Ph.D. Research Proposal

Passive Seismic Imaging

Brad Artman[1]

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LELAND STANFORD JUNIOR UNIVERSITY
ORGANIZED 1891

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[1] **email:** brad@sep.stanford.edu

ABSTRACT

The passive seismic imaging problem

For 35 years, the theory for passively imaging the subsurface of the earth has been available to the seismic exploration community. The proof that the information contained in a transmission record is fundamentally related to the reflection seismic experiment allows for the manufacture of seismic cross-sections of the earth without the use of an energy source. While this theory has stood in the literature, it has not graduated to the seismic toolbox as a practical methodology available for answering subsurface questions in the exploration community.

According to Claerbout's 1968 article, a seismogram recorded at the surface due to a buried source (transmission record) carries the same information as the recording from a surface source and receiver at the same location. The relationship is shown as the auto-correlation of the transmission record being equivalent to the reflection seismogram record.

Thus, without requiring the application of a source, this relationship allows for the manufacture of subsurface images with conventional seismic processing techniques by first correlating the passive seismic recordings. These stations can be distributed across the surface of the earth, left to record the ambient noise-field, and then the data retrieved for processing without mobilizing a synthetic source or waiting for earthquake events.

Importance to the scientific community

The manifold utility of imaging the subsurface has been proved repeatedly in engineering, characterization, monitoring, and exploration applications. Academic interest in imaging the subsurface abounds with investigations ranging from a few kilometers depth to the crustal scale. Seismic investigation of the near and deep subsurface finds ready customers in any one or several of the above communities with existing reflection experiment methods. The practicalities and costs of reflection seismic data acquisition however, particularly the mobilization of people and equipment to new and removed sites, sometimes makes acquiring a survey, or repeated surveys, undesirable or impossible.

Specifically, the man-hours, permitting, and materiel associated with the seismic source are burdensome. Geophones, however, are fairly inexpensive, can be laid out and retrieved quickly, and even fixed in the field permanently if usable information can be routinely produced. The passive seismic imaging experiment, capitalizing on the ambient noise-field in the earth, has the potential to alleviate the problems and costs of source detonation by not requiring the application of a source at all. This could be of immense utility to academic earth investigators who are typically cash constrained.

Not needing an active source could greatly increase the number of sites available for any community to investigate as the permitting process will be much easier without the introduction of heavy source trucks or explosives. Last, with an instrumented monitoring program deployed in the field, repeated images of the subsurface collected over time can be of immense value to the monitoring of temporal processes in the subsurface. The most obvious application is to fluid flow (water, hydrocarbons, contaminates), though structural monitoring of tectonically active regimes would also be applicable. Further, if the methodology is shown effective for large scale deployments such as the Santa Clara Valley Seismic Experiment (to be introduced later) it can add a previously unexplored look into the subsurface using available data sets or proposed deployments.

Proposal to address the validity of the method

I propose to answer whether or not the passive seismic experiment as outlined below can be used as a practicable methodology for subsurface imaging and/or monitoring. Answered in the affirmative, I will delineate the range of subsurface parameters necessary to the success of this type experiment as well as estimate the sensitivity of the methodology to common earth parameter ranges. Conversely, if the various investigations to be described fail, it will be important to fully understand the reasons underlying its failure so as to put to rest the question of applicability of this methodology to the exploration seismic community.

Toward answering this question, the data driven nature of this department and this science makes the acquisition of passive seismic data sets imperative to accomplish this goal. Thus far, I have secured several firm commitments to acquire exploration oriented data sets and more efforts are still pending. Data from the solar and earth seismology and volcanic monitoring groups are also available for manipulation. Finally, I have collected a small scale data set on the beach at Moss Landing. The following list reflects the specifics of each:

- 1000 channel linear acquisition riding on a planned mobilization in Southern California by the United States Geological Survey (USGS). **Confirmed, September 2002**
- 1000 channel linear acquisition riding on a planned mobilization in Santa Clara Valley, by the United States Geological Survey (USGS). **Confirmed, September 2002**
- $\sim$ 10K channel areal acquisition riding on a planned mobilization in South Texas by the Compagnie Générale de Géophysique (CGG). **Confirmed, August 2002**
- 65536 channel areal acquisition around a solar flare on the sun by the Stanford-Lockheed Institute for Space Research. **In-house**
- 48 channel areal acquisition within the Santa Clara Valley by the USGS. **In-house**
- 72 channel areal acquisition over buried objects and water table on Moss Landing beach by me. **In house**
- 960 channel parallel linear acquisition of ocean-bottom cable (OBC) passive seismic by Petroleum Geo-Services previously acquired. **In transit**
- Unspecified linear acquisition by Petroleum Geo-Services. **Pending**

- 100 channel volumetric deployment of monitoring stations throughout the INCO nickel mine in Ontario, Canada. **Pending**
- Unspecified areal acquisition by Saudi Aramco. **Pending**
- Various array strategy experiments publicly available in international seismic data libraries. **Available**

With these data sets, I will be able to test the efficacy of the passive imaging premise for two and three dimensions. The availability of these data sets is immensely important to the success of this research. Furthermore, the availability of several data sets of such widely varying nature will facilitate a thorough investigation into the practicality and use parameters of this novel seismic tool. This research will conclude upon the understanding of how and when to use the passive seismic experiment or the reason(s) that it fails us.

INTRODUCTION

Theory

In order to conceptualize the details of the experiments I propose, we must first define the earth-model and geometry needed to develop the mathematics that underly the passive imaging idea. Figure 1 shows the original 1D layered model used to arrive at the auto-correlation conjecture of equation (1) posited in Claerbout (1968). I will present the argument in the Fourier domain through the use of the Z-transform. I will define $U(Z)$ as the transmission wave-field, and the wave-field measured in the reflection experiment as the sum of the source, the up-coming, and the down-going wave-fields $1, R(Z)$, and $R(\frac{1}{Z})$ respectively. The simplified proof of the auto-correlation relationship in Claerbout (1979) finishes with the result

$$1+R\left(\frac{1}{Z}\right)+R(Z) \quad = \quad U\left(\frac{1}{Z}\right)U(Z) \tag{1}$$

to within a constant of proportionality.

The proof of relationship in equation (1) begins by considering the conservation of energy through each layer after the assumption that that U wave-fields in both panels of Figure 1 are equivalent through reciprocity. Conserving energy propagating through each layer without loss means that the sum of the spectra of up- and down-going wave-fields times the impedance (Y_i) in each each layer must be the same. Therefore

$$\begin{aligned} Y_1\left\{-R\left(\frac{1}{Z}\right)R(Z)+\left[1+R\left(\frac{1}{Z}\right)\right][1+R(Z)]\right\} &= Y_k U\left(\frac{1}{Z}\right)U(Z) \\ 1+R\left(\frac{1}{Z}\right)+R(Z) &= \frac{Y_k}{Y_1}U\left(\frac{1}{Z}\right)U(Z)\,. \end{aligned} \tag{2}$$

This 1D proof with auto-correlations on the right side of the equations can be bolstered by our intuition considering Figure 2 below. The cartoon in panel **a** shows incident plane-wave

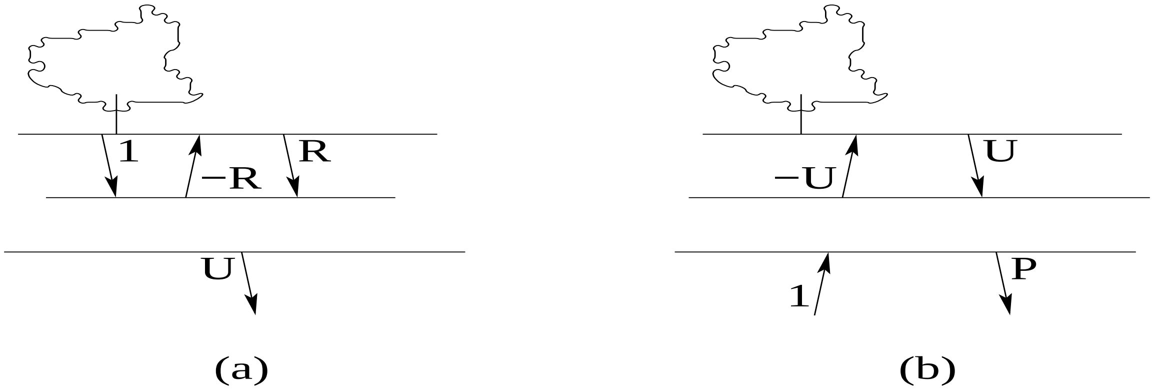


Figure 1: Panel (a) shows wave-fields representative of the reflection seismic experiment. 1 represents an impulsive source, $-R$ is the up-going wave-field and R is the down-going wave-field in the first layer. Energy escapes past our notice into the earth as U. Panel (b) is representative of the seismologic geometry where an incident wave-field, 1, propagates through the surface layer as $-U$, is reflected by the free-surface to return to depth as U and finally as the unrecoverable quantity P. The wave-fields U in the two panels are equivalent due to reciprocity. (after (Claerbout, 1979) $\boxed{\text{1d}}$ [NR]

energy reflecting from the surface and then again on a subsurface reflector. We see then that the energy arriving at receiver $r1$ acts as a source for the reflection recorded at receiver $r2$ in the time series represented in panel **b**. Inspecting this diagram, we notice that energy arriving away from vertical will not reflect back to the location of the *source*-receiver. Therefore, correlation of traces between each other, as represented with panel **c**, may be useful as well as the auto-correlation indicated by equation (2). Thus our intuition can guide us to extend the 1D proof offered above to a laterally variable earth-model by decomposing our wave-fields into plane-wave constituents.

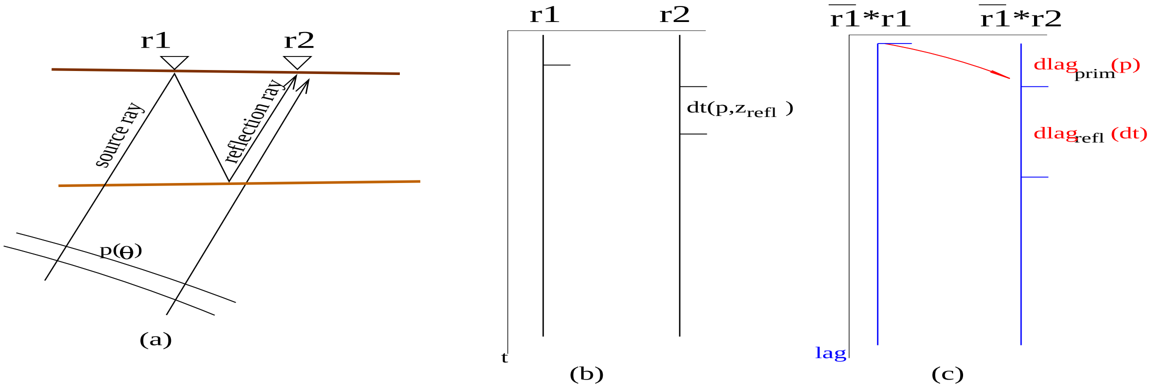


Figure 2: (a) Cartoon showing the incident plane-wave energy reflecting from the free surface and then again from a buried reflector. (b) Time-series built from arrivals depicted in left panel. (c) Correlations of signals from receivers $r1$ and $r2$. $\boxed{\text{noise}}$ [NR]

Zhang (1989) provides the formalism for this idea through the use of plane wave decomposition of a wave-field. The auto-correlation of traces from surface recorders capturing a transmission wave-field, $u(x,t)$, after cascade through transformations to the slant-stack (barred variables) and frequency (capital variables) domains, will be defined as $\bar{Q}(p,\omega)$. Therefore,

$$\bar{Q}(p,\omega) \;=\; \bar{U}(p,\omega)\overline{\bar{U}(p,\omega)}\,. \tag{3}$$

This means that $\bar{Q}(p,\omega)$ is the reflection data calculated by equation (1) for any specified ray-parameter, p. Working back toward an interpretable domain, we need an inverse slant-stack transform followed by inverse Fourier transform. The first step is

$$\begin{aligned} Q(k,\omega) &= \frac{1}{|\omega|}\bar{Q}(\frac{k}{\omega},\omega) \\ &= |\omega|\,U(k,\omega)\overline{U(k,\omega)} \end{aligned} \tag{4}$$

through the identities

$$\bar{X}(p,\omega) \;=\; |\omega|\,X(\omega p,\omega) \quad \text{and} \quad p \;=\; \frac{k}{\omega}\,.$$

The inverse discreet Fourier transform of equation (4) then is

$$q(x,t) \;=\; \rho(t)\sum_{x'}\sum_{t'} u(x',t)\,u(x+x',t+t')\,. \tag{5}$$

Ignoring the $\rho(t)$ proportionality term, we notice that we can decompose this double sum into a sum over position of cross-correlations between time series recordings at positions $u(x')$ and $u(x)$. Naming this correlation function $r_{x',x}(t)$, equation (5) becomes

$$q(x,t) \;=\; \sum_{x'} r_{x',x+x'}(t)\,. \tag{6}$$

The remaining sum in equation (6) stacks the correlations to the zero-offset position that the auto-correlation step of equation (1) implies. Note that the summation operates along the diagonals of the correlation cube (constant offset sections). This results in loss of spacial integrity of the output. Given a stationary model, like the solar data set to be introduced later, this summation makes no difference. If, however, we hope to image a laterally inhomogeneous subsurface, this summation is best left out of the processing flow. Thus, $r(x',x,t)$ taken before summation over x' represents a volume of *pseudo*shot-gathers like shot-records from a conventional acquisition. This allows us to manipulate the correlation volume as we would the multi-dimensional data-space from a conventional reflection seismic experiment.

Status

The exploration community has not definitively answered the questions of how and under what circumstances to apply this idea to the suite of subsurface issues that face them. Small-scale experiments to test the premise have been performed utilizing the ambient noise-field (Claerbout et al., 1988) and a rotating drill-bit (Yu and Schuster, 2001). Results from the experiment using the ambient noise-field showed limited success that neither disproved the method as infeasible nor generated convincing arguments for its utility. The auto-correlation migration of drill-bit data returned a usable subsurface profile that corroborates the fundamental tenet of the conjecture and fuels the effort to fully explore the capabilities of the proposed methodology.

The seismologic community is steadily progressing toward the idea of passive imaging. Currently, array transmission records can be inverted for subsurface structure and properties from both forward scattering of an incident wave-field and the backscattered reflections from the free surface. Both methods however require knowledge of earthquake source energy and are thus not truly passive.

The engineering community has, with the work of Louie (2001), instituted a form of the passive seismic methodology into their toolbox of available methodologies. By passively recording cultural noise, engineers can make site characterization studies with standard reflection seismology equipment. This method does not image the shallow subsurface however.

PREVIOUS WORK

The body of previous work on this subject can be divided into three categories: Stanford Exploration Project (SEP) history, auto-correlation migration, and seismologic inversion. The bulk of this sum is located in SEP reports **60** to **86** during which period the SEP students spent much energy investigating data collected in house and described in Claerbout et al. (1988). A brief revival of the subject later appears with Rickett and Claerbout (1996). The next category includes general correlation migration developed by Schuster and Rickett (2000). Therein, Schuster presents a Kirchoff related prestack migration for correlated passive data sets. Analogous to this effort, Yu and Schuster (2001) shows the migration of data collected from a surface array during drilling operations utilizing the imaging condition of the backscattered wave-field. Finally, Bostock et al. (2001) develops and demonstrates a methodology very similar to the previous one. Using teleseismic event energy, Bostock inverts for rock parameters and structure for crustal scale investigations.

The history of investigation into the passive imaging concept at SEP is extensive and rich. Having deployed an experiment to investigate this problem in 1988 and subsequently working on this data set for the next few years, former students have provided a wealth of insight and infrastructure unparalleled. Unfortunately, true imaging of the subsurface was not possible due to complicated geology, limited areal coverage and, possibly too short recordings. Extensive analysis of this acquisition effort over years after its collection led to much insight, but only proved the existence of steeply emergent energy within the data set. While the success of my imaging project is predicated on the existence of such energy, capturing only a minor amount of this energy did not allow imaging previously. This leaves us with a positive though incomplete result toward proving the practicality of this concept. Through this previous research the power of analysis in the (τ, p)-domain and beam-steering methodologies have been made clear and provide valuable insight for my research. One specific idea that merits immediate attention with currently available data is that presented in Zhang (1989). This work details recasting the imaging problem as a deconvolution using prediction error filters. Promising results on synthetics were presented in that work. Details of this method are provided in Appendix A.

More recently, Rickett and Claerbout (1999) presented results of the correlation methodology applied to a solar seismology data set that was given to SEP by the Hansen Experimental Physics Laboratory at Stanford. Because the subsurface of the sun is laterally homogeneous and density increases with depth smoothly (strictly $v(z)$), the results did not image any deep structure of the sun. However, Figure 3 shows multiple orders of plunging waves that travel down and back up through the subsurface due to the velocity gradient of the sun. The data set donated to the group includes an active solar flare that presents further challenges for imaging to be explored in the near future.

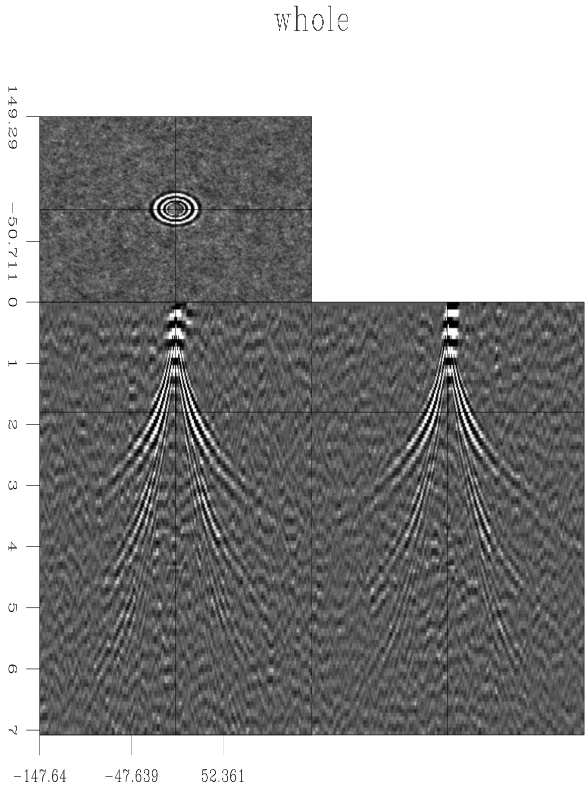


Figure 3: Auto-correlated image of solar data produced by Rickett and Claerbout (1999). Travel-time curves for 1st, 2nd, and 3rd order plunging waves overturning and returning to the surface are brought out through the processing. Somewhere in this data there is a solar flare that I will attempt to image capitalizing on evanescent energy. sun [NR]

The imaging condition presented by Schuster can be focused for the wave-field backscattered from the free surface or the location of an energy source. Both imaging conditions can be used simultaneously if desired. Using a linear array extending from a drill-site, Schuster's group has produced successful images of the subsurface with the imaging condition for the backscattered wave-field. This experiment is directly analogous to the proposed imaging technique. While processing shortcuts were used to capitalize on approximate knowledge of the location of the drill-bit source, the fundamental processing concept is that of the passive imaging experiment described here. Contrary to the proposed method, however, this experiment does use an active source of seismic energy. It should be noted that this migration method requires the correlation of the records from each receiver prior to migration.

Bostock's method is a Kirchoff based development that images reflectors both from the transmission wave-field and the wave-field backscattered from the free surface. Contrary to the previous discussion, this method requires knowledge of the source function, though is tolerant of dispersive wave-trains and long codas. The need for a source function separates this from a truly passive technique. Separation of the incident teleseismic event is accomplished by assuming that shear-wave arrivals between the compressional and shear first arrivals must be due to a mode conversion of a compressional wave-front at the crust/mantle boundary. Accepting some time window around this wavelet as a source function, he compiles similar data sets from major teleseismic arrivals during the deployment of a receiver array. The varying azimuthal coverage due to different epicenter locations provide areal coverage of the subsurface. To date, only linear arrays have been utilized.

COMPLETED INVESTIGATIONS

Is 2D possible?

Full coverage of plane waves arriving from all azimuths and with all incidence angles is necessary to fully illuminate the subsurface for this experiment. Either case of absent ray parameter constituents or over-representation of a few can confound the correlation approach to passive imaging. Also problematic could be energy arriving from perfectly perpendicular azimuths to a linear receiver spread. This energy would have infinite ray parameter values, and be indistinguishable from vertical waves arriving from the deep earth.

To explore this issue, I undertook an analysis of the solar seismic data set in Artman (2002b). This effort showed positive indications that a linear acquisition strategy could provide meaningful results. Similarly, the success of the drill-bit migration scheme of Yu and Schuster (2001) using a linear array also indicates that the azimuthal limitations of a 2D survey will not invalidate the experiment. Figure 4 is the product of only one of the available reciever lines from the solar data, and shows at least the first order plunging waves from figure 3.

Several data sets listed in the abstract are linear acquisition strategies and will directly address this question. Further, the ocean-bottom cable data from PGS enjoys two co-linear cables 600 meters apart that can enhance my imaging ability as concluded in Artman (2002b).

Reformulation as migration

At the SEP annual meeting in April, 2002 I presented a reformulation of the passive imaging concept as shot-profile migration. Inspecting the imaging condition for shot-profile migration

$$I(\mathbf{x},z) = \sum_{\omega} P^{g}(\mathbf{x},z,\omega)\overline{P^{s}(\mathbf{x},z,\omega)} \tag{7}$$

(where P's are geophone and source wave-fields), I noticed that the correlation of the source and receiver extrapolated wave-fields at each depth step should satisfy the correlation for creating shot-gathers in equation (6). Therefore, without making the intermediate processing step

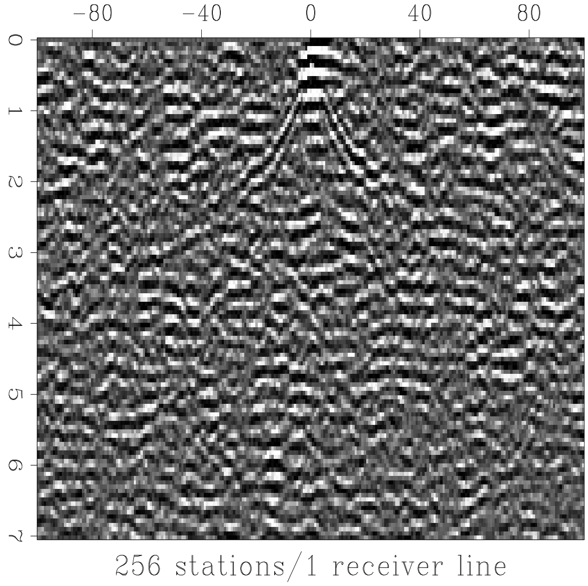


Figure 4: Using only one line of receivers from the data set used to generate Figure 3, this degraded though interpretable image indicates the feasibility of linear acquisition strategies for the passive imaging experiment. $\boxed{\text{2d}}$ [NR]

of correlating all traces with each other, we can use the recorded wave-field as a source and propagate it downward in place of the impulse commonly used in standard migration. This is easily implemented by acknowledging $P^g = P^s$ in this methodology. This is intuitively satisfying when one inspects the cartoon shown in Figure 2 as well. Because each geophone records the incident wave-field reflected at the free-surface and well as the resulting reflections, it is kinematically satisfying to use the same records for both extrapolations.

I tested this hypothesis by modeling a passive data set over an earth-model consisting of two flat reflectors. The raw data reveals nothing but white noise and is not included. The results of the migration are shown in Figure 5. Inspecting this image, we see that the strength of the center of the reflections overwhelms the edges. Because we enjoy a source at every receiver location in this experiment, the data space exhibits a perfect fold ramp from 1 at the perimeter of the survey to the total number of receivers at the center. Undoubtedly, this level of redundant information in the middle of the survey is not necessary and can provide opportunity to limit processing or acquisition efforts.

Inversion

Obvious in the left panel of Figure 6 is the poor quality of the shot-gather generated by the correlation technique described above. The figure is noisy and events are somewhat discontinuous compared to conventional shot-gathers. I produced the right panel of Figure 6 to provide motivation for an inversion technique to improve the quality of the output of the correlation processing. The architecture of such an inversion would take the form

$$\begin{aligned} 0 &\approx Lm - d \\ 0 &\approx Am \end{aligned} \tag{8}$$

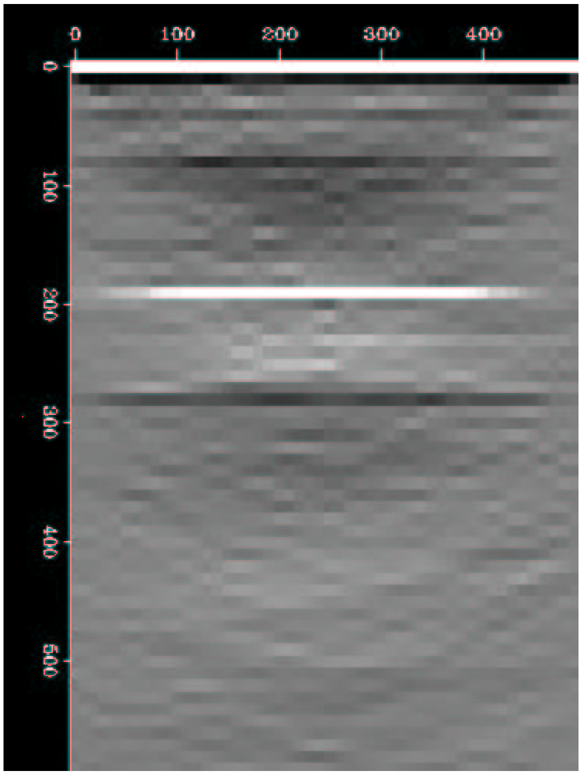


Figure 5: Areal source shot-profile migration of synthetic passive data over a two-layer model. The 0-lag correlation peak has been clipped to show the reflectors. migraw2 [NR]

where d is the raw data, m is the output shot-gathers, L is a convolution matrix and A would be a roughener. The form of L is dictated by the fact that convolution is the transpose of correlation which is required in the least-squares inversion of equation (8). While results of such an inversion are not yet available, the right panel suggest that such an effort will be fruitful because this image is essentially the first step of an iterative least-squares inversion without the inclusion of the regularization operator in equation (8). This treatment not only quiets much of the random noise, it eliminates the virtual multiple seen at 0.1 seconds on the left panel and significantly subdues the fan of direct arrivals.

Sampling the ambient wave-field

Hardware storage limitations may often make the recording of extremely long time series impractical or impossible. Storage of such series from large arrays similarly presents a problem. To investigate methods of ameliorating these problems, I have made several experiments with the modeled data set described previously. The first method is to window long data series into sections an order of magnitude longer than the depth of the deepest target reflection. Stacking these smaller chunks of data should preserve energy that arrives late in the time series. This methodology is forced upon us when a recording unit has insufficient memory or disk space and must stack many short time records rather than continuously recording.

Windowing in the time domain is mathematically multiplication by a box function. Defining the box function with increasing lag times produces the piecing effect described above.

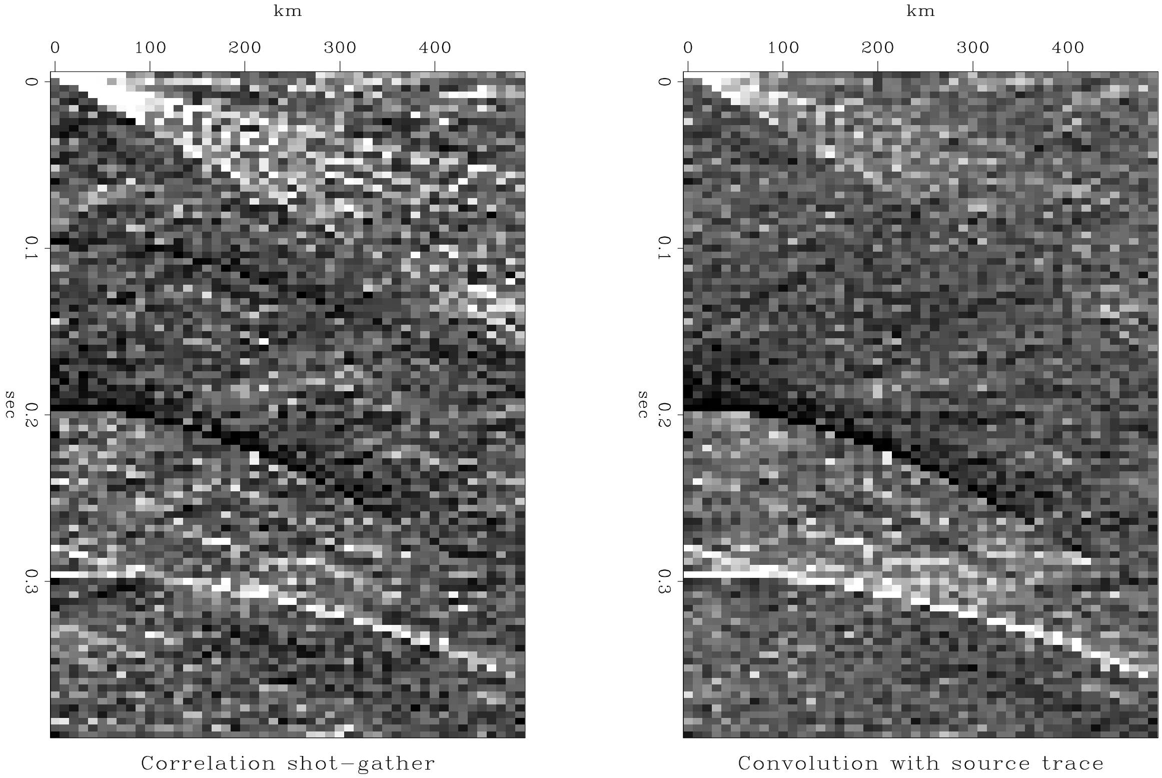
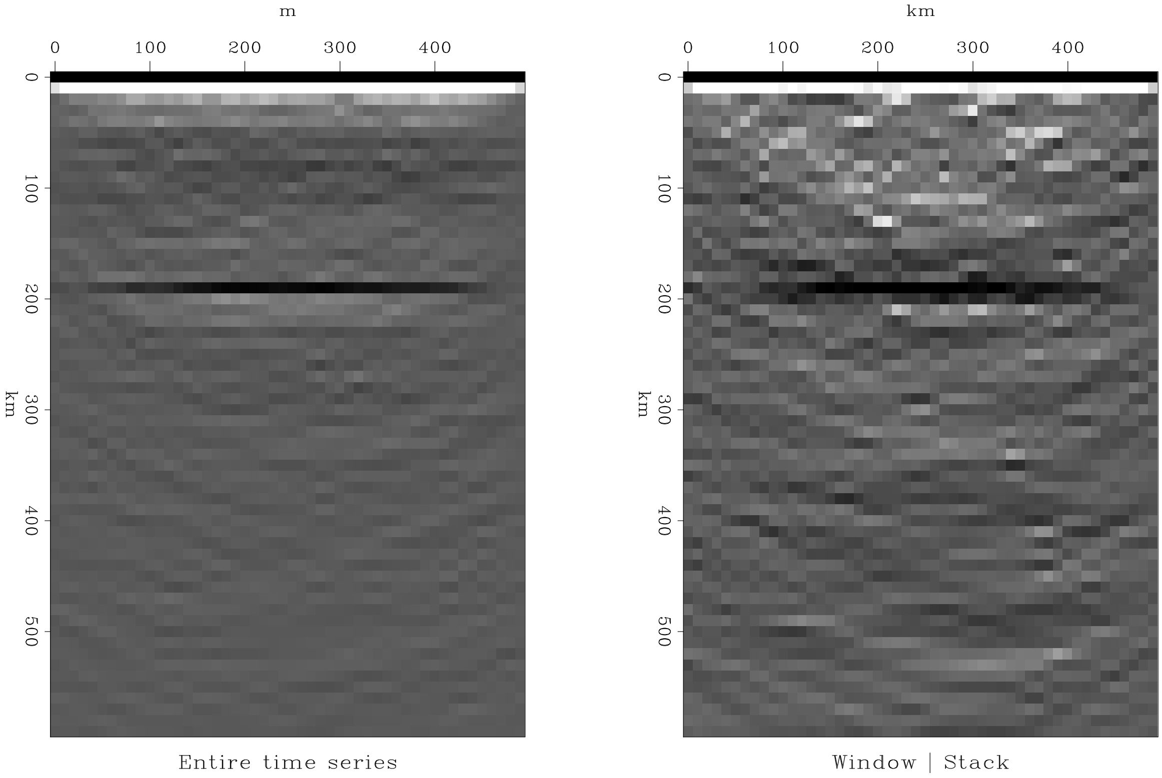


Figure 6: Raw data are generated with 100 random plane waves propagating through a two-layer earth model. Raw transmission traces are correlated with each other to produce pseudo-shot gathers like the left panel. Here the first trace of the raw data is correlated with the others to act as the "source". Notice the linear fan of energy due to the direct arrivals of the plane-waves and the virtual multiple at 0.1 seconds due to the non-zero correlation of the two events with each other (the time from zero to the multiple is the same as the time between the two events). The second panel is the result of convolution of the left panel with the same raw source trace. The cascade of adjoint operators is essentially the first step of an iterative inversion scheme. Many noise features of the left panel are subdued. comp.neg [NR]

In the Fourier domain, we remember that convolution is the dual of multiplication and box function transforms to the $sinc$ function. This process is defined in the Fourier domain as

$$\sum_{k=0}^{N-1} D(Z)\star W(Z) Z^{Lk} \tag{9}$$

where D is the data, W is the windowing function, N is a power of 2 integer computed as the length of the data divided by desired output length L. Thus Z^{Lk} shifts the window function over L samples.



Entire time series

Window | Stack

Figure 7: Stacking windowed sub-series from a single long time-series results in serious degradation of the resulting image. If this were not the case major savings in processing and storage costs could be realized. comp.win [NR]

A comparison of the migration results are shown in Figure 7. The second panel, the result of the window/stack process, is not as clear as when the entire time series is processed as in the first panel. Experiments varying the window length, the padding length, and the order of stacking and padding have all been carried out to little improvement of the image. I believe this is because each windowed sub-series of the data shares an almost identical spectrum in the modeled data (all of them are white). This means that the summation in equation (9) tends toward a simple scaling of the first sub-series. If correlable energy across the receiver array arrives over focused time intervals during field experiments, this problem may not manifest itself. However, if the spectrum of every sub-series is approximately the same, recording the full length trace may be imperative. Experiments to explore this detail are currently underway with the data recently collected at Moss Landing described in the next section.

Shape of the ambient noise-field

Of critical importance to the success of this experiment is the understanding of the necessary characteristics of the ambient noise-field that acts as the source for the passive imaging experiment. The auto-correlation in equation (1) implies that the noise-field should have a white spectrum. In the succesful modeling exercises presented herin, this criteria has been assumed and complied with. However, the successful images of the plunging waves from the solar data are the result of data that does not have a white spectrum.

