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GEOPHYSICAL TOMOGRAPHY IMAGING SYSTEM

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ABSTRACT

The Cooperative Research and Development Agreement (CRADA) between Lockheed Martin Energy Systems, Inc., and Geophex, Ltd., was established to investigate high-resolution, shallow acoustic imaging of the subsurface. The primary objectives of the CRADA were accomplished, including the evaluation of a new tomographic imaging algorithm and the testing and comparison of two different acoustic sources, the hammer/plate source and an electromagnetic vibratory source. The imaging system was composed essentially of a linear array of geophones, a digital seismograph, and imaging software installed on a personal computer. Imaging was most successful using the hammer source, which was found to be less susceptible to ground roll (surface wave) interference. It is conjectured that the vibratory source will perform better for deeper targets for which ground roll is less troublesome.

OBJECTIVES

A key objective of this CRADA was the testing of a new diffraction tomography algorithm designed for acoustic, high-resolution imaging of the shallow subsurface. A secondary objective was to evaluate different acoustic sources and compare their relative effectiveness. Potential applications of shallow acoustic imaging are numerous, including the detection and characterization of buried solid waste, unexploded ordnance, and clandestine man-made underground structures associated with treaty verification (e.g., tunnels, underground storage facilities, hidden bunkers).

The original CRADA statement included the objective of integrating and packaging a compact imaging system, but it was found that a commercial seismograph, in this case the EG&G Geometrics StrataView 75095, was ideally suited for the digital recording and storing of the acoustic data. This instrument, together with an array of geophones and a personal computer, comprised the essential hardware components of the imaging system. The seismograph offers automatic gain control, 18-bit reso-
solution, floating-point digital filtering and high-capacity digital storage (120 Mbytes) from which the stored data can be downloaded to a personal computer for image reconstruction. There was an early concern that the A/D sampling rates required for shallow imaging at higher frequencies might exceed a commercial instrument's capability, since such instruments are generally used for recording seismic data from deeper structures at lower frequencies. It was decided, however, that the Strataview could meet the required specifications (i.e., A/D rate, sample resolution and storage capacity), thus avoiding the cost of assembling a customized digital data-acquisition system.

An additional CRADA objective was the investigation of different acoustic sources. The first of these was an impulsive source produced by striking a steel plate on the ground with a sledgehammer. This approach has the advantages of portability and ease of use but the drawback of a relatively limited frequency spectrum extending to a few hundred Hz. On the other hand, one apparent advantage of the hammer source, at least for the shallow target investigated, was that it was less susceptible to contamination of the data from ground roll (surface waves). A second source tested was a commercial electromagnetic vibrator that transmits a sinusoidal wave into the ground. This vibratory system was originally designed for subsurface profiling based on the frequency-dispersion of surface waves. It proved to be more prone to creating ground roll in the data, as discussed later. A third source, built by Geophex, consisted of a continuous wave signal fed to an audio speaker coupled to the ground through the air. For the buried test target used, this source appeared to be too weak; but it may still show promise for very shallow imaging (e.g., of objects a few feet in depth). Advantages of this source include its simplicity, ease of use, and versatility; for example, a wide range of frequencies and transient waveforms can be readily generated. However, it is felt that the speaker source needs more experimentation to evaluate its capabilities.

A new filtered backprojection algorithm was applied to the data to reconstruct subsurface images. The algorithm worked well on the hammer data, but provided poorer images for the vibratory data due to severe ground roll contamination. This algorithm is described in detail in a later section.
To summarize, the primary objectives of the CRADA have been achieved, namely the demonstration of a new tomographic algorithm and the evaluation of several different acoustic sources. The tests clearly show that ground roll is a significant problem for very shallow imaging and that, currently, the impulsive hammer source appears to be more effective in minimizing ground-roll artifacts.

