ABSTRACT

SCHEIP, COREY MICHAEL. Acoustic Variability of a Seismic Airgun Survey in the Lau Back-Arc Basin. (Under the direction of Dr. DelWayne Bohnenstiehl.)

During January – February 2009, an active-source seismic survey was performed over the Eastern Lau Spreading Center in the Lau Back-Arc Basin (-21°, -176°). Acoustic signals generated by the R/V Marcus G. Langseth’s airgun source array were recorded within the deep sound channel at offsets of 29 – 416 km. The local acoustic environment is everywhere bottom limited, with seafloor depths within the study domain ranging from ~1700 – 2800 m. Low-frequency (4-125 Hz) sound levels are monitored using root-mean-square, energy flux-density and zero-to-peak measurement techniques. From these field data, transmission loss is found to exceed the predictions of a geometrical spreading model, with loss coefficients of 23.3, 24.9 and 25.6 dB/log10(R), respectively. At similar offsets from the source, arrival amplitudes may vary by an order of magnitude and durations by factors of three to six. This variability is correlated with the depth of the seafloor beneath the source array, with airgun shots over shallower seafloor producing more impulsive, higher amplitude, shorter duration arrivals. The strength of this correlation varies between stations that lie at different azimuths to the survey area. This highlights the importance of seafloor aspect and slope in the coupling of bottom interacting acoustic energy into the sound channel through scattering and specular reflections. Range dependent ray tracing predicts impulsive waveforms are a product of sound-channel-borne arrivals, which originate over shallow seafloor, while emergent waveforms result from a series of bottom reflections along the propagation path and originate over deeper seafloor. Several studies have investigated the role of topography in facilitating basin scale acoustic propagation, but these field measurements are the first to demonstrate a correlation between bathymetry and acoustic signal properties at intermediate ranges.
Acoustic Variability of a Seismic Airgun Survey in the Lau Back-Arc Basin

by
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BIOGRAPHY

Though born in Pennsylvania, Corey Scheip considers himself a North Carolinian. After living in the Troutman, NC area for most of his childhood, Corey attended the University of North Carolina at Asheville for his undergraduate studies, earning a B.S. in Environmental Studies (Earth Science). It was during this time that he fell in love with the mountains of North Carolina and the Appalachia region as a whole. Corey came to North Carolina State University (NCSU) to pursue his M.S. in Geology, hoping this advanced degree would lead to further opportunities in the Appalachia region. He has always had a knack for mathematics, computers and the natural sciences. His time at NCSU has allowed for those interests to flourish and hopefully, future experiences will do the same.
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1. Introduction and Environmental Setting

1.1 Introduction

In recent decades, noise in the ocean has increased significantly over historic levels. Anthropogenic activities, such as commercial shipping, drilling, military and civilian use of sonar, and hydrocarbon exploration are chiefly responsible for this increase, which includes both ambient and transient acoustic inputs [NRC, 2003; Andrew et al., 2002; Hildebrand, 2004; McDonald et al., 2006]. In recent years, scientists, the public and policy makers have become increasingly concerned about marine mammal conservation and the potentially harmful effects of increased levels of ocean noise [NRC, 2003]. The concern is broad in scope, as continuous sources (e.g. commercial shipping) and transient sources (e.g. seismic airgunning) both may inhibit a marine species’ ability to continue life-sustaining activities such as communicating, feeding, breeding and navigation [Richardson et al., 1995; Madsen, 2002; NRC, 2003; Hildebrand, 2004, 2005; Madsen et al., 2006; Soto et al., 2006; Parks et al., 2007; Southall et al., 2007].

Andrew et al. [2002] and McDonald et al. [2006] have independently shown 10-12 dB increases in ambient ocean noise within the frequency band of 20-80 Hz and 30-50 Hz, respectively, off the western coast of the United States within the past three to four decades. This is consistent with the near doubling in the number of ships and the general increase in propulsion power (speed) and vessel size over the same time period [Chapman and Price, 2011]. The increase in low-frequency (5-200 Hz) ocean noise has been attributed to such effects as the increase in start frequencies of Atlantic Right Whale upcalls since the mid 20th century [Parks et al., 2007]. In the mid-latitude Pacific, the Lombard effect has been shown in Killer Whales as a result of a noisier ocean and it is reasonable to expect the energetic cost of this increased call amplitude might lead to increased stress levels or generally make it more difficult for inter-pod communication [Holt et al., 2009].

While increasing ambient noise levels may have significant ecological impacts, high intensity transient signals also threaten marine animals, and in rare cases may be associated with physical injury [Richardson et al., 1995; NRC, 2003]. Perhaps the most well known example is the link of mid-frequency naval sonar to mass strandings of Cuvier’s beaked
whales [NRC, 2003]. Behavioral changes, however, are more common than physical injury. In field experiments, surfacing, respiratory and diving changes in baleen whales have been observed at received levels above 142 dB re 1μPa and active avoidance observed at received levels above 152 dB re 1μPa [Ljungblad et al., 1988; Richardson et al., 1995].

In recent years, increasing environmental concern and regulation has been levied at seismic surveying operations [e.g. Malakoff, 2002; D'Spain et al., 2006], which generate transient acoustic energy using an array of pneumatic airguns. These activities are aimed at imaging the geology of the sub-seafloor environment, primarily in support of hydrocarbon exploration. Even though the duty cycle of the airgun source array is only 0.3%, Hildebrand [2004] estimates that on an annual basis, the acoustic energy introduced into the oceans by these surveys rivals the combined contribution of military sonar and the global fleet of super tankers. Moreover, due to their dominantly low frequency spectrum (≤ 100-200 Hz), airgun signals are transmitted efficiently within the deep ocean and have been detected at ranges exceeding 3000 km [Nieuwirk et al., 2004].

As underwater sounds propagate through the oceans, the signals become delayed, distorted and weakened [Urick, 1983]. Being able to quantify this signal degradation increases the accuracy of sound level predictions at a given range and allows for improved environmental impact assessment and mitigation. In addition, many applications of marine geophysics such as seismic and volcanic monitoring [Fox et al., 1995], enforcement of the comprehensive nuclear test ban treaty [de Groot-Hedlin and Orcutt, 2001b] and undersea communications rely heavily on understanding the decay of range-dependent signal propagation.

During January-February of 2009, the R/V Marcus G. Langseth carried out an active-source seismic survey along a ~100 km section the Eastern Lau Spreading Center near 20° S 175° W [Dunn and Martinez, 2011]. The ship fired approximately 9400 shots, using a 36-gun array (6600 in³ total volume) towed at a depth of 9 m below the sea surface. These sound sources persisted intermittently for 28 days, with an average shot separation of 210 s [Dunn and Martinez, 2011]. An array of autonomous underwater hydrophones (AUH) [Bohnenstiehl et al., 2010], part of a separate though concurrent project, recorded the seismic survey from a
distance of 29 – 416 km (Figure 1). These receivers were calibrated omni-directional sensors sampling at 250 Hz and moored at a depth of 1000 m within the basin’s deep sound channel. Although a total of eight instruments were deployed during the survey, two sensors are excluded from our analysis due to problems with their pre-amplifier, which introduced unwanted noise into the analysis frequency band. Four of these remaining stations are part of a small aperture diamond-shaped array (~2 km separation between moorings), known as M3, and will be treated as a single station unless otherwise noted.

Previous studies have addressed the propagation of anthropogenic airgun transients at short ranges, on the order of up to several kilometers [Green and Richardson, 1988; Tolstoy et al., 2004, 2009; Madsen et al., 2006; Breitzke and Bohlen, 2010; Diebold et al., 2010] and long ranges, on the order of thousands of kilometers across ocean basins [Blackman et al., 2004; Nieukirk et al., 2004]. Despite the potential for behavior impacts [e.g. Malakoff, 2002], few field studies have investigated transient airgun noise levels at the intermediate ranges investigated here. Our objectives are to empirically quantify range-dependent signal characteristics and transmission loss within the Lau Basin and identify factors influencing the variability in the signal amplitude and duration at a given range. The impact on local marine species is not a direct focus of this study.

1.2 Geo-Acoustic Environment

The active source survey of Dunn and Martinez [2011] was located along the central portion of Eastern Lau Spreading Center (ELSC), one of several back-arc spreading centers within the Lau Basin (Figure 1). At the latitude of the survey (20 – 21° S), the local spreading rate is ~65 mm/yr, and the ELSC topography transitions from a narrow axial high (south) to a broad, faulted axial valley (north) [Taylor et al., 1996; Martinez et al., 2006]. Side-scan sonar imagery shows high amplitude acoustic backscatter along the axis of the rift, consistent with the presence of a thinly sedimented basaltic basement [Martinez et al., 2006]. Backscatter strength decreases as sediment thickness increases off-axis, with volcaniclastic turbidites and nano-fossiliferous clays [Taylor and Natland, 1995] ponding within local fault-bounded basins. To the east, the Tongan volcanic arc supplies clastic sediments that form a westward-thinning apron.
The ocean acoustic environment of the tropical Lau Basin is everywhere bottom limited, meaning that the critical depth of the sound channel, at ~5500 m depth, lies well below the relatively shallow (2000-2500 m) depth of the seafloor (Figure 2a). For an airgun source near the sea surface, a numerical simulation (Appendix 2) indicates that even rays with sub-horizontal departure angles are refracted downward and intersect the seafloor. For a flat-lying seafloor, these rays are reflected and return to the sea surface, where they are reflected again, repeating the process (Figure 2b).

Depending on the local depth, slope and aspect of the seafloor, these bottom-interacting signals may become entrapped in the sound fixing and ranging (SOFAR) channel [Ewing and Worzel, 1948], where they propagate with minimal transmission loss for very long distances [Tolstoy and Ewing, 1950; Urick, 1983]. The most commonly proposed mechanisms for SOFAR entrapment are downslope conversion [Johnson et al., 1963] and seafloor scattering [de Groot-Hedlin and Orcutt, 1999, 2001a; Park et al., 2001]; these mechanisms operate concurrently and are not mutually exclusive.

Downslope conversion is a mechanism through which the grazing angles of acoustic rays are progressively decreased through a series of reflections off of a downward sloping seafloor, eventually leading to the entrapment of some rays in the low velocity sound channel [Johnson et al., 1963; Talandier and Okal, 1998]. It is called upon most commonly to explain the coupling of seismo-acoustic energy across continental and island shelves, where long and continuous slopes exist; however, for the sloped and facetted seafloor associated with an oceanic rift, specular reflections may become entrapped after only one or two seafloor bounces (Figure 2c).

Due to the roughness and heterogeneity of the sea bottom, acoustic energy also is scattered back into the water column [Bradley and Stephen, 1996; Park et al., 2001]. This is often modeled using a normal mode representation. In this view, low order modes, which are equivalent to low grazing angle rays, represent acoustic energy trapped in the SOFAR channel with minimal seafloor interaction. Neglecting variability in seabed parameters, scattering at shallower seafloor depths preferentially excites these low order modes; whereas
higher order modes, which interact more strongly with the seafloor, are excited with increasing seafloor depths [de Groot-Hedlin and Orcutt, 1999, 2001a; Park et al., 2001]. The geometry of the Lau Basin AUH array is such that the M3 stations lie to the west of the ELSC on ~2 Ma seafloor. Propagation paths cross a deepening seafloor cut by inward and outward facing normal fault scarps trending ~10° east of north (Figure 3). Station M4, however, lies to the northwest of the survey, with the acoustic rays traversing faulted terrains formed at both the Eastern and Central Lau Spreading Centers. Propagation to M5 is predominately along the spreading ridge axis and parallel to the seafloor fabric. Because the received signal packet is effectively the sum of many signals that have traveled along different paths [Greene and Richardson, 1988; Madsen et al. 2002], these path dependent bathymetries contribute to variability in recorded signal properties—as demonstrated empirically in this study.

The complex tectonics of the Lau Basin create a naturally noisy acoustic environment, with active seismo-acoustic sources associated with the subduction interface and slab, the many shallow submarine volcanoes within the arc, and the ridge-transform systems within the back arc [Conder and Weins, 2011]. There were 22 seismic events with a magnitude of >4.2 during the time period of the R/V Langseth survey [International Seismological Centre, 2001], and ongoing analysis of the hydroacoustic records has located several thousand smaller earthquakes and volcano-acoustic signals that occurred during this period. For the purposes of this study, these natural signals are considered noise. Section 2.3 describes the procedures used to identify and exclude shot arrivals containing coincident volcanic and seismic energy.

2. Methods

2.1 Data Sources and Acquisition

All of the AUH sensors sampled at 250 Hz and recorded continuously throughout the survey, between 27 January – 24 February 2009, capturing a total of 56394 arrivals (9399 shots x 6 stations). The receivers recorded changes in acoustic pressure as a digitized voltage with 16-bit resolution. Details of the conversion to pressure (µPa) can be seen in the appendix (1.1). Before further processing, a high-pass 4 Hz Butterworth filter is applied to all
data to filter out low frequency ocean noise and cable strumming, which is represented by a peak near 2 Hz on a power spectral density plot (Figure 4). The effective bandwidth for the analysis is 4 –125 Hz.

2.2 Signal Characteristics

Dunn and Martinez [2011] provided the airgun shot locations and times from cruise MGL0903. From these meta-data, arrival times were estimated at each of the AUH recorders, assuming a constant sound speed of 1490 m/s. For each arrival, a 30 second data window centered on the predicted arrival time is extracted from the waveform database. In keeping with other airgun propagation studies [Madsen et al., 2005, 2006; Tolstoy et al., 2009; Diebold et al., 2010], a cumulative energy method is used to select the 90% energy window and determine the duration of each arrival. This involves generating a cumulative sum of the squared amplitudes across the initial 30-second data window, and selecting the start and stop times of the arrival packet as the points encompassing 5% and 95% of the energy in the signal. Selection of a larger cumulative sum window, such as 97% [Madsen, 2005], has minimal impact on the results.

