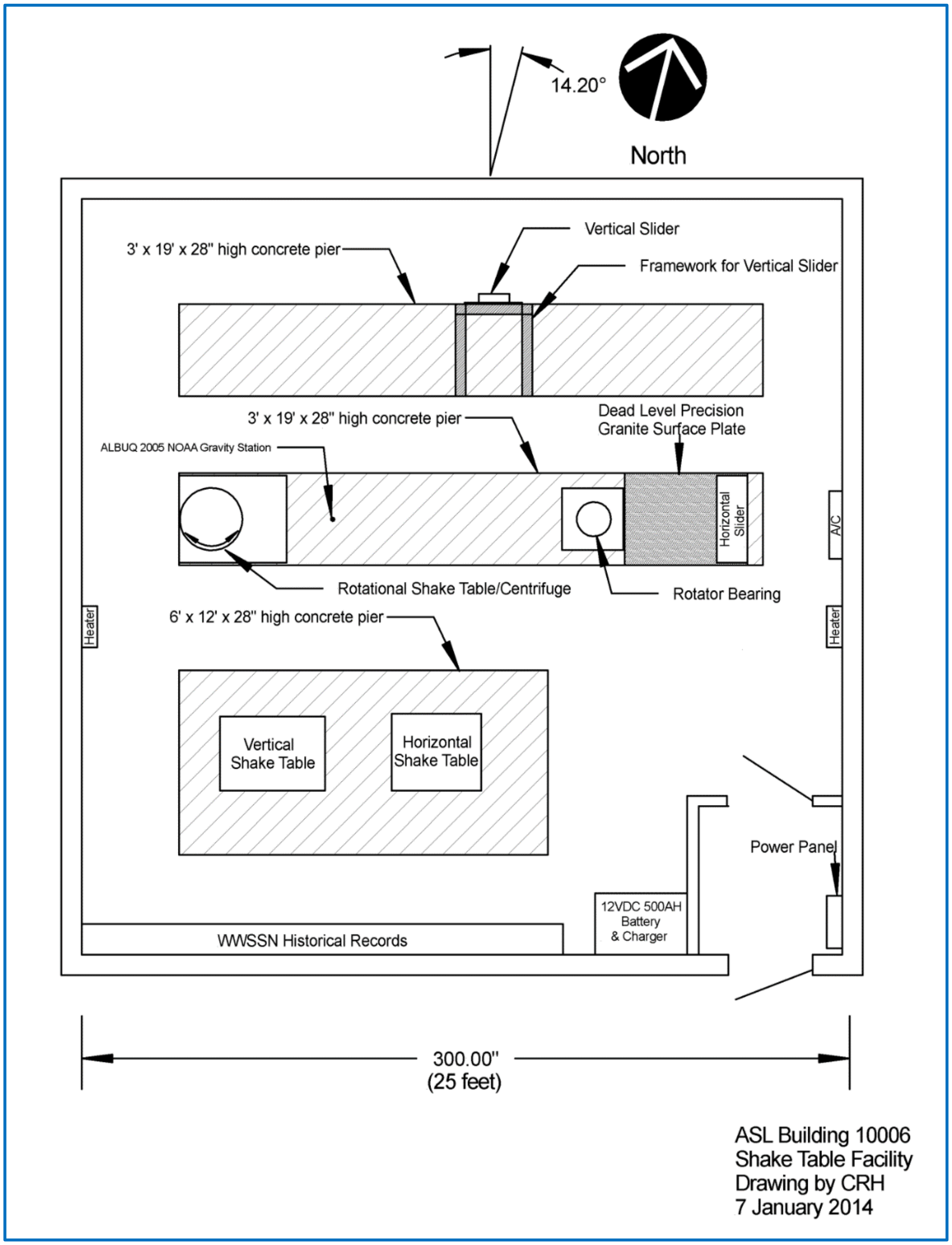


Figure 14: Shake Table Facility. This is a 25’ x 25’ surface building with large concrete piers poured directly on outcropping Pre-Cambrian granite. It contains several shaking tables and other devices used for both static and dynamic testing various types of ground motion sensors. 12 VDC battery power is available.

