INJECTION MONITORING WITH SEISMIC ARRAYS
AND ADAPTIVE NOISE CANCELLATION

Final Report

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Introduction

Reservoir stimulation by in-situ mass injection is an accepted and widely used method for modifying the properties of a reservoir. In-situ secondary waterflooding, tertiary steamflooding, and hydrofracturing are all useful techniques to enhance oil recovery in otherwise depleted fields. Water injection in some geothermal fields is used to enhance steam production. Steam injection has been proposed to enhance contaminant recovery in groundwater aquifer waste cleanup efforts. In all these applications, knowledge of the in-situ movement and distribution of injected mass is very important in determining the portion of the reservoir influenced by the stimulation and in planning the distribution of injector wells to optimize the volume of the reservoir that is influenced.

Unfortunately, no geophysical monitoring scheme has proven effective in monitoring any of these in-situ reservoir stimulation techniques. Consequently, the portion of a reservoir influenced by a particular stimulation injector can only be inferred based on knowledge of the gross reservoir geology, injected mass, and on the change in producer well recovery rates. This makes it difficult to optimize injector locations and significantly increases overall recovery costs.

The Lawrence Livermore National Laboratory (LLNL) Treaty Verification Program has been conducting research on seismic arrays and array processing techniques to monitor potential low-yield nuclear testing treaties for a number of years. As a result, LLNL has developed extensive seismic array processing software, seismometer and data acquisition hardware, and expertise in seismic array design and deployments. In looking for new applications for this seismic array technology consideration has been given to using seismic arrays to passively monitor in-situ reservoir stimulation processes.

Although the application of seismic methods, active and passive, to monitor in-situ reservoir stimulation processes is not new, seismic arrays and array processing technology coupled with a new noise cancellation method has not been attempted. Successful application of seismic arrays to passively monitor in-situ reservoir stimulation processes depends on being able to sufficiently cancel the expected large amplitude background seismic noise typical of an oil or geothermal production environment so that small amplitude seismic signals occurring at depth can be detected and located. The new noise cancellation method consists of old and new

techniques. Shallow sensor burial and array processing, well known noise reduction techniques, are coupled with an active noise cancellation technique that identifies and monitors large seismic noise sources for real-time cancellation of the recorded array noise.

This report describes the results of a short field experiment conducted to test both the application of seismic arrays for in-situ reservoir stimulation monitoring and the active noise cancellation technique in a real reservoir production environment. Although successful application of these techniques to in-situ reservoir stimulation monitoring would have the greatest payoff in the oil industry, the proof-of-concept field experiment site was chosen to be the Geysers geothermal field in northern California. This site was chosen because of known high seismicity rates, a relatively shallow production depth, cooperation and some cost sharing with the UNOCAL Oil Corporation, and the close proximity of the site to LLNL. The body of this report will describe the Geysers field experimental configuration then discuss the results of the seismic array processing and the results of the seismic noise cancellation followed by a brief conclusion.

Geysers Field Experiment

The Geysers Geothermal Field, located in California's Sonoma and Lake counties is about 90 miles north of San Francisco (see Figure 1). UNOCAL Oil Co. is the principal operator in this, the world's largest geothermal development. The field experiment was conducted on a UNOCAL lease in cooperation with UNOCAL. UNOCAL supplied electric power, telephone, site space, and field support. The field support included heavy equipment and operators for digging and burying the seismometers. A site use agreement with UNOCAL allowed unlimited access to the experimental site for the duration of the experiment.

The field layout of seismometers was determined to allow the two major concepts of the experiment to be tested: 1) Use of passive seismic arrays to monitor seismic energy releasing processes at depth that do not necessarily consist of distinct events, and 2) Adaptive noise cancellation techniques to adaptively cancel noise from distinct sources of high surface noise. The rugged topography of the Geysers restricted the aperture size of the seismic array since the seismometer elevations across the array need to be constant. A flat area near a producer well was chosen for the array location since the site met the following criteria:

- 1) Flat topography allowing for a 50m array aperture.
- 2) Upslope and on the edge of the Geysers field to restrict the bearing to major noise and signal sources.
- 3) Near a region of major interest to UNOCAL.
- 4) In line-of-site to the central recording trailer located across the valley.
- 5) Road to site allowing easy access.
- 6) Known high local seismicity.
- 7) A nearby large seismic noise source.

