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Passive Seismic Monitoring for Rockfall at Yucca Mountain: Concept Tests

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Abstract

For the purpose of proof-testing a system intended to remotely monitor rockfall inside a potential radioactive waste repository at Yucca Mountain, a system of seismic sub-arrays will be deployed and tested on the surface of the mountain. The goal is to identify and locate rockfall events remotely using automated data collecting and processing techniques. We install seismometers on the ground surface, generate seismic energy to simulate rockfall in underground space beneath the array, and interpret the surface response to discriminate and locate the event. Data will be analyzed using matched-field processing, a generalized beamforming method for localizing discrete signals. Software is being developed to facilitate the processing. To date, a three-component sub-array has been installed and successfully tested.

Introduction

The Engineering Geophysics Laboratory (EGL) at UNLV is in the process of deploying, calibrating, and testing a passive seismic array on the surface at Yucca Mountain, the site of a proposed repository for high-level nuclear waste. The purpose of the array is to remotely monitor repository opening stability during construction and waste emplacement, and beyond. The primary goal is to monitor and validate the structural integrity of the emplacement drifts through identifying and localizing rockfalls that could compromise drift access, hinder waste retrievability, and potentially reduce the effective life of waste canisters. Collateral benefits of the proposed work include the ability to address some outstanding uncertainties regarding seismic wave attenuation in the vicinity of the repository, and provision of a tool for security monitoring of the repository, to guard against unauthorized access and entry. Advantages of using remote monitoring include cost effectiveness reduced risk of instrumentation failure due to heat produced by waste within the repository, access to instrumentation for data collection and maintenance, and cost effectiveness.

In this paper we present a three-year plan to install and test a network of seismic sub-arrays. We describe the signal processing techniques that will be used to analyze the data. We also summarize the work that is being performed during this first year of the project, including lessons learned from a preliminary test that has been completed. Test development work to date is detailed in a companion paper by Twilley and others (2003).

Project Overview

The objective of the research project is to establish the feasibility of a passive seismic array as a means to establish and catalogue seismic activity within the Yucca Mountain repository block. The targeted events are primarily rockfall due to opening instabilities but also include natural tectonic events and unexpected intrusion. For instrument accessibility, as well as safety considerations, the instrumentation must be configured to monitor the site remotely. For long-term cost-effective performance, for rapid and repeatable discrimination of events, and to facilitate the analysis of large data sets, the data collection and analysis techniques must be automated.

The three-year plan for the research project involves installation of a system of six, six-component seismic sub-arrays on the ground surface in close proximity to the underground Exploratory Studies Facility (ESF) at Yucca Mountain, generation of seismic energy inside the ESF to simulate rockfall, and interpretation of the surface response to identify and locate the event. Once data from the sub-arrays are acquired, concepts of matched-field waveform processing (Baggeroer et al. 1993) will be used to calibrate the surface arrays, thereby enhancing the fidelity with which subsurface events can be discriminated and localized. Through a repeatable calibration process, the system will be trained empirically to trigger on and locate the events. Software is under development at UNLV to facilitate the processing.

We are now in the first year of the project. This year we are installing one six-component sub-array, developing software, and testing the system for feasibility. In the second and third years, we intend to install the five additional sub-arrays and perform quantitative event localization.

Matched-Field Processing

Matched-Field Processing (MFP) is a sophisticated data inversion technique for localizing source energy in the vector sense, and evaluating model accuracy. It was initially developed for use in ocean acoustics (Baggeroer et al. 1993). Recently, a research team at Lawrence Livermore National Laboratory (LLNL) has applied it to track moving vehicles. These researchers are partners with UNLV in the current study.

There are three steps to implementing MFP. First, measurements of the seismic "field" are collected using multiple sensors or groups of sensors, where the number of sensors represents a balance between accuracy and computational intensity. Second, a propagation model appropriate to describe the field is selected. Values of the model parameters (e.g. wave propagation speed) are assumed and applied with the selected model to compute the field. Third, the predicted (modeled) field is correlated with the measured field. Through iteration, the candidate field with the highest correlation is determined to represent the true location of the source.