There are two dynamic voice-coil-driven shaking tables, one vertical and one horizontal (Figure 15a). These two shaking tables were obtained from the "Russian Technologies" company in Moscow in 1992. The test platform of each is approximately 500mm x 500mm and will support a test load of up to 50 Kg. They are useful for producing seismic motion from 0.01 to 20 Hz over an amplitude range of 1.E-6 to 1.E-2 meters. They were designed to have off-axis shaking amplitude less than 3% of on-axis amplitude, although tests have shown that the horizontal table has off-axis amplitude of about 0.1% (-60 dB) at 1 Hz. This characteristic allows testing of cross-axis coupling of seismometers. The voice coils are driven by a low-distortion signal generator (Stanford Research Systems DS360) and DC-coupled power amplifier. The test platform of both tables is connected to the heavy frame through the use of four 50-cm arms connected at both ends by cross-flexures, with the vertical table test platform also being supported by an adjustable spring. As a result, the motion of the platform of each table is not perfectly rectilinear, but instead moves through an arc defined by the length of the support arms. That is, the horizontal table platform also moves slightly in the vertical direction and the vertical table platform moves slightly in the horizontal direction. In spite of this feature, these shaking tables are useful for dynamic excitation of seismic instruments.

Also available are two Anorad linear positioning stages with very accurate position control (to 1.E-6m). One is mounted horizontally (Figure 15b), the other may be mounted vertically. These are useful for imparting exact displacements to SM accelerometers and double-integrating the output to determine if the input displacement can be reproduced. This is a very thorough dynamic test of accelerometer hysteresis, linearity, and sensitivity.

A dead-level granite precision surface plate (Figure 15d) is available for static testing of accelerometers having DC response. When such an accelerometer is mounted in an available box having faces accurately machined at 90 degrees to each other (Figure 15d), the box can then be placed on this very level surface on all six faces to determine exact sensitive axis orientation and DC sensitivity of the accelerometer. This is known as a "box flip test."

An Aerotech rotational shaking table (Figure 15c) is available with a 2' diameter test platform that can be set for operation in horizontal, vertical, or 45° from horizontal planes. The control electronics allows the platform to be driven with nearly any waveform including sine waves or arbitrary waveforms. It is possible to program a series of waveforms limiting the need of intermediate user interaction. This table is useful for driving rotational sensors with rotational displacements or velocities having frequencies ranging from 0.01 Hz or less up to about 100 Hz, although it has a resonance at about 22 Hz. It can also be rotated at constant velocities high enough to produce up to 6g acceleration at the outer rim of the test platform, making it useful for DC sensitivity tests of accelerometers up to 6g. There are two 25-pin connectors on the rotation test platform that are connected through a slip-ring assembly to matching 25-pin connectors on the frame, allowing power and signals to be routed to the Unit Under Test (UUT) without worries about wires or cables being twisted or flexed.

Other pieces of test equipment available include:

- A large Helmholtz coil and a magnetometer that is useful for measuring the magnetic response of seismometers.
- A Wielandt-designed calibration step table that is used for determining (within about 1%) the mid-band sensitivity of seismometers having a flat response to earth velocity
- A Quanterra Supertonal ultra-low distortion oscillator/waveform generator capable of generating programmable waveforms that begin at precise times controlled by a high-precision GPS clock. For 1 to 3 Hz sine waves, typical total harmonic distortion (THD) is less than -130dB. This is useful for performing distortion tests and time-tagging tests on seismometers and data loggers.

Figure 15a: Erhard Wielandt using horizontal shaking table to determine cross-axis sensitivity of an STS-2 BB seismometer. Vertical table is in background.

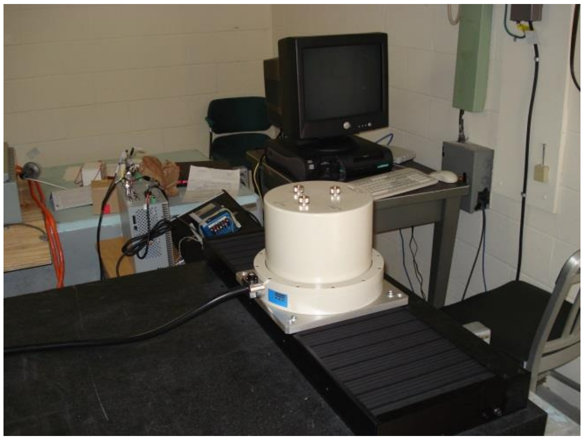


Figure 15b: Using Anorad horizontal positioning stage (“horizontal slider” in Figure 10) to perform velocity-to-displacement integration test of a strong motion velocity sensor. The horizontal positioning stage is mounted on the dead-level granite precision surface plate that is also used for “box flip tests” of accelerometers.

Figure 15c: John Evans, with Czech Academy of Science colleagues, using the Aerotech rotational shaking table to test rotational sensors.