SPONSOR BENEFITS

The work reported here was supported by the DOE Office of Nonproliferation and National Security (NN-20). A key concern of this office is the detection of man-made underground structures for the purpose of treaty verification and arms control. Acoustic imaging should be effective in the high-resolution characterization of such structures once they have been found. Acoustic techniques are not particularly well suited for broad-area searches, however, because deployment of equipment is relatively labor-intensive compared with other geophysical methods, such as magnetometry and electromagnetic induction. High-resolution, shallow acoustic imaging could, however, be very beneficial in other areas of interest to DOE, such as imaging buried waste and detecting unexploded ordnance.

TECHNICAL DISCUSSION

A. Imaging Algorithm

This section describes the principles of the imaging algorithm. For simplicity, it is convenient to model the medium as a distribution of discrete scatterers in which the $i$-th scatterer has scattering strength $\sigma_i$. The scatterers are assumed embedded in a medium of constant velocity $v_0$. It is possible to generalize the theory to include a background velocity that is spatially varying (e.g., a layered earth), but this was not attempted in the current work. Suppose that the scatterers are illuminated by a single acoustic source modeled as a point source, and assume that an array of $N$ geophones lies along the $z$-axis with coordinates $z_n, n = 1, \ldots, N$ (the geophones need not be evenly spaced). Let the $z$-coordinate denote depth into the earth. Here, a two-dimensional problem is assumed, in which the scatterers lie in the $x$–$z$ plane.
However, the theory can be readily generalized to three dimensions, in which case the linear array is replaced by an area array.

Consider for the moment a single point scatterer located at \((x_i, z_i)\) and illuminated by a source at \((x_m, 0)\). If an impulse were emitted by the source, then the round-trip arrival time, \(\tau_{mn}(x_i, z_i)\), of the scattered acoustic waveform recorded by the geophone at coordinates \((x_n, 0)\) would be given by

\[
\tau_{mn}(x_i, z_i) = \left( \sqrt{(x_i - x_m)^2 + z_i^2} + \sqrt{(x_i - x_n)^2 + z_i^2} \right) / v_0. \tag{1}
\]

Thus \(\tau_{mn}(x_i, z_i)\) merely denotes the round-trip delay from the \(m\)-th source to the \(i\)-th scatterer to the \(n\)-th geophone.

To describe the imaging algorithm, let \(f_{mn}(t)\) signify the time-domain waveform recorded by the \(n\)-th geophone when using the \(m\)-th source. Now define \((x_i, z_i)\) as the coordinates of an image point. Denoting by \(I(x_i, z_i)\) the value of the image at \((x_i, z_i)\), the imaging algorithm is defined by the following equation:

\[
I(x_i, z_i) = \sum_{m=1}^{M} \sum_{n=1}^{N} \tilde{f}_{mn}[\tau_{mn}(x_i, z_i)], \tag{2}
\]

where \(\tilde{f}_{mn}(t)\) is a filtered version of the data \(f_{mn}(t)\), \(\tau_{mn}(x_i, z_i)\) is the delay computed from Eq. (1), and \(M\) and \(N\) are, respectively, the number of sources and geophones. The filter applied to \(f_{mn}(t)\) to give \(\tilde{f}_{mn}(t)\) is discussed shortly.

The above imaging formula can be interpreted as a form of limited angle tomography. This interpretation is useful in deriving an optimal filter to be applied to the time-domain signals prior to summation. The tomographic interpretation can be explained as follows. A particular time point in the trace \(f_{mn}(t)\) comprises the sum of all signals scattered from the locus of points in the (2-D) scattering medium consisting of an elliptical path whose foci lie at the \(m\)-th source location and the \(n\)-th geophone location. To state this more precisely, for a given image point \((x_i, z_i)\), this path is the locus of points \((x, z)\) for which \(\tau_{mn}(x, z) = \tau_{mn}(x_i, z_i)\), where \(\tau_{mn}(x, z)\) is defined by Eq. (1). From a different perspective, the value of the received signal at a particular point in time is the path integral of a reflectivity function along this elliptical path (i.e., the sum of all scattered waves originating from points along this path). The summation procedure defined by Eq. (2) thus represents, in tomographic parlance,
the process of backprojecting (i.e., summing) the signals over all elliptical paths that intersect the image point under reconstruction. For an array of finite length, the elliptical paths do not intersect the image point from all directions, and one actually has the analogue of a limited-angle tomographic reconstruction problem. It is well known that, for a proper tomographic reconstruction, an optimal filtering operation needs to be applied to the projections prior to backprojection. The classic tomographic filter has a transfer function of the form $|\omega|$ out to some band limit, beyond which it cuts off. A similar “tomographic” filter can be applied to the time-domain data prior to summation. As a general rule, the $|\omega|$ frequency weighting function has more impact when the signals are very wideband, which is desirable, and relatively little impact when the signals are narrowband.

Suppose that the form of the received pulse scattered from an isolated point scattered is known (or measurable) and is given by $p(t)$. If we regard the source–earth–geophone as a linear system, then $p(t)$ is its impulse response. Let $P(\omega)$ denote the Fourier transform of $p(t)$, and assume that $P(\omega)$ begins to drop off significantly beyond some cutoff frequency $\omega_c$. The following “tomographic” filter can then be employed with transfer function $H(\omega)$, defined by

$$H(\omega) = \begin{cases} \frac{|\omega|P(\omega)^*}{|P(\omega)|^2 + \epsilon_0}, & |\omega| \leq \omega_c \\ \frac{|\omega_c|P(\omega_c)^*}{|P(\omega_c)|^2 + \epsilon_0}, & |\omega| \geq \omega_c, \end{cases}$$

(3)

where $\epsilon_0$ is a Wiener–like noise parameter and $^*$ denotes complex conjugate. The parameter $\epsilon_0$ may be empirically determined, although if Eq. (3) is interpreted as a form of Wiener filter, then $\epsilon_0$ plays the role of the average power spectral density of the noise. Note that beyond the cutoff $\omega_c$, the transfer function goes to zero as $P(\omega)^*$.

Now suppose that the backscattered wave is of the general form

$$f(t) = \sum_i \sigma_i p(t - t_i),$$

(4)

where the sum is over the scatterers and $t_i$ is the round–trip time delay associated with the scatterer of strength $\sigma_i$. If $F(\omega)$ is the Fourier transform of $f(t)$, then the Fourier transform of Eq. (4) is
\[ F(\omega) = P(\omega) \sum_i \sigma_i e^{-i\omega t_i}, \]  

and from Eq. (3) the filtered signal is

\[ \tilde{F}(\omega) \equiv H(\omega)F(\omega) = \frac{|\omega||P(\omega)|^2}{(|P(\omega)|^2 + \epsilon_0)} \sum_i e^{-i\omega t_i}, \]

for \(|\omega| \leq \omega_c\). Thus when \(|P(\omega)|^2 \ll \epsilon_0\), the frequency weighting in front of the sum reduces approximately to the correct tomographic transfer function \(|\omega|\), as desired. If \(P(\omega)\) is extremely narrowband, that is, if \(P(\omega)\) peaks up about some center frequency, then the \(|\omega|\) weighting in Eq. (6) will, as noted, have relatively little effect on the filtered signals. However, even if the \(|\omega|\) factor varies insignificantly over a narrow bandwidth, the factor \(P(\omega)^\ast\) in \(H(\omega)\) defines essentially a correlation (or matched) filter, which gives rise to a symmetrical transformed pulse. Upon transforming Eq. (6) back into the time domain, each of these symmetrical pulses will be precisely centered on the delays \(t_i\). This is advantageous, since if the original pulse \(p(t)\) is asymmetrical and no filtering is performed, the times \(t_i\) may not coincide exactly with the pulse peaks; and the coherent summation defined in Eq. (2) must be performed with care to take this into account. The above filtering scheme avoids this problem.

To summarize, the recorded acoustic signals are first filtered in the Fourier domain by multiplying by the transfer function (3) and then inverse transforming. This was accomplished with the aid of the fast Fourier transform algorithm. Other filtering operations can be conveniently applied at this stage, such as high-pass filtering to reduce ground roll. After filtering, the signals are summed over all source and geophone coordinates in accordance with Eq. (2).

B. Field Tests

A buried, empty 55-gallon drum was employed as a test target. The drum was buried in a test site on the premises of Geophex, Ltd., in Raleigh, N.C. The drum’s axis was horizontal, with its top edge 3 feet below the surface of the earth. Three sources were tested: the hammer/plate source, the electromagnetic vibratory source, and a small audio speaker source. The latter source was found to be too weak to produce a useful response from the target, so signals were not recorded with this
source. However, the speaker source may well be suitable for shallower objects. The hammer and vibratory sources did generate significant scattered energy from the buried target, and data were recorded for both. Two parallel arrays of 12 geophones were placed along a line directly over and centered on the target. The geophones were spaced at 1.5-foot intervals. The geophones were connected to the StrataView seismograph and data were recorded and stored. In the first experiment, the hammer source was employed at 12 source locations parallel to the geophone array. In the second experiment, the vibratory source was used at 6 locations parallel to the array.

The hammer data were recorded and downloaded to a Pentium PC where images were reconstructed using the algorithm defined by Eq. (2). The upper image in the figure is one example. The bright spot in the image represents scattering from the top of the buried drum. This is a reasonable assumption since one would expect little penetration of acoustic energy into or through the drum. Although individual time-domain data traces showed evidence of ground roll, the coherent integration performed by the imaging algorithm on the data from all source/geophone combinations tended, for the hammer data at least, to cancel the ground roll. Moreover, the incident impulse created by a hammer impact produces a surface wave that propagates away from the nearby geophones and thus does not interfere with the subsurface (body-wave) signals for those geophones within some small radius of the source. This may not be the case, however, for the more distant geophones for which the surface-wave and body-wave delays are comparable. One curious result noticed was that the individual data traces were considerably longer than the maximum round-trip delays anticipated to and from the target; this may indicate some resonance phenomenon, for example, circumferential waves around the outside of the drum or multiple-scattering between the drum and the surface.

Images reconstructed using the vibratory source data were of poorer quality due, evidently, to less ground-roll cancellation in the data integration. Because the target was relatively shallow, some surface-wave energy will extend to and below the target, thus contributing to the ground roll artifact. The lower image in the figure was obtained using the vibratory data; note that the target image is displaced to the surface. This image may, in fact, show more evidence of surface-wave scattering from the target and less body-wave (subsurface) scattering, which is consistent with the
image at the surface. One might expect, as a result, that the vibratory source would perform better for deeper targets beyond the reach of the surface-wave displacement.

To summarize, the algorithm was successfully validated on this simple test data set. Improvements to the algorithm are possible, such as incorporating the effects of an inhomogeneous background medium (e.g., a layered earth). Differences in performance between the two sources were observed, but this difference may be partly a consequence of the nature and depth of the particular test target employed.

DISCUSSION AND CONCLUSIONS

No inventions were created in this work, but commercial possibilities could arise out of the development of the imaging algorithms and software, although further research would be desirable. Further experimentation with new sources is certainly needed, as well as the development of methods for reducing the effects of ground-roll interference. Ground-roll minimization could be attempted in software by filtering or by exploiting optimal spacings of sources and geophones. The contractor has worked in the past with Geophex on analyzing other geophysical data, and future collaborations on acoustic techniques are expected. New opportunities to continue the development of acoustic tomography should arise in the context of jointly funded research or contract work by Geophex on the detection of unexploded ordnance or buried waste.
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