Three methods are used to report received sound levels, as measured over the determined 90% energy windows. The values in decibels are calculated as follows:

\[
\text{Root-mean-square: } \quad dB_{RMS} = 20 \log_{10} \left( \frac{1}{n} \sum_{i=1}^{n} (s_i - \bar{s})^2 \right)^{\frac{1}{2}} \quad \text{[re 1\,µPa]} \quad (1)
\]

\[
\text{Energy flux-density: } \quad dB_{EFD} = dB_{RMS} + 10 \cdot \log_{10} (d) \quad \text{[re 1\,µPa}^2\cdot\text{s]} \quad (2)
\]

\[
\text{Zero-to-Peak: } \quad dB_{Z2P} = 20 \cdot \log_{10} \{ \max(|s|) \} \quad \text{[re 1\,µPa]} \quad (3)
\]

Where \(s\) is the signal pressure time series (µPa) and \(d\) is the duration in seconds of the \(n\)-point, analysis window capturing 90% of the signal energy.

The root-mean-square pressure of the signal is the standard measure used in ambient (continuous) noise monitoring studies. The use of this measurement in describing transient
sound sources is problematic in that the RMS level is sensitive to the choice of arrival window [Madsen, 2005]. Despite this limitation, the U.S. National Marine Fisheries Service (NMFS) has adopted RMS criteria for permitting and regulating active source seismic surveys. The received levels presently defined as safety criteria (intended to avoid risk of auditory impairment or injury) are 190 and 180 dB_{RMS} for pinnipeds and cetaceans, respectively, with 160 dB_{RMS} identified as the level above which there is likely to be behavioral disturbance [Battelle, 2005].

The energy flux density (EFD) of the signal is proportional to the energy per unit area [Young, 1970] and the sound exposure level (SEL) for a plane wave propagating in an unbounded medium [Madsen et al., 2006]. It is defined as the product of the square of the RMS amplitude and the duration of the arrival packet. Although current NMFS regulations do not utilize this measure, EFD is arguably a robust indicator of exposure due to a correction factor for signal duration, and it is increasingly cited in acoustic monitoring and conservation studies [Madsen 2005, Tolstoy et al. 2009; Diebold et al., 2010].

Zero-to-peak (Z2P) is a measure of the maximum signal amplitude within the arrival packet and is commonly used to report sound levels of impulsive (transient) signals. For an aperiodic wave, Z2P levels are often higher than RMS values by 15 dB or more [Madsen, 2005].

For each signal, a noise window is selected having the same duration as the arrival window (Figure 5). This window is positioned to end two seconds prior to the onset of the arrival window, as determined by the 90% cumulative energy approach. Signal-to-noise ratios (SNR) at each station are approximately normally distributed with significantly different means for the M3 quad-array (27.5 ± 5.6 dB), M4 (13.7 ± 6.7 dB) and M5 (18.5 ± 5.4 dB) stations (Figure 6). As background noise levels are shown to be within a few dB of each other (see Results section), this largely reflects the different ranges at which the signals are recorded, with M4 being positioned approximately five times further from the airgun survey relative to the M3 quad.
2.3 Arrival Data Selection

Both signal-to-noise ratios and cumulative energy goodness-of-fit criteria are used to rid the dataset of arrivals contaminated by coincident volcanic and seismic signals. For each station, arrivals with a SNR less than \( SNR - \sigma \) are excluded from the analysis. This removes 5835 arrivals (21%) from the total of 28197. However, given the high rate of seismic and volcanic activity and the fact that many of these natural signals are of long duration, there are many contaminated arrivals that exhibit acceptable or even elevated SNR’s and are therefore not removed by this criterion (Figure 7).

Integrating the broadband signal energy (squared-amplitudes) over the original 30-second data window, which is centered on the predicted arrival time, reveals that these suspect arrivals typically exhibit a cumulative envelope shape that deviates from the expected pattern. A simple goodness-of-fit test is established, whereby signals are accepted only if their cumulative energy is below 5% at \( t = 14 \) s and above 35% at \( t = 20 \) s (Figure 8). These values were selected based on the average trend of all cumulative sum curves amongst all hydrophones.

The cumulative sum shape test removed an additional 4871 (17%) arrivals not captured by the SNR test. This leaves a dataset of 17491 arrivals for analysis. The number of rejected arrivals from individual hydrophones varied, with 1900 arrivals removed from M3, 5799 removed from M4 and 3007 removed from M5. A total of 2398 shots had arrivals that passed to all three stations. Using the accepted arrivals at each station, the associated noise window measurements are averaged to estimate the ambient noise floor during the survey.

2.4 Estimation of Transmission Loss

A principal motivation in calculating acoustic received levels (RL) at varying ranges (R) is the determination of the transmission loss (TL), or the change in sound level relative to a reference distance of one meter:

\[
TL = |x| \cdot \log_{10}(R) \quad [\text{dB re 1 m}]
\]

where the TL coefficient \( x \) represents the slope on a logarithmic plot of RL versus R. Common values for \( x \) range from 10 (i.e. cylindrical spreading) to 20 (i.e. spherical...
spreading) [Urick, 1983]. In the bottom-limited Lau Basin, a value higher than 20 is expected because of scattering and reflection loss, which are not accounted for in geometrical spreading models [Jensen et al. 1995]. To estimate the source level of the airgun array at an offset of one meter, TL (eq. 4) is summed with the calculated RL (section 2.2):

\[ SL = TL + RL \]  \[ \text{[dB @ 1 m]} \] (5)

Due to the closely-spaced nature of the M3 quad (~2 km between individual instruments), the four instruments are averaged both for range and received level to avoid giving greater weight to these short-offset arrivals. The decibel RL vs. \( \log_{10}(R) \) data are regressed in a least squares sense, with the slope of the best fit line indicating the TL coefficient (eq. 4) and the y-intercept providing an estimate of the acoustic source level referenced to the standard one meter offset. These parameters are summarized in Table 1. Reported uncertainty in the slope and intercept are determined using a standard bootstrap procedure (n=1000).

3. Results

3.1 Signal Characteristics and Transmission Loss

The recorded RMS sound levels vary from 94 to 135 dB\(_{\text{RMS}}\) at ranges of 29 to 416 km, between ~17 and 28 dB above ambient noise levels. The transmission loss coefficient is -24.9 ± 0.1 and the back-calculated source level is 241.0 ± 0.4 dB\(_{\text{RMS}}\) @ 1m (Figure 9a). For all ranges, one standard deviation of the data plot within 3 dB of the best-fit approximation. The most extreme variation in received level at a similar range occurs at the M4 station, exhibiting more than 15 dB spread at nearly the same offsets.

Arrival durations varied from 0.9 seconds to 15.2 seconds, with average window lengths of 8.1 ± 1.4 (M3), 9.6 ± 2.3 (M4) and 10.9 ± 1.1 (M5) seconds (Figure 10). Since nearly all of the arrival durations exceed one second, EFD sound levels will typically exceed their RMS equivalents (following eq. 2). This shift, however, is not uniform because of variability and range dependence in the estimated signal durations (Figure 9d).

When the EFD data are fit, the transmission loss coefficient is found to be -23.3 ± 0.1 and a back-calculated source level is 242 ± 0.3 dB\(_{\text{EFD}}\) @ 1m (Figure 9b). One standard deviation of the data plot within 2.5 dB of the best-fit line. The most extreme variation in
received level at a similar range again occurs at the M4 station; however, the spread is reduced to ~10 dB.

Regression of the decibel Z2P vs. $\log_{10}(R)$ data indicate a best fitting transmission loss coefficient of -25.6 ± 0.1 and an acoustic source level of 259.2 ± 0.6 dBZ2P @ 1m. For all measurement methods, received level variability about the best-fitting prediction increases with increasing range, though Z2P methods exhibit higher variability than RMS and EFD measures even at close offsets, with a $1\sigma$ value of ± 4.7dB about the prediction.

The R/V Langseth’s seismic array is slightly longer athwart ship (24 m) compared to its fore-aft dimension (16 m), though in relation to the ranges studied here, this is still a largely symmetrical array. Findings here are similar to those found during the R/V Langseth’s calibration cruise: no azimuthal effect with respect to the ship’s heading is evident in the received level dataset [Tolstoy et al., 2009]. This is not always the case, as some source array geometries lend to directional trending sufficient for the exclusion of shots recorded at these azimuths [e.g. Tolstoy et al., 2004].

4. Discussion

4.1 Interpreting Sound Levels and Transmission Loss

Regardless of the method used to characterize sound levels, the observed transmission loss exceeds $20 \cdot \log_{10}(R)$ (i.e. spherical spreading loss). These high coefficients result from the strongly bottom-limited acoustic environment and the shallowness of the source, which leads to significant interaction with the ocean-atmosphere and ocean-seafloor boundaries [Jensen et al., 1995; Urick, 1983]. The back-calculated sources levels estimated in the present study are ~17-20 dB lower than values reported for a deep site (1700 m) in the Gulf of Mexico during the R/V Langseth’s calibration cruise (Table 1 and Appendix 1.2-1.3). Tolstoy et al. [2009] used direct arrivals only, which had source-receiver offsets of approximately 500 – 2900 m and calculated sound pressure levels (SPL) over a 5 – 25000 Hz frequency band, with most energy in the 10-300 Hz band.

Even at the nearest ranges studied here, sound levels fall short of United States Level B harassment thresholds (160 dB$_{RMS}$) [Battelle, 2005] and the142 dB$_{RMS}$ level where disruptions in diving patterns have been observed among some cetacean populations.
[Ljungblad et al., 1988]. The arrivals, however, are well above the ambient noise floor at all ranges and the frequency content of the airgun source is within the zone of audibility for baleen whales and other marine species [Ljungblad et al., 1988, Richardson et al., 1995]. To gain some perspective on the contribution of the survey to the local noise budget, the acoustic energy is estimated from the EFD source level. Assuming the EFD back-calculated source level of $242 \pm 0.3 \text{ dBEFD} @ 1\text{m}$, a water density of $1025 \text{ kg/m}^3$ and an average sound speed of $1500 \text{ m/s}$, $3.3 \times 10^{10} \pm 6.8\% \text{ J}$ of acoustic energy was released during the one-month-duration survey (Appendix 1.4). Compared to other anthropogenic sources, this is a significant number. It is approximately equivalent to 48 oil tankers transiting for 30 days (100% duty cycle) or military SURTASS LFA sonar operating for 6 days (10% duty cycle). Both of these sources operate at similarly low frequencies to airguns, typically $\leq 300 \text{ Hz}$ [Hildebrand, 2004].

Within such a volcanically and tectonically active basin, however, sustained periods of similarly high intensity sound are produced regularly from natural sources. For example, during 17-21 March 2009, the seamount Hunga Ha'apai erupted semi-continuously with a volcanic explosivity index of 2 [Vaughan and Webley, 2010]. It produced a repeating series of pheromagmatic explosions at a range of 146 km from M3E. Integrating this station’s data over 8 second windows (the mean duration of airgun arrivals to M3E), the average sound levels are estimated over 12, 24, 48, and 72 hour periods starting at 16:00 UTC 16 March 2009 (Figure 9a-c and Table 2). Sustained received levels during the first 12 hours are $138.0 \pm 5.9 \text{ dB}_{\text{RMS}}, 147.0 \pm 6.0 \text{ dB}_{\text{EFD}}$ and $148.8 \pm 0.6 \text{ dB}_{\text{Z2P}}$ compared to the predicted levels of $112.1 \pm 0.8 \text{ dB}_{\text{RMS}}, 121.8 \pm 0.6 \text{ dB}_{\text{EFD}}$ and $127.1 \pm 1.2 \text{ dB}_{\text{Z2P}}$ produced only intermittently by the seismic survey.

Another example is the Mw 8.1 tsunamigenic earthquake that occurred along the outer rise of the Tonga trench on 29 September 2009 [Lay et al., 2010] at a distance of 500 km from station M5. Integrating this station data over 11 second windows (the mean duration of arrivals to M5), the sound levels are estimated over 1, 3, 12 and 24 hour periods (Figure 9a-c and Table 2). Decibel values of $146.0 \pm 9.4 \text{ dB}_{\text{RMS}}, 156.4 \pm 9.4 \text{ dB}_{\text{EFD}}$ and $154.8 \pm 8.8 \text{ dB}_{\text{Z2P}}$
are observed over the first hour. By comparison, the predicted received levels of a transient airgun arrival at this range are $98.8 \pm 0.8 \text{ dB}_{\text{RMS}}$, $109.3 \pm 0.7 \text{ dB}_{\text{EFD}}$ and $113.4 \pm 1.2 \text{ dB}_{Z2P}$.

An alternative way to compare these natural events to the seismic survey is computing the cumulative energy input to the ocean soundscape. Over the first 72 hours of the Hunga eruption, $4.9 \times 10^{13} \text{ J}$ of acoustic energy is produced and $3.8 \times 10^{14} \text{ J}$ are produced in the first 24 hours after the $M_w$ 8.1 earthquake, capturing the mainshock and immediate aftershocks. When compared to the entire seismic survey, the energy contributions of these geophysical events are 3-4 orders of magnitude higher; this is especially significant because these events are only analyzed for 72 (eruption) and 24 (earthquake) hours, while the seismic survey lasts 675 hours.

4.2 Correlating Signal Characteristics and Bathymetry

Each receiver lies in a different azimuthal direction from the seismic survey, promoting variable seafloor interactions along the propagation paths (Figure 1). Seafloor aspects cluster around $100^\circ$ and $280^\circ$ (Figure 11), representing the inward and outward dipping normal fault scarps associated with the $\sim10^\circ$ trending ELSC. The M3 station records signals that propagate at azimuths between $225-338^\circ$, sub-parallel to the dominant seafloor aspect direction. Signals received at M4 propagate at azimuths of $\sim340^\circ$, oblique to dominant aspect directions, and signals received at M5 propagate nearly orthogonal to dominant aspect directions at azimuths of $\sim18^\circ$ (Figure 11). The seafloor generally deepens with range between the ELSC and the M3 station, experiencing an average of $889.7 \pm 120.8 \text{ m}$ of net relief along path. The M4 and M5 station are moored above seafloor of virtually the same depth, however, the variation of seafloor depths toward these receivers is different, with averages of $940.9 \pm 102.1 \text{ m}$ and $694.5 \pm 145.0 \text{ m}$ of net relief, respectively. Signals received at M4 must cross the ELSC and CLSC, as well as some shallow seamounts, where signals toward M5 typically travel parallel to the seafloor fabric and associated rift valley.