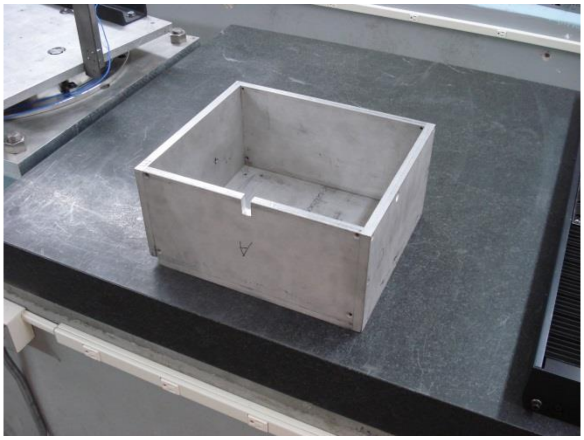


Figure 15d: Box having faces that are precisely orthogonal, sitting on the dead-level granite precision surface plate. This surface is level to within 0.001” per foot. Used for determination of accelerometer sensitivity and axis orientation.

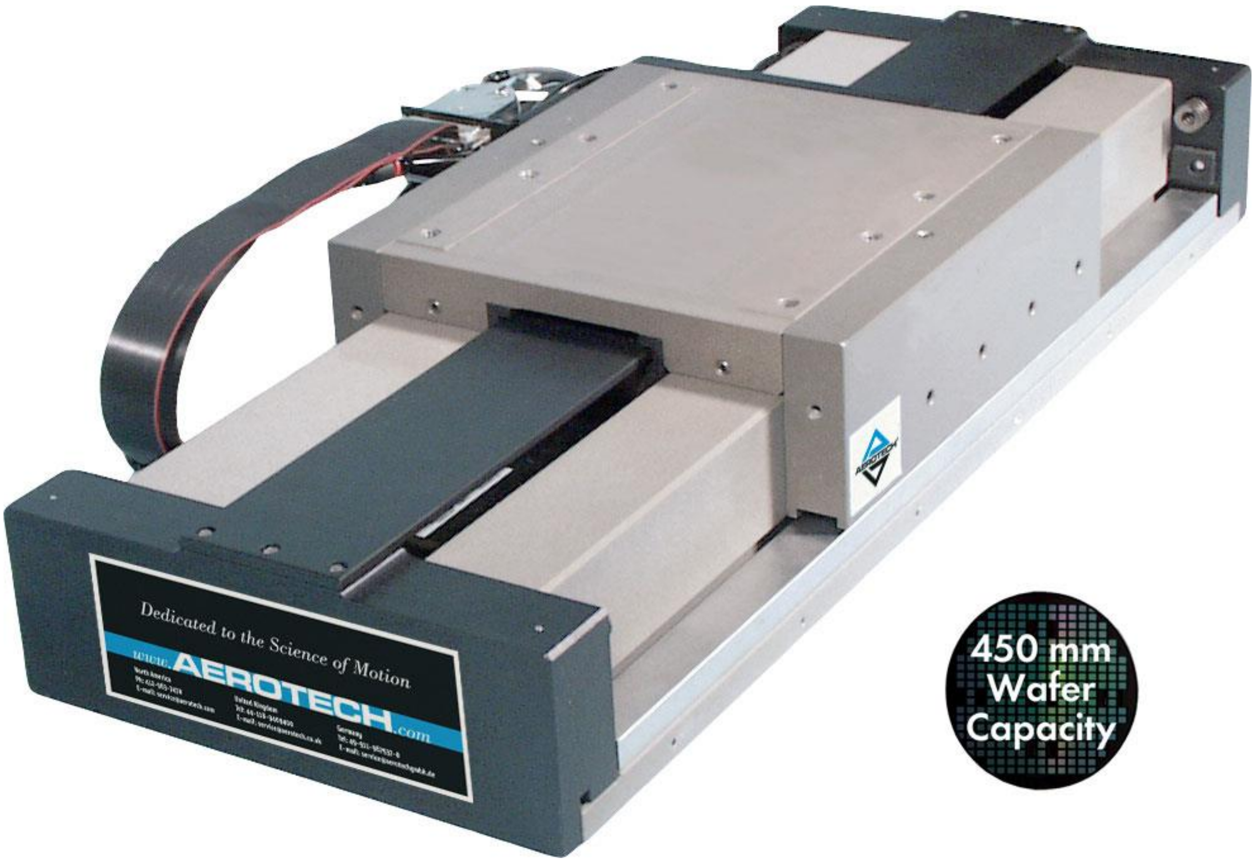
Late Breaking News (April 2015): The Russian shake tables are no longer operational.