The initial array consisted of 8 stations of a single vertical seismometer and one 3-component station. This was later expanded and modified to consist of 11 stations as shown in Figure 2. The seismometers used were Geotech S-13's. Data was sampled at 150 samples/sec. for each seismometer and digitized by Reftek-72 data acquisition units. The digitized data was telemetered to the central recording trailer. Each data acquisition unit digitized three seismometer channels. An anemometer was also installed and the signal digitized on a separate channel to monitor wind for later correlation with seismic noise.

The recording trailer received the multiplexed radio telemetered seismic and anenometer signals, demultiplexed and archived the recordings and allowed on-site computer analysis of the data. A Sun Sparc-1 CPU served as the on-site analysis computer.

Seismic Array Processing Results

The seismic array was operated in event detect mode and continuous record mode to accumulate a suite of earthquake events in the immediate area, estimate the seismicity rate detected by the array, and obtain a long period of seismic noise for deep seismic noise source analysis.

Many local earthquake events were recorded during the brief deployment. Some of the earthquakes recorded were not recorded by the UNOCAL Geysers area seismic network. Although this increase in detection threshold was a result of the quality of the site chosen and the seismicity in the immediate area, an array detection algorithm would further increase the detectability of microearthquakes in the immediate area.

An example of a typical local earthquake recorded by one of the array stations at the Geysers is shown in Figure 3. The bottom plot is the time waveform of the seismic event and pre-event noise. The top plot is a spectrogram of the time waveform plot. The vertical axis is the frequency content of the waveform at a particular time. In the spectrogram, note the relatively complex structure of the pre-event and post-event noise below about 20 Hz. Also note significant energy in the relatively high frequencies for the local earthquake. This indicates a nearby event.

For the same event, using all the station recordings in the array, a Broad Band Frequency Wavenumber (BBFK) analysis is performed to determine the bearing from the array and the wave velocity that is consistent with the signal time delays and signal power received by the array. Figure 4 shows the results plotted in polar coordinates with the angle as bearing from the array and radius proportional to wavenumber (i.e. inverse velocity). The contours are of signal power received by the array. The figure shows this earthquake event epicenter was northwest of the array and the received waves were of high velocity (around 5 km/sec). The high velocity waves indicate an event at depth since a surface source would predominantly excite surface waves which have low velocity (under 2 km/sec). An actual depth determination of the event and epicenter location requires more than one array. The relatively poor resolution in velocity determined by the BBFK analysis is because the array aperture is very small. This was because of the severe topographic limitations on array placement at the Geysers due to the rugged terrain.

Performing a BBFK analysis on a longer time record, 100 sec, of pre-event or post-event seismic noise allows one to identify surface noise

sources. Figure 5 is one example of such an analysis showing a tight sequence of power contours centered 60 degrees east of north with a large radius (i.e. low velocity) indicative of surface seismic energy. Of particular importance is the contouring near the center (i.e. high velocity) which indicates seismic body waves from depth. This intriguing result supports the claim that seismic arrays may be useful for detecting and locating seismic energy sources at depth that are not clear events with wave phase arrivals but rather a summing of tiny microevents that become a bulk source of "noise" at depth. This source of "noise" at depth may provide important information about the reservoir stimulation processes if identified and located. It must be pointed out that Figure 5 is supportive but by no means provides conclusive proof that this is a noise source at depth. It could, for example, be a shallow horizon reflection of surface noise source body waves. BBFK analyses on other noise time records has, however, shown some examples of minimal surface energy (low velocity) sources and a large body wave energy (high velocity) source. The "noise" source could be water exiting the injector well into the formation. It will require several arrays and monitoring the injector well flow rate to determine if this is such a "noise" source.

Performing repeated BBFK analyses on a sliding 100 sec analysis window over a long period of continuous recording allows one to analyse the full time record for noise sources and events. Figures 6 and 7 show the results of this analysis over a 6 hour period of continuous recording. The two figures both have a 10 Hz bandpass but differ in the center frequency analysed: Figure 6 is centered at 18 Hz and Figure 7 at 28 Hz. Any specific horizontal slice across the two images in these figures is a BBFK 100 sec window analysis result at that specific time. The images are grey scaled so that black represents low energy and white high energy. The information portrayed in a specific horizontal slice is identical to the plots shown in Figures 4 and 5: wave energy as a function of bearing from the array and phase velocity.

The results shown in Figure 6 show that most noise energy received by the array in the 18 Hz band is of relatively high seismic phase velocity (above 6 km/sec). A clear event occurred at about hour 142.7 with a dominant phase velocity of about 8.8 km/sec and at a bearing of about 270 degrees from the array. Of particular interest is the section between hour 139 and 141. Here, an energy source that persists for two hours or so, is shown with a consistent phase velocity of about 9.3 km/sec and a bearing changing from about 300 degrees at hour 141 to about 280 degrees at hour 139. The high phase velocity indicates an energy source at depth.

The results shown in Figure 7 have some energy at low phase velocity and a distinct event at about hour 144.3 with a phase velocity of about 12.5 km/sec and a bearing of about 280 degrees. This event is also seen in Figure 6 but at lower relative energy. It should be noted that the phase velocities used here are actually apparent phase velocities since the velocities are computed by the time delay between the individual array seismometers assuming a horizontally propagating plane wave. Waves from depth, having a vertical component, will result in an overestimate of the actual phase velocity.

Although the seismic array results were for a very short proof-of-concept experiment, several intriguing results, warranting further research, were obtained. First and most important, the results indicate that the array may be recording and identifying sources of continuous noise at depth. This needs to be conclusively demonstrated in future deployments but holds the promise for increasing the importance and potential usefulness of passive seismic monitoring methods. Second, seismic arrays, added to an area seismic network can be useful for lowering detection thresholds in particular areas of importance and provide special processing possibilities for event recordings in that particular area.

Seismic Noise Cancellation Results

High background seismic noise due to process machinery in production oil or geothermal fields can present a major problem for active seismic studies such as reflection and refraction surveys, and passive seismic studies such as microearthquake monitoring. In these operations, apart from burying the sensors, it is often impossible to escape high noise conditions by moving instruments away from the noise sources. An application of adaptive noise cancellation (Widrow, et al., 1975) was conducted to attempt to suppress noise recorded at a primary monitoring site using reference noise recorded at a major nearby noise source. The idea is a simple one and seems an obvious application of widely-used cancellation principles, but the authors know of no previous similar application reported in the geophysical literature. Consequently, the initial results are presented on the use of cancellation in a geophysical application.

The method was applied at a microearthquake monitoring site in The Geysers Geothermal Field in northern California (McLaughlin and Donnely-Nolan, 1981), and partial cancellation of noise generated by a nearby power plant was obtained. The results show that although the power plant noise is reduced at several discrete frequencies, the cancellation operation has little effect on recorded microearthquake signals, effectively raising the signal-to-noise ratio (SNR) at those frequencies.

Adaptive noise cancellation is an appropriate approach whenever the noise field is dominated by a few distinct, localized sources. The sources must be located and instrumented to provide reference signals for the cancellation algorithm. The locations of the sources might be obvious (as in this application) or might be discovered by analyzing the noise field with a small aperture array of seismometers. An estimate of the transfer function necessary to account for propagation from each noise source to the principal receiving site has to be made. This filter matches the phase and amplitude of the noise reference to those of its received component at the primary recording location. The filtered reference waveform can then be subtracted from the primary received waveform to suppress the noise. Only those components of the noise spectrum contributed by the instrumented sources are suppressed in this manner.

The test location at The Geysers is within 10 kilometers of 25 operating power plants: the closest is about 500 meters away, and the rest are more than 1500 meters distant. The site is also close to water injection and steam production wells, and an above-ground network of pipes for transporting steam and condensed water. Because of the large number and wide distribution of noise sources, the Geysers is probably not the ideal test location for adaptive cancellation. In spite of this fact, the noise field was found to be dominated by the power station closest to the monitoring site at some frequencies. This site was convenient and provided an indication of the method's feasibility.

The experimental layout is diagrammed in Figure 8. The primary sensor was a Geotech S-13 seismometer situated on bedrock and buried to a depth of about one meter. Three additional S-13 seismometers were buried adjacent to the power plant as reference instruments about 500 meters from the primary instrument and 100 meters lower in elevation. The reference instruments were spaced at 30 meter intervals along the power plant perimeter, between it and the primary sensor. Data were synchronously digitized at all the sensors at 125 samples/second, then transmitted over narrowband FM telemetry to a central recording location. Noise samples were taken at half-hour intervals over a 6 hour period; event-detected signals were collected over a period of several days.

The noise field at the primary recording site does appear to be dominated by the process machinery in the geothermal field, which operated continuously during this deployment. One line of evidence for this assertion is the stationarity of the noise field. The noise at the primary sensor was sampled over a 6 hour interval. Since there is almost no variation in the noise power spectra with time, it seems likely that the background noise is cultural. In addition, the spectra are punctuated by many lines which are probably due to rotating machinery in the nearest power plant.

Adaptive Noise Cancellation

The standard cancellation approach shown in Figure 9 is used to suppress noise propagating from the power station to the primary seismometer location. The reference signals are filtered to account for propagation, then subtracted from the primary signal. The term "adaptive" is used to denote a statistical estimation of the required propagation transfer functions. The filters are estimated from the data to minimize the expected power of the cancellation residual. The estimation problem is a

standard Wiener input-output filter design problem where the inputs are the reference waveforms and the output is the primary sensor signal.

Multiple reference sensors are important when instrumenting a complex, distributed source. In the ideal situation, a complex source would be treated as a collection of individual sources (pumps, for example), with each source separately instrumented. The filters would adapt to represent the Green's functions describing propagation from each source to the primary sensor. If the number of individual sources exceeds the number of sensors, the filters will probably represent some weighted combination of Green's functions along the separate paths, with the weights determined by the relative amplitudes and phases of the sources. These observations help determine the necessary filter lengths. The duration of the filters should be at least the expected propagation delay between the sources and the primary sensor, accounting for delays due to multipath propagation.

The filters are particularly simple to design since they are estimated from the recorded data. The process requires no *a priori* knowledge or model of the propagation paths. The principal requirement is to choose reference waveforms with a high noise-to-signal ratio to prevent unintended cancellation of desired signals. Reference instruments placed close to large noise sources satisfy this requirement.

Any of several popular algorithms can be used to design the cancellation filters. This experimental investigation used the Widrow algorithm for its simplicity. This algorithm has the ability to track temporal changes in the statistics of the noise field, an ability which could be important in this application when instrumenting a complex source with a small number of sensors. If the components of the source are non-stationary, the weighted combination of Green's functions the filters represent could change. Some temporal adaptation may track these variations.

Example 1: Wideband Noise Suppression

Cancellation effectively suppresses discrete line components of the background noise over a wide band at the Geysers site. This effect was demonstrated by applying cancellation to a 200-second segment of background noise using 4-second filters (501 coefficients/filter). The spectra of the uncanceled background noise and of the cancellation residuals using one, two and three noise reference waveforms are displayed on a linear scale in Figure 10 to emphasize the discrete spectral

components. Cancellation suppresses five spectral lines, but has little effect on the general background level of the noise. The spectra of the 3 reference waveforms are superimposed at the bottom of the figure to demonstrate that the cancelled lines are strongly recorded at the power station, as expected.

Cancellation is more effective as the number of reference sensors increases, an effect attributed to the complexity of the noise source. The power station has a large bank of cooling towers, a turbine room and many pumps distributed over several acres. A single noise sample cannot adequately characterize so complex a noise source, especially if the reference sensors picks up non-propagating noise components. With multiple reference sensors, there is the potential for the cancellation algorithm to separate the components of a complex source, and to filter and weight them individually (zero weight for non-propagating components) for optimum cancellation at the primary sensor.

Example 2: Narrowband SNR Improvement

Although cancellation suppresses noise components it does not affect superimposed signals significantly. This effect is demonstrated in Figure 11, which shows the primary waveform containing a signal from a microseismic event, and the cancellation residual using three reference stations. The data have been filtered to a very narrow band (39-40 Hz) to demonstrate the effect of removing the line at 39.5 Hz in the time domain. The event is small enough that it produces no perceptible signal at the reference stations. Consequently, the signal is not removed by cancellation, though the noise component correlated with the reference station waveforms is removed.

The examples from this limited deployment demonstrate that noise cancellation is feasible. At the Geysers location, the noise field is composed of a discrete line spectrum super-imposed on a smoother background. The results show successful suppression of some narrowband noise components, which were assumed to arise from rotating machinery at the nearby power station which were instrumented with reference seismometers. However, the smooth component of the noise spectrum, accounting for most of the noise power (60%), is unaffected by cancellation. It is speculated that this spectral component is the aggregate contribution of all other noise sources in the region. Since only the closest noise source was instrumented, the limited cancellation obtained is reasonable. Better results may be expected in other regions having fewer sources.

Other methods that might be used to suppress noise line spectra are not as feasible as adaptive cancellation. Notch filtering would remove not only the noise at specific frequencies, but also the signal. Cancellation affects the signal minimally, as Figure 11 shows. Subtraction of simple sinusoidal signals generated to match the amplitude and phase of the spectral lines is probably unworkable. Variation in the phase and amplitude of the discrete noise components can frustrate such deterministic approaches. Variations may be caused by load changes in the machinery responsible for the noise. As seen in the narrow-band example, noise contributions that appear to be single spectral lines may be due to a combination of several sources at closely-spaced, but separate frequencies, complicating a deterministic approach. Cancellation, on the other hand, requires no a priori knowledge or estimation of the frequencies of discrete noise components.

Conclusions

This brief proof-of-concept experiment has demonstrated that seismic arrays can lower the detectability threshold of the UNOCAL Geysers area seismic network in the immediate array area. Consequently, seismic arrays placed in areas of particular interest or concern can supplement and enhance the value of an area-wide seismic network. Furthermore, these results indicate that in the Geysers environment seismic arrays may be detecting continuous sources of seismic energy at depth. Detecting and locating such energy sources at depth provides unique information that may help in understanding the in-situ reservoir and geothermal processes at the Geysers. Further research using seismic arrays at the Geysers is warranted. The next Geysers experiment using seismic arrays should use multiple arrays of wider aperture and with some variation in sensor elevation to adequately determine the source of continuous seismic energy and determine the continuous energy source location accuracy that can be accomplished with arrays.

Although seismic noise cancellation was not necessary in the Geysers seismic environment to receive seismic events and continuous energy source noise well above the background seismic noise, the adaptive noise cancellation concept was tested. The examples shown demonstrate that adaptive noise cancellation is feasible, although the Geysers is not an ideal location for this method because of the large number of noise sources.

The use of seismic arrays, array processing techniques, and adaptive noise cancellation to monitor in-situ seismic processes has shown a great deal of potential in the short proof-of-concept Geysers deployment. The concepts and techniques used at the Geysers need to be field tested in an oil field environment for monitoring a secondary or tertiary enhanced oil recovery (EOR) process. The most likely EOR process to provide detectable seismic signals after noise cancellation is shallow depth hydrofracturing. The next field experiment should be in an oil field with several scheduled hydrofracturings to allow several opportunities for recording the hydrofract seismic signals and several chances to reconfigure the field sensors if data analysis indicates a different field configuration is desirable.

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Figure 1) Map showing the Geysers geothermal field in relation to the San Francisco bay area and the northern California coast.

Figure 2) Map showing the array station locations at the Geysers.

Figure 3) A microseismic event recording from one array station with pre-event and post-event noise (bottom) and the corresponding spectrogram displaying frequency content changes with time. Note the relatively high frequency content of the microseismic event.

Broadband Wavenumber Spectrum

Maximum Radial Wavenumber: 0.50000

Linear contour spacing

Figure 4) Broadband Frequency Wavenumber (BBFK) analysis of the event shown in Figure 3). The plot shows incident wave energy contours in polar coordinates as a function of bearing angle from the array and wavenumber radius (inverse velocity). The small radius length to the energy peak indicates a large phase velocity suggesting an event at depth.

Broadband Wavenumber Spectrum
Maximum Radial Wavenumber: 1.0000
Linear contour spacing

Figure 5) BBFK analysis of 100 sec of pre-event seismic noise. Notice the low velocity (large radius) energy source at 60 degrees east of north typical of surface sources and a high velocity peak indicating a continuous seismic energy source at depth.

Figure 6) BBFK analyses on 6 hours of continuous recording using 100 sec time windows and a 10 Hz bandpass centered at 18 Hz. Any horizontal slice through the two images gives the same information as a BBFK polar plot where low energy is black and high energy is white. Note the distinct event at about hour 142.7 and the consistent phase velocity with changing bearing between hours 139 and 141.

Figure 7) The same BBFK analyses as shown in Figure 6) except the frequency passband is 10 Hz centered at 28 Hz.

Figure 8) Simplified schematic of the experimental layout. Although many power plants exist in the region, only one was instrumented.

Figure 9) Signal processing operation applied to the primary and reference signals.

Figure 10) Cancellation suppresses spectral lines associated with the power plant. (a) Noise spectrum at the primary sensor prior to cancellation. (b) Cancellation residual spectra using data from 1,2, and 3 sensors. Cancellation improves with increasing numbers of reference sensors. (c) Superimposed spectra of reference waveforms. The strong lines in these spectra generally are the lines suppressed by cancellation in the primary sensor spectrum, suggesting a causative link.

Figure 11) Narrowband time-domain cancellation example. The signal from a microseismic event is essentially unaffected by the cancellation operation. The seismic noise, however, is strongly reduced. The vertical scale is equal for all 3 waveforms.