Arrival durations, as defined by the 90% cumulative energy window, generally increase with increasing source-receiver offset (Figure 9d). Many received signatures, however, deviate below a $1\sigma$ confidence limit; this is especially notable at stations M3 and
M4. When those shots with the longest and shortest durations (defined as above and below the best-fit ± 1σ) are plotted on a map of the seismic survey, a geographic trend becomes apparent (Figure 12a), whereby the short duration arrivals originate above shallow topography and long duration arrivals originate within the deeper valley. Similarly, arrivals with high and low peak amplitudes plot preferentially along the ridges and valley, respectively (Figure 12b); extreme RMS values follow a similar, though less pronounced pattern (Figure 12c) and extreme EFD values show an even weaker spatial correlation (Figure 12d).

Comparing signal duration and the back-calculated source levels to the depth at each shot location supports the geographic trends just identified. As a function of depth, signal duration and Z2P source level estimates have similarly high Pearson’s correlation coefficients, \( r = 0.45 \pm 0.11 \) and \( r = 0.44 \pm 0.10 \), respectively (Figure 13a-b). RMS source levels as a function of depth exhibit a weaker correlation, \( r = 0.37 \pm 0.01 \) (Figure 13c) and EFD source levels exhibit an even weaker correlation, \( r = 0.32 \pm 0.01 \) (Figure 13d). Correlation coefficients also show a pattern based on receiver; depth at the seismic shot location correlates most strongly with durations from the M3 station and source level estimates from the M4 station. Duration and amplitude data from the M5 station always show the weakest correlation with depth beneath the airgun shot location.

This study is not the first to present evidence linking depth and seafloor properties with variability in acoustic received levels. Blackman et al. [2004] has shown that a receiving station thousands of kilometers away detected seismic airgun shots fired above a sloping seafloor near the Ninety East Ridge in the Indian Ocean, while that same receiver did not detect shots fired at closer ranges, but in deep water (> 4000 m). Modeling results indicated that shots fired over the ridge typically coupled into the SOFAR channel by downslope conversion and increased the SNR proportionately [Harben et al., 2002], while other shots relied on seafloor scattering from shallow secondary sources for SOFAR entrapment [Blackman et al., 2004]. Observations from Blackman et al. [2004] and Harben et al. [2002] are consistent with the present study, where peak amplitudes and arrival durations can be correlated to seafloor parameters near the source array.
The link between seafloor and received signal characteristics is further supported by the study of T-phases, which are hydroacoustic signals generated by the conversion of seismic P and S-waves at the ocean-crust boundary [Tolstoy and Ewing, 1950]. Tolstoy and Bohnenstiehl [2003] have shown that deep-water intra-plate earthquakes exhibit systematically lower acoustic source levels (RMS and P2P) than equivalent magnitude earthquakes along shallow ridge crests. While they could not rule out variations in hypocentral depth, their ray tracing result indicated that T-phases emanating from deep seafloor entrain less energy into the SOFAR channel than those emanating from shallow seafloor.

4.3 Mechanisms for Variable Acoustic Propagation in a Bottom Limited Setting

The sound velocity structure in the Lau Basin is such that the minimum velocity, and thus the SOFAR axis, is at a depth of ~1100 m and the critical depth is ~ 5500 m (Figure 2a). The airgun source is shallow (9 m) and consequently acoustic energy cannot be refracted directly into the SOFAR channel. Rather, signals scatter and specularly reflect from some area beneath the airgun array; this can generate low grazing angle rays (low order modes) that propagate nearly adiabatically for very long ranges [Talandier and Okal, 1998; Park et al., 2001]. Sites of seafloor scattering, which radiate energy both in and out of the propagation plane, may locally be viewed as secondary acoustic sources [Yang and Forsyth, 2003; Williams et al., 2006].

Back-calculated source levels, which remove range dependency from received levels, correlate strongly with arrival durations (-0.90 < r < -0.56), where shorter durations are indicative of higher source level estimates (Figure 14). This follows that those arrivals following a bottom reflection regime both lose energy and spread out in time with each reflection. RMS and Z2P source level estimates correlate best with arrival durations (-0.90 < r < -0.70) and EFD estimates show the weakest correlation (-0.82 < r < -0.56).

The influence of scattering from the rough and heterogeneous ELSC crust is evident in the arrival durations, which are often an order of magnitude higher than direct arrivals reported by Tolstoy et al. [2009]. With increasing depths beneath the source array,
increasingly large areas of seafloor are insonified, leading to the positive correlation between seafloor depth and arrival duration (Figures 12a and 13a). This is numerically validated by a ray-trace model that predicts signals originating over deeper seafloor arrives via many bottom reflections, whereas those signals originating over the shallower flanks of the ELSC arrive via relatively few bottom bounces (Figure 15). Increasing the source-receiver offset also lends to longer arrival durations (Figure 9d). This follows that signals propagating through a bottom reflection regime have a greater number of bottom interactions, with each secondary source spreading the signal out in time.

The negative correlation between received levels and seafloor depth (Figures 12 and 13) is consistent with the greater coupling of scattered energy into the sound channel at shallower seafloor depths [e.g. de Groot-Hedlin and Orcutt, 1999, 2001a; Park et al., 2001]. In addition to enhanced scattering efficiency, specular reflections also contribute to the generation of impulsive, high amplitude arrivals, as supported by a numerical ray trace. The impulsivity of a received waveform is highest when energy is entrained in the SOFAR channel following a single bottom bounce (Figure 16). This is consistent with Talandier and Okal [1998], who noted that downslope conversion paths requiring repeated reverberations tend to produce T-waves that are of longer duration and lower amplitude relative to those paths where acoustic energy may couple into the sound channel after only one bottom bounce.

The entrapment of seafloor reflected energy into the sound channel is favored when the depth of the seafloor increases along the propagation path [e.g. Williams et al., 2006]. Once rays entrain within the SOFAR channel, shallowing bathymetry or abrupt topographic highs can cause a refracting ray to undergo a series of sea bottom reflections. For seismic shots originating over the shallow ridges adjacent to the ELSC, bathymetry tends to deepen along path to M3. The M4 station is northwest of the survey location and paths tend to cross both the ELSC and central Lau spreading center (CLSC). Overall, paths to this station exhibit relatively high relief but show no general shallowing or deepening trend. Station M5 lies to the north of the ridge valley such that source-receiver paths tend to shallow or stay relatively flat.
For a ray that intersects the seafloor, each bottom bounce reflects and scatters the incoming energy; the strength and directivity of which depends on the ray’s incident angle and the slope and aspect of the seafloor [Blondel, 2009]. Signals propagating at azimuths nearly perpendicular to predominant seafloor aspects will scatter much of their energy outside of the propagation plane. This partly explains the lack of high amplitude, low duration arrivals to the M5 station. Conversely, the M3 and M4 stations receive more of these impulsive arrivals, representative of propagation paths that are nearly perpendicular to the seafloor fabric.

Different sound level measures (RMS, EFD, Z2P) show similar trends with regard to seafloor depth and arrival duration (Figures 13 and 14), but exhibit different levels of correlation because they highlight different characteristics of the received signal (eqs. 1-3). A main difference in sound-channel-borne arrivals and multipath, scattered arrivals is the peak amplitude, leading Z2P values to be most representative of propagation patterns. The correlation between seafloor depth and the estimated source level is weaker when expressed in terms of the RMS measurements, which represent the average signal amplitude across the 5-95% cumulative energy window and therefore encompass the scattered energy within the coda. Amplitude data show the least variability when expressed in terms of the EFD RL (Figure 9b), and consequently the correlation with seafloor depth and arrival duration is the weakest (Figures 13 and 14).

5. Summary

In the bottom-limited acoustic setting of the Lau Back-Arc basin, signals received at offsets of 29 – 416 km decay more rapidly than pure spherical spreading, with acoustic amplitudes decreasing at 23.3 – 25.6 dB/log_{10}(R). At similar offsets, peak amplitudes vary by an order of magnitude and durations can vary by factors of three to six. Spatial patterns are identified that show impulsive arrivals originate over shallow bathymetry, whereas emergent arrivals originate over deeper seafloor. Water depth beneath the seismic shot correlates with arrival duration ($r = 0.33 – 0.55$) and peak amplitude ($|r| = 0.33 – 0.46$), where signal impulsivity is highest for shots performed above shallow seafloor. Long and short arrival durations correspond with low and high back-calculated peak source levels, respectively,
with correlation coefficients $|r| = 0.69 – 0.86$. This evidence suggests some rays entrap within the SOFAR channel and propagate with relatively little transmission loss, while others propagate through a series of bottom reflections.

A combination of downslope conversion and seafloor scattering is suggested as a physical explanation for these phenomenon, which is consistent with previous literature that correlates seafloor parameters with received signal characteristics [Talandier and Okal, 1998; de Groot-Hedlin and Orcutt, 1999, 2001a; Park et al., 2001; Yang and Forsyth, 2003; Blackman et al., 2004; Williams et al., 2006]. Numerical evidence for sound-channel-borne arrivals is provided by a Bellhop ray trace model [Porter, 2011] that predicts sound channel borne arrivals originate over shallow topography. Though the mechanisms for sound channel entrapment are typically shown to operate over ocean basin scales [e.g. Talandier and Okal, 1998; Blackman et al., 2004], this study demonstrates their applicability to intermediate ranges.

The main implication of these findings is for regulatory bodies interested in the preservation of marine biota. By understanding the relationship between local seafloor parameters and acoustic propagation, marine seismic surveyors can more accurately estimate sound levels at range. This will increase the effectiveness of current thresholds (e.g., NMFS behavior and risk sound thresholds) and give regulatory bodies counsel when assessing and updating regulations.
REFERENCES


Blondel, P. (2009), Acoustic Signals and Data Acquisition, in The Handbook of Sidescan Sonar, 7-34, Praxis Publishing Ltd., Chichester, UK.


**FIGURE DESCRIPTIONS**

**Figure 1.** Bathymetric map of Lau Basin. Red circles denote locations of moored autonomous underwater hydrophones, black line shows seismic survey track and purple lines are spreading center traces. ELSC = Eastern Lau Spreading Center and CLSC = Central Lau Spreading Center. Data compilation courtesy of F. Martinez.

**Figure 2.** a) Sound velocity structure of the Lau Basin. The sound speed profile (20.5°S, 176°W) is calculated from World Ocean Atlas data (Antonov et al. 2005, Locarnini et al. 2005) using January – March average values and is representative of the entire survey area. SOFAR axis depth is ~1100 meters (black dashed line), the average depth is 2360 m (gray dashed line) and the critical depth of the sound channel is ~5500 meters (red solid line). b) Sub-horizontal, low grazing angle rays (<10°) emitted from a shallow source show that a flat seafloor can result in bottom reflection/surface reflection propagation for the entire source-receiver path. c) A similar simulation, though replacing flat seafloor with sloping bathymetry can cause a ray emitted at a similar grazing angle to become entrapped in the low-velocity zone and follow a continuously refracting path.

**Figure 3.** a) A bathymetric map of the seismic survey (gray dashed line) area. b) Three depth profiles crossing the ELSC are extracted, highlighting a deepening rift valley to the north and a transition to axial high morphology in the south.

**Figure 4.** a-c) Power spectral density (PSD) plots of all passed arrivals at each hydrophone. The averaged PSD (blue solid line) shows a peak around ~2 Hz at each receiving station, representing low-frequency ocean noise. A 4 Hz high pass filter removes this component, yielding an effective bandwidth for analysis of 4 – 125 Hz. Variation in the PSD to a particular AUH partially reflects the varying ranges of the received signatures; the degree of variation is represented by plus/minus one standard deviation of the data (red dashed line).
Figure 5. Waveform of shot 8000 received at AUH M4 (range = 330 km) overlain by cumulative energy sum plot (green). The red window (right) represents the 90% energy window used for signal level calculation (time between 5% and 95% of total cumulative energy). The black window (left) is a window of equal length situated such that it ends two seconds before the signal window begins; this is used for noise level calculations.

Figure 6. SNR distribution for each AUH where dashed portions of each curve represent where $SNR < \bar{SNR} - 1\sigma$. Arrivals with SNR in this range are not used for analysis. The average SNR is shown by a black circle along the histogram and a table provides numerical values. Note that the four instruments at the M3 site are averaged and are represented here by a single distribution.

Figure 7. a) Waveform and b) spectrogram of shots 4309, 4140 and 7008, all as recorded by the M4 station. From left to right, the presence of coincident seismo-acoustic energy is responsible for a low, average and high SNR where low and high is defined as $\bar{SNR} \pm 1\sigma$ on a plot of SNR vs. source-receiver offset. b) Spectrograms are calculated within 0.25 s windows with 50% overlap. c) Plotting received levels for sequential shots illustrates anomalies; coincident seismo-acoustic energy corresponds to increased received levels relative to clean airgun arrivals of a similar range and propagation path.

Figure 8. a) Cumulative energy verses time for three shots received at the M3E hydrophone. The data are positioned such that $t=15$ seconds represents the predicted arrival time. All shots pass the SNR test, but only one passes the cumulative sum goodness-of-fit test (see text). b) Shot 955 (blue) exhibits a cumulative-sum curve with rapid onset and steadily decreasing coda amplitudes through time. This shape is typical for an airgun arrival at intermediate ranges, and the event is retained for analysis. c) Shot 3417 (red) has transient noise arriving prior to the airgun arrival. The cumulative energy exceeds the 5% threshold at $t=14$ seconds, and therefore the arrival is rejected from consideration. d) Shot 6038 (magenta) exhibits seismo-acoustic energy arriving coincidently with airgun signal. The signal is reject because
the cumulative energy within the uncharacteristically long duration coda does not exceed the 35% threshold at t=20 seconds.

**Figure 9.** a-c) Received levels as a function of range are reported as a) RMS, b) EFD and c) Z2P. A least squares best-fit line is plotted (red) as well as a 95th percentile line (dashed red), indicating where 95% of the data fall below. Black lines represent the ambient noise floor for each hydrophone station ± 1σ. Also included are the Hunga Ha’apai eruption and Samoa Mw 8.1 earthquake with received levels for four different time iterations. For both events, the duration begins with initial event arrivals (e.g. eruption or mainshock). d) 90% Arrival durations are plotted a function of range. The best-fit prediction is shown (solid red line) with ±1σ confidence limits (dashed red line).

