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Evaluation and correction of timing inconsistencies from the Thor 1 and Thor 2 experiments at the Nevada National Security Site

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Evaluation and correction of timing inconsistencies from the Thor 1 and Thor 2 experiments at the Nevada National Security Site

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Abstract

Active source seismic data was collected at the Nevada National Security Site using the Seismic Hammer™ (SH), under contract from HK Exploration. The SH generates a seismic pulse by dropping a 13 metric ton mass from a height of 1.5 m. Post-survey evaluation of collected data revealed inconsistencies in shot trigger time that required additional analysis and correction using cross-correlation and/or time shifts derived from manual picks of trigger times. While the primary analysis for which this data set was collected is independent of the knowledge of shot trigger time, other processing methods require highly precise knowledge of the trigger time. In order to make the Thor data set more usable to the larger community, additional work was undertaken. Results using the preferred method of cross-correlation were found to be satisfactory. An improved timing fiducial approach is required to reduce timing errors.

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NOMENCLATURE

DOE	Department of Energy
NNSS	Nevada National Security Site
SH	Seismic Hammer™
SNL	Sandia National Laboratories
SPE	Source Physics Experiment
PZ	Piezoelectric or Piezoelectric Switch

1. INTRODUCTION

1.1. Seismic Hammer Experiment

Two active source seismic surveys were performed at the Nevada National Security Site using the Seismic Hammer™ (SH, Figure 1). The SH creates a signal by dropping a 13,000 kg weight from a height of 1.5 meters. The purpose of the experiment was to provide better subsurface characterization of the Yucca Flat sedimentary basin, the proposed site for investigations of explosive-source phenomenology in the second phase of the Source Physics Experiment (SPE)¹.

The first survey, called Thor 1, was a north-south transect of the Yucca Flat with a total length of about 23 km and shot points every 200 meters. Each shot was observed by approximately 350 to 380 three-component 2-Hz geophones with variable spacing of 10, 20, and 100 meters. The second survey, Thor 2, was an east-west transect of the Yucca flats with a length of about 11 km and similar sensor spacing. The locations of shot points for both experiments are shown in Figure 2.

Analysis of the data from Thor 1 and Thor 2 revealed some inconsistencies in shot trigger times. Although these uncertainties did not impact the primary analysis performed with the data, additional analysis was performed to understand and correct the timing in order to make the data more broadly useful. The source of trigger time “dither” and methods used to correct them are discussed in the next section.

¹ The Source Physics Experiment (SPE) consists of a series of chemical explosions at the Nevada National Security Site. Between 2011 and 2015, four explosions were detonated in the Granite Climax Stock with a variety of yields and depths of emplacement. A fifth shot is planned in the same location for Spring, 2016. The main goal of the experiment is to improve our understanding of explosion-source phenomenology and ability to characterize explosions occurring at a variety of yields, depths of burial, and in complex media through the use of new physics-based modeling techniques.



Figure 1: Photo of SH hoisted by crane

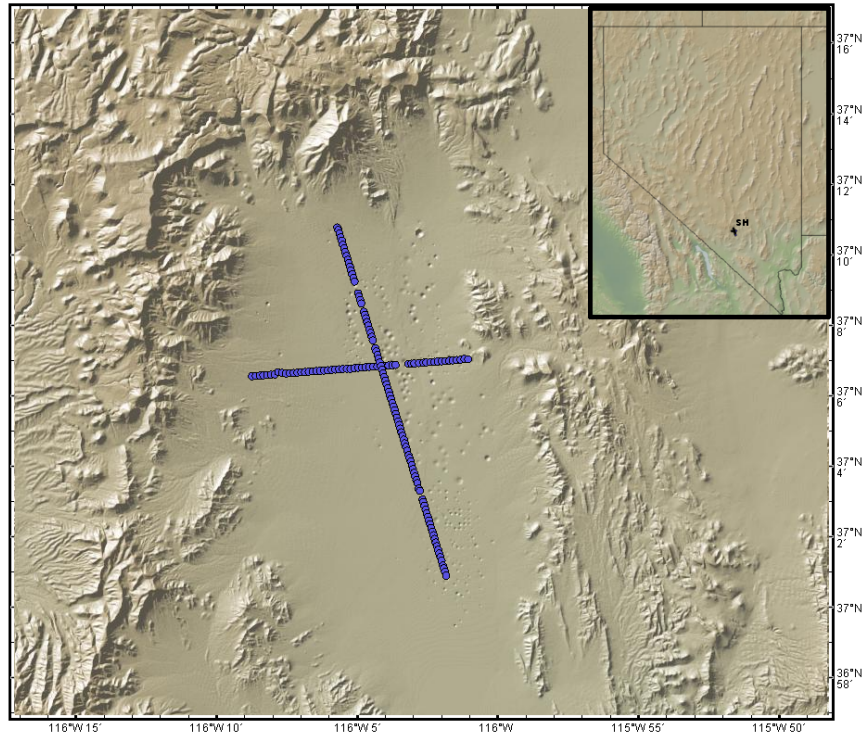


Figure 2: Seismic Hammer Shot Locations for Thor 1 and Thor 2 (blue circles)