Total weight was 2700 pounds for the two tables.

Problems:

Z had broken hinges.
H coils dragging on magnets (difficult to adjust).

New horizontal shake table coming by October 2015: Aerotech horizontal air-bearing table with 1.2m displacement.



Future: Vertical air-bearing table, probably with smaller displacement.

Present Capabilities

Sensor Testing

The ASL can perform tests on weak- (<1g) and strong-motion (>1g) instruments, short period (natural frequencies 1-4 Hz) and broadband (flat response curves 0.002-100Hz) velocity sensors (both surface vault and borehole configurations), and rotational sensors. The following tests can measure the ability of Commercial Off-the-Shelf (COTS) equipment or new equipment designs to meet specifications required by the U. S. Geological Survey, other government agencies, and collaborating institutions.

1. Self-Noise Evaluation
   - Measure the electronic and mechanical signals not attributed to ground motion — noise inherent to the instrument
   - One-Instrument Method
     - * Appropriate for some strong-motion sensors because of the low-noise environment at the ASL (the self-noise of such sensors is usually well above the ASL background noise)
   - Two- or Three-Sensor Coherency Evaluation
     - * Used for weak-motion instruments where ASL background noise levels exceed instrument self noise
     - * Two-sensor: Must know *a-priori* the response function of both instruments
     - * Three-sensor: Can determine instrument self noise without *a-priori* knowledge of response functions (response may be needed to express self noise in terms of ground motion)
2. Settling-Time Evaluation
   - Determine the time a sensor requires at start-up before the recorded data are considered adequate for the purposes at hand
3. Temperature, Pressure, and Humidity Effects
   - Measure the effects of these environmental factors on sensitivity, offset, self noise, and frequency response
4. Sensitivity, Frequency Response and Bandwidth
   - Measure the sensor’s ratio of output voltage to input motion over the flat frequency response or at a given frequency therein
   - Determine the sensor’s transfer function through perturbation of poles and zeros using step calibrations or random calibrations
5. Effect of Power Supply Voltage on Sensitivity

- Measure the effect of power changes on the sensor’s sensitivity

6. Effect of Power Supply Noise and Voltage on Instrument Noise
   - Measure the effect of significant power supply variations on the recorded signal
7. Power Demand at Start-up and in Steady State
   - Measure initial and steady-state power requirements
8. Clip Level and Operating Range
   - Estimate the clip or distortion level to help define operating range
9. Linearity and Distortion
   - Estimate least squares straight-line fit between the sensor’s output and a controlled input signal of each channel
10. Orientation and Orthogonality of the Axes
    - Evaluate the sensitivities of X, Y, and Z axes to determine how nearly orthogonal the axes are relative to one another and to exterior alignment marks on the instrument
11. Step Displacement Test
    - Highly sensitive measurement of how accurately a sensor signal can reproduce a step-displacement input signal to verify sensitivity, distortion, and linearity

Digitizer and Data Logger Testing

The ASL can perform a variety of tests on data acquisition units (DAUs) also known as digitizers or data loggers

1. Sensitivity (DC Accuracy or digital scale factor)
   - Measure the ratio of direct current (DC) input to output counts
2. Clip Level
   - Estimate the clip or distortion level to help determine the operating range
3. Noise Evaluation
   - Measure the digitizer self-noise with a terminated input simulating the output impedance of a sensor
   - Measure digitizer noise and distortion under large-signal conditions by a two-tone method
4. Time-Tag Accuracy
   - Calculate the accuracy of time tags applied to recorded data within 1ms precision
5. Total Harmonic Distortion
   - Measure the ratio of total power in harmonics to the power of the fundamental frequency to gage the distortion by the instrument of an input signal (one-tone method)

6. Temperature Effects
    - Determine how temperature influences measured quantities in tests 1 – 5

Resources

The ASL has a number of resources that support its instrumentation testing and development capabilities.