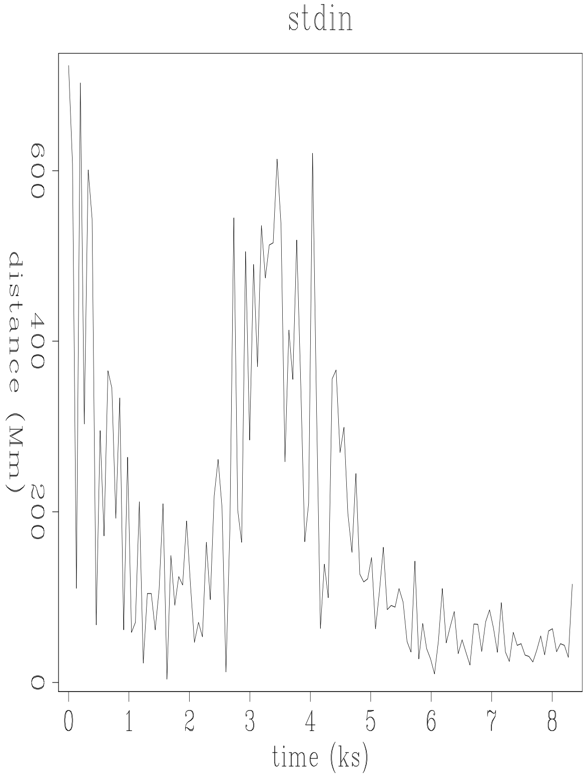


Figure 8: Frequency spectrum of the raw solar data. Figure 3 was produced after a low-cut filter removed the first energy peak. spec [NR]

Analysis of the noise-field of the solar data set has hinted at alternate requirements for success. The spectrum of the data is shown in Figure **??**). The result of the solar exercise by Rickett and Claerbout (1999) shown in Figure 3 was produced using only the hump of middle frequencies in the spectrum. The peak of low frequencies does not provide an image. Deconvolution of the data with a prediction error filter estimated on a band-passed version of the data containing only the middle frequencies produces a somewhat more crisp image than without the deconvolution, but detailed investigation of this result to identify its impact has yet to be completed.

Artman GeoServices

During the week of May 28, 2002 I collected a passive data set on the beach at Moss Landing, California. The sand of this beach provides an outstanding acoustic laboratory. Although the sand is low velocity (275 m/s), very high frequencies (800 Hz) readily propagate over large relative distances with very little attenuation. It is hoped that receiver arrays to attenuate low apparent velocity and low frequency surface energy will not be necessary by operating in the higher range afforded by this site.

Using Ran Bachrach's dense shallow seismic receiver array, I collected passive data during calm mornings, windy afternoons, and quiet nights. A 72 channel Geometrics StrataviewR seismogram was continually triggered to stack five second traces over several hours. Receivers are deployed on a $0.25cm$ square grid. The experiment has four goals:

- Investigate the listening time necessary to generate a robust image.
- Attempt to image four previously identified reflectors: a lithology layer, the water table, a buried pipe, and a buried metal trash can.
- Investigate patch acquisition strategies.
- Investigate effect of stacking short time series compared to long recordings.

Manipulation of the data is presently underway.

FUTURE WORK

Acquiring Data

One of the most important aspects of the work accomplished to date has been the acquisition of one data set and securing commitments from outside sources for obtaining old data and collecting new data. The list of data included in the abstract above is as current as possible, but other sets are currently being solicited, and some listed will invariably fall away. It is my goal to collect as many commitments as possible in hopes of receiving at least four data sets in house. I believe it will be very important to process data representative of as many acquisition parameters as possible to better delineate those that will most readily adapt themselves to this new method. Also important, is the existence of conventional data in the same location to serve as ground truth against which to evaluate the success of this tool.

Artman GeoServices

After evaluating the effectiveness of the Moss Landing beach experiment, I have plans for similar experiments later in the summer. Tentative plans have been made to acquire additional data sets with Ran Bachrach in Michigan with his receiver array over different subsurface environments. Professor Bachrach's system also has the ability to couple the receivers to asphalt surfaces. The experiments will be designed to collect passive recordings in urban environments surrounded by varying amounts of cultural noise.

Contractor data collection

The predominance of data acquisition will take place by organizations outside of the Stanford community. These data will provide the true test-bed for answering the fundamental research objective of this proposal. The bulk of these data are scheduled for delivery late in the summer or fall of 2002, while a few may be ready as quickly as one month from now. Regardless of the order of acquisition, the schedule outlined in the abstract is full.

The details of the individual surveys are predominantly little known at this time. Some surveys have yet to be acquired, or need to be unearthed to investigate. What is known is that the suite of examples to be available will cover a wide range of parameters. Linear, co-linear and areal strategies are included. Receiver spacings of $0.25cm, 12m, 25m, 160ft,$ and $4km$ and others are included in the range of design parameters. After initial work to establish an idea of a standard processing sequence is accomplished, the bulk of these data can be analyzed in moderately short time frames to prepare for a comparative analysis.

Santa Clara Valley Seismic Experiment (SCVSE)

The SCVSE data represents the seismologic data type to which I plan to apply the passive imaging concept. Six months of continuous data records are in-house and ready for manipulation. Preliminary efforts in using this data set have not been successful, but as capabilities for 3D processing evolve, there is still hope for positive results. Because teleseismic event timing is easily available to the public, some 250 earthquake events that occurred while the instruments were in the field may be useful for the processing of the data. By focusing my efforts around, or maybe away from, the arrivals of significant seismic energy I may be able to obtain low frequency structural images of the Santa Clara Valley.

Solar imaging

The plunging waves shown in the results of Rickett and Claerbout (1999) provide a model for the velocity-depth profile of the sun. Having thus obtained a measured velocity model of the sun, I am currently working on imaging the flare contained in the data. Two assumptions about the structure of the flare make imaging its disturbance difficult. First, the lateral contrast in acoustic parameters between the non-disturbed subsurface and the body of the flare are small. Second, the contrast should be geometrically steep.

These two assumptions lead to the conclusion that the signal I will attempt to image is weak and near vertical. Both of these problems are formidable. To solve them, I am close to finishing code for the up-down wave-field extrapolator from Claerbout (1985) that saves evanescent energy during downward continuation of the wave-field. Secondly, absorbing boundary conditions during the extrapolation will be very important to stop spurious correlations among the traces due to energy reflecting from the sides of the model space. I plan to incorporate the work of Shan (2002) into the present architecture to address this problem.

The physicists with the Solar Oscillations Investigation (SOI) project that supplied the solar data set maintain that there is a a large density drop near the surface. It may be possible to image this layer if the change is sufficiently quick compared to the wavelength of our data to allow for a reflection.