1.2. Data Collection Methodology and Challenges

The mass of the SH is designed to hit a strike plate a single time and then be caught to avoid reverberations. The SH can consistently perform up to 3 hits per minute (Jones, 2014). At each shot point, there were about 30 to 45 hits of the SH. The data was recorded and converted to Seg-Y format using iSeis Sigma™ and Sigma™ harvesting software. The signals recorded by the geophones show the signal from the seismic hammer as well as a precursory signal generated by elastic rebound of the ground from the mass unloading (Figure 3). The hit is detected by a piezoelectric (PZ) transducer, which operates as a switch to determine zero time. Receiver gathers (a collection of all hits recorded from a source point on a single receiver) display “dither” in trigger times (Figure 4). Ideally, all traces in the receiver gather would be aligned in time. The uncertainty in trigger times is due to the PZ switch not being sensitive enough to consistently record the very first part of the hit. Estimated trigger time offsets ranged from a few milliseconds up to 25 milliseconds or greater (for example see shift in trace 2 between Figure 9a and Figure 9b/c).

Due to the great amount of energy put into the ground, the SH compacts the *in situ* soil, modifying its response for future hits. Most of this modification occurs during the very first hit or first few hits at a new source location (see traces 1 and 2 on Figure 4b). In addition, during the 30-40 hit cycle at a particular source point, the SH can become tilted off center, which necessitates the SH being picked up and re-leveled before data acquisition can continue. While re-leveling, loose soil is shoveled under the SH so that it tilts back towards vertical. The first hit (or few hits) after re-leveling often show the same compaction phase as the original hit (Figure 4b, Traces 23 and 27). The PZ switch was not ranged correctly to pick up this compaction phase

and triggered sometime during the hit (probably when the compaction was complete for that hit). Our analysis indicates that the compaction phase of the hit does produce waves that propagate to geophones, and that a properly ranged PZ switch would be a great improvement.

Due to the need for very accurate timing for certain geophysical techniques, such as seismic reflection which may require timing to be known to within ~5 ms depending on the frequencies used, two different methods were considered for resolving the dither in the trigger times: a cross-correlation method to automatically determine the needed time shifts, and manually picked trigger times on the traces from an accelerometer mounted on the hammer. The picked accelerometer traces were then used to derive the time shifts applied to the receiver data.