1. Low Noise Environment
    - The ASL site provides year round access to a quiet location away from most cultural noise sources
2. Test Tunnel in Granite
    - Tunnels in granite providing one of the seismically quietest sites available over most frequency bands; sensors can be partially isolated from atmospheric and weather effects as well
3. Deep (100 meter or greater) boreholes for borehole seismometer testing
    - 6.5-inch ID and 12-inch ID boreholes are available
4. Shallow Vault Testing and Design
    - An area segregated from the main facilities is used to test current and experimental shallow-vault designs; these vaults are dug into sediment above granite bedrock, providing a quiet shallow hole setting for testing temporary-deployment field configurations
    - Shallow (10 m) boreholes also are available to test “post hole” and similar field configurations
5. Step Calibration Tables
    - Two Wielandt Step Calibration Tables used to test velocity sensors
    - Determine sensitivity within ±1 percent
6. Tilt Table
    - For sensitivity calibrations at various angles
7. Translational Shake Tables
    - For testing velocity and acceleration sensors
8. Rotational shake table, Centrifuge, and Tilt Table
    - For testing rotational sensors and accelerometers
    - For linearity and cross-axis tests of translational sensors
    - As a centrifuge, test clip levels of accelerometers up to ~6g
    - Rotational-rate accuracy < 10^{-4} radians/s
9. Reference and Monitoring Sensors and High-Precision Data Loggers

- The ASL has temperature, pressure, and humidity sensors, reference broadband, acceleration, and rotational seismic sensors and data loggers (26-bit resolution at up to 200 sps and 24-bit resolution at 1000 sps) to independently monitor and record test data

10. Temperature Control Chamber
    - Cincinatti Subzero chamber to precisely control environmental temperature
    - Test chamber size 38” x 38” x 38”
    - Temperature range: -73°C to +190°C
11. 8.5-Digit Agilent Voltmeter
12. Quanterra Supertonal Ultra-Low Distortion Signal Source
    - Generates test sine waves with better than -130 dB total harmonic distortion
    - Arbitrary waveform generation, timed to start precisely on UTC minute transition (within 1 microsecond)
13. Precision Granite Surface Plates
    - Flat-ground granite slabs coupled to the Earth and precisely leveled
    - Slabs form the base for many tests and ensure common input motions for two- and three-sensor noise tests
14. Pressure-Tight Chambers
    - Containers used in which sensors experience a controlled pressure environment to reduce temperature and pressure effects on mechanical components
15. Analysis software
    - Time series analysis software, including Matlab, Python, and SAC
    - PQLX software for analyzing noise characteristics
    - XYZ and XMAX software for data quality control
    - Instrument response modeling (Step and Random calibration)
    - Other ASL-developed software
16. GSN, ANSS Databases
    - Access to national and international data sets for reference and baseline evaluations
17. Data quality evaluation
    - Long-term data quality monitoring (instrument gain changes and noise level changes)
    - Large-event station-quality analysis
18. Sensor Deployment Recommendations by Type (Site Noise Levels and Monitoring Effort *vs* Sensor Type and Installation Method)
19. Verification of Sensitivity, Orientation, Location (SensOrLoc)
20. Tools, Electronic Cables, Parts, and Technician Support

21. Deployment and Testing Expertise

Future Capabilities

This section describes equipment, tools, and resources that would enable ASL to perform additional tests or improve upon the capabilities listed above. Some efforts are underway in several of these topics.

1. Testing Quality Control
    - Obtain a formal laboratory certification (we are not currently certified)
    - Obtain NIST Traceability
        - Regular calibration of test equipment using an external reference
2. Database of Instrument-Testing Data
    - Improve the ASL archive of test data (an initial seismometer testing database has been developed, but further development is necessary)
3. Standardize and Automate Test & Calibration Reports
    - Creation of a test report template for auto generation
    - Tie in with the Test Database
4. Three Co-located Deep Boreholes
    - Required for 3-sensor noise testing of borehole-type seismometers in boreholes. While it is possible to perform this type of test in our underground vault, the noise levels in a deep borehole would be lower, resulting in more meaningful noise tests.
    - Requires a borehole wide enough to accommodate three borehole sensors or three borehole casings welded to each other and cemented into a large drill hole.
    - If techniques are developed to install three borehole sensors in a single, large borehole, then it may be possible to use ASL's existing 12.5" inside diameter borehole (formerly used for testing Russian borehole instruments).
5. Radio Frequency Interference and Electromagnetic Interference (RFI/EMI) Susceptibility Effects
    - Install and operate a laboratory room and equipment that can create a controlled environment for these inputs to assess the effects RFI/EMI on seismometers and data loggers
6. Reference Sensors for Common Sensor Types
    - Calibrated reference sensors for field deployment tests or tunnel and lab tests
    - Currently have one high gain Streckeisen STS-2 and one set of STS-1s for reference for tunnel tests
    - Other reference sensors needed (wish list):