Recast as deconvolution

I plan to develop the codes required for analyzing passive seismic data sets as a deconvolution problem as described by Zhang (1989). The SEPlib tools previously developed around application of the helix to multidimensional convolution problems should make this task readily accomplishable. A detailed description of this concept is provided in Appendix A.

Wave-field Separation

Upon inspection of the cartoon of plane-wave energy arriving at the earth's surface in Figure 2, it is clear that each reciever in this experiment records both source and receiver signals. It would be advantageous to be able to separate the up- and down-going components of the wave-feild recorded by the geophones in a processing step before correlation, or migration, or to use for a deconvolution approach.

In Artman (2002a) I presented a possibility for separating the summed wave-field recorded at the surface and represented by the left side of Equation (1). The separation is presented by Kennet (1991) from the seismology community. This concept is based on the manipulation of the full reflection matrix available from three-component acquisition.

We know that the wave field will give rise to displacements at any boundary. So we can construct a relation between the displacements and the wave field such as

$$u = E\ L\ R \tag{10}$$

where $\mathbf{E}$ is the eigenvector matrix that relates the Fourier components of the wave-fields to physical parameters, $\mathbf{L}$ is composed of reflection and transmission matrices within a layer, and $\mathbf{u_o}$ is the column vector composed of the compressional and two shear propagation modes sampled in the experiment.

Considering a very thin layer just below the surface that all energy is transmitted through, and no energy is reflected from, $\mathbf{L}$ becomes identity and we only need a form for $\mathbf{E^{-1}}$ to solve (estimate) the up-going wave field. Because $\mathbf{E}$ arises through solving the ODE's that relate displacement and tractions to a wave field, we can find expressions for the necessary operator and evaluate it at the special case of the free surface.

Because the down-going energy is the true source, it could be more accurate to extrapolate only this portion of the wave-field as P^s during the migration. Application of this technique to a three-component data set is planned to see if better images can be constructed. This technique may simply remove the strong zero-lag energy noted in Figure 5 or the fan of direct arrivals in both shot-gathers in figure 6.

Viewing the passive seismic data as the result of a convolution of the earth's structure with an unknown probing energy source is an alternative presented above. Separating the wave-field components using algorithms designed from the physics of wave propagation as described above can lead to a more stable result than the cascade of estimations described in appendix A.

The three-component OBC data from PGS will be the ideal test of this idea.

Processing capabilities

I have already finished parallel correlation code for irregular 3D geometries to use for processing these data. A 3D code for shot-profile migration will be a product of the solar imaging exercise. The wave-field extrapolator from this experiment will also provide modeling capabilities to enhance the tests presented here that are admittedly low-tech.

TIME-LINE

- Summer 2002
    - 3D up-down extrapolator
    - Incorporate absorbing boundary conditions
    - Image solar flare, submit for publishing
    - Image Moss Landing beach water table
    - Collect engineering scale urban passive data experiment
    - Continue collection effort with outside institutions
    - Participate in SEG Passive Seismic Workshop
- Fall 2002
    - Image Santa Clara Valley, submit for publishing
    - Gather several passive seismic data sets
    - Process data, submit for publishing
    - Physics 210 - Particle mechanics
- Winter 2002 - Spring 2003
    - Continue with data collection and processing
    - Computer Science 238 - Parallel methods in numerical analysis
- Summer 2003
    - Outside internship

- Fall 2003 - Spring 2004

  Comparative analysis of successes and failures

  Elucidate range of earth parameters conducive to passive seismic experiment, submit for publishing

- Summer 2004

  Statistics 110 - Statistical methods in engineering and physical sciences

  Process data, compare, finish outstanding projects

- Fall - Winter 2004

  GES 251 - Sedimentary Basins

  PE 284 - Optimization

  Write thesis and journal articles detailing results of study

- Summer 2004

  Finalize deliverables for graduation

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APPENDIX A

Passive imaging as deconvolution

We could also cast the passive imaging problem as a deconvolution. With the transmission series recorded at the surface of the earth, one may attempt to manufacture the subsurface profile by predictive deconvolution. Acknowledging the band-limited nature of likely seismic energy included in the passive experiment, this methodology was developed for SH-waves by (**?**). This reality is contrary to the implied assumption of equation (1) that the source function be white. I will follow the development of (Zhang, 1989) for compressional waves.

First we define our transmission recording in terms of a convolutional model that we can apply a deconvolution to. We will operate in the frequency domain, and call our recordings, U, the result of the convolution of the transmission function of the earth, T, and a probe or source function, S.

$$U = T S . \tag{11}$$

Allowing for our inability to know the phase characteristics of our source function, we can view S as the product of an operator that turns a white source W and some transfer function H that operates to output the real signal that has probed the subsurface. Thus

$$S = H W , \tag{12}$$

and

$$U = T H W . \tag{13}$$

With these definitions i n mind one can design a prediction error filter (PEF) on the data, U, that has the inverse spectrum of the transmission series. I call the PEF F. By definition then,

$$F U = W . \tag{14}$$

Therefore F itself must have the form

$$F = W U^{-1} \tag{15}$$

which simplifies to

$$F = \hat{H}^{-1} T^{-1} , \tag{16}$$

after substitution of equation (13). The hat on $\hat{H}$ reflects that this formulation develops a minimum phase function that plays the same role as H and enjoys the same spectrum, but is not necessarily H. Thus we have named our data PEF the product of two minimum phase filters that have significance for our model. Further, the second, T^{-1}, is directly related to the physical properties of the subsurface. To separate these two filters, (Zhang, 1989) assumes that T^{-1} is approximately white and should have information spaced sufficiently so that its auto-correlation converges to 0 within the length of $\hat{H}^{-1}$. Estimating a second PEF on F then has the form $\hat{H}$ that when applied to F yields T^{-1}. Alternatively, (**?**) approximates $\hat{H}$ as the beginning of the F series. They increase the length of $\hat{H}$ until the deconvolved output (T^{-1}) is minimum phase. Claerbout, 1985 (FGDP) shows that T^{-1} is a minimum phase polynomial from which one can extract the reflection coefficients of the subsurface via recursive polynomial division.

This method has yet to be implemented by me. However, positive synthetic results on a 2D model are shown in (Zhang, 1989).