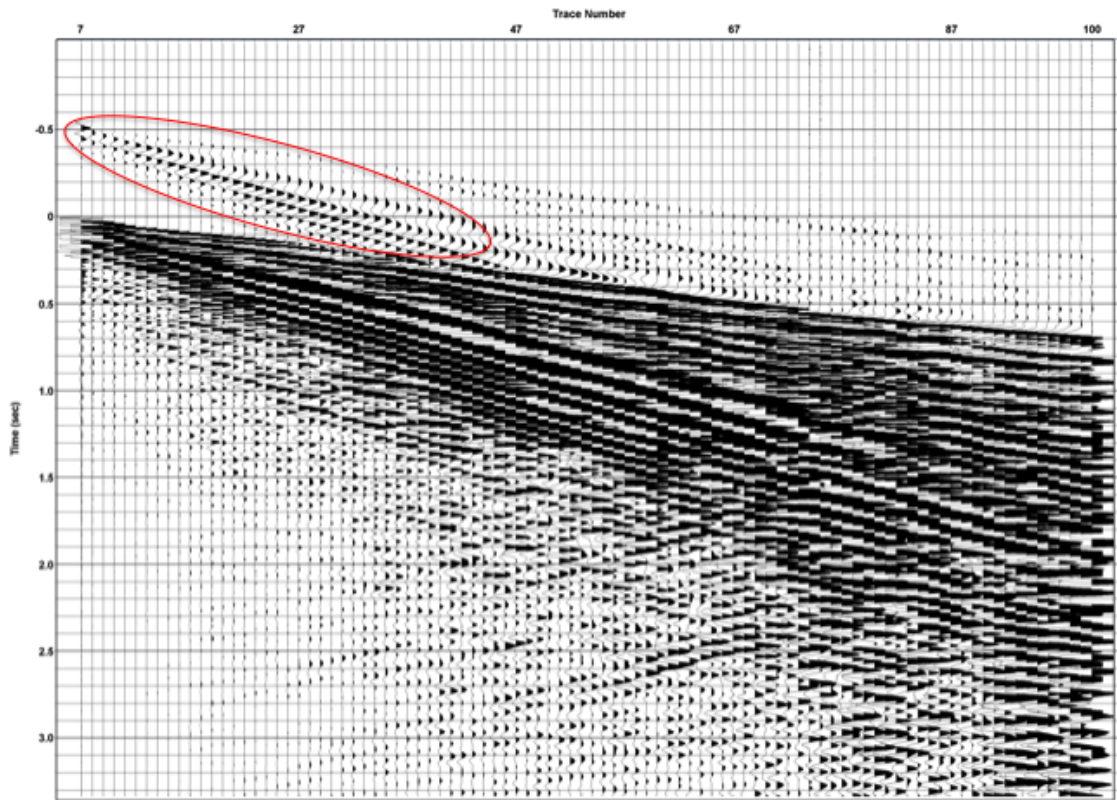


Figure 3: SH signal from Thor 2, Shot 7, with unloading precursor circled in red

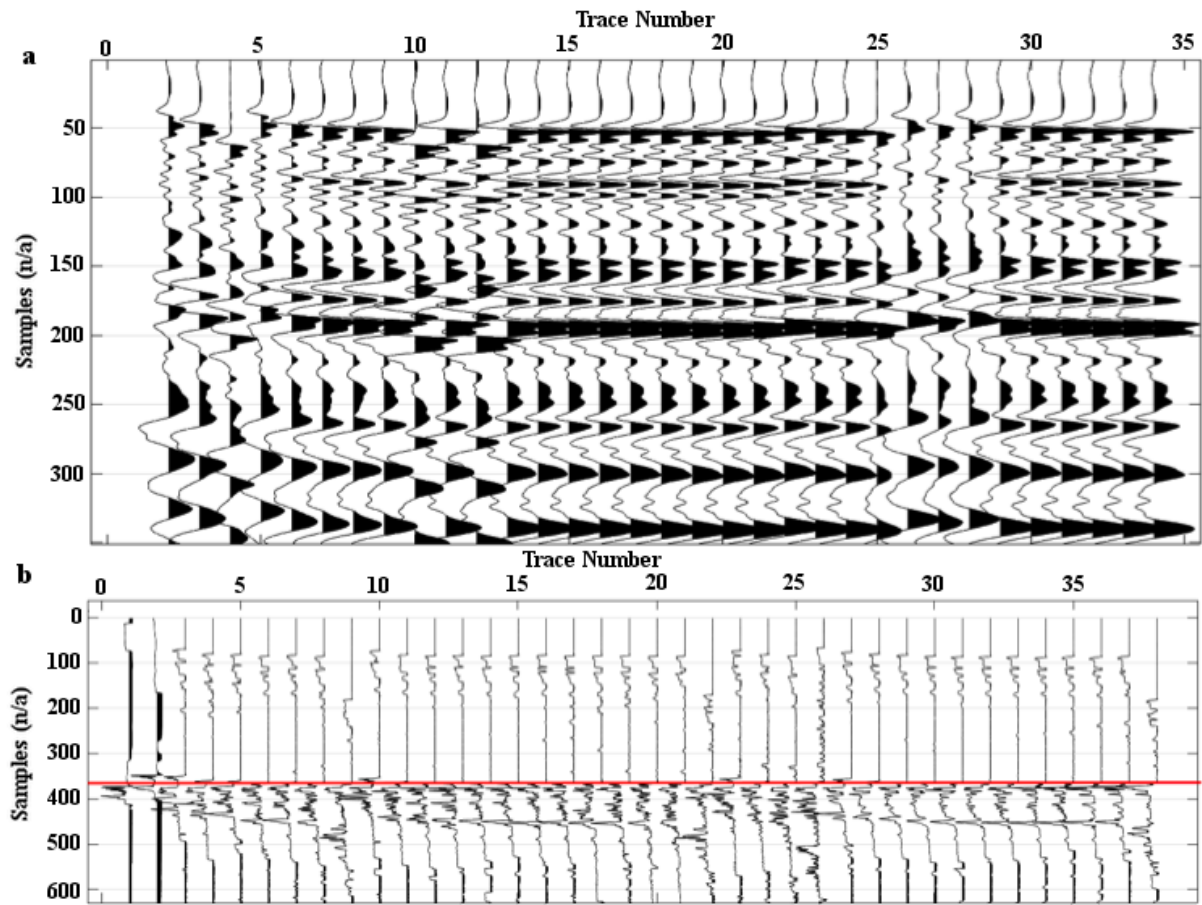


Figure 4: Trigger time issues. a) Receiver 45 of Shot 25 (hits 1-38) for Thor 2. b) Receiver 2 of Shot 25 (accelerometer on the hammer). Note the precursors for traces numbers 10, 23, and 27, which are offset in (a).

