Differential surface-wave interpretation of temporal changes

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- Concepts and objectives
- Site-specific problem
- Innovative approach and results
- Plans
- Desired test sites

Concepts and objectives

•The objective of differential surface-wave interpretation is to identify temporal perturbations in the shear-wave velocity.

Perturbations in phase velocity are measured by computing the Fourier transform of the difference of normalized traces. The perturbed structure can then be computed relative to a reference structure that need only approximate the actual structure. In effect, the perturbations of surface-wave group or phase velocity are inverted directly to velocity perturbations instead of inverting the dispersion curve for shear-wave structure.

Soil Velocity as a Function of Stress

The key to differential surface-wave interpretation is recognizing that there exists a measurable sensitivity of shear-wave velocity to stress.

Most observations of soil velocities suggest that the dependence of velocity on stress is adequately expressed as an exponential,

$$V_s(z) = \alpha(\sigma)^{\beta}$$

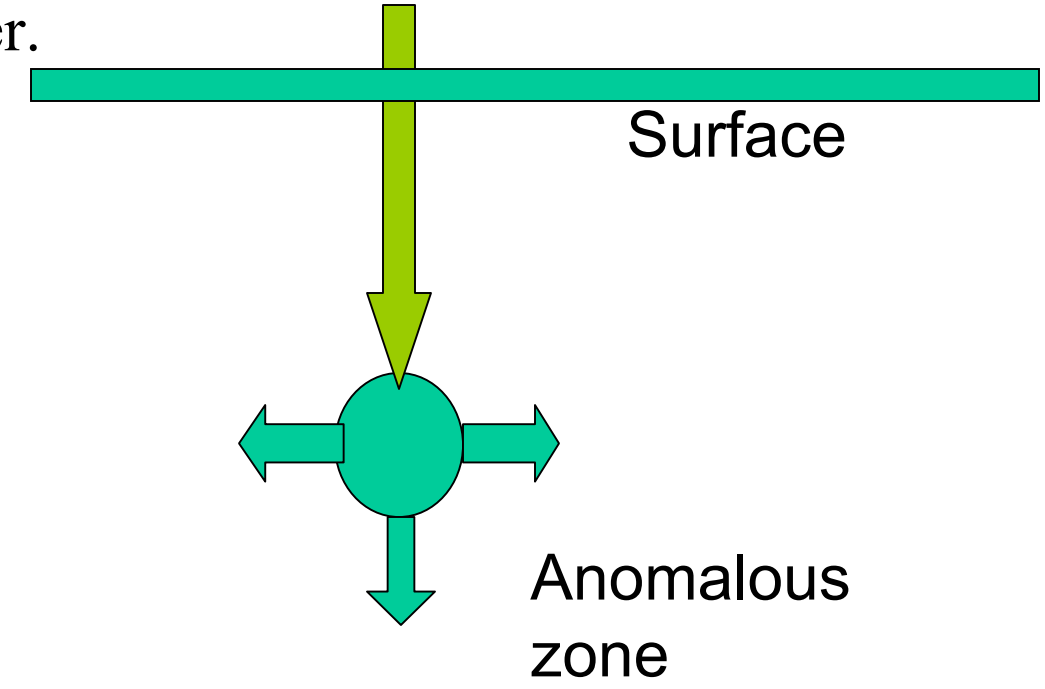
where α is the velocity at 1.0kPa, or approximately 0.05 m depth and ranges from 20 to 80 m/s depending on the sand versus clay mixture, σ is the stress in kPa, and β has a value of approximately 0.3, but also depends on the value of α.

Site-specific problem

The proposed technique will measure changes in the velocity structure of near-surface soils where temporal changes in velocity may be induced by natural processes, (e.g. rainfall) or by pumping and withdrawal of fluids. In alluvium the changes in surface-wave velocity could identify flow paths in areas where fluids modify the fluid pressure and, hence, the shear-wave velocity.

Example 1:

Definition of areas reached during a pump and treat operation. Depth of anomalous zone should be less than 10 meters. Could be applied at PNNL for sites near river.



Example 1 Cont.:

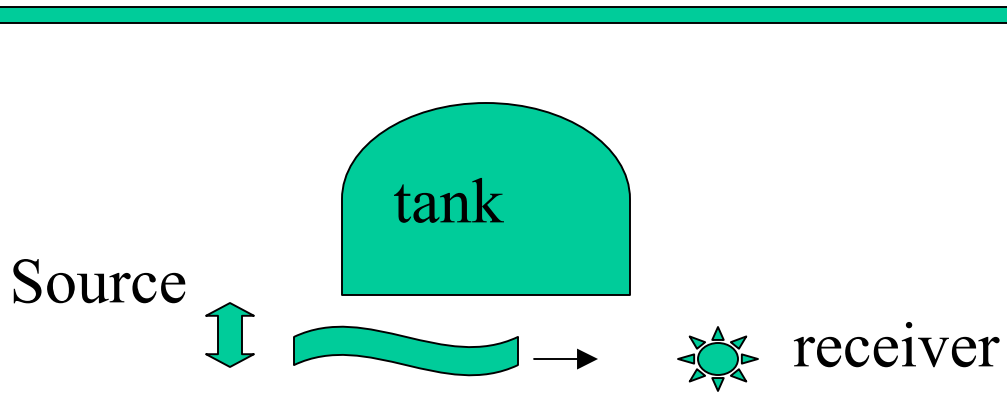
- Detection of locations of gas generation during bioremediation and monitoring of success of migration of bioremediation.
- Monitoring of air sparging operations to determine areas affected.
- Source identification for fluids during pumping to extract fluids.
- Determine paths of fluids during pumping to flush contaminated areas.
- Help determine nature of fluid flow, fingers versus diffusive flow, fractal versus stochastic.

Example 2:

Use to detect and monitor depth migration of ground water resulting from surface saturation, for example from a flood or heavy rain. Works best at shallow depths, but using larger sources or natural background noise could extend to as deep as 200 ft. A surface array could be used to determine phase velocity. This would give background information on the possible downward flushing of contaminants and could give information on the rate of downward migration of contaminants in tank farm at PNNL.

Example 3:

Channel waves have many of the dispersion properties of surface waves and can be used in the same way. The high velocity cement of the tank base and a positive velocity gradient in the soil below a tank forms a channel. A signal from one side would be detected at the other. Multiple sensors would allow tomographic mapping of anomalous zones. The differential technique would detect new or accelerated leaks.



Innovative approach and results

Differential surface wave inversion requires determination of the average structure and a set of perturbation functions that allow a transformation from the dispersion curves to structure. We use a linearly independent set of continuous functions to represent smooth perturbations in velocity as a function of depth. For an anomalous structure, the velocity is given as,

$$\Delta V(z) = V(z) - \overline{V}(z) = \sum_{i=1}^{N} k_i O_i(z) \qquad (2)$$

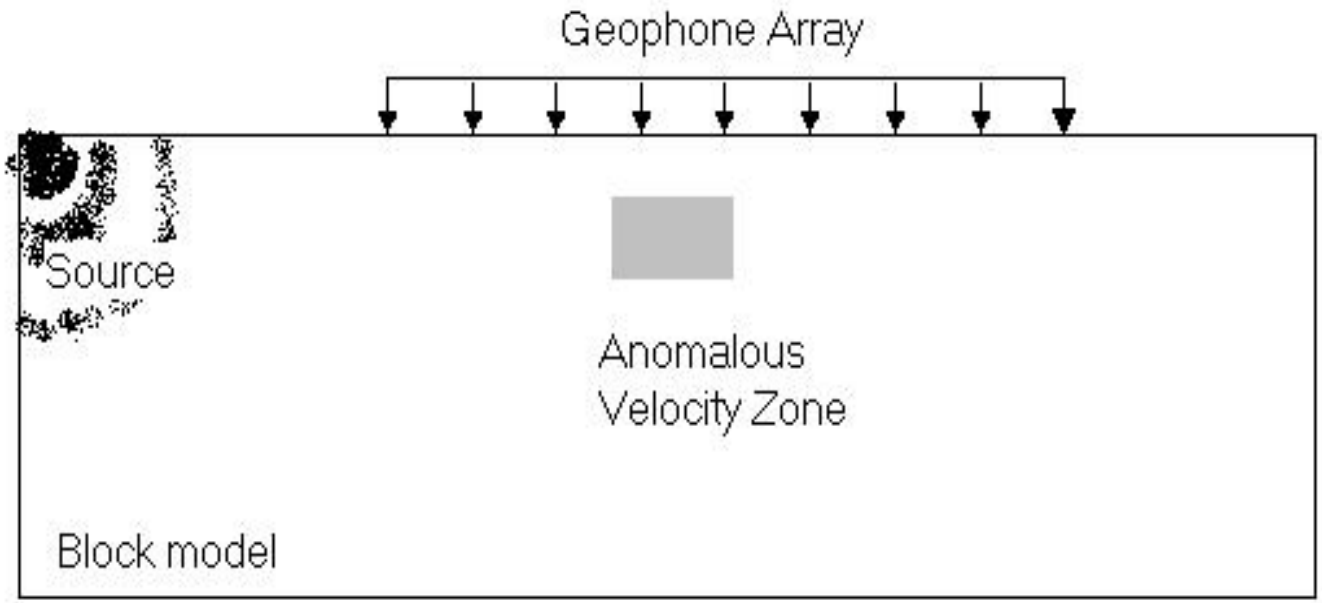
where k_i is a constant measuring the contribution of each linearly independent function, $O_i(z)$, to the perturbed velocity structure.

Likewise, each independent perturbation function generates a perturbation, $\Delta U_i(\omega)$, in the dispersion curve. The difference between the reference dispersion and the observed dispersion can be expressed as,

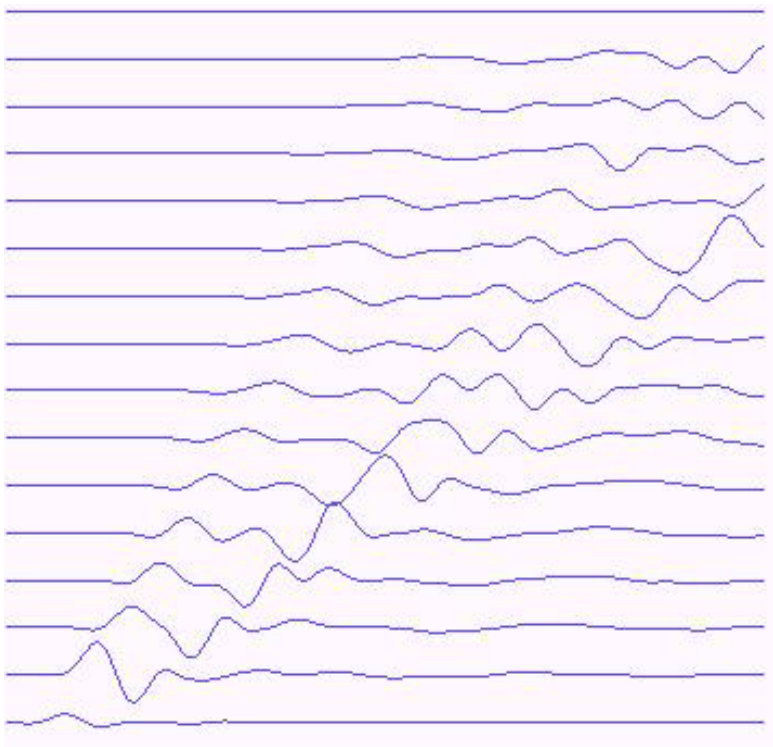
$$\Delta U(\omega) = \sum_{i=1}^{N} k_i \Delta U_i(\omega) \qquad (3)$$

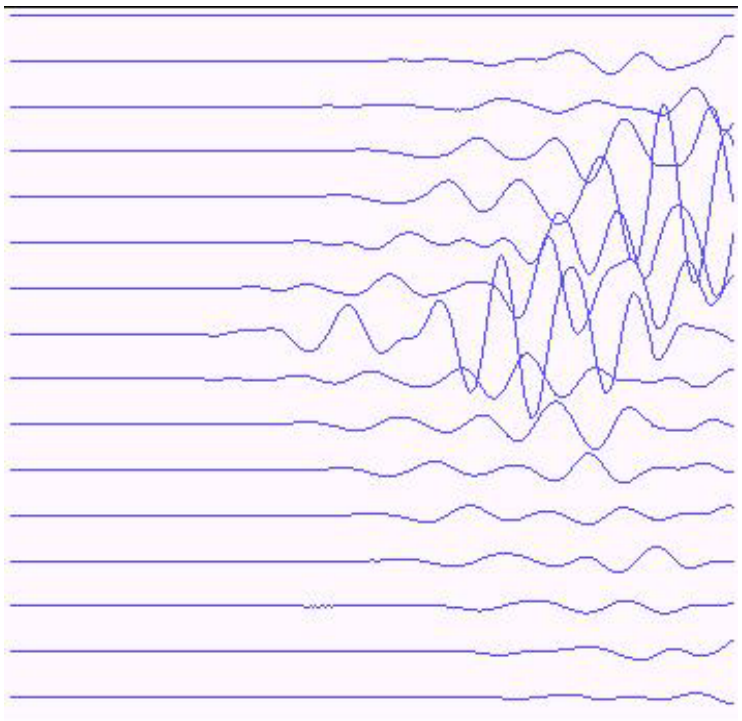
Given perturbations in group velocity observed at a set of discrete frequencies, equation (3) is solved for certain values of k_i and by direct substitution of the k_i into equation (2) an estimate of the perturbation of the velocity structure is obtained.

Typical detection arrangement



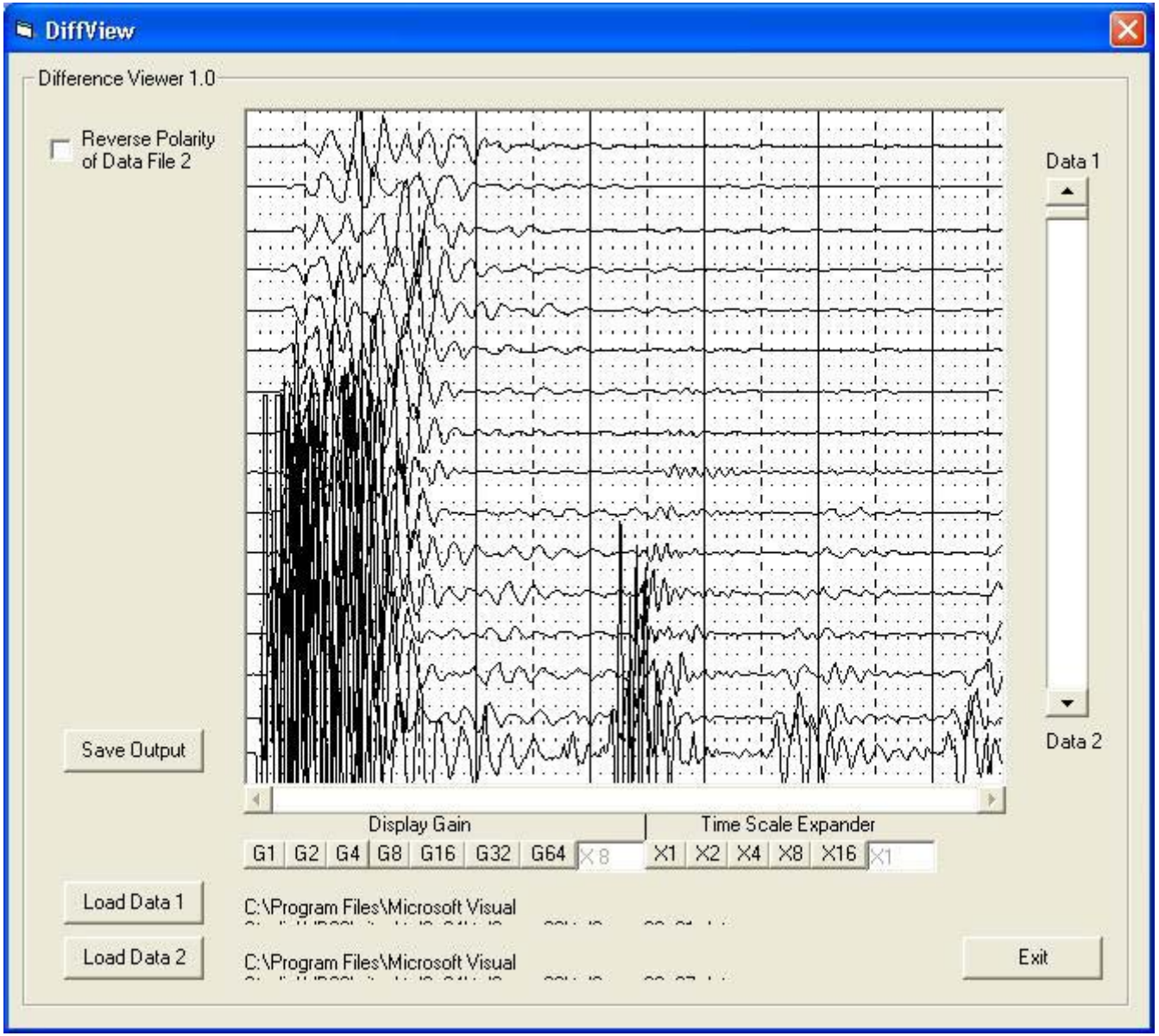
Left block shows traces with the anomalous structure.
Right block (gain x 20) represents the difference.





Real data are not as clean. The following slides show the response to a change in surface load. The load was placed in the middle of the line. Notice that the early arrivals before the load cancel out while the surface waves slide through a phase change without going to zero amplitude. The first slide is with the load. The next 5 slides are at the same gain setting, but have different amounts of the two traces thus showing different degrees of cancellation.

Note: compare the first box in an area not susceptible to changes and the second box, most susceptible to velocity changes.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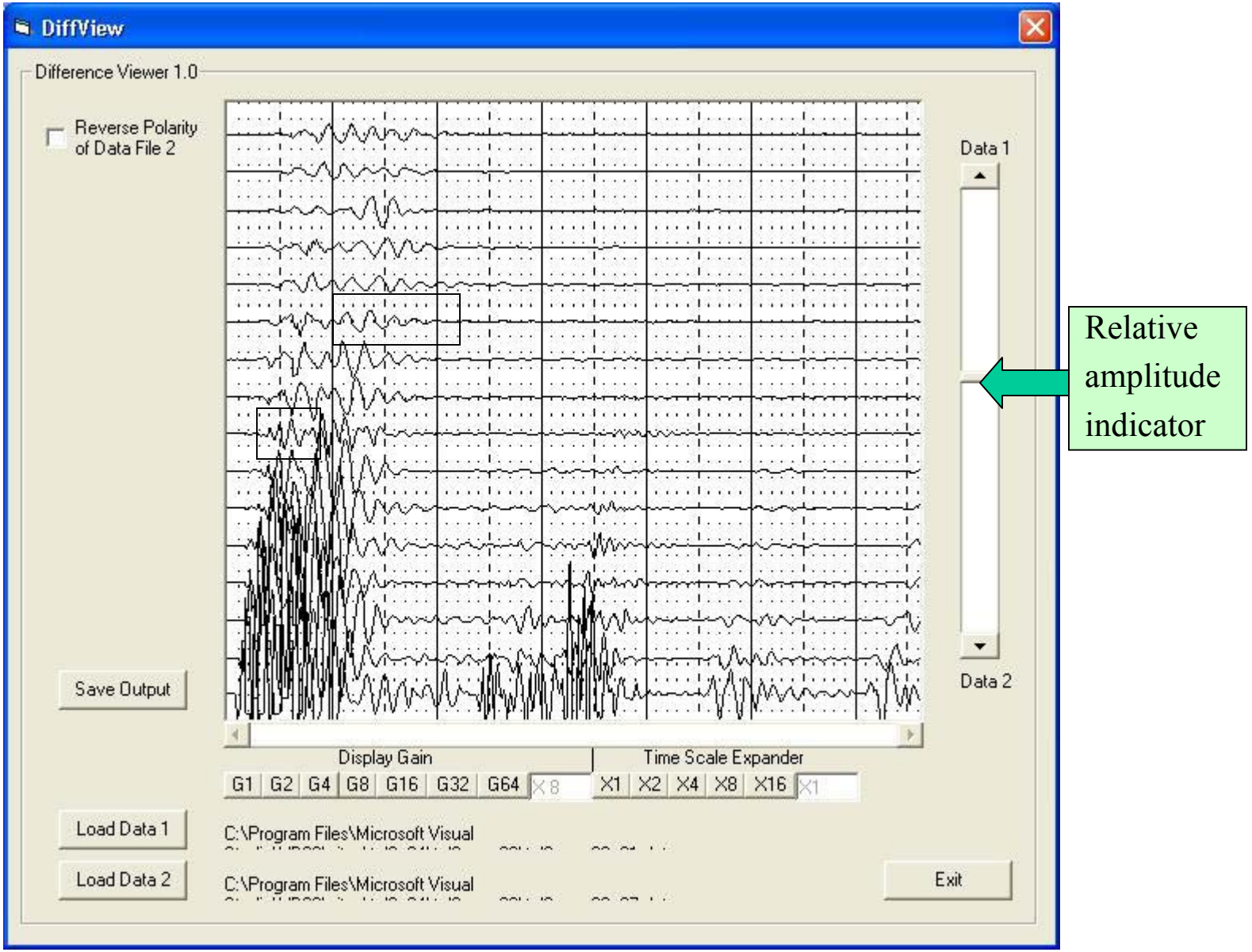
Difference Viewer 1.0
Reverse Polarity of Data File 2
Data 1
Data 2
Save Output
Display Gain
Time Scale Expander
G1 G2 G4 G8 G16 G32 G64 X8
X1 X2 X4 X8 X16 X1
Load Data 1
C:\Program Files\Microsoft Visual
Load Data 2
C:\Program Files\Microsoft Visual
Exit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Difference Viewer 1.0
Reverse Polarity of Data File 2
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Data 2
Relative amplitude indicator
Save Output
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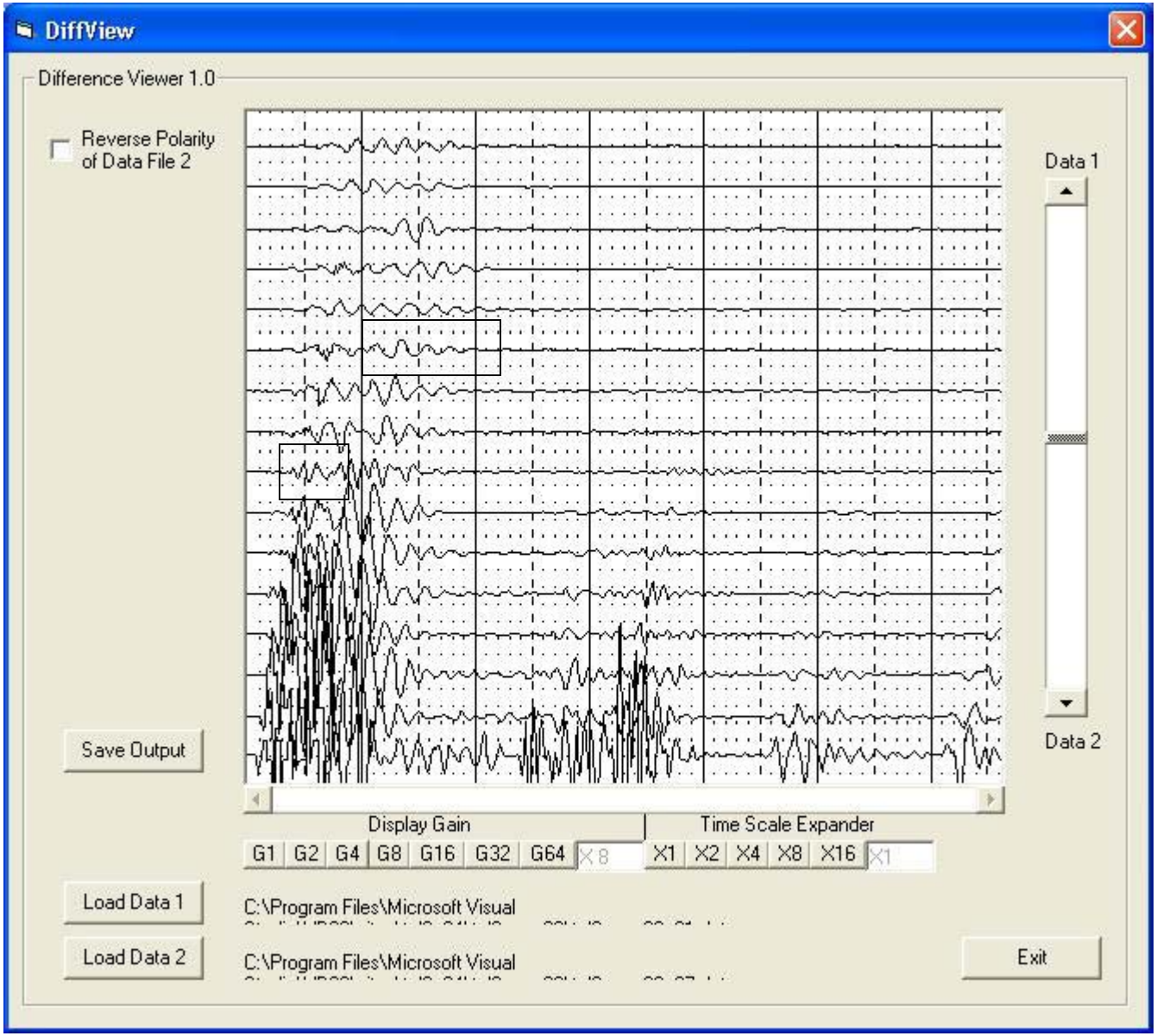