    * Nanometrics Trillium T240 and T120
    * Geotech KS54000 (although a KS54000 is part of the GSN station ANMO)
    * Guralp CMG-3TB (although a CMG-3TB is part of the GSN station ANMO)

7. High Precision Humidity Control Chamber
    - Upgrading the current ASL temperature chamber with humidity control capability will allow testing of digitizer and datalogger humidity effects
8. Instrumentation Development Program (Unique Instrument Models)
    - Development or participation in development of rotational seismometers
    - Development or participation in development of alternative transducer technologies (such as optical interferometric transducers or digital feedback) that may allow larger dynamic ranges than are possible with current technologies
9. Ring Laser Seismic Detector
    - Measuring the rotational signal from earthquake, explosion, and noise sources
    - Tilt and strain analysis
10. Low-Noise Rotational Sensor
    - For noise reduction, rotation-to-rotation and rotation-to-translation cross axis testing, and research purposes
11. Superconducting or Atomic Interferometry Gravimeter
    - Measuring gravity to 10^{-11} m/s^2 (12 digits)
12. Atom-Interferometry Broadband Seismometer as Reference Instrument
    - From DARPA project when available
13. High-Purity Low-Noise Mechanical Sine Generator
    - Actuator for shake tables in distortion and response tests, or
    - Replace Russian shaking tables with more modern, rectilinear motion design
        * Problems with existing Russian shaking tables include curvilinear motion of test platform and rubbing of coils on magnets, requiring frequent adjustment
14. Noise-Isolation Between Temperature/Humidity Chamber and Seismometer Under Test
15. Improve Standard Operating and Testing Procedures for Sensors and Data Loggers
    - Hutt, C. R., J. R. Evans, F. Followill, R. L. Nigbor, and E. Wielandt, 2010, Guidelines for Standardized Testing of Broadband Seismometers and Accelerometers: U.S. Geological Survey OFR 2009-1295, 62 p.
    - Evans, J. R., F. Followill, C. R. Hutt, R. P. Kromer, R. L. Nigbor, A. T. Ringler, J. M. Steim, and E. Wielandt, Method for Calculating Self-Noise Spectra and Operating Ranges for Seismographic Inertial Sensors and Recorders, *Seis. Res. Lett.*, **81**, no. 4, 639–645, 2010. (doi:10.1785/gssrl.81.4.639)

- Example tests using these Guidelines have been performed by ASL (Ringler et al., 2010 and 2011)

Acknowledgements

The ASL facilities have been developed over a number of years and with contributions from several organizations. In particular, the Incorporated Research Institutions for Seismology (IRIS) contributed to the drilling of several new shallow holes in order to test shallow posthole installation techniques for the Transportable Array in Alaska and of two new boreholes at 30m and 60m for testing borehole seismometers and evaluating the tradeoff of noise versus depth. IRIS has also provided the reference STS-1 seismometers and one of the two step calibration tables.

The Air Force Technical Applications Center (AFTAC) funded test borehole #6 (ASL BH6) and the five foot deep concrete pit in the borehole test area.

Tom de la Torre developed an early version of this document. We thank him for his efforts.

Publications

de la Torre, T. L., C. R. Hutt (2010). Comprehensive Temperature Test Report (ASL Internal Report).

Evans, J. R., R.L. Nigbor, and C.R. Hutt (2006). C-Language Software for Computing Strong Ground Motion Metrics and Seismograph Self Noise: U.S. Geological Survey OFR 2006-1369, 6 p.

Evans, J. R. , A. Cochard, Vladimir Graizer, Bor-Shouh Huang, Kenneth W. Hudnut, Charles R. Hutt, H. Igel, William H.K. Lee, Chun-Chi Liu, Eugeniusz Majewski, Robert Nigbor, Erdal Safak, William U. Savage, U. Schreiber, Roman Teisseyre, Mihailo Trifunac, J. Wassermann, and Chien-Fu Wu (2006). Rotational Seismology Workshop of February 2006: U.S. Geological Survey OFR 2007-1145, 20 p.

Evans, John R. and International Working Group on Rotational Seismology (2009). Suggested Notation Conventions for Rotational Seismology: Bulletin of the Seismological Society of America, 99, p. 1073 - 1075.

Evans J. R., F. Followill, C. R. Hutt, R. P. Kromer, R. L. Nigbor, A. T. Ringler, J. M. Steim, and E. Wielandt (2010). Method for Calculating Self-Noise Spectra and Operating Ranges for Seismographic Inertial Sensors and Recorders: Seismological Research Letters, 81(4), p. 640-646.