2. TIMING CORRECTIONS

2.1 Cross-Correlation

For each shot location, each hammer hit is detected by the array of geophones. When all the geophones for each hit are arranged according to their common trigger time, the major arrivals are expected to line up exactly. One method of correcting the data when the traces do not align in time is to perform a simple cross-correlation over all the hits for each receiver (Figure 5). Time shifts are calculated to maximize the correlation with the hit chosen as the reference trace. Traces with the highest correlation coefficient were used to estimate a relative time shift. If at least 3 traces do not have a correlation coefficient of 0.8 across the gather, a new reference trace is chosen and the current reference trace is removed. In cases where there were too many bad channels, good channels were hand selected. All gathers for every hit and shot point required some degree of timing correction. A comparison of the corrected and uncorrected traces can be seen in Figure 6. Although in most of the cases the time shifts were small, there is an observable shift for trace numbers 1, 2, 3, 13, 19 and 40. The traces in the bottom plot, after the time shift, show a better match between the timing of major arrivals. This method was performed to correct all of the data for Thor 1 and Thor 2 but had a few drawbacks. These drawbacks include the possibility of the code incorrectly using a precursory arrival in the correlation (see Figure 4b). As a check of this method, we also examined the first arrivals on the SH-mounted accelerometer traces and used manual picks to determine the correct trigger times. This is discussed in the next section.

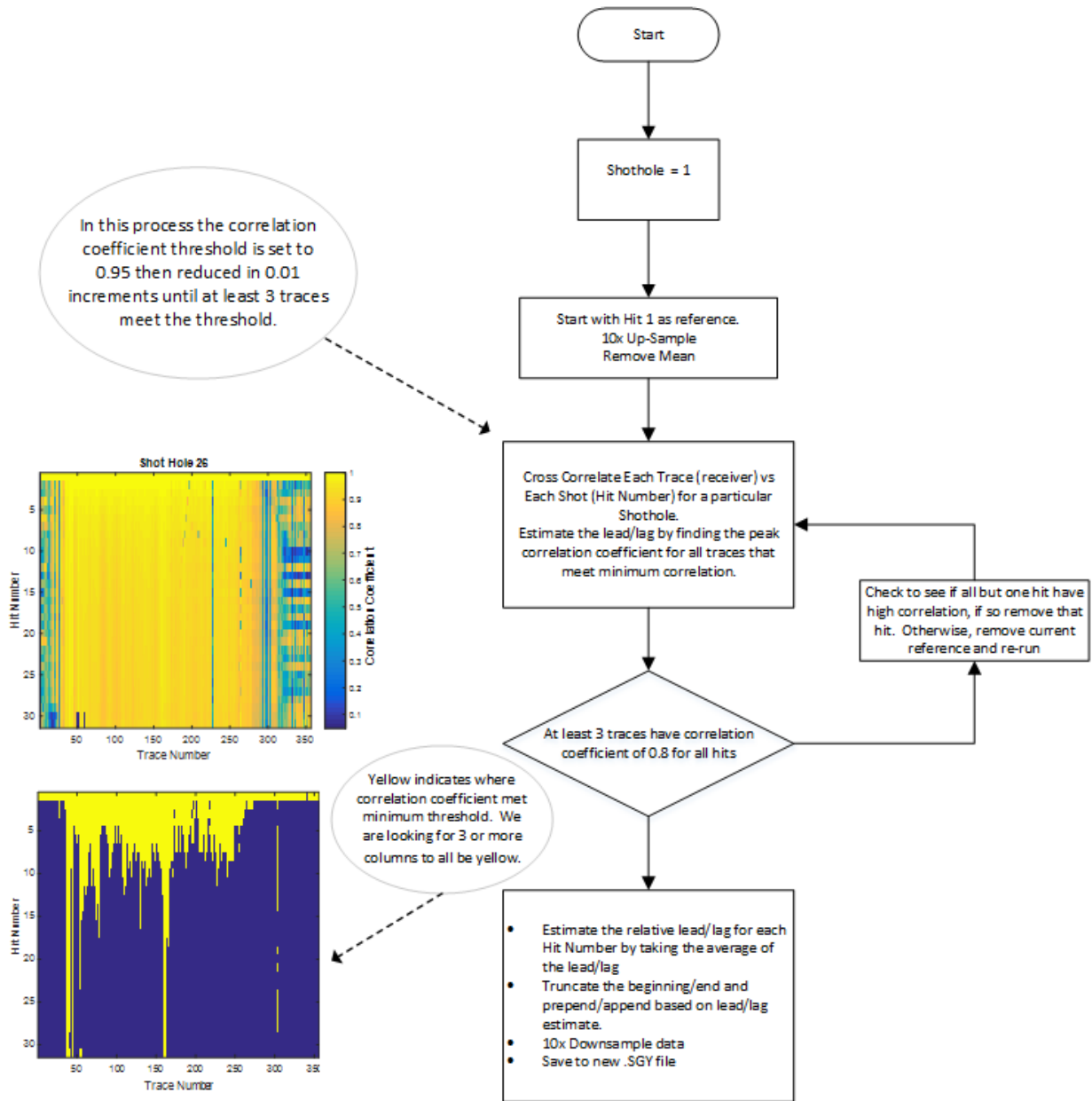


Figure 5: Flow chart of cross-correlation methodology

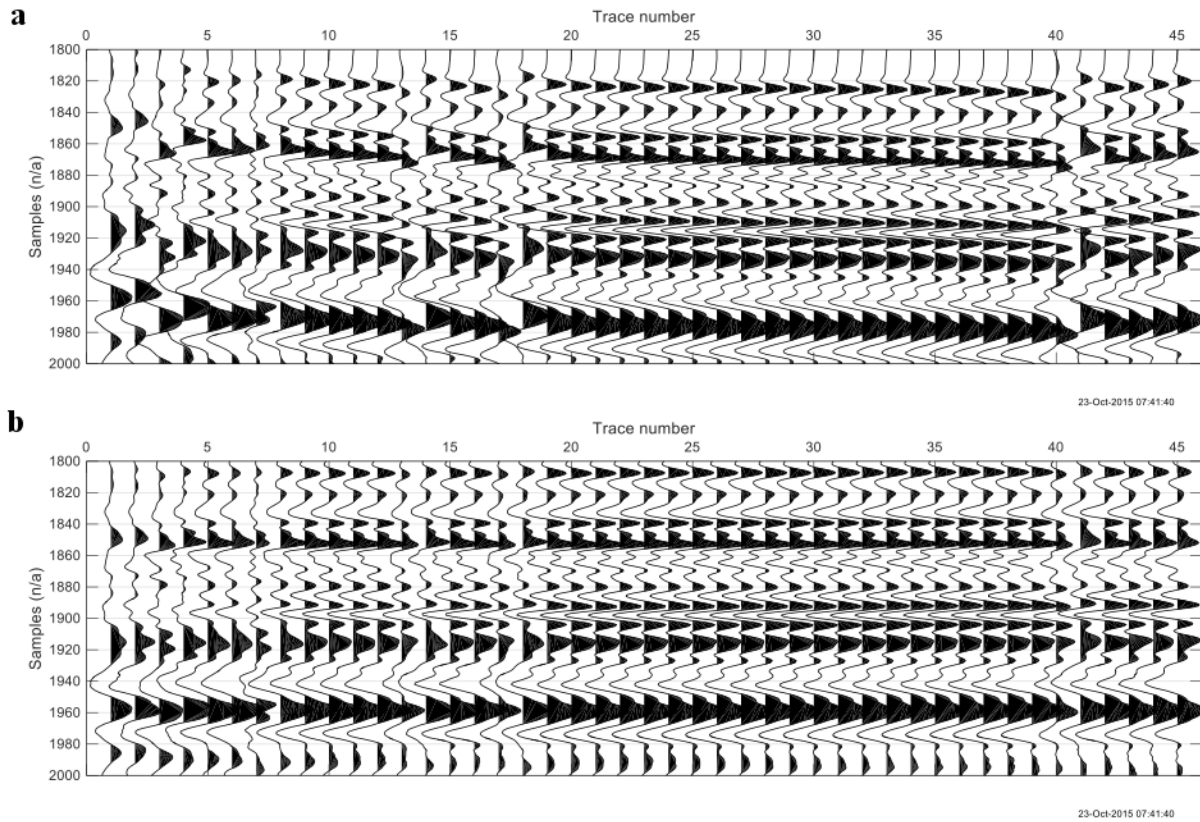


Figure 6: Cross-correlation results for Thor 1, Shot 10, Receiver 39. a) Uncorrected traces. b) Corrected traces

2.2 Manual picking of accelerometer traces

An independent verification of trigger times can be obtained by manual picking of the first arrivals on the traces from an accelerometer mounted on the SH. The accuracy of the picks can be determined through comparison with far-field geophone traces; for example if a large offset is observed in the accelerometer traces, there should be a corresponding offset in the far-field first arrival times. For direct comparison of accelerometer traces and the geophone records, the accelerometer data would need to be integrated from acceleration to velocity. However, in this case such a comparison was not needed and the accelerometer traces were left as accelerations for improved accuracy of first arrival picks. A sample of accelerometer traces can be seen in Figure 7 for Shot 4 of Thor 2. A noticeable offset of trace number 11 can be observed in both the accelerometer traces and far-field geophone record. This is most likely the first hit after a hammer level reset. However, in some cases the accelerometer traces can be more complex and the picks not as clear, as is the case in Figure 8.