**Figure 10.** Histogram of arrival durations at each hydrophone. Duration is defined using the 5-95% cumulative energy sum method (see text).

**Figure 11.** a) The azimuthal direction from the shot locations to each hydrophone (colored lines) is compared to the aspects of the seafloor in the study site (thick gray line, peaks highlighted by dashed gray lines). b) An aspect map shows the ~10° trending ELSC and associated faulting, which generates aspect peaks of 100° and 280°. Black line delineates survey area, black circle denotes M3 location and arrows point toward M4 and M5.

**Figure 12.** The spatial distributions of airgun shots associated with arrivals having extreme low- (1st column) and high- (2nd column) valued signal properties are overlain on the local bathymetry. Measured properties of signal a) duration, b) Z2P, c) RMS and d) EFD received level are shown for arrivals at each station. Measurements deviating from the expected value at a given range by more than ± 1σ (3rd column) are defined as extreme. White line delineates the limits of the survey area. Arrivals (at a given range) with the shortest durations and highest amplitudes typically plot along bathymetric highs (2nd
The longest duration and lowest amplitude arrivals cluster along the deeper sections of the ELSC (1st column).

**Figure 13.** a) Arrival duration and b) Z2P, c) RMS and d) EFD back-calculated source levels plotted against the seafloor depth at the corresponding seismic shot locations. Arrival durations exhibit the strongest correlation, and decreasing correlation strength is seen with Z2P, RMS and EFD received levels. Black lines represent a linear best fit of the data. Arrival durations correlate positively with depth, whereas received levels correlate negatively with depth.

**Figure 14.** Arrival durations are plotted as a function of back-calculated source levels. a) RMS, b) EFD and c) Z2P values are shown. Z2P and RMS values show strongest correlations, whereas EFD shows the weakest correlation for all hydrophones. For each measure (RMS, EFD, Z2P), received signals to M4 exhibit the strongest correlation while signals received at M3 and M5 correlate similarly.

**Figure 15.** a) The geographic origin of extreme arrivals is represented with black dots, with long duration and/or low received levels (left) and short duration and/or high received levels (right). Data shown are only for those arrivals that have also been modeled (white dots). b) Geographic origin of arrivals modeled as having many (left) or few (right) bottom bounces. Model run includes data from 2398 shots, for a total of 7194 unique arrivals (white dots). The number of bottom bounces used for classification (i.e., many or few) is shown in the lower right of each map.

**Figure 16.** Airgun arrivals record at stations a) M3E, b) M4 and c) M5. For each arrival, the pressure waveform (blue), cumulative energy curve (green) and spectrogram are shown. These examples illustrate the variable characteristics of the arrivals, with both impulsive, short-duration, higher-amplitude signals and more emergent, longer-duration, lower-amplitude signals observed for shots at similar ranges. For each shot, a range-dependent
acoustic ray-tracing model [Porter, 2011] is performed using 3000 rays with take off angles evenly distributed between ±89°. Plotted rays are those with the fewest number of bottom bounces. Impulsive waveforms are associated with propagation paths that allow rays to become trapped in the sound channel after a small number of bottom bounces; more emergent waveforms are more typically associated with signals that propagate laterally through a series of bottom reflections.
### Table 1. Transmission loss coefficients and estimated array source levels

<table>
<thead>
<tr>
<th>Technique</th>
<th>Trans. Loss</th>
<th>SL Estimate</th>
<th>Trans. Loss</th>
<th>SL Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS</td>
<td>-24.9 ± 0.1</td>
<td>241.0 ± 0.4</td>
<td>-29.21</td>
<td>260.45</td>
</tr>
<tr>
<td>EFD</td>
<td>-23.3 ± 0.1</td>
<td>242.3 ± 0.3</td>
<td>-32.34</td>
<td>258.98</td>
</tr>
<tr>
<td>Z2P</td>
<td>-25.6 ± 0.1</td>
<td>259.2 ± 0.6</td>
<td>Not Reported</td>
<td>Not Reported</td>
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</table>

### Table 2. Energy contribution from natural events for varying durations

<table>
<thead>
<tr>
<th>Duration (hrs)</th>
<th>RL (dB_{RMS})</th>
<th>RL (dB_{EFD})</th>
<th>RL (dB_{Z2P})</th>
</tr>
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<tr>
<td><strong>Hunga Ha'Apai Eruption</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>138.0 ± 5.9</td>
<td>147.0 ± 6.0</td>
<td>148.9 ± 6.0</td>
</tr>
<tr>
<td>24</td>
<td>135.7 ± 5.7</td>
<td>144.7 ± 5.8</td>
<td>146.8 ± 5.9</td>
</tr>
<tr>
<td>48</td>
<td>131.1 ± 10.0</td>
<td>140.1 ± 10.0</td>
<td>142.4 ± 10.5</td>
</tr>
<tr>
<td>72</td>
<td>127.9 ± 12.6</td>
<td>136.9 ± 12.6</td>
<td>139.2 ± 13.3</td>
</tr>
<tr>
<td><strong>Samoa Earthquake M_w 8.1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>146.0 ± 9.4</td>
<td>156.4 ± 9.4</td>
<td>154.8 ± 8.8</td>
</tr>
<tr>
<td>3</td>
<td>138.1 ± 10.0</td>
<td>148.5 ± 10.0</td>
<td>147.3 ± 9.7</td>
</tr>
<tr>
<td>12</td>
<td>129.2 ± 8.7</td>
<td>139.6 ± 8.7</td>
<td>138.7 ± 8.6</td>
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<td>24</td>
<td>125.2 ± 8.4</td>
<td>135.6 ± 8.4</td>
<td>135.0 ± 8.4</td>
</tr>
</tbody>
</table>
FIGURES
Figure 2. Sound velocity profile for Lau Basin and ray-trace for contrasting bathymetries
Figure 3. Zoom in of study site highlighting three depth profiles
Figure 4. PSD plot for passed shots to each hydrophone
Figure 5. Signal and noise windows overlaid on a pressure waveform
Figure 6. SNR histograms for passed shots to each hydrophone

Histogram of SNR for All Passed Arrivals

- Used in analysis
- Not used in analysis
- Mean SNR for AUH

<table>
<thead>
<tr>
<th>Hydrophone</th>
<th>Mean ± 1σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUH</td>
<td>27.5 ± 5.6</td>
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<tr>
<td>M3</td>
<td>13.7 ± 6.7</td>
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<td>M4</td>
<td>18.5 ± 5.4</td>
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<tr>
<td>M5</td>
<td></td>
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</table>
Figure 7. Coincident earthquake energy causing low, average and high SNR
Figure 8. Cumulative sum filter methods highlighting three waveforms.
Figure 9. Received levels and arrival durations as a function of source-receiver offset
Figure 10. Histogram of arrival durations for all passed shot to each AUH
Figure 11. Comparison of propagation direction and seafloor aspects, aspect map
Figure 12. Arrivals with extreme characteristics plotted by geographic origin
Figure 13. Received levels and arrival durations as a function of depth beneath shot origin
Figure 14. Estimated source levels as a function of signal duration for each AUH
Figure 15. Comparison of observational and model-generated results
Figure 16. Modeling propagation paths and comparing to signal duration and amplitude
Impulsive and Non-Impulsive Signature and Ray-Trace - M3

Impulsive and Non-Impulsive Signature and Ray-Trace - M5
Impulsive and Non-Impulsive Signatures and Ray-Traces - M4

# of bounces = 11

# of rays with one bounce = 15

$\text{SNR} = 26.04 \text{ dB}$

$90\%$ Duration $= 2.94 \text{ s}$

$\text{SNR} = 13.72 \text{ dB}$

$90\%$ Duration $= 12.14 \text{ s}$

$\text{SNR} = 23.37 \text{ dB}$

$90\%$ Duration $= 2.70 \text{ s}$

$\text{SNR} = 15.98 \text{ dB}$

$90\%$ Duration $= 11.80 \text{ s}$

M4/4930

M4/8664

M4/8017

M4/6283
APPENDIX 1: CALCULATIONS

1.1 Geophysical Data Conversion

To convert digital counts to units desirable to acousticians, µPa, the following series of equations is used:

To convert from raw counts data to volts:

\[ V = \frac{(C - \overline{C}) \cdot R}{B} \]  \hspace{1cm} (A1.1)

\[ V = \text{volt value (V)} \]
\[ C = \text{count value (counts)} \]
\[ \overline{C} = \text{arithmetic mean of count values (counts)} \]
\[ R = \text{volt range} = 2.5 \text{ (volts)} \]
\[ B = \text{bit range} = 16 \text{ bit} = 2^{16} = 65,535 \text{ (counts)} \]

To determine the system gain:

\[ G(f) = s + p(f) + g \]  \hspace{1cm} (A1.2)

\[ G(f) = \text{frequency dependent system gain (dB)} \]
\[ s = \text{AUH sensitivity (dB)} \]
\[ p = \text{frequency dependent pre-amp constant (dB)} \]
\[ g = \text{gain adjustment (gain value x 6 dB)} \]

A frequency response correction is applied using laboratory-measured values from the pre-amplifier boards installed in the AUH instruments. Once this frequency correction is applied, the volts measurement can be converted into µPa:

\[ P(f) = \left( \frac{V(f)}{G(f)} \right) \left( \frac{10^{20}}{20} \right) \]  \hspace{1cm} (A1.3)

\[ P(f) = \text{frequency dependent pressure (µPa)} \]
V(f) = fast Fourier transform of the frequency response corrected volt level from A1.1 (V)

\[ 10^{\frac{V}{\mu Pa}} = \text{frequency dependent system gain from A1.2 in linear units} \left( \frac{V}{\mu Pa} \right) \]

Once this data conversion is complete, the data are now in an acceptable format to begin analyzing sound levels. The conversion is applied to all data points.

1.2. Pertinent Results from the R/V Marcus G. Langseth Calibration Survey

<table>
<thead>
<tr>
<th></th>
<th>RMS x SL @ 1 km</th>
<th>EFD x SL @ 1 km</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Best Fit</strong></td>
<td>-29.21</td>
<td>172.82</td>
</tr>
<tr>
<td><strong>95% Fit</strong></td>
<td>-29.21</td>
<td>175.64</td>
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</table>

1.3. Source Level Conversion

Data reported by Tolstoy (2009) from the R/V Langseth calibration cruise (Appendix 1.2) indicate the received level as a function of range according to:

\[ RL_1 = -32.34 R + 161.96 \] (A3.1)

Where \( R \) is the \( \log_{10} \) of the offset (m) and \( RL_1 \) is the received level (dB\_EFD) 1 km from the source when \( R=0 \) for 95% of the data at a deep site (~1700 m) with the 4-string array. To convert this into an equation representing the RL 1 meter from the source, \( i.e. \)

\[ RL_0 = -32.34 R + 258.98 \] (A3.2)

\[ RL_0 = -32.34 R + 161.96 + \log_{10}(1000m)(32.34) \]

This leads to a transmission loss coefficient, \( x = 32.34 \) and a back-calculated source level, \( SL = 258.98 \text{ dB}_\text{EFD} @ 1 \text{ m.} \)
1.4. Energy Contribution from Seismic Survey

Variable definitions:

$\text{SL}_{\text{EFD}} = 242.3 \pm 0.3 \text{ dB}_{\text{EFD}}$

$\rho = 1025 \text{ kg/m}^3$

$c = 1500 \text{ m/s}$

$t = 0.030 \text{ s}$

$A = \pi \text{ m}^2 \text{ s}^2$ (Radiation into a half sphere)

$N = 9399 \text{ shots}$

Initially, the pressure is calculated from the array source level estimate:

$$P = \frac{10^{\left(\text{SL}_{\text{EFD}} \frac{\text{dBA}}{20}\right)}}{1 \times 10^6 \mu \text{Pa}} \quad \text{(Pa·s)} \quad (A5.1)$$

From this value, acoustic intensity is calculated:

$$I = \frac{P^2}{\rho c} \quad \text{(kg/s}^3) \quad (A5.2)$$

And lastly, the directionality ($A$) and number of airgun shots ($N$) is accounted for:

$$E = I \cdot A \cdot N \quad \text{(Joules)} \quad (A5.3)$$

The final value, $E$, is the energy in joules for all seismic shots during the survey.
APPENDIX 2: PROPAGATION MODELING

Bellhop is a beam-tracing program that allows the user to calculate several variables related to the acoustic pressure field in an ocean environment [Porter, 2011]. For this study, Bellhop and modified scripts determine physical ray paths (as range and depth coordinates). The model incorporates range-dependent bathymetry and range and depth-dependent sound speeds to model a user-specified number of rays along each shot-receiver path, with user-defined departure angle limits. Rays are only included for analysis if they arrive within ±150 vertical meters of the hydrophone. This is consistent with the resolution of the bathymetry plus the depth uncertainty of the instrument because of a varying watch circle about the seafloor mounted anchor. For all models, the source frequency is 50 Hz, the source depth is 9 m, the receiver is modeled at a depth of 1000 m and the sound speed profile is computed from salinity and temperature data from the World Ocean Atlas (Antonov et al. 2005, Locarnini et al. 2005) for the approximate center of the seismic survey (20.5° S, 176° S) using annual average values.

Shallow grazing angle rays leaving the source array are modeled to determine the minimum depth at which refraction back toward the sea surface occurs (Figure A2.1). This model run is designed to draw 200 rays with evenly spaced departure angles of 0-5°. Bathymetry is modeled as a flat seafloor with a depth of 10 km for 400 km range. Results indicate that rays leaving the source in a horizontal direction will reach their first inflection point at near 5700 m depth; rays leaving at greater departure angles reach their first inflection point at greater depths. With the exception of subduction trenches and very deep abyssal plains, global seafloor depths are always shallower than this value. Therefore, acoustic emissions from a shallow source can be expected to result in a series of sea bottom reflections, almost irrespective of geographic location.
APPENDIX 3: INVESTIGATION OF ARRAY DIRECTIONALITY

Because the source array of the R/V Marcus G. Langseth is slightly shorter (16 m) than athwart-ship (24 m), there is reasonable concern for directional effects of the array. To determine if these effects are present in our received dataset, the ship heading is determined at each shot location. Similarly, the azimuthal direction from each shot location toward each receiver is calculated. The difference in these values, that is, the azimuth from source receiver minus the ship heading, can be categorized as fore/aft/port/starboard (hereafter referred to as shot category). Received signals are binned according to these delineations and plotted as $R_{EFD}$ vs. $R$ for a total of four plots (Figure A3.1). For each shot category, a least-squares best-fit line is calculated, yielding the transmission loss coefficient and the estimated array source level.

Due to the geometry of the array, if directional effects are present, they will result in preferentially higher received levels in the fore and aft directions [e.g. Tolstoy et al., 2004]. While results indicate that received levels are highest for arrivals received in the aft direction (Figure A3.1), the fore direction clusters best with the port and starboard categories. Overall, there is not a clear trending of fore and aft received arrivals to be of higher amplitude than athwart-ship received arrivals. Therefore, we can neglect array directionality as a factor in the observed acoustic variability.
APPENDIX 4: SUPPLEMENTAL FIGURES

Figure A2.1. a) The sound speed profile is determined for the approximate center of the survey (-20.5°, -176°). b) Two hundred rays are plotted with evenly spaced departure angles between 0-5°. Bathymetry is set to a constant depth of 10 km for a range of 400 km.

Figure A3.1. a) Arrivals amplitudes (EFD) are plotted as a function of range in bins according to the direction they traveled from source-receiver (fore/aft/port/starboard). b) Similar TL coefficients (slope) and source level estimates (y-intercept) indicate no directional effects. c) The delineations of fore/aft/port/starboard arrivals.
Supplemental Figure A2.1. Ray-trace for a deep and flat seafloor
Supplemental Figure A3.1. Array directionality

<table>
<thead>
<tr>
<th>AUH</th>
<th>Trans. Loss Coefficient</th>
<th>Source Level Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fore</td>
<td>-24.9 ± 0.1</td>
<td>250.6 ± 0.6</td>
</tr>
<tr>
<td>Aft</td>
<td>-26.0 ± 0.1</td>
<td>255.8 ± 0.6</td>
</tr>
<tr>
<td>Starboard</td>
<td>-24.6 ± 0.1</td>
<td>248.2 ± 0.6</td>
</tr>
<tr>
<td>Port</td>
<td>-24.3 ± 0.1</td>
<td>246.9 ± 0.6</td>
</tr>
</tbody>
</table>
APPENDIX 5: MATLAB SCRIPTS AND FUNCTIONS
Arrival_times_shots_stations_v2.m

% Calculate arrival time of each shot at each station
% Author: Corey M. Scheip
% This m-file calculates the epoch arrival times of each airgun shot at
% each hydrophone.

tic;
% load data
load Langseth_shots.dat
lat1=Langseth_shots(:,7);
lon1=Langseth_shots(:,8);
load Langseth_AUH_coords.txt
v=1490; % Sound speed in water (m/s)
yr=Langseth_shots(:,1);
hr=Langseth_shots(:,4);
mn=Langseth_shots(:,5);
sc=Langseth_shots(:,6);
jd=dayofyear(yr',Langseth_shots(:,2)',Langseth_shots(:,3)');
ept=24*60*60*(datenum(yr,1,jd,hr,mn,sc)- datenum(1970,1,1,0,0,0)); % Calculate epoch time
st=ept; % Shot time from R/V Langseth in epoch time
at_outs=['at_M3S';'at_M3E';'at_M3N';'at_M3W';'at_M04';'at_M05'];

% arrival_out=zeros(length(shots),length(Langseth_AUH_coords));
% tt_out=zeros(length(shots),length(Langseth_AUH_coords));

% This creates a unique travel time matrix for each station
for i=1:length(Langseth_AUH_coords) % To account for each station
    lat2=Langseth_AUH_coords(i,1);
    lon2=Langseth_AUH_coords(i,2);
    tt=deg2km(distance(lat1,lon1,lat2,lon2))*1000/v; % Travel time from shot to station in seconds
    tt_out(:,i)=tt; % Builds matrix with rows=shots, col=stations and entries=travel time between
    % tt i=tt_out(:,i);
    txt=['at_outs(:,i)='[(ept+tt),yr,jd,hr,mn,(sc+tt)]
    eval(txt);
    txt=['k=' at_outs(i,:) '
    eval(txt);

for t=(1:length(Langseth_shots))
    fl=floor(k(t,6)/60); % Divisible by 60? (sec)
    if fl>0

k(t,5)=k(t,5)+fl; k(t,6)=k(t,6)-(fl*60);
end

fl2=floor(k(t,5)/60); %................. % Divisible by 60? (min)
if fl2>0
    k(t,4)=k(t,4)+fl2; k(t,5)=k(t,5)-(fl2*60);
end

fl3=floor(k(t,4)/24); %................. % Divisible by 24? (hr)
if fl3>0
    k(t,3)=k(t,3)+fl3; k(t,4)=k(t,4)-(fl3*24);
end

txt=[at_outs(i,:) '=k;];
eval(txt);
end
tstop=toc;

% save /G3/d_cmscheip/research_lau/d_airgun/airgun_arrivals_1490.mat at_M3S at_M3E at_M3N at_M3W
at_M04 at_M05
function [t2,y2]=return_rsp(chan,search_epoch,dur_sec)

% Author: Corey M. Scheip
% --HELP--
% Pulls volt count data and ept axis from given channel and ept time for a
% given duration
%
% [t2,y2]=return_rsp(chan,search_epoch,dur_sec)
%

I1 = strmatch(chan, strvcat('B','M3S','H41'),'exact');
if ~isempty(I1)
    id='3S'; auhid='H41'; end
I1 = strmatch(chan, strvcat('C','M3E','H34'),'exact');
if ~isempty(I1)
    id='3E'; auhid='H34'; end
I1 = strmatch(chan, strvcat('D','M3N','H36'),'exact');
if ~isempty(I1)
    id='3N'; auhid='H36'; end
I1 = strmatch(chan, strvcat('E','M3W','H31'),'exact');
if ~isempty(I1)
    id='3W'; auhid='H31'; end
I1 = strmatch(chan, strvcat('F','M4','M04','H16'),'exact');
if ~isempty(I1)
    id='04'; auhid='H16'; end
I1 = strmatch(chan, strvcat('L','M5','M05','H30'),'exact');
if ~isempty(I1)
    id='05'; auhid='H30'; end
%
%--------------------------------

samprate=250;
[yr,jd,hr,mn,sc]=epoch2jd(search_epoch);
if hr<12
    hrid='00';
elseif hr >=12
    hrid='12';
end

txt=[['fid=fopen(''/Volumes/G3/d_laursp/d_lau' id '_rsp' auhid '/' auhid '_' num2str(yr) sprintf('%03.0f',jd) '_' hrid '_DC.w'',''r'',''b'');']];
eval(txt)
y=fread(fid,'int16');
fclose(fid);
%
if hrid=='00'
hrid=0;
elseif hrid=='12'
    hrid=12;
end
ept=24*60*60*(datenum(yr,1,jd,hrid,0,0)- datenum(1970,1,1,0,0,0)); % Calculate ept for start of file
%
ept2=24*60*60*(datenum(yr,1,jd,hrid,mn,sc) - datenum(1970,1,1,0,0,0)); % Calculate ept for end of file
%  
t=t:1/samprate:ept2-(1/samprate);

b=find(t > search_epoch & t < search_epoch+dur_sec); %
tmax=max(t);
t2=t(b);
y2=y(b);

%--------------------------------

%%% %--------------------------------
% Accounts for when the arrival time is too close to beginning or end of
% file and then pulls the next file, cats the data, and bam! you have your
% desired duration of data
if length(t2)<dur_sec*samprate-2/samprate
    if hr<12
        hrid='12';
    elseif hr >=12
        hrid='00';
        jd=jd+1;
    end
    txt=['fid=fopen(''/Volumes/G3/d_laursp/d_lau' id '_rsp' auhid '/' auhid '_' num2str(yr) sprintf('%03.0f',jd) '_' hrid
                  '_DC.w','r','b');'];
eval(txt)
y=fread(fid,'int16');
fclose(fid);
% if hrid=='00'
    hrid=0;
elseif hrid=='12'
    hrid=12;
end

ept=24*60*60*(datenum(yr,1,jd,hrid,0,0)- datenum(1970,1,1,0,0,0)); % Calculate ept for start of next file
%  
if hrid==12
jd=jd+1;
hrid=00;
mn=0;
sc=0;

elseif hrid==00
    hrid=11;
mn=59;
sc=.996*60;
end

ept2=24*60*60*(datenum(yr,1,jd,hrid,mn,sc) - datenum(1970,1,1,0,0,0)); % Calculate ept for end of next file
%
t=ept:1/samprate:ept2-(1/samprate);
b=find(t > search_epoch & t < search_epoch+dur_sec); %
tmax=max(t);
t2b=t(b);
y2b=y(b);

t2=[t2; t2b'];
y2=[y2; y2b];
end

%--------------------------------


%---------------------------------------------------  you may comment this out if you don't want to plot
%---------------------------------------------------  and you don't need spectrogram info
% figure; subplot(2,1,1); hold on;
% plot((t2-t2(1)),y2); % convert time back to seconds since start of file
% subplot(2,1,2);
% [B,FR,T]=spectrogram(y2,ceil(samprate*0.125)*2,ceil(samprate*0.125),1024,ceil(samprate)); % Changed
% spectrogram resolution but "samprate*0.125" samprate alone provides 1 second resolution
% imagesc(T,FR,20*log10(abs(B)));axis xy;

%---------------------------------------------------
peak_arrivals_v2.m

function [pkarr_diffs, pkarr_realtimes, pkarr_times, pkarr_amps] = peak_arrival_v2(chan, shots, freq, win, plotid)

% This function will detect the peak arrival time for a given shot or set of shots to a given channel.
% Author: Corey M. Scheip
%
% INPUTS
% chan: specify channel as 'M3S' or 'M4' etc
% shots: specify shots as 1:9399 or 100:200:1000, etc
% freq: what frequency for envelope to pass? i.e. small frequency (<2)
% yields very smooth envelope
% plotid: 1 calls plots, 0 says do not plot
%
% OUTPUTS
% Output is a [1 x length(shots)] matrix
%
% [pkarr_diffs, pkarr_realtimes, pkarr_times, pkarr_amps] = peak_arrival(chan, shots, freq, plotid)
% For de-bugging...
% chan='M3S'; shots=4796; freq=1.5; win=30; plotid=1;

% Orient matrix
s=size(shots);
if s(1)==1
    shots=shots;
elseif s(1)~=1
    shots=reshape(shots,1,length(shots));
end

% Load constants
load('airgun_arrivals_1490.mat')  % calc'd arrival times
load('pre_amp.mat')             % pre amp levels
load('gainm.txt')                % gain levels

% Load/assign constants
fs = 250;  % sampling frequency of 250Hz
enwin=0.5*win;  % to find peak, we don't need to look at the full window length of data

i1=strmatch(chan, 'M3S'); if ~isempty(i1) atmat=at_M3S(shots,1);
    pre_amp=pa_M3S;gain=gainm(1); end
i1=strmatch(chan, 'M3E'); if ~isempty(i1) atmat=at_M3E(shots,1);
    pre_amp=pa_M3E;gain=gainm(2); end
i1=strmatch(chan, 'M3N'); if ~isempty(i1) atmat=at_M3N(shots,1);
    pre_amp=pa_M3N;gain=gainm(3); end
i1=strmatch(chan, 'M3W'); if ~isempty(i1) atmat=at_M3W(shots,1);
    pre_amp=pa_M3W;gain=gainm(4); end
i1=strmatch(chan, strvcat('M4','M04'),'exact'); if ~isempty(i1)... 
    atmat=at_M04(shots,1); pre_amp=pa_M4;gain=gainm(5); end
i1=strmatch(chan, strvcat('M5','M05'),'exact'); if ~isempty(i1)...
atmat=at_M05(shots,1); pre_amp=pa_M5; gain=gainm(6); end

%% Envelope signal
envmat=zeros(length(shots),win*fs+1); % pre-allocate for speed
dsqmat=zeros(length(shots),win*fs+1);
pkarr_times=zeros(1,length(shots));
pkarr_realtimes=zeros(1,length(shots));
pkarr_diffs=zeros(1,length(shots));
pkarr_amps=zeros(1,length(shots));

% Pull out data
for i=1:length(shots);
    [t2,y2]=return_rsp(chan,atmat(i,:)-0.5*win,win);
    at=find(t2-atmat(i,:)>0,1,'first');  % Finds indice of arr. time in t2

    % Apply butterworth high pass filter to y2 signal to filter out low
    % frequency, ambient ocean noise, volcanoes, quakes
    [bfilt,afilt]=butter(5,4/125,'high');
    [H,f]=freqz(bfilt,afilt,1024, fs);
    y3=filtfilt(bfilt,afilt,y2);

    % Convert to uPa
    filt=2; % Filter adjust for all channels is 2
    if pre_amp==3; % M3N and M6
        [d]=AUHcorsignal_rev3(y3,fs,filt,gain);
    elseif pre_amp==4; % All others
        [d]=AUHcorsignal_rev4(y3,fs,filt,gain);
    end

    % Create envelope, square signal
dsq=d.^2; % square signal

    % Apply low pass filter
    [bfilt,afilt]=butter(1,freq/125,'low'); % (order, corner freq/nyquist freq, filter type (low, high, bandpass))
    [HH,ff]=freqz(bfilt,afilt,1024,fs); %#ok<NASGU> % 1024 is number of points to calculate
    env=filtfilt(bfilt,afilt,dsq);

    % Assign to matrix
    envmat(i,1:length(env))=env;
dsqmat(i,1:length(dsq))=dsq;

    % Find peak for each shot
    pkarr_win=(at-(envwin*.5*fs) :(at-(envwin*.5*fs)+(envwin*fs)); % indices for peak detection window
    pkarr_v=max(envmat(i,pkarr_win)); % amplitude of peak arrival in envelope
    pkarr_i=find(envmat(i,:)==pkarr_v); % index of peak arrival in envmat

    pkarr_t=pkarr_i/fs; % <= this is the peak arrival time in the analysis window
    pkarr_times(:,i)=pkarr_t; % assign pkarr_t into matrix
pkarr_realt = t2(at)+pkarr_t -(0.5*win); % << this is the peak EPOCH arrival time, 0.5 multiplier because the window is centered around calc'd arrival
pkarr_realtimes(:,i)=pkarr_realt; % assign pkarr_realt into matrix

pkarr_df = pkarr_realt-t2(at); % how different is calculated and actual peak arrival?
pkarr_diffs(:,i) = pkarr_df; % assign to matrix

pkarr_amps(:,i)=sqrt(max(dsqmat(i,:))); % << this is the peak amplitude
% pkarr_amps(:,i)=sqrt(max(dsqmat(i,pkarr_win))); % << this is the peak amplitude
end

%% Plot envelope, spectrogram, calculated and peak arrival
if plotid == 1
    figure;
    tdur=linspace(0,win,length(t2));
    figure; whitebg([0.7 0.7 0.7]); ax(1)=subplot(2,1,1); plot(tdur,d);
    hold on; % k=find(env<0); env(k)=NaN;
    plot(tdur,sqrt(env),'g','LineWidth',1)
    % Plot calc'd arrival time
    x=find(t2-atmat(i,:)>0,1,'first')/fs;        % To find calculated arrival time in tdur
    line([x,x],[-max(d),max(d)],'Color','k','LineStyle',' --','LineWidth',2);

    % Add spectrogram
    samprate=250;
    [B,FR,T]=spectrogram(y2,ceil(samprate*0.125)*2,...
        ceil(samprate*0.125),1024,ceil(samprate));
    ax(2)=subplot(2,1,2); imagesc(T,FR,20*log10(abs(B)));axis xy;
    line([x,x],[-max(d),max(d)],'Color','k','LineStyle','--','LineWidth',2);

    % Add peak arrival
    hold on; subplot(2,1,1);
    line([pkarr_times(i),pkarr_times(i)],...[
        -max(sqrt(dsqmat(i,:))),max(sqrt(dsqmat(i,:)))],...
        'Color','w','LineStyle',' --','LineWidth',2);
    subplot(2,1,2);
    line([pkarr_times(i),pkarr_times(i)],...[
        -max(sqrt(dsqmat(i,:))),max(sqrt(dsqmat(i,:)))],...
        'Color','w','LineStyle',' --','LineWidth',2);

    % labels
    subplot(2,1,1)
    eval(['title(''Channel ' chan ', shot ' num2str(shots(:,i)) ''', ' fontsize', ' num2str(14) ', ' fontweight ', ' ''b'' ')'])
    xlabel('Time (seconds)', 'fontsize',14)
    ylabel('Pressure (uPa)', 'fontsize',14); grid on;

    subplot(2,1,2)
    xlabel('Time (seconds)', 'fontsize',14)
    ylabel('Frequency (Hz)','fontsize',14);
    linkaxes(ax,'x')
end; end
rlcalc_run90.m

% Author: Corey M. Scheip
% Last update: 5 Sep 2011
%
% -- HELP --
% This m-file will calculate the received level of all shots to all
% stations. Run the m-file and wait for plots and results.
%
% shots=251:236:9399; chan='M4'; plotid=1;
tic;
% assign constants
shots=1:9399; auhid=1:6;
chan=['M3S';'M3E';'M3N';'M3W';'M04';'M05'];
plotid=1; fs=250;
tr=[14 20 5 35]; % [20 25 5 30]; 40s

% load data
load('airgun_arrivals_1490.mat'); load('pre_amp.mat'); load('gainm.txt');

% pre-allocate matrices
srms=zeros(length(shots),length(auhid)); sefd=zeros(size(srms));
sp2p=zeros(size(srms)); sp2p=zeros(size(srms)); snrm=zeros(size(srms));

for j=1:6; % start channel loop
    weird=[]; csfail=[]; cspass=[];
    % Assign AUH specific constants
    if      auhid(j)==1; r=at_M3S(shots,1); pre_amp=pa_M3S; gain=gainm(1);
    elseif auhid(j)==2; r=at_M3E(shots,1); pre_amp=pa_M3E; gain=gainm(2);
    elseif auhid(j)==3; r=at_M3N(shots,1); pre_amp=pa_M3N; gain=gainm(3);
    elseif auhid(j)==4; r=at_M3W(shots,1); pre_amp=pa_M3W; gain=gainm(4);
    elseif auhid(j)==5; r=at_M04(shots,1); pre_amp=pa_M4;  gain=gainm(5);
    elseif auhid(j)==6; r=at_M05(shots,1); pre_amp=pa_M5;  gain=gainm(6);
    end

win=30;
fwin=3*win; % to pull data fore and aft calc'd arr

% Assign AUH specific constants
if      auhid(j)==1; r=at_M3S(shots,1); pre_amp=pa_M3S; gain=gainm(1);
elseif auhid(j)==2; r=at_M3E(shots,1); pre_amp=pa_M3E; gain=gainm(2);
elseif auhid(j)==3; r=at_M3N(shots,1); pre_amp=pa_M3N; gain=gainm(3);
elseif auhid(j)==4; r=at_M3W(shots,1); pre_amp=pa_M3W; gain=gainm(4);
elseif auhid(j)==5; r=at_M04(shots,1); pre_amp=pa_M4;  gain=gainm(5);
elseif auhid(j)==6; r=at_M05(shots,1); pre_amp=pa_M5;  gain=gainm(6);
end

% pre-allocate for speed
ncsmat=zeros(length(shots),win*fs+1);
eval(['csfail_' chan(j,:) '+=[  ];']);
eval(['cspass_' chan(j,:) '+=[  ];']);

% Centered at calculated arrival time
[t,y]=return_rsp(chan(auhid(j),:),r(i)-0.5*fwin,fwin); % cntrd at calc'd arrs
at_cal=find(t-r(i)>=0,1,'first');  % Finds index of calc'd arr in t
[bfilt,afilt]=butter(5,4/125,'high'); % highpass at 4 Hz (ocean noise)
yf=filtfilt(bfilt,afilt,y); % [~,w]=freqz(bfilt,afilt,1024);

% Convert to uPa
filt=2;         % Filter adjust for all channels is 2
if pre_amp==3; [dc]=AUHcorsignal_rev3(yf,fs,filt,gain); % M3N
elseif pre_amp==4; [dc]=AUHcorsignal_rev4(yf,fs,filt,gain); % All others
end

% SIGNAL
dwin=dc(at_cal-(0.5*win*fs):at_cal+(0.5*win*fs)); % cntrd at calc'd arr
scs=cumsum(dwin.^2);              % cumulative ENERGY
normscs=scs/max(scs)*100;         % normalize to 0-100%
nscsmat(i,1:length(scs))=normscs; % assigns data to matrices

% CS TEST
% eval(['normscs=nscsmat_' chan(j,:) '(i,:); '])
eval(['ent_' chan(j,:) '(i,1)=' num2str(normscs(tr(1)*fs)) '; '])
eval(['ent_' chan(j,:) '(i,2)=' num2str(normscs(tr(2)*fs)) '; '])
eval(['if ent_' chan(j,:) '(i,1)>' num2str(tr(3)) ' || ent_' chan(j,:) '(i,2)<' num2str(tr(4)) '; '...
' 'csfail_' chan(j,:) '=[csfail_' chan(j,:) '; i]; '...
' 'else; '...
' 'cspass_' chan(j,:) '=[cspass_' chan(j,:) '; i]; '...
' 'end'])

% 90% indices and energy calculations
s90ind=find(normscs>5 & normscs<95)+(win*fs);
n90ind=min(s90ind) -2*fs:length(s90ind);
if numel(s90ind)==0 || min(n90ind)<=0
    s90amps=NaN; n90amps=NaN;
    weird(i,j)=1;
else
    swstart(i,j)=s90ind(1)/fs;         % 90% start time
    swstop(i,j)=s90ind(end)/fs;        % 90% stop time
    swl(i,j)=length(s90ind)/fs;        % 90% window length
    s90amps=dc(s90ind(1):s90ind(end)); % signal amps for 90% window
    n90amps=dc(n90ind(1):n90ind(end)); % noise amps for 90% window
end

srms(i,j)=20*log10(std(s90amps));
sefd(i,j)=srms(i,j)+10*log10(length(s90amps)/fs);
sz2p(i,j)=20*log10(max(abs(s90amps)));
sp2p(i,j)=20*log10(max(s90amps)+abs(min(s90amps)));

nrms(i,j)=20*log10(std(n90amps));
nefd(i,j)=nrms(i,j)+10*log10(length(n90amps)/fs);
nz2p(i,j)=20*log10(max(abs(n90amps)));
np2p(i,j)=20*log10(max(n90amps)+abs(min(n90amps)));

% 71
\[
\text{snrm}(i,j) = 20 \times \log_{10}\left(\frac{\text{std}(s90\text{amps})}{\text{std}(n90\text{amps})}\right); \quad \% \text{signal to noise ratio}
\]

end % for shot loop

% Assign data to AUH specific matrices for analysis
eval(['nscsmat_ chan(j,:) = nscsmat;']);

%% PLOTTING
if plotid==1
eval(['normscs = nscsmat_ chan(j,:) (i,:); '])
eval(['nscsmat = nscsmat_ chan(j,:); '])
tax = linspace(0,win,length(normscs));
figure; plot(time,nscsmat,'b'); hold on;
ylabel('Cumulative Energy (%)','fontsize',12); grid on; hold on;
title('Cumulative Energy as a Function of Time');
ylim([-5 105]); xlim([0 30]);
eval(['for y=1:length(cspass_ chan(j,:));
   plot(time,nscsmat(cspass_ chan(j,:)),''r'');
end '])
eval(['mnscs = geomean(nscsmat(cspass_ chan(j,:)));']) % geomean to suppress outliers
plot(time,mnscs,'g','LineWidth',2); grid on;
eval(['print -djpeg /Users/cmscheip/Desktop/chan(j,).jpg'])
close

% histograms
% subplot(1,2,1); eval(['hist(ent_ chan(j,:)'(cspass_ chan(j,:)'1),100)];
% grid on; title('Energy at 14 seconds');
% subplot(1,2,2); eval(['hist(ent_ chan(j,:)'(cspass_ chan(j,:)'2),100)];
% grid on; title('Energy at 20 seconds');
end % for plot and save loop

eval(['disp(''%%%%%% Finished Channel ' num2str(j) ''*))

%% CS FILTER ASSIGNMENTS
eval(['chan(j,:) _G_CS = cspass_ chan(j,:);']) % assign to AUH specific matrix
eval(['chan(j,:) _B_CS = csfail_ chan(j,:);']) % assign to AUH specific matrix
end % for channel loop

%% SNR FILTER
mnsnr = dbave(snrm,1); stdsnr = nanstd(snrm);
minsnr = mnsnr - stdsnr;
for j=1:6
gind = find(snrm(:,j)>=minsnr(j));
eval(['chan(j,:) _G_SN = gind;'])
bind = find(snrm(:,j)<minsnr(j));
eval(['chan(j,:) _B_SN = bind;'])

clear gind bind
end

%% ASSIGN AND SAVE REJECTED SHOTS
rejectedM3S=(unique([M3S_B_CS; M3S_B_SN]));
rejectedM3E=(unique([M3E_B_CS; M3E_B_SN]));
rejectedM3N=(unique([M3N_B_CS; M3N_B_SN]));
rejectedM3W=(unique([M3W_B_CS; M3W_B_SN]));
rejectedM03=(unique([M3S_B_CS; M3E_B_CS; M3N_B_CS; M3W_B_CS; ...
M3S_B_SN; M3E_B_SN; M3N_B_SN; M3W_B_SN]));
rejectedM04=(unique([M04_B_CS; M04_B_SN]));
rejectedM05=(unique([M05_B_CS; M05_B_SN]));

save /Volumes/G3/d_cmscheip/research_lau/d_airgun/rejected90.mat rejectedM*

%% ASSIGN AND SAVE PASSED SHOTS
passedM3S=(intersect(M3S_G_CS, M3S_G_SN));
passedM3E=(intersect(M3E_G_CS, M3E_G_SN));
passedM3N=(intersect(M3N_G_CS, M3N_G_SN));
passedM3W=(intersect(M3W_G_CS, M3W_G_SN));
passedM03=(mintersect(M3S_G_CS, M3E_G_CS, M3N_G_CS, M3W_G_CS, ...
M3S_G_SN, M3E_G_SN, M3N_G_SN, M3W_G_SN));
passedM04=(intersect(M04_G_CS, M04_G_SN));
passedM05=(intersect(M05_G_CS, M05_G_SN));

save /Volumes/G3/d_cmscheip/research_lau/d_airgun/passed90.mat passedM*

%% NOISE FLOORS
load rng;
nrms_cl=nrms; nefd_cl=nefd; nz2p_cl=nz2p; np2p_cl=np2p;

% passed shots
for j=1:6
eval(['bi=unique([ chan(j,:) _B_CS; chan(j,:) _B_SN]);']);
nrms_cl(bi,j)=NaN;
nefd_cl(bi,j)=NaN;
nz2p_cl(bi,j)=NaN;
np2p_cl(bi,j)=NaN;
end

% quad average
qav_rng=[mean(rng(:,1:4))' rng(:,5:6)];
nrms_cla=[dbave(nrms_cl(:,1:4),0)' nrms_cl(:,5:6)];
nefd_cla=[dbave(nefd_cl(:,1:4),0)' nefd_cl(:,5:6)];
nz2p_cla=[dbave(nz2p_cl(:,1:4),0)' nz2p_cl(:,5:6)];
np2p_cla=[dbave(np2p_cl(:,1:4),0)' np2p_cl(:,5:6)];

save /Volumes/G3/d_cmscheip/research_lau/d_airgun/d_noise/noisemats_90.mat...
nrms_cl nefd_cl nz2p_cl np2p_cl nrms_cla nefd_cla nz2p_cla np2p_cla qav_rng

%% Clean and Average
% For de-bugging this section
load goodbad_07262011.mat; load rlmats_v7.mat
% rngkm=rng/1000; load noisemats_v7.mat;
% chan=['M3S';'M3E';'M3N';'M3W';'M04';'M05'];

load rng;
rms_cl=srms; efd_cl=sefd; z2p_cl=sz2p; p2p_cl=sp2p; snr_cl=snrm; swl_cl=swl;

% passed shots
for j=1:6
    eval(["bi=unique([ chan(j,:) '_B_CS; ' chan(j,:) '_B_SN']);"]));
rms_cl(bi,j)=NaN;
efd_cl(bi,j)=NaN;
z2p_cl(bi,j)=NaN;
p2p_cl(bi,j)=NaN;
snr_cl(bi,j)=NaN;
swl_cl(bi,j)=NaN;
end

% quad average
qav_rng=[mean(rng(:,1:4),2) rng(:,5:6)];
rms_cla=[dbave(rms_cl(:,1:4)',0)' rms_cl(:,5:6)];
efd_cla=[dbave(efd_cl(:,1:4)',0)' efd_cl(:,5:6)];
z2p_cla=[dbave(z2p_cl(:,1:4)',0)' z2p_cl(:,5:6)];
p2p_cla=[dbave(p2p_cl(:,1:4)',0)' p2p_cl(:,5:6)];
snr_cla=[dbave(snr_cl(:,1:4)',0)' snr_cl(:,5:6)];
swl_cla=[dbave(swl_cl(:,1:4)',0)' swl_cl(:,5:6)];

save /Volumes/G3/d_cmscheip/research_lau/d_airgun/d_rlmats/cleaned_90RLs.mat...
    rms_cl efd_cl z2p_cl p2p_cl rms_cla efd_cla z2p_cla p2p_cla...
    qav_rng snr_cl snr_cla swl_cl swl_cla

%%% Finish strong
% tstop=toc;
save
/Volumes/G3/d_cmscheip/research_lau/d_docs/d_important_workspaces/09282011/goodbad_09092011.mat
M*_B_* M*_G_*
save
/Volumes/G3/d_cmscheip/research_lau/d_docs/d_important_workspaces/09282011/WS_09092011_success90.mat
save /Volumes/G3/d_cmscheip/research_lau/d_airgun/d_rlmats/rlmats_90.mat srms sefd sz2p sp2p nrms nefd
nz2p np2p snrm swl
save /Volumes/G3/d_cmscheip/research_lau/d_airgun/swl90.mat swl swl_cl swl_cla swstart swstop
load handel; sound(y,Fs);
tlco.m

% Get linear best fit TL coefficients for 90 and 97% methods, all
% integration techniques

% 90%
load cleaned_90RLs.mat
ok=find(isnan(rms_cla)==0);

[TL90_RMS,~]=polyfit(log10(qav_rng(ok)),rms_cla(ok),1)
[TL90_EFD,~]=polyfit(log10(qav_rng(ok)),efd_cla(ok),1)
[TL90_Z2P,~]=polyfit(log10(qav_rng(ok)),z2p_cla(ok),1);
[TL90_P2P,~]=polyfit(log10(qav_rng(ok)),p2p_cla(ok),1);

% 97%
load cleaned_97RLs.mat
ok=find(isnan(rms_cla)==0);

[TL97_RMS,~]=polyfit(log10(qav_rng(ok)),rms_cla(ok),1)
[TL97_EFD,~]=polyfit(log10(qav_rng(ok)),efd_cla(ok),1)
[TL97_Z2P,~]=polyfit(log10(qav_rng(ok)),z2p_cla(ok),1);
[TL97_P2P,~]=polyfit(log10(qav_rng(ok)),p2p_cla(ok),1);

save /Volumes/G3/d.cmscheip/research_lau/d_airgun/tlco.mat TL9*
% Does azimuth of shot have any play in RL?
% Author: Corey M. Scheip
% This m-file calculates azimuth characteristics of propagating seismic
% shots and creates fore/aft/port/starboard plots.

tic; shots=1:9398; load('Langseth_shots.dat');
AUHc=load('Langseth_AUH_coords.txt'); load rng; load cleaned_90RLs.mat

% Quad Aves
rng=[mean(rng(:,1:4),2) rng(:,5:6)];
efd_cl=[dbave(efd_cl(:,1:4)',1)' efd_cl(:,5:6)];
AUHc=[mean(AUHc(1:4,1)) mean(AUHc(1:4,2))];
AUHc(5:6,:);

% Create ship heading, azimuth, difference matrices
% Creates azimuth of ship heading (relative to N) matrix
for i=1:length(shots)
    lat1=Langseth_shots(shots(i),7); lon1=Langseth_shots(shots(i),8);
    lat2=Langseth_shots(shots(i)+1,7); lon2=Langseth_shots(shots(i)+1,8);
    azshipmat(:,i)=azimuth(lat1,lon1,lat2,lon2);
end

% Creates azimuth of shot relative to AUH matrix
for j=1:length(AUHc)
    for k=1:length(shots)
        lat1=Langseth_shots(shots(k),7); lon1=Langseth_shots(shots(k),8);
        lat2=AUHc(j,1); lon2=AUHc(j,2);
        azAUHmat(j,k)=azimuth(lat1,lon1,lat2,lon2);
    end
end

% azAUH-azShip yields azimuth from ship heading to AUH location
for l=1:length(shots)
    for m=1:length(AUHc)
        az=azAUHmat(m,l)-azshipmat(:,l);
        azmat(l,m)=az;
    end
end

% azshipmat=azshipmat';
azmat(find(azmat<0))=azmat(find(azmat<0))+360;

% Bin NS and EW (Fore/Aft/Starboard/Port)
bN=find(azmat(:)>315 | azmat(:)<45);
bS=find(azmat(:)>135 & azmat(:)<225);
bNS=[bN; bS];
bE=find(azmat(:)>45 & azmat(:)<135);
bW=find(azmat(:)>225 & azmat(:)<315);
bEW=[bE; bW];

R=[25:450]*1000; % Range in m

% Plots
% Plot 1: NS vs EW bin
figure; semilogx(rng(bNS),efd_cl(bNS),'b.'); grid on; title('NS Bins'); ylim([100 150])
figure; semilogx(rng(bEW),efd_cl(bEW),'b.'); grid on; title('EW Bins'); ylim([100 150])
figure; semilogx(rng(bNS),efd_cl(bNS),'b.', rng(bEW),efd_cl(bEW),'b.');
grid on; title('All'); ylim([100 150])

% Plot 2: Plot all 4 cardinal directions against each other
figure;
efd_clN=efd_cl(bN); rngN=rng(bN);
subplot(3,3,2); semilogx(rngN,efd_clN,'b.'); hold on; grid on;
ok=find(isnan(efd_clN)==0);
[pN,~]=polyfit(log10(rngN(ok)),efd_clN(ok),1);
bestfit=pN(1)*log10(R)+pN(2);
semilogx(R,bestfit,'r','linewidth',2); title('N Bin'); ylim([100 160])
set(gca,'xticklabel','[10 100 1000]','fontsize',11);
efd_clW=efd_cl(bW); rngW=rng(bW);
subplot(3,3,4); semilogx(rngW,efd_clW,'b.'); hold on; grid on;
ok=find(isnan(efd_clW)==0);
[pW,~]=polyfit(log10(rngW(ok)),efd_clW(ok),1);
bestfit=pW(1)*log10(R)+pW(2);
semilogx(R,bestfit,'r','linewidth',2); title('W Bin'); ylim([100 160])
efd_clE=efd_cl(bE); rngE=rng(bE);
subplot(3,3,6); semilogx(rngE,efd_clE(bE),'b.'); hold on; grid on;
ok=find(isnan(efd_clE)==0);
[pE,~]=polyfit(log10(rngE(ok)),efd_clE(ok),1);
bestfit=pE(1)*log10(R)+pE(2);
semilogx(R,bestfit,'r','linewidth',2); title('E Bin'); ylim([100 160])
efd_clS=efd_cl(bS); rngS=rng(bS);
subplot(3,3,8); semilogx(rngS,efd_cl(bS),'b.); hold on; grid on;
ok=find(isnan(efd_clS)==0);
[pS,~]=polyfit(log10(rngS(ok)),efd_clS(ok),1);
bestfit=pS(1)*log10(R)+pS(2);
semilogx(R,bestfit,'r','linewidth',2); title('S Bin'); ylim([100 160])

% Plot 3: Histogram to compare bin populations
figure; hist(azmat(:),360); grid on;

save /Volumes/G3/d_cmscheip/research_lau/d_airgun/azmat90.mat
tstop=toc;
natural.m

% Calculate sound levels of natural events for comparison to seismic survey

%% Event 1: Hunga Eruption
% Date: 2009/3/16/15/26/0 UTC
% Location: -20.57, -175.38
% Closest AUH: M3E

% Assign constants
load swl90.mat
hungc=[-20.57, -175.38]; % lat/lon of volcano
AUHc=load('Langseth_AUH_coords.txt'); AUHc=AUHc(2,:);

ept=(datenum(2009,3,16,15,0,0)-datenum(1970,1,1,0,0,0))*60*60*24; % start ept
auh='M3E'; load gainm.txt; gain=gainm(2); fs=250; filt=2; load tlco.mat;

dur=round(nanmean(swl_cl(:,2))); % duration of each integration window
rngm=deg2km(distance(hungc,AUHc));
TL=TL90_EFD(1)*log10(rngm*1000);
tims=[43200 86400 86400*2 86400*3]; % 12hrs, 1 day, 2 days, 3 days

for j=1:length(tims)
    tim=round(tims(j)/dur)*dur; % integrate for following 'tim' seconds
    its=round(tim/dur); % 1 iteration every 'dur' for 'tim' seconds

    % Extract amplitudes, calculate sound levels
    for i=1:its+1
        [~,yf]=return_rsp(auh,ept-(dur/2)+(dur*(i-1)),dur);
        [d]=AUHcorsignal_rev4(yf,fs,filt,gain);
        hrms(i,j)=20*log10(std(d));
        hefd(i,j)=hrms(i,j)+10*log10(dur);
        hz2p(i,j)=20*log10(max(abs(d)));
    end

    % Calculate Energy (joules) for each window
    % Assign constants for energy calculation
    z=1025*1500; % acoustic impedance
    A=2*pi; % geometric constant (m^2*s^2)

    % Energy Calculation
    RL=hefd(i,j);
    SL=RL+abs(TL);
    p=10.^(SL/20)/(1e6); % pressure in Pa·s
    I=(p.^2)/z; % acoustic intensity
    P=A*I; % acoustic power
    HEN(i,j)=P; % assign to matrix
end
% Average sound levels +/- 1 std
hrms(hrms(:)==0)=NaN; hefd(hefd(:)==0)=NaN; hz2p(hz2p(:)==0)=NaN;
hrms_val=[dbave(hrms,1); nanstd(hrms)]
hefd_val=[dbave(hefd,1); nanstd(hefd)]
hz2p_val=[dbave(hz2p,1); nanstd(hz2p)]
Hunga_EN=sum(HEN);

save /Volumes/G3/d_cmscheip/research_lau/d_airgun/d_rlmats/HungaVAR2.mat...

hrms hefd hz2p hrms_val hefd_val hz2p_val ept tims dur rngm Hunga_EN HEN

%% Event 2: Samoa M8.1
% Date: 2009/9/29/1748/10 UTC
% Location: -15.509, -172.034
% Closest AUH: M5

clear;

% Assign constants
load swl90.mat
samc=[-15.509,-172.034]; % lat/lon of epicenter
AUHc=load('Langseth_AUH_coords.txt');  AUHc=AUHc(6,:);
ept=(datenum(2009,9,29,17,49,0)- datenum(1970,1,1,0,0,0))*60*60*24;
auh='M05'; load gainm.txt; gain=gainm(6); fs=250; filt=2; load tlco.mat
dur=round(nanmean(swl_cl(:,6)));  % duration of each integration window
rngm=deg2km(distance(samc,AUHc));  % % of each integration window
TL=TL90_EFD(1)*log10(rngm*1000);
tims=[3600 3600*3 3600*12 3600*24];  % 1 hr, 3hrs, 12hrs, 24hrs

for j=1:length(tims)

tim=round(tims(j)/dur)*dur;  % integrate for following 'tim' seconds
its=round(tim/dur);  % 1 iteration every 'dur' for 'tim' seconds

% Extract amplitudes, calculate sound levels
for i=1:its+1
    [~,yf]=return_rsp(auh,ept-(dur/2)+(dur*(i-1)),dur);
    [d]=AUHcorsignal_rev4(yf,fs,filt,gain);
    srms(i,j)=20*log10(std(d));
    sefd(i,j)=srms(i,j)+10*log10(dur);
    sz2p(i,j)=20*log10(max(abs(d)));

% Calculate Energy (joules) for each window
% Assign constants for energy calculation
z=1025*1500;  % acoustic impedance
A=2*pi;  % geometric constant (m^2s^2)
% Energy Calculation
RL = sefd(i,j);
SL = RL + abs(TL);
p = 10.^(SL/20)/(1e6); % pressure in Pa·s
I = (p.^2)/z; % acoustic intensity
P = A*I; % acoustic power
SEN(i,j) = P; % assign to matrix
end
end

% Average sound levels +/- 1 std
srms(srms(:)==0)=NaN; sefd(sefd(:)==0)=NaN; sz2p(sz2p(:)==0)=NaN;
srms_val = [dbave(srms,1)'
            nanstd(srms)'];
sefd_val = [dbave(sefd,1)'
            nanstd(sefd)'];
sz2p_val = [dbave(sz2p,1)'
            nanstd(sz2p)'];
Samoa_EN = sum(SEN);
save /Volumes/G3/d_cmscheip/research_lau/d_airgun/d_rlmats/SamoaVAR2.mat...
  srms sefd sz2p srms_val sefd_val sz2p_val ept tims dur rngm Samoa_EN SEN
energy.m

% Author: Corey Scheip
%
% This m-file is to calculate total energy from this seismic survey in
% joules that was introduced to the Lau Basin. Comparative calculations are
% the energy levels of Oil Tankers, Sonar, Hunga Ha'Apai and Samoa M8.1.
%
% E=pi*P^2*dur/z*num_events
%
% Use all shots, must assume that all left the guns appropriately.