MFP can be implemented using an assortment of both narrowband and wideband signal models. Wideband MFP requires a detailed model of seismic wave propagation through the medium. This method involves forward projecting from each source point through the models and comparing the resulting observations. This can produce a highly resolved signal if the model is known precisely and the problem is properly posed. Unfortunately, it is unrealistic to expect that a suitably precise, detailed seismic wave propagation model of Yucca Mountain can be developed. Hence, we turn to narrowband MFP. Narrowband MFP can reduce the problem to a linear algebra formulation. The medium propagation model is simplified to just a few parameters. This results in a more efficient model, but this simplified model can lead to ambiguities in source location. However, by characterizing multiple narrow bands the results can be combined to improve accuracy. Complexity increases linearly with number of bands. For our application, the situation is simplified somewhat in this regard because the potential events will be confined to a single plane.

Software is under development in the Computer Graphics and Image Processing Laboratory at UNLV to facilitate data processing. The software reads seismic data files and graphs them. To date, exploratory tools implemented include: low-pass filter, band pass filter, fast Fourier transform, spectrum viewing, audio sampling, and cross-correlation. Beyond these processing tools, techniques for MFP are being adapted and coded. Three different MFP processors are being examined: the Linear Processor, the Minimum Variance Processor and the Multiple Constraint Processor (Baggeroer et al. 1993).

The Linear Processor method directly correlates the measured data with the modeled data. The advantages of this method are its simplicity and ease. Also, it has been shown that the Linear Processor method is the least sensitive of all the processor methods to errors in the modeled fields. A disadvantage of the method is the strong potential for ocurrence of false positive responses (Tolstoy 1993). Thus, a response surface produced from a Linear Processor might have ambiguities in the form of multiple peaks, which makes it difficult to pinpoint which peak corresponds to the correct source location. These phenomena occur when the modeled signal correlates with the noise.

The Minimum Variance (MV) Processor is also named the Maximum Likelihood Method (Capon et al. 1967). This processor suppresses the false positives of the linear processor by minimizing the output power of the noise. This is achieved by incorporating a filter that gives maximum output when the signal of interest is detected and consistently smaller values for all other inputs, thereby minimizing the variance of the noise. The main disadvantage of the MV processor is that its performance degrades very rapidly in the presence of errors in the modeled fields, or if the resolution of the search through the modeled fields is insufficient. The consequence of this is that the output might not show any peaks at all.

The Multiple Constraint (MC) Processor (Schmidt et al. 1990) can overcome some of the drawbacks of the MV processor. The MC processor is similar to the MV processor except that the filter is designed so that the output is maximized for a set of input signals instead of just one input signal. In other words, a spot or neighborhood is designed where the signal could pass with minimum distortion, rather than a point.

These different matched field algorithms will be evaluated to determine which method or combination of methods will give the best results for our application. The technique will then be tested using data acquired in the field.

The Seismic Sub-Array

Detection of rockfall inside the tunnel by monitors on the surface of the mountain relies on the ability of the surface sensors to adequately identify the seismic signature of the rockfall events. This focus on seismic body wave energy differs from the terrestrial application of MFP technology by LLNL, where the focus was on surface wave energy. The feasibility of the method for this situation must be determined experimentally.

This year, UNLV will install and test a sub-array consisting of six, vertical seismometers on the surface of Yucca Mountain over a test area in the underground ESF. We use sub-arrays to enhance results by correlating signal while suppressing noise. The configuration being considered is the Golay array (Harvey and Ftaclas 1995). This array was used successfully by LLNL in their vehicle-tracking project.

Field test equipment includes seismometers and a data acquisition system (DAS). The seismometers are Geotech Instruments, LLC, model S-13J, which are high-gain sensors with low self-noise. ***Need to add more specifics here.*** The data recorders are Refraction Technology model RT130, which are six-channel, 24-bit units capable of kilohertz sampling rates. Global positioning system technology is used for accurate time recording. The units are powered by solar cells to permit continuous operation in remote settings.

A series of rockfall simulation tests is planned to verify system operation, and then calibrate, validate, and exercise the array processing schemes. Our sub-array will complement a regional seismic monitoring array already in place for Yucca Mountain, that is operated by the Nevada Seismological Laboratory *(**ref**)*. We envision eventually tying into this array for efficiencies in data transmission, and also to enhance documentation and localization of near-field microtremors. In our preliminary tests, we will compare results to data collected by NSL on one surface sensor and one underground sensor.

At present, a three-component sub-array consisting of three vertical seismometers and a continuously-recording data acquisition system has been installed on the surface over a test area in the underground Exploratory Studies Facility (ESF) known as Alcove 5. A series of preliminary tests to check the operation of the sub-array was performed on September 26, 2002. The sub-array installation, the preliminary tests, and the analysis of the test data are detailed in the companion paper (Twilley et al. 2003). To summarize, seismic signals were produced within the ESF by a train that is used to transport people and equipment, and by hammering on rockbolts. Results indicate that the system can record sufficiently strong signals produced within the ESF.

To explore capabilities to distinguish between seismic sources, we compared recorded waveforms and spectra between the signals caused by the train with signals resulting form a nearby earthquake *(**x km distant, moment magnitude y**).* As discussed by Twilley et al. (2003) and shown through unfiltered data in Figure 1, the earthquake response clearly differs in its longer period energy content, lower corner frequency, and clear onset. Based on these and similar observations not reported here, we are optimistic that the array can be configured with the capacity to discriminate targeted seismic events.

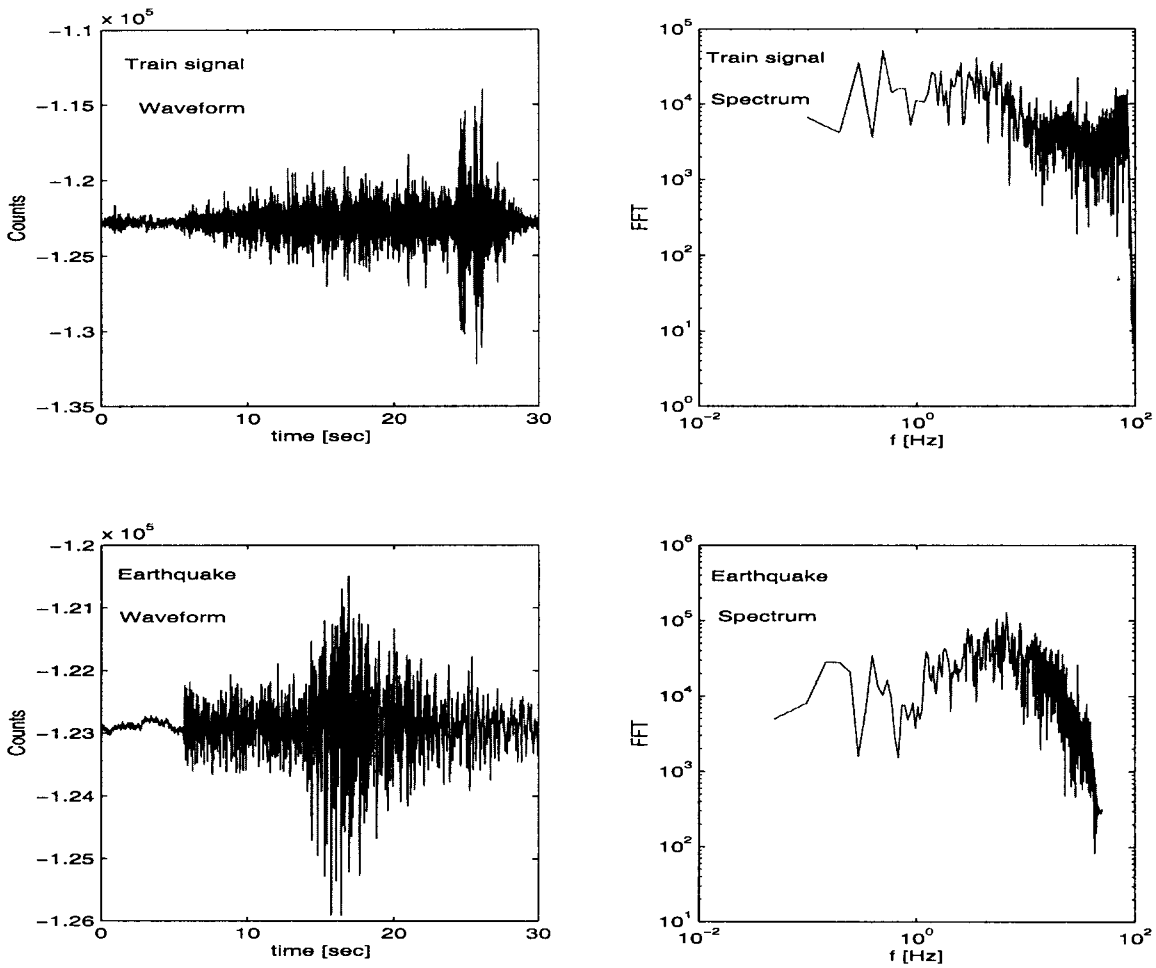

Fig. 1 - Comparison of waveforms and spectra for train and earthquake signals, measured on one component of the surface sub-array

Rockfall Simulation Testing

The preliminary test demonstrated that the surface seismometers were able to distinguish seismic events originating in the ESF. To test and calibrate the array for rockfall events, however, it is necessary to test an event with a seismic signature similar to rockfall. In the next phase of testing, concrete weights will be dropped underground to simulate rockfall events. The first of these tests is expected to happen soon after final submission of this paper.

The weights to be dropped are 55-gallon *(**x-m^{3**})* drums that have been filled with concrete. This will occur at two locations in Alcove 5. The weights will be dropped out of a mucker bucket, from a height of approximately 2 m. Test locations were selected primarily for accessibility and safety, to minimize the potential for injury or damage from a loose weight that rolls after being dropped.

On the surface, data will be collected with the broadband DAS connected to the sub-array. Underground, an identical DAS will be used to collect near-field data next to the source event. The underground data are valuable to provide a control for timing of events and also to characterize the near-field seismic signature of the events. The underground DAS will be time-synchronized using GPS technology before being taken underground and again immediately after completion of testing, and drift will be adjusted linearly. Redundant data will be collected from a geophone and from a seismometer of the same type that is installed on the surface. The geophone is preferred for collecting data underground because it is more robust, but we have not yet determined whether the senisitivity and accuracy of the S13J unit will be required.