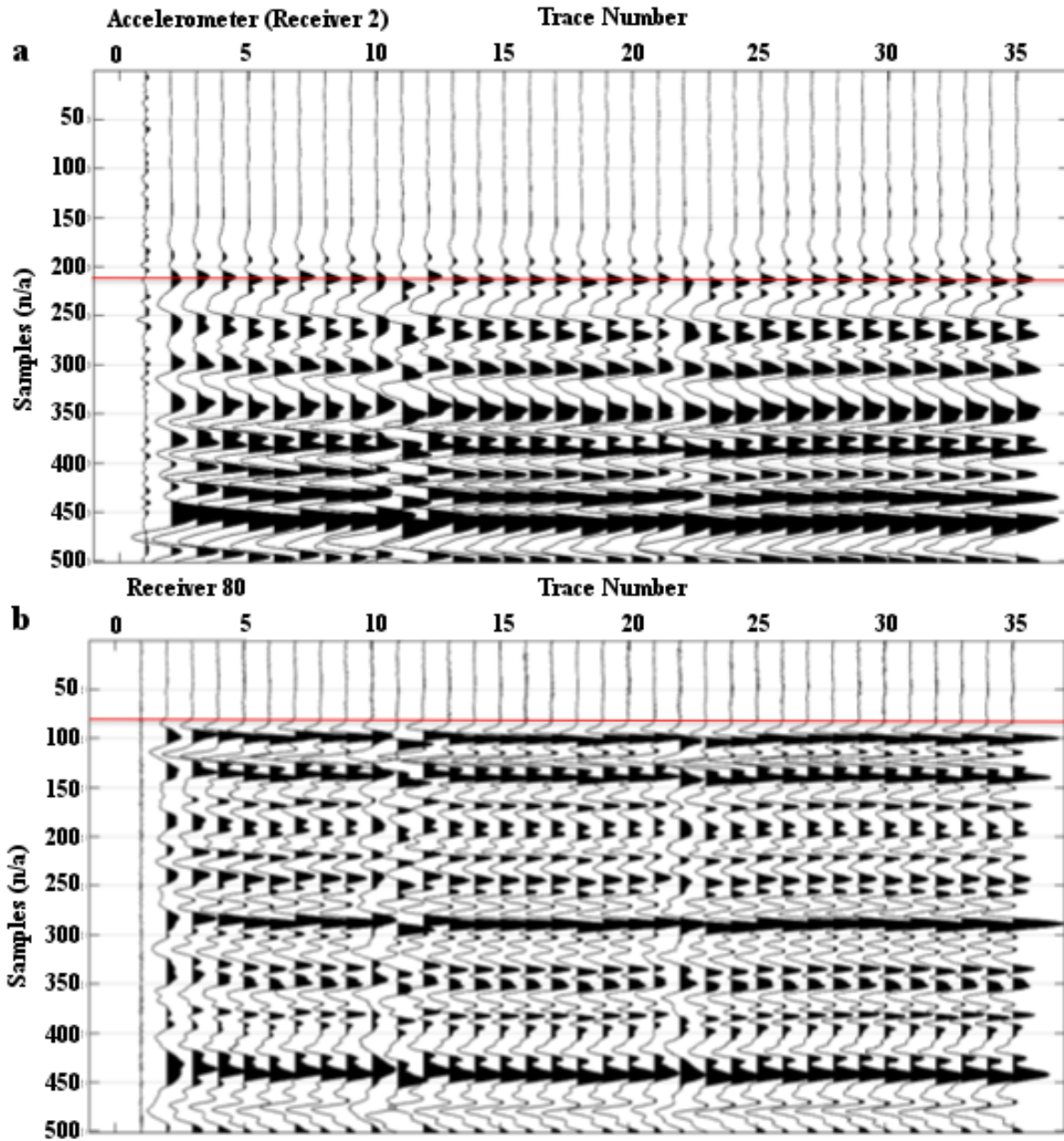


Figure 7: Manual accelerometer picking example for Thor 2, Shot 4 a) accelerometer traces, b) far field geophone. Red lines for orientation of constant arrivals