%% Seismic Airguns
% Assign back-calculated source level +/- 1 std
slc=[242.3 0.3];  % EFD Use 237.77 for Hildebrand's numbers
SL=[slc(1)-slc(2) slc(1) slc(1)+slc(2)];
noevents=9399;  % number of shots

% Assign constants for energy calculation
rho=1025;   % kg/m3
C=1500;     % m/s
z=rho*C;    % acoustic impedance
A=pi;       % geometric constant (m^2·s^2)

% Energy Calculation
p=10.^(SL/20)/(1e6);   % pressure in Pa·s
I=(p.^2)/z;            % acoustic intensity
P=A*I;                 % acoustic power

% Energy for all events
Esum=P*noevents;

% Calculate and assign confidence limits (conf limits in percent)
Eair=[Esum(2)... ((Esum(3)-Esum(2) + Esum(2)-Esum(1))/2)/Esum(2)*100]

%% Oil Tanker
% Assign constants for energy calculation
dur=3600;   % 1hr, to later calculate how many hours to equal airguns
A=2*pi;     % geometric constant (m^2·s^2)

% Assign back-calculated source level
SL=198+10*log10(dur);  % EFD for 1hr

% Energy Calculation
p=10.^(SL/20)/(1e6);   % pressure in Pa·s
I=(p.^2)/z;            % acoustic intensity
P=A*I;                 % acoustic power for 1hr of exposure
% Number of hours to equal airgun exposure
nohrsTANKER=Eair(1)/P  % number of hrs for tanker = airguns

% Alternate method to check math
% TEFD=20*log10(sqrt(Eair(1)/2/pi*z*(1e6)*(1e6)));
% TRMS=198;
% nohrsTANKER=10*((TEFD-TRMS)/10)/60/60;

 %% Military Sonar (SURTASS LFA)
% Assign constants for energy calculation
A=pi;  % geometric constant (m^2*s^2)

% Assign back-calculated source level
SL=235+10*log10(50);  % EFD  % hildebrand uses 50s for energy calcs

% Energy Calculation
p=10.^(SL/20)/(1e6);  % pressure in Pa*s
I=(p.^2)/z;  % acoustic intensity
P=A*I;  % acoustic power per ping

% Number of hours to equal airgun exposure
nodaysSONAR=Eair(1)/P*494/60/60/24  % # of days  (1 ping/494s)

%% Hunga Ha'Apai
% Assign constants for energy calculation
A=2*pi;  % geometric constant (m^2*s^2)

% Assign back-calculated source level
load HungaVAR.mat; load tlco.mat; clear TL97*
SL=abs(TL90_RMS(1))*log10(rngm*1000)+hrms_val(7)+10*log10(72*3600);  % EFD SL

% Energy Calculation
p=10.^(SL/20)/(1e6);  % pressure in Pa*s
I=(p.^2)/z;  % acoustic intensity
Ehunga=A*I  % acoustic power for "dur" of exposure

%% Samoa 8.1
% Assign constants for energy calculation
A=pi;  % geometric constant (m^2*s^2)

% Assign back-calculated source level
load SamoaVAR.mat;
SL=abs(TL90_EFD(1))*log10(mgm*1000)+sefd_val(4)+10*log10(72*3600);  % EFD SL

% Energy Calculation
p=10.^(SL/20)/(1e6);  % pressure in Pa*s
I=(p.^2)/z;  % acoustic intensity
Esamoa=A*I  % acoustic power for "dur" of exposure
function [bb,sb,da] = bouncecount(rayfil,envfil,r,tbath,auhdep,misstol)

% Plot the RAYfil produced by Bellhop
% usage: plotray( rayfil )
% where rayfil is the ray file (extension is optional)
% e.g. plotray( 'foofoo' )
% 
% MBP July 1999
% 
% MODIFIED BY CMS SEPT 2011
% rayfil='working.ray'; envfil='working.env'; misstol=200;

if isempty(misstol)
    misstol=max(tbath);
end

if strcmp( rayfil, 'RAYFIL' ) == 0 && isempty( findstr( rayfil, '.ray' ) )
    rayfil = [ rayfil '.ray' ]; % append extension
end

% plots a BELLHOP ray file

fid = fopen( rayfil, 'r' );   % open the file
if ( fid == -1 )
    disp( rayfil );
    errordlg( 'No ray file exists; you must run BELLHOP first (with ray output selected)', 'Error' );
end

% read header stuff

TITLE  = fgetl(  fid );
FREQ   = fscanf( fid, '%f', 1 );
NBEAMS = fscanf( fid, '%i', 1 );
DEPTHT = fscanf( fid, '%f', 1 );
DEPTHB = fscanf( fid, '%f', 1 );

% Extract letters between the quotes
nchars = strfind( TITLE, '''' );   % find quotes
TITLE = [ TITLE( nchars( 1 ) + 1 : nchars( 2 ) - 1 ) blanks( 7 - ( nchars( 2 ) - nchars( 1 ) ) ) ];
TITLE = deblank( TITLE );  % remove white space

% read rays
for ibeam = 1:NBEAMS
    alpha0    = fscanf( fid, '%f', 1 );
nsteps    = fscanf( fid, '%i', 1 );
    NumTopBnc = fscanf( fid, '%i', 1 );
NumBotBnc = fscanf( fid, '%i', 1 );
if isempty( nsteps ); break; end

% assign matrices
ray = fscanf( fid, '%f', [2 nsteps] );
r = ray( 1, : );
z = ray( 2, : );

if z(end)<auhdep+misstol && z(end)>auhdep-misstol
    bb(ibeam)=NumBotBnc;
sb(ibeam)=NumTopBnc;
da(ibeam)=alpha0;
else
    bb(ibeam)=NaN;
sb(ibeam)=NaN;
da(ibeam)=alpha0;
end

eend % next beam

fclose(fid);
bhray_runall.m

% Author: Corey Scheip
% Execute bellhop for all passed arrivals, save bounce counts
% (surface and bottom) and departure angles for all rays.
%
% dir=pwd; odir=cd(pwd);
if strcmp(dir,'/d_pkgs/d_models/d_bellhop')==0
   cd /d_pkgs/d_models/d_bellhop
end

% Shots/Receivers
load cleaned_90RLs.mat
[okr,okc]=find(isnan(rms_cla)==0);
okrM3=okr(okc==1);
okrM4=okr(okc==2);
okrM5=okr(okc==3);
clearvars -except okr*
pind=zeros(9399,3);
pind(okrM3,1)=1;
pind(okrM4,2)=1;
pind(okrM5,3)=1;
shots=[1:9399]; shots=[shots shots shots];

shots(~pind)=NaN;
auh=4:6;

% Count bounces?
ctbnc=1;  % 0=No /// 1=Yes

% Plot rays?
plotid=0; % 0=No /// 1=Yes

% Assign constants
freq=50; model_type='R'; loadgrid;
hspsc_ssp=2000; hspsc_roh=2.2; hspsc_attn=0.4;
tracksp=0.25; auhdep=load('auhdepths.txt'); sdpt=9;
auhco=load('Langseth_AUH_coords.txt'); shotco=load('Langseth_shots.dat');
load swl90.mat;

for t=1:length(auh)
   auhid=auh(t);
for s=1:length(shots)
   shot=shots(s,auhid-3);
if isnan(shot)==0

% load data matrices, assign constants
sclat=shotco(shot,7); sclon=shotco(shot,8);
rclat=auhco(auhid,1); rclon=auhco(auhid,2);

% shotco = shot lat/lon
% sclat = source latitude
% sclon = source longitude
% auhco = hydrophones lat/lon
% rclat = receiver longitude
% rclon = receiver longitude
% freq = frequency for model to run at (hz, try around 50)
% auhdep = hydrophone depths
% sdpt = source depth
% hsfc_roh = density of halfspace in g/cc (i.e. seafloor)

% calculate track
npts=ceil(deg2km(distance(sclat,sclon,rclat,rclon))/tracksp); % number of points to run along track
[tlat,tlon]=track2(sclat,sclon,rclat,rclon,[],'degrees',npts);
r=deg2km(distance(sclat,sclon,tlat,tlon)); % range, shot-each pt along trk
rng=deg2km(distance(sclat,sclon,rclat,rclon))*1000; % range, shot-auh (m)
rngkm=rng/1000;

% calculate depth values (bathymetry) along track
tbath = floor(ltln2val(bathgrd,RB,tlat,tlon)); % interpolate depth along track
tsedth= floor(ltln2val(sedgrd,RS, tlat,tlon)); % interpolate sed thickness along track
tsedth(isnan(tsedth))=quantile(tsedth,.05); % crude interpolation
tbotm= tbath-tsedth; % bedrock depth

% figure; subplot(3,1,2); plot(r,tbath,'k',r,tbotm,'g'); axis xy
% figure; subplot(3,1,2); plot(r,tbath,'k',r,tbotm,'g'); axis xy

% read SSP at midpoint from shot-receiver
mi=ceil(length(tlat)/2); mlat=tlat(mi); mlon=tlon(mi); % midpoint lat/lon

[-~,~,~,ssp_spline,stderrpts]=getsspPt_local(mlat,mlon,14,0);

dep=ceil(max(tbath)/500)*500; % dep = max(tbath); % maximum depth for SSP calculation
sspDpts=linspace(0,dep,30); % to smooth SSP
sspDpts=0:100:dep;

sspint=interp1(stderrpts,ssp_spline,sspDpts); % smoothed SSP

%%% write environmental file
if model_type=='R' % all rays saved and plotted
  nrays2sketch=3000; NR=1; NRD=NR; rcdpt=auhdep(auhid); intmeth='SVF'; anglim=[-89 89];
elseif model_type=='E' % only rays that make it are saved and plotted
  nrays2sketch=2000; NR=1; NRD=NR; rcdpt=auhdep(auhid); intmeth='CVF'; anglim=[-21 21];
else
  nrays2sketch=1000; NR=1; NRD=NR; rcdpt=auhdep(auhid); intmeth='CVF'; anglim=[-21 21];
endif

step=0; zbox=dep+500; rbox=rngkm;

% write *.env file
fid = fopen('working.env', 'w');
fprintf(fid, '''working.env file''                     ! Title 
');
fprintf(fid, '%.1f                                     ! Model Frequency (hz) 
', freq);
fprintf(fid, '1                                        ! Number of media (always 1 for Bellhop) 
');
fprintf(fid, '''%s''                                    ! Interpolation method 
', intmeth);
fprintf(fid, '51  0.0  %.1f                          ! 2 Constants, then depth of bottom (m) 
', dep);
for i=1:length(sspDpts)
  fprintf(fid, '%5.1f %6.2f  / 
', sspDpts(i), sspint(i));
end
fprintf(fid, '''A*'' 0.0                                ! Acousto-elastic halfspace, ''A*'' calls for bathymetry below 
');
fprintf(fid, ' %.1f %.2f 0.0 %.1f %.1f /          ! Halfspace parameters (depth ssp 0 density) 
', dep, hfspc_ssp, hfspc_roh, hfspc_attn);
fprintf(fid, '1                                      ! NSD number of source depths
');
fprintf(fid, '%.1f  /                                 ! SD(1:NSD) (m) sdpt 
', sdpt);
fprintf(fid, '%.0f                                  ! NRD number of receiver depths 
', NRD);
fprintf(fid, '%.1f %.1f  /                        ! RD (1:NRD) (m) rcdpt (min max) for a linear interpolation of 
depths\n,rcdpt,rcdpt);
fprintf(fid, '%.0f                              ! NR number of ranges 
', NR);
fprintf(fid, '0.0 %.3f  /                       ! R(1:NR) (km) rcrng 
', rngkm);
fprintf(fid, '''%s''                                    ! ''R/C/I/S/E'' 
', model_type);
fprintf(fid, '%.0f                                      ! Number of beams 
', nrays2sktch);
fprintf(fid, '%.1f %.1f  /                          ! Angle limits for rays \n, anglim(1), anglim(2));
fprintf(fid, '%.1f  %.1f  %.1f                    ! Step (m), Zbox (m), Rbox (km)\n, step, zbox, rbox);fclose(fid);

% write *.bty file
fid = fopen('working.bty','w');
fprintf(fid, '''L''
'); % interpolation method (L = linear, C = Curvilinear)
fprintf(fid, '%.0f
', length(tbath));
for i=1:length(tbath)
  fprintf(fid, '%4.2f %.0f 
', r(i), tbath(i));  % print range and bathymetry
endfclose(fid);

%% run bellhop
bellhop('working')  % create .shd and .prt files

%% plots
if plotid==1
  plotrayspass('working.ray','working.env',r,tbath,auhdep(auhid),200); xlim([1475 1550])
end
%% bounce count and plots
if ctbnc==1
    [bb,sb,da]=bouncecount('working.ray','working.env',r,tbath,auhdep(auhid),200);

    % assign to matrix
    if auhid==4;
        bbm_M3(:,s)=bb'; sbm_M3(:,s)=sb'; dam_M3(:,s)=da';
    elseif auhid==5
        bbm_M4(:,s)=bb'; sbm_M4(:,s)=sb'; dam_M4(:,s)=da';
    else
        bbm_M5(:,s)=bb'; sbm_M5(:,s)=sb'; dam_M5(:,s)=da';
    end
end % Bounce count

elseif isnan(shot)==1
    % assign to matrix
    if auhid==4;
        bbm_M3(:,s)=NaN*ones(3000,1); sbm_M3(:,s)=NaN*ones(3000,1); dam_M3(:,s)=NaN*ones(3000,1);
    elseif auhid==5
        bbm_M4(:,s)=NaN*ones(3000,1); sbm_M4(:,s)=NaN*ones(3000,1); dam_M4(:,s)=NaN*ones(3000,1);
    else
        bbm_M5(:,s)=NaN*ones(3000,1); sbm_M5(:,s)=NaN*ones(3000,1); dam_M5(:,s)=NaN*ones(3000,1);
    end
end % Next shot

eval(['disp(''%%%%%%%%%%%% Finished Channel ' num2str(auhid) ''')'])

end % Next channel

save /Volumes/G3/d cmscheip/research_lau/d airgun/d downslope_prop/bounces3000_v3.mat
cd(odir)