The dropped-weight rockfall simulation test is a critical step toward evaluating the feasibility of using a passive seismic array to identify underground rockfall. Besides providing test data to support software development, the test will address questions regarding array location, configuration, and range. Results will drive decisions for placement of the additional three seismometers. While LLNL used the Golay array for their vehicle-tracking project, the shift of focus from surface wave energy to body wave energy may demonstrate the need for a different sub-array configuration. The test will also tell us whether surface-mounting of sensors is adequate. We will learn whether the low confinement and weathered nature of the near-surface zone, and surface noise from wind or other elements excessively corrupt the signal. Although we are encouraged by indications from the preliminary tests that the system has an acceptable signal to noise ratio, the rockfall simulation tests are needed to be sure.

In followup testing, we will repeat weight-drop tests with weights of different sizes.

Once the first six-component sub-array is in place, we will explore possibilities to calibrate the MFP system by conducting a test sequence using an elastic-wave generator (EWG) as a source. This device has the advantage of producing sizable, repeatable, seismic impulses. It will be deployed at regular intervals down the main drift of the ESF.

The combination of weight-drop and EWG tests will allow us to vary source energy and source location sufficiently to determine the effective range of the subarray and establish thresholds for discriminating rockfall events.

Summary and Conclusion

The program of field testing and signal processing we describe herein will establish the feasibility of using a passive seismic array system to monitor rockfall within the underground facilities at Yucca Mountain.

The capacity of matched-field processing techniques to identify and locate these events will be tested using data acquired using a system of seismic sub-arrays on the ground surface during simulated rockfall events underground.

To date, a small sub-array has been installed on the surface of the mountain and a preliminary test has been performed. From the positive results of this test we are optimistic that the signature from simulated rockfall tests can be resolved on the surface. By comparing temporal and spectral responses recorded by one of our surface seismometers to two seismic events, one local and one distant, we provided evidence that we will be able to discriminate different sources.

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