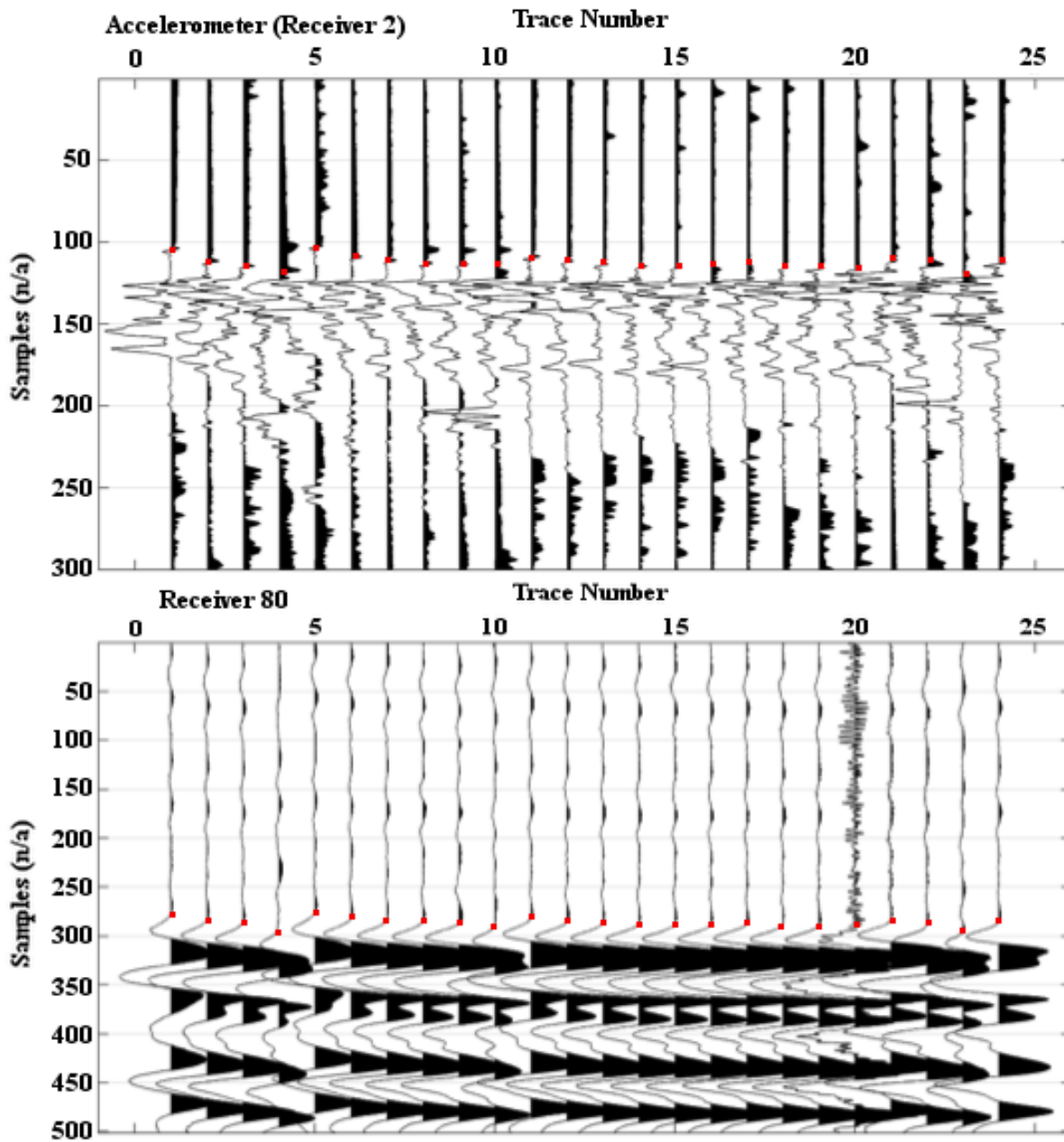


Figure 8: Complex accelerometer waveforms for Thor 2 Shot 46 a) accelerometer waveforms with possible picks as red circles, b) far field geophone with possible picks

Although hand-picked accelerometer picks can adequately correct the far-field trigger time jitter in many cases, this method has the disadvantages of higher cost in terms of the time required to perform many picks, as well as higher probability that geophone gathers will still be misaligned after the time shifts if the accelerometer traces are complex. An example can be seen in Figure 9, which shows a case in which the correlation method does a better job than manual picking in producing alignment between traces. However manual picking may also in some cases give better physical results or a better idea of the true timing error by not forcing alignment, which may ignore some of the physics.

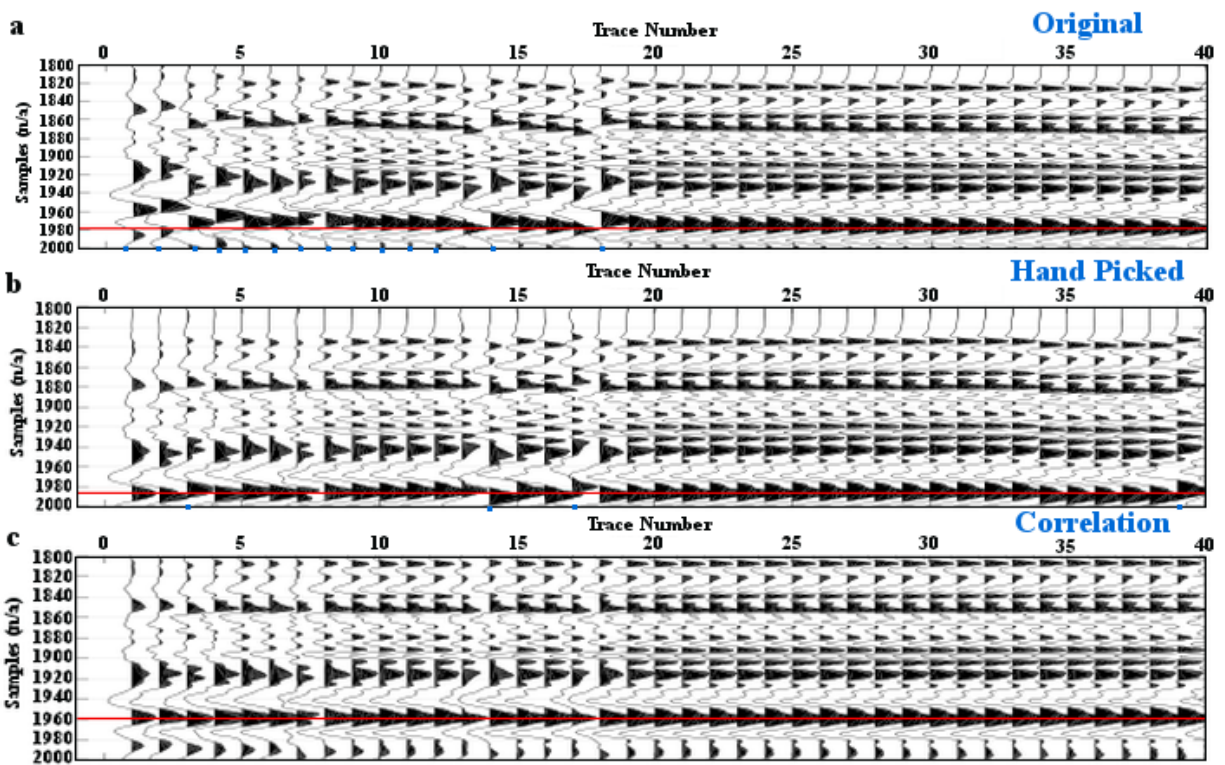


Figure 9: Comparison of cross-correlation and hand-picked methods. a) Uncorrected traces from Thor 1 Shot 10 Receiver 39. b) Traces corrected using time shifts derived from manual hand-picking of accelerometer traces. c) Traces corrected by cross-correlation. Red lines show average value for a sample arrival. Blue dots on bottom axis show noticeable deviations from the average.

3. CONCLUSIONS AND RECOMMENDATIONS

The seismic hammer experiment produced a wealth of valuable data for geophysical subsurface information in the Yucca Flats at NNSS in Nevada. This characterization will provide constraints for numerical modeling of explosions for the Source Physics Experiment. However, for the information to be broadly useful for a variety of applications such as seismic reflection, the trigger time needs to be known to within a few milliseconds. Inaccurate triggering, most likely caused by an insufficiently sensitive piezoelectric switch, required a reanalysis of the data to correct for the dither in trigger times. The two methods considered for correcting the data were cross-correlation of traces and calculating shifts from manual picking of accelerometer traces. However, due to the complexity of some of the accelerometer traces, which increases the possibility of wrong picks, cross-correlation was determined to be the preferred method. An analysis of the time-corrected traces showed that this method produced satisfactory results.

In the future, careful attention to experimental design can minimize some of these timing errors and reduce the need for correcting the data before analysis can be performed. For example, having multiple switches of differing sensitivities and requiring the agreement of at least two switches to determine trigger time could reduce the likelihood of mis-triggering or no triggering in the case of a PZ failure. The data suggest that the compaction phase of the SH hit (the portion the PZ switch often misses) does propagate energy to the far field. Properly triggering off this phase will greatly improve the consistency of the data.

4. REFERENCES

1. Jones, K.R *Infrasound Generation from the HH Seismic Hammer*. SAND2014-19350, Sandia National Laboratories, Albuquerque, NM, October 2014.

APPENDIX A: DATA AVAILABILITY

Time corrected segy files were created for each shot in Thor 1 and Thor 2 with source/receiver geometry included and the noisiest traces removed. A diversity stack was performed over all the hits, keeping 80% of the quietest data for each receiver. This data is not available for public release until the two-year data hold period has completed. Please contact Robert Abbott at Sandia National Laboratories to request access to the seismic hammer data.

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