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Reverse Polarity of Data File 2
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Time Scale Expander
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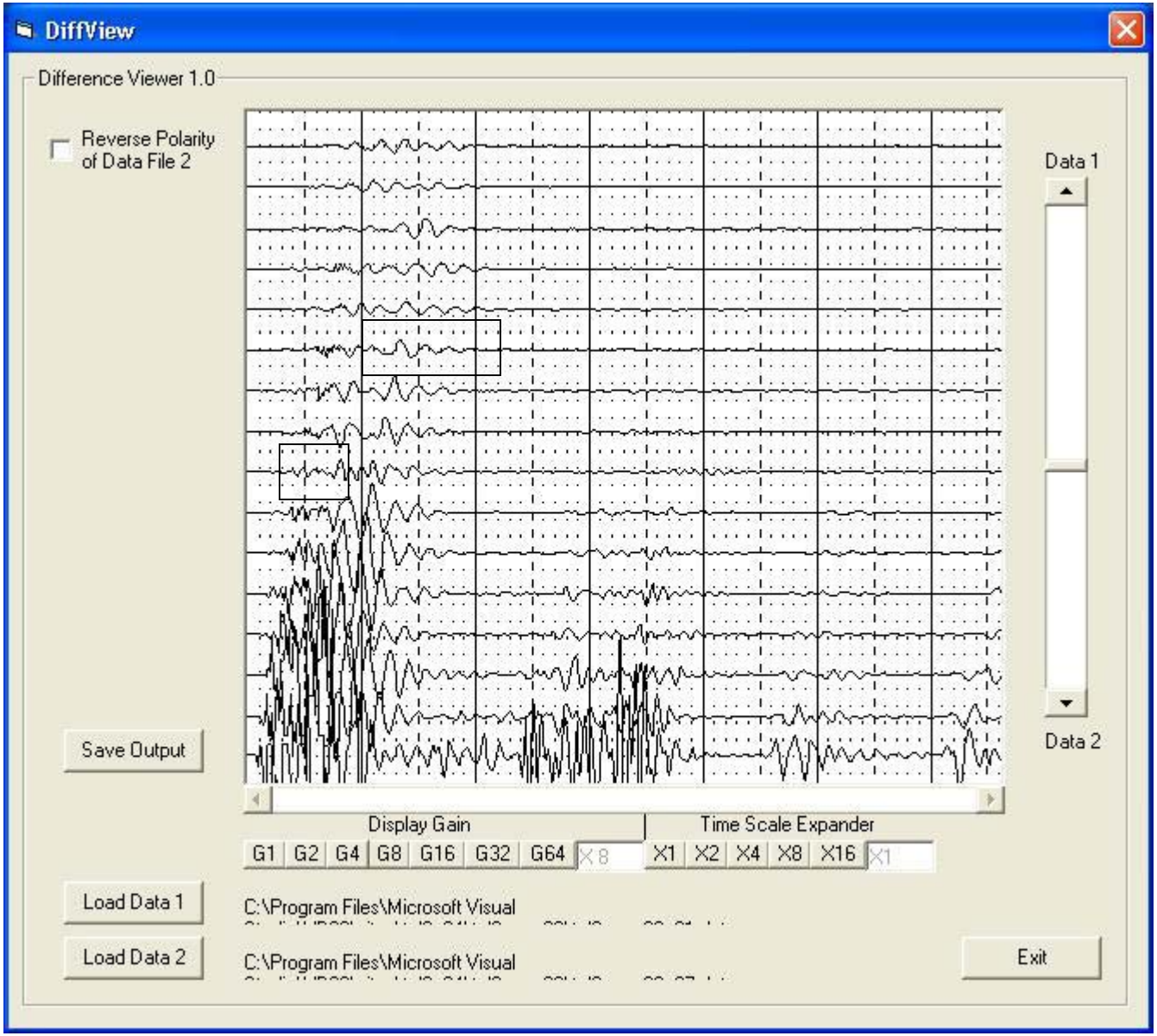
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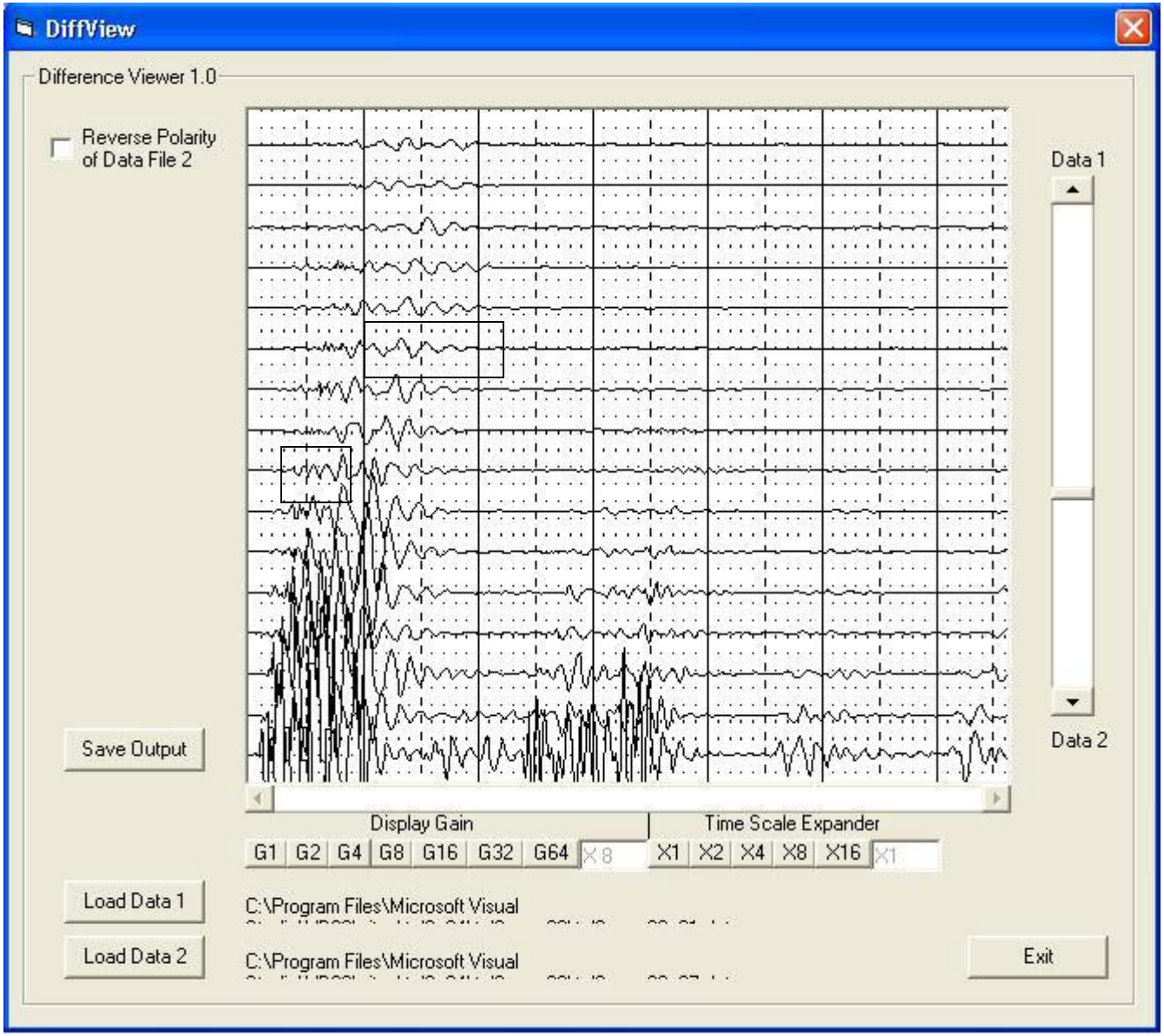
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