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A Comparison of Methods for 3D Target Localization from Seismic and Acoustic Signatures

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ABSTRACT

An important application of seismic and acoustic unattended ground sensors (UGS) is the estimation of the three dimensional position of an emitting target. Seismic and acoustic data derived from UGS systems provide the raw information to determine these locations, but can be processed and analyzed in a number of ways using varying amounts of auxiliary information. Processing methods to improve arrival time picking for continuous wave sources and methods for determining and defining the seismic velocity model are the primary variables affecting the localization accuracy. Results using field data collected from an underground facility have shown that using an iterative time picking technique significantly improves the accuracy of the resulting derived target location. Other processing techniques show little advantage over simple crosscorrelation alone in terms of accuracy, but may improve the ease with which time picks can be made. An average velocity model found through passive listening or a velocity model determined from a calibration source near the target source both result in similar location accuracies, although the use of station correction severely increases the location error.

1. Target localization, unattended ground sensors, seismic analysis

1. INTRODUCTION

In many facilities, targets which emit seismic and acoustic energy are an integral part of the infrastructure or the primary function of the facility. Monitoring of these seismic and acoustic emissions can not only help to determine and characterize the function of the facility, but can also aid in locating the position of the targets of interest within the facility. Over the past several years, we have been recording and analyzing seismic and acoustic emissions from a variety of targets in a variety of facilities in an effort to improve our capabilities to locate continuous-wave (CW) sources using signals recorded by a distributed network of UGS.

Our method of location is based on a technique employing least-squares inversion of seismic travel times and bearings to the source, if available, to determine a best-fit source location in a 3D sense¹. A seismic velocity model for the wave mode of interest is assumed and the travel times between a trial source location and the sensor locations are calculated. The difference between these calculated travel times and the observed travel times is then used to estimate the location of the source iteratively until a location is found that minimizes the difference between the observed and calculated travel times in a least-squares sense. When bearing information is available, the final location solution must also minimize the difference between the observed and calculated bearings.

In general, the inversion of the travel times, rather than the bearings, is the deciding factor in the final location. For this reason, the accuracy of the travel time picks from the data and the accuracy of the velocity model used in the inversion are the two most critical factors in obtaining an accurate target location. This paper will focus on methods we have explored to improve the accuracy of these two critical factors. For improvements in the time picking for CW sources, we have studied frequency filtering, crosscorrelation, the application of smoothed coherence transforms, Hilbert Transform enveloping, and iterative time picking. The seismic velocity model was first determined from the arrival time change with distance for target sources resulting in a homogeneous model, then refined by incorporating station corrections based on systematic variations from the homogenous model, and finally further refined by taking data from known sources to define source regions that employ different velocity models.

The different processing techniques and the different velocity models all have varying effects on the accuracy of the final location. Exploring the dependency of the final location on each of these aspects will highlight the critical inputs to aid in the design criteria and processing parameters of future monitoring tests.

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2. PROCESSING TECHNIQUES FOR IMPROVEMENT OF TIME PICKS

For the purposes of this study, we have analyzed CW sources, i.e. sources that initiate and run for long periods of time in a near steady-state mode. In some cases, a transient in these signals allows time picks based on the change in the signal at the point of the transient, but in general, the onset of the signal is emergent and a start time is difficult to pick. For this reason, all of our analyses included a crosscorrelation step, with the other processing steps applied concurrently. The following sections discuss each of the techniques used.

2.1. Crosscorrelation

Crosscorrelation is a mathematical process that provides a measure of the similarity of two waveforms and can be expressed by the formula

$$C_{xy}(t) = \int_{-\infty}^{\infty} x(\tau)y(\tau+t)d\tau, \quad (1)$$

where $C_{xy}(t)$ is the crosscorrelation of signals $x(t)$ and $y(t)$. When crosscorrelating two received signals from different distances from the source, where a similar waveform will appear but with a time shift equal to the travel time difference between the two sensors, the resulting crosscorrelation function will show a peak at the time offset equal to the this travel time difference. By picking the time of this peak, the relative travel times between the sensor locations can be determined for input into the inversion process. In the present work, for each target event the sensor with the shortest arrival time from a cursory examination of the unprocessed data was chosen as the reference sensor and crosscorrelated with the remaining sensors.

One of the difficulties when using the crosscorrelation technique with CW sources is that when the source has dominant frequencies, the resulting crosscorrelation function will have the same dominant frequency and be "ringy" in nature making it difficult to select a peak in the function. For this reason, non-steady state regions of the signals were used, usually initiation sequences or shut-down sequences.

2.2. Filtering

Low-pass digital filtering of the recorded signals retains only the low frequency portion of the waveform. In propagation through an attenuating medium such as the earth, these low frequencies have much less attenuation and therefore higher signal-to-noise at greater distances than the high frequency portion. The wavelengths of the low frequencies are also long enough that many of the localized inhomogeneities in the earth are essentially invisible to the wave resulting in less complexity in the recorded signal. Additionally, the waveform of the resulting crosscorrelation has fewer peaks with a corresponding greater ease in time picking. These characteristics make low-pass filtered data easier to analyze and pick accurate times from. For our purposes, a 30 Hz low-pass Chebyshev Type I filter was applied with zero-phase, two zeros, and 1/2 dB of ripple.

2.3. Hilbert transform enveloping

One of the problems encountered with time picks based on the peak of the crosscorrelation function is that this assumes stationarity of the waveforms, i.e. no phase shift occurs as the signal propagates from one sensor to another. When this is the case, the maximum amplitude of the crosscorrelation function does give the relative time shift between the two signals. When this is not the case, however, as is common when propagating through earth media, a phase shift is introduced in the crosscorrelation function so that the actual time shift may be represented by something other than a maximum point, and possibly even a minimum point. To remove these possible phase shifts, a Hilbert transform envelope^{2,3} is applied to the data.

The envelope function is actually the instantaneous amplitude determined from the analytic signal or complex-valued trace $z(t)$ expressed as

$$z(t) = x(t) - iH(x(t)), \quad (2)$$

where $H(x(t))$ is the Hilbert transform of the signal $x(t)$. The envelope function $e(t)$ is calculated from

$$e(t) = +\sqrt{x(t)^2 + (H(x(t)))^2}. \quad (3)$$

For ease of calculation, the envelope is actually created in the frequency domain with the expression

$$E(\omega) = X(\omega) \cdot (1 + \text{sgn } \omega), \quad (4)$$

where $E(\omega)$ and $X(\omega)$ are the Fourier transforms of the envelope function and the original signal respectively, and sgn is the signum function ($\text{sgn} = -1$ when $\omega < 0$; $\text{sgn} = 1$ when $\omega > 0$; $\text{sgn} = 0$ when $\omega = 0$). The effect of the enveloping on the time pick can be seen in Figure 1 where a series of phase-shifted synthetic crosscorrelation functions result in identical envelope functions with the peak of the envelope function indicating the true time shift desired.

Figure 1: Example of Hilbert transform envelopes (dotted lines) for a simulated crosscorrelated signal with varying phase shifts (solid lines).

2.4. Smoothed coherence transform (SCOT)

As mentioned in the description of the crosscorrelation process, when working with CW sources that have dominant frequencies, a "ringiness" in the crosscorrelation function is common, even when working with transitional portions of the CW signal. This "ringiness" is a result of a non-smooth and non-flat frequency spectrum and makes the picking of the true peak in the crosscorrelation function difficult. A process for decreasing the "ringiness" is to flatten the spectrum by weighting the crosscorrelation function. The SCOT uses a weighting function $W(\omega)$ in the frequency domain that is a function of both the reference signal and the signal with which it is being crosscorrelated as follows^{4,5}:

$$W(\omega) = \frac{1}{\sqrt{G_{xx}(\omega)G_{yy}(\omega)}} \quad (5)$$

where $G_{xx}(\omega)$ and $G_{yy}(\omega)$ are the autocorrelation power spectra (the power spectrum of the crosscorrelation of a signal with itself) for the reference signal $x(t)$ and the signal with which it is being crosscorrelated, $y(t)$, respectively. The expression for the crosscorrelation with the frequency-domain weighting applied now becomes

$$C_{xy}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{1}{\sqrt{G_{xx}(\omega)G_{yy}(\omega)}} G_{xy}(\omega) e^{j\omega t} d\omega. \quad (6)$$

The disadvantage with the SCOT is that in the process of flattening the spectrum, it may also boost the background noise, decreasing the signal-to-noise ratio of the resulting data.

2.5. Iterative picking

Often in the processing of the real data, the resulting crosscorrelation function will have several peaks of nearly equal amplitude and significantly different times with ambiguity as to which peak represents the true arrival time of interest. Iterative time picking is a method by which the derived location and the velocity model are fed back into the time picking process to resolve this ambiguity and refine the time picks.

To implement this technique, an initial set of time picks is derived from the data using whatever processing techniques are desired and these initial time picks are used to derive an initial location estimate with the least-squares minimization process described in the introduction. Using the distance to each sensor from this location estimate and the velocity model used to derive the estimate, a predicted arrival time at each sensor can be determined, with an upper and lower time bound based on expected velocity variations as a result of inaccuracies in the velocity model, in this case ± 300 m/s. The processed data are re-examined and time picks are adjusted to peaks within or directly adjacent to the predicted time window within each signal. These adjusted time picks are used to derive a new location and the process is repeated until the location no longer varies significantly between iterations.

Figure 2 displays the effects of several combination of the processing techniques described above. As more of the techniques are applied, the arrival time becomes more readily selected, but the accuracy of the time pick may degrade due to distortion introduced by the processing. By examining the location results using time picks from real data with different combinations of techniques applied, it is hoped that an optimal combination of techniques can be determined.

Figure 2: Effects of different combinations of processing techniques on a data trace. Resulting time picks at the peak of each function are shown by vertical bar with S label.

3. VELOCITY MODEL DETERMINATION

The determination of the seismic velocity model is the second critical aspect in accurate determination of locations from UGS. Presently, the location algorithm uses an inversion model made up of a one-dimensional velocity model (velocity as a function of depth) with added fixed-time station corrections to adjust for localized variations in velocity and sensor elevation if desired. The appropriate parameters for the velocity model can be determined through passive listening of activities at the

Figure 3: Location of sensors (dots) and calibration explosions (asterisks). Shaded area is region containing targets.

Figure 4: Arrival time differences as a function of distance from the reference station. Solid lines represent least-squares linear fit to data closer than 600 m (1200 m/s) and data farther than 600 m (1320 m/s).

site with unknown origin times and locations and using relative travel times between stations, or by actively creating sources at known locations and times and determining absolute travel times.

For the current study, an array of 20 sensors was deployed in the vicinity of the target region (Figure 3) within 600 m of the sources. An additional linear array of four sensors not shown in the figure extended to the northeast to a range of 2.5 km from the source region. The study site encompassed primarily a limestone ridge with some sensors located in an adjacent valley filled with alluvium and volcanic deposits. Topographic relief was significant with a maximum difference of approximately 125 m.

3.1. Velocity model determination through passive listening

Arrival times were picked for numerous uncontrolled events at various locations. The sensor with the earliest arrival time was chosen as the reference station for that event and the travel time difference to each other sensor versus the distance to each other sensor was plotted (Figure 4). The distribution of arrival times fell into two different regions, sensors within 600 m from the source and sensors at distances greater than 600 m from the source, indicating a two-layer velocity model. A linear least-squares fit can be done to the data in each of these regions with the inverse of the slope of the resulting line giving the average velocity for the region. The resulting approximate velocities of 1200 m/s for the near-source region and 1320 m/sec for sensors beyond 600 m range give the basic values for the average velocity model used in the location inversion process. Velocity values in this range for limestone indicate that the waves generated by the targets of interest consist primarily of shear (S) waves or surface waves, which travel at approximately 0.9 of the shear wave velocity. Since all of the sensors used in the inversion process are within the 600 m range, the average velocity model used for the site was a simple homogeneous model with a velocity of 1200 m/sec. This average velocity model was used as the first inversion model tested.

The amount of scatter in the arrivals shown in Figure 4 indicates that there is a great deal of localized velocity variation within the site. To attempt to compensate for this, the arrivals were grouped by sensor and the difference between the arrival times calculated with the homogenous velocity and the measured arrival times were calculated. The resulting time corrections for each sensor with error bars of $\pm$ one standard deviation are shown in Figure 5. The sensor corrections show trends that agree to some extent with the known geology of the site. For example, sensors B1 and C3 lie in the valley adjacent to the limestone ridge within the lower velocity alluviums and volcanics, so it would be expected that their recorded travel times would be longer than those predicted by the homogeneous velocity model. The resulting time correction should work to alleviate this error by subtracting some time amount from the measured arrival times, and indeed this is the case.

The second inversion model tested, the station corrected model, uses the same average velocity model as described above, but applies these station corrections to the measured travel times prior to inverting for the location.

3.2. Velocity model determination through active surveying

A second velocity model was determined through the use of controlled explosions or shots at three different locations around the seismic network (Figure 3). With a controlled source at a known location with a known time, the measured travel times no longer are plotted relative to the closest station, but can now be plotted as a function of absolute travel time and absolute distance. Although the number of arrival times determined is much fewer, the accuracy of both the travel times and the ranges is much greater.

The velocities using the active sources were determined in much the same way with a linear fit to the observed data (Figure 6). The two-layer velocity structure of the region is much more apparent in these data. The velocities determined, however, are the compressional (P) wave velocities, as is expected from explosion sources. We assume that the average P-wave velocity determined from the explosion data corresponds to the average S-wave velocity determined from the passive listening, giving us a V_p/V_s ratio of 2.17.

The advantage of the controlled source data is that now we can tailor our velocity model as a function of source zone. Since our target sources are near the location of explosion 1, using only the explosion 1 arrival times to determine a velocity may provide a velocity model that is nearer to what will be encountered by waves generated by our target sources. The P-wave velocity determined in this way is 2875 m/s, which translates to an S-wave velocity of 1325 m/s using the V_p/V_s previously determined. This provides a third inversion model, the zone model, to test during the inversion for location.

Figure 5: Station corrections derived from scatter in data in Figure 4.

Figure 6: Arrival time versus distance data from calibration explosion 1 (diamonds), 2 (squares) and 3 (triangles). Lines show least-squares fit to data with obvious change in slope at 600 m.

Each of the inversion models can be combined with any combination of the processing techniques for time picking to provide a source location estimate. The optimal combination will consistently provide the location estimate that most closely matches the true source location.

4. TESTING OF PROCESSING TECHNIQUES AND VELOCITY MODELS

4.1. Testing of processing techniques

The processing techniques described in section 2 each have advantages and disadvantages relative to the ease with which the time picks can be made and the accuracy of the resulting picks. In order to determine which combination of techniques gives the best location results, a set of 11 events from two different target types were analyzed, using both initiation and shut-down portions of the target signatures. Crosscorrelation (C) was used in every analysis with the following combinations, or streams, of additional processing techniques: crosscorrelation/filtering (CF), crosscorrelation/SCOT (CS), crosscorrelation/enveloping (CE), crosscorrelation/filtering/SCOT (CFS), crosscorrelation/filtering/enveloping (CFE), crosscorrelation/SCOT/enveloping (CSE), crosscorrelation/SCOT/filtering/enveloping (CSFE), crosscorrelation/filtering/iteration (CFI), and crosscorrelation/SCOT/filtering/enveloping/iteration (CSFEI).

Time picks for the ten different processing streams were then inverted for a location estimate using each of the three inversion models: average velocity, average velocity with the station corrections applied, and zone velocity. The only exception to this is when the iterative time picking was applied. This technique was only done using the average velocity model due to the processing time involved with this technique. Both a 2D (lateral location) and full 3D (lateral location plus depth) location were calculated for each set of time picks and velocity models.

The derived location estimates were then compared to the known target locations and a location error was produced. The degree of location error will vary dependent upon such things as time-dependent background noise and the number of sensors used in the inversion. To isolate the processing effects from these other considerations, the location errors were normalized by the median of the location errors from all the processing technique combinations applied for each particular event and each velocity model. In this way, the techniques that gave better results would have normalized values of less than one and those with less accurate results, a normalized location error of greater than one. The normalized location errors were then averaged for each processing stream over all the events and all the velocity models to obtain a final average normalized location error for each stream.

The average normalized location errors for both 2D and 3D locations are shown in Figure 7. As expected, the 3D locations are more sensitive to the processing stream primarily due to the decreased stability of the depth variable in the inversion process. Both 2D and 3D location errors show the same general trends, however, the most surprising of which is that crosscorrelation by itself does as well as any combination of processing techniques until you add the iterative time picking technique. For a simple 2D location, even the addition of iterative picking only improves the location accuracy slightly and then the improvement is only statistically significant at a 50% probability level.

For 3D locations, the three processing streams that give essentially the same accuracy are the C, CFS, and CSFE streams. The added processing time above and beyond simple crosscorrelation appears only necessary for the ease of use of the operator, since time picks are more readily apparent with CSFE processing. In addition, as the process streams become more fully automated, the more processed traces may have better automatic time picks. The real advantage is in the use of the iterative time picking. Here the improvement is statistically significant and it is recommended that this process be employed no matter what other processing techniques are used.

Using just one processing technique in addition to crosscorrelation appears to have a detrimental impact on the location error, especially the SCOT without any low pass filtering. This is a result of the boosting of the high frequency noise by the application of the SCOT making accurate time picking more difficult. The Hilbert transform envelope appears to have little effect on the accuracy of the location as can be seen by comparing the CF and CFE results and the CFS and CSFE results, though again it may have some impact in the automation of the time picking.

Figure 7: Average normalized location errors for both 3D (a) and 2D (b) locations for various processing streams.

4.2. Testing of inversion velocity models

To compare the effect of the inversion velocity models, the derived location errors were again normalized, but this time by the median of the errors of all the inversion velocity models and all the processing streams for each event as opposed to previously where each inversion velocity model was normalized separately. Since the iterative time picking was only applied to the average inversion model data, processing streams using this technique were not included in these calculations. The results shown in Figure 8 show similar trends as noted above in the location accuracy as a function of the processing stream with a few exceptions. The average model shows trends indicating slightly better results than the zone model, but not with any statistical significance. The station corrections, however, have a great negative effect on the location estimates and should not be used in their current form. This is most likely a result of the assumption that the timing differences are a result of localized effects around the sensor. This might be the case if, for example, only elevation differences were causing the timing error. In our case, however, not only are there significant elevation differences, but there are also significant geologic differences. Times that differ from the average velocity model are no longer just a function of the sensor location, but also a function of the source location and the complexity of the travel path from source to sensor. In these cases, station corrections will not perform properly and indeed have a detrimental effect on the location accuracy.

Figure 8: Comparison of normalized location error as a function of both processing stream and velocity model. Results shown for average velocity model (light gray), zone 1 velocity model (white), and average velocity model with station corrections applied (dark gray).

5. CONCLUSIONS

Analysis of the errors resulting from location estimates made from time picks with ten different processing streams and inverted with three different velocity inversion models, have shown that the greatest effect on the accuracy of the location, beyond simple crosscorrelation, is derived from iterative time picking. Additional processing techniques can be applied to improve the ease and automation of the time picking process, but must be applied judiciously and in conjunction with other appropriate techniques to avoid degrading the location estimate.

Additional location accuracy resulting from changes in the homogenous velocity model does not appear to be possible. Attempts at adding station corrections do more harm than good due to the complexity of the site and the inaccuracies in the derived station corrections. Any further improvements will require moving to a full 3D velocity model and the ability to implement this 3D model in the inversion code.

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