Holcomb, L. G. (1989). A direct method for calculating instrument noise levels in side-by-side seismometer evaluations: U.S. Geological Survey OFR 89-214, 35 p.

Holcomb, L. G. (1990). A numerical study of some potential sources of error in side-by-side seismometer evaluations: U.S. Geological Survey OFR 90-406, 41 p.

Holcomb, L.G. (2002). Experiments in seismometer azimuth determination by comparing the sensor signal outputs with the signal output of an oriented sensor: U.S. Geological Survey OFR, 02-183, 205 p.

Holcomb, L. Gary; Charles R. Hutt (1992). An Evaluation of Installation Methods for STS-1 Seismometers: U.S. Geological Survey OFR 92-302, 37 p.

Holcomb, L. Gary, Leo Sandoval, and Bob Hutt (1998). Experimental Investigations Regarding The Use of Sand as an Inhibitor of Air Convection in Deep Seismic Boreholes: U.S. Geological Survey OFR 98-362, 53 p.

Hutt, C. R. (1990). Standards for seismometer testing—A progress report: Albuquerque, N. Mex., unpublished report available from Albuquerque Seismological Laboratory.

Hutt, C. R., Evans, J. R., and Yokoi, I. (2008). A Brief Test of the Tokyo Sokushin VSE–355G3 Strong Motion Velocity Seismometer: U.S. Geological Survey OFR 2008–1311, 44 p.

Hutt, C.R., and Ringler, A.T. (2009). A Summary of STS-2 Low-Noise Installation Methods Tested at the USGS Albuquerque Seismological Laboratory, 12 p. (ASL Internal Report)

Hutt, C. R., R. L. Nigbor, and J. R. Evans (2009). Proceedings of the Guidelines for Seismometer Testing Workshop, Albuquerque, New Mexico, 9–10 May 2005 ("GST2"): U.S. Geological Survey OFR 2009-1055, 48 p.

Hutt, C. R., J. R. Evans, F. Followill, R. L. Nigbor, and E. Wielandt (2010). Guidelines for Standardized Testing of Broadband Seismometers and Accelerometers: U.S. Geological Survey OFR 2009-1295, 62 p.

Hutt, C. R., and A. T. Ringler (2011). Some Possible Causes of and Corrections for STS-1 Response Changes in the Global Seismographic Network: Seismological Research Letters, 82 (40), p. 560-571.

McNamara, D. E., and R. P. Buland (2004). Ambient noise levels in the continental United States: Bulletin of the Seismological Society of America 94 (4), p. 1,517–1,527.

McNamara, D. E., C. R. Hutt, L. S. Gee, R. P. Buland, and H. M. Benz (2009). A method to establish seismic noise baselines for automated station assessment: Seismological Research Letters, 80 (4), p. 628–637.

McNamara, D.C., A.T. Ringler, C.R. Hutt, L.S. Gee (2010). Seismically observed seiching in the Panama canal: J. Geophys. Res., 116, B04312, doi:10.1029/2010JB007930.

Nigbor, Robert L., John R. Evans, and Charles R. Hutt (2009). Laboratory and Field Testing of Commercial Rotational Seismometers**,** Bulletin of the Seismological Society of America, 99, p. 1215 - 1227.

Peterson, J. (1993). Observations and modeling of seismic background noise: U.S. Geological Survey OFR 93-322, 94 p.

Ringler, A.T., C.R. Hutt (2010). Self-noise models of seismic instruments: Seismological Research Letters, 81 (6), 972-983.

Ringler A. T., L. S. Gee, C. R. Hutt, and D. E. McNamara (2010). Temporal Variations in Global Seismic Station Ambient Noise Power Levels: Seismological Research Letters, 81(4), p. 605-613.

Ringler, A. T., J. R. Evans, C. R. Hutt, and L. D. Sandoval (2011). A comparison of seismic instrument self-noise analysis techniques: Bulletin of the Seismological Society of America, 101 (2), 558-567.

Ringler, A. T., J. D. Edwards, C. R. Hutt, and F. Shelly (2012). Relative azimuth inversion by way of damped maximum correlation estimates, *Comp. and Geosci.*,43, 1-6.

Ringler, A. T., L. S. Gee, B. Marshall, C. R. Hutt, and T. Storm (2012). Data quality of seismic records from the Tohoku, Japan, earthquake as recorded across the Albuquerque Seismological Laboratory networks, *Seis. Res. Lett.*, 83 (3), 575-584.

Ringler, A. T., C. R. Hutt, R. Aster, H. Bolton, L. S. Gee, and T. Strom (2012). Estimating pole-zero errors in GSN-IRIS/USGS network calibration metadata, *Bull. Seis. Soc. Amer.*, 102 (2), 836-841.

Ringler, A. T., C. R. Hutt, and K. Persefield (2013). Seismic station installation orientation errors at ANSS and IRIS/USGS stations, *Seis. Res. Lett.*,84 (6), 926-931.

Ringler, A. T., C. R. Hutt, L. S. Gee, L. D. Sandoval, and D. Wilson (2014). Obtaining Changes in Calibration-Coil to Seismometer Output Constants using Sine Waves, *Bull. Seis. Soc. Amer.*, 104(1), p. 582-586.

Ringler, A. T., R. Sleeman, C. R. Hutt, L. S. Gee (2014). Seismometer Self-Noise and Test, Earthquake-Engineering Encyclopedia, in press.

Working Group on Instrumentation, Siting, Installation, and Site Metadata of the Advanced National Seismic System Technical Integration Committee (2008). Instrumentation guide lines for the advanced national seismic system: U.S. Geological Survey OFR, 2008-1262, 41 p.

References

Peterson, J. (1993). Observations and modeling of seismic background noise: U.S. Geological Survey OFR 93-322, 94 p.

McMillan, J. R. (2002). Methods of Installing United States National Seismographic Network (USNSN) Stations – A Construction Manual: U.S. Geological Survey OFR 02-1444.

Appendix: Example Facility Service/Use Agreement

USGS FACILITY SERVICE/USE AGREEMENT
AUTHORIZED BY 15 USC 3710 (A) AS AMENDED

1. Name & Address USGS Facility: USGS Albuquerque Seismological Laboratory (ASL)
2. Name & Address of Collaborator: DUNS: TIN:
3. **Describe type of technical assistance to be furnished by USGS** .
4. **Benefit of project work to USGS missions**
5. **Collaborator explanation of how the specified research activity assists your company, program or project work.**
6. **Project term/Delivery date:**
7. **Reimbursement/Cost Share**:
8. Contacts (name/address/phone/email) USGS: Technical: USGS: Financial:
9. Other Terms: a) Collaborator has determined that the capabilities of the above listed facility are unique, and not readily available from the private sector. b) Scientific results will be provided on a "best efforts" basis by USGS. c) USGS MAKES NO WARRANTIES ABOUT THE INFORMATION IT DELIVERS OR ITS USEFULNESS FOR A PARTICULAR PURPOSE. d) The parties do not anticipate the development of any intellectual property (IP) as part of this agreement. However in the event that IP, which is defined as patents, copyrights, new inventions, or discoveries, is created in the course technical assistance, such IP shall be the property or joint property of the organization employing the respective individual(s) who made the invention or discovery. Any IP developed will be reported by the developer to his/her Technical Contact who will in turn notify the other party's Technical contact. e) Collaborator/User understands that government work will have priority over this project in the event that a scheduling conflict develops in the laboratory. f) Both USGS and Collaborator may utilize the generated information developed by USGS in databases, papers or as part of other scientific information. g) This Agreement may be cancelled on 30 days written notice by either party to the other. Work in process at the time of cancellation will be completed and billed to the appropriate party. The obligation to make and the ability to accept payments survive the effective dates of the actual Agreement. h) The Technical Contacts listed herein shall attempt to jointly resolve any disputes arising from the Agreement. Any dispute that they are unable to resolve shall be submitted to the Director of the USGS, or his designee; and the President or his designee of Collaborator, for final resolution. i) For purposes of this Agreement and all services to be provided hereunder, each party shall be, and shall be deemed to be, an independent entity and not an agent or employee of the other party. j) The terms of this Facility Use Agreement are the only terms that govern the party's agreement and the research /technical work to be completed by USGS. USGS is not bound by and does not accept any additional or supplemental terms or conditions contained in any Purchase Order or other document used by Collaborator to order or pay for research services. Such documents are

accepted by USGS solely as a convenience to the Collaborator and are not intended to modify or expand the terms of the party's agreement.

U.S. Geological Survey	**Collaborator**
Dr. Jill McCarthy	(name here)
Signature Date	Signature Date
Title Director, Geologic Hazards Science Center	Title:

USGS Tech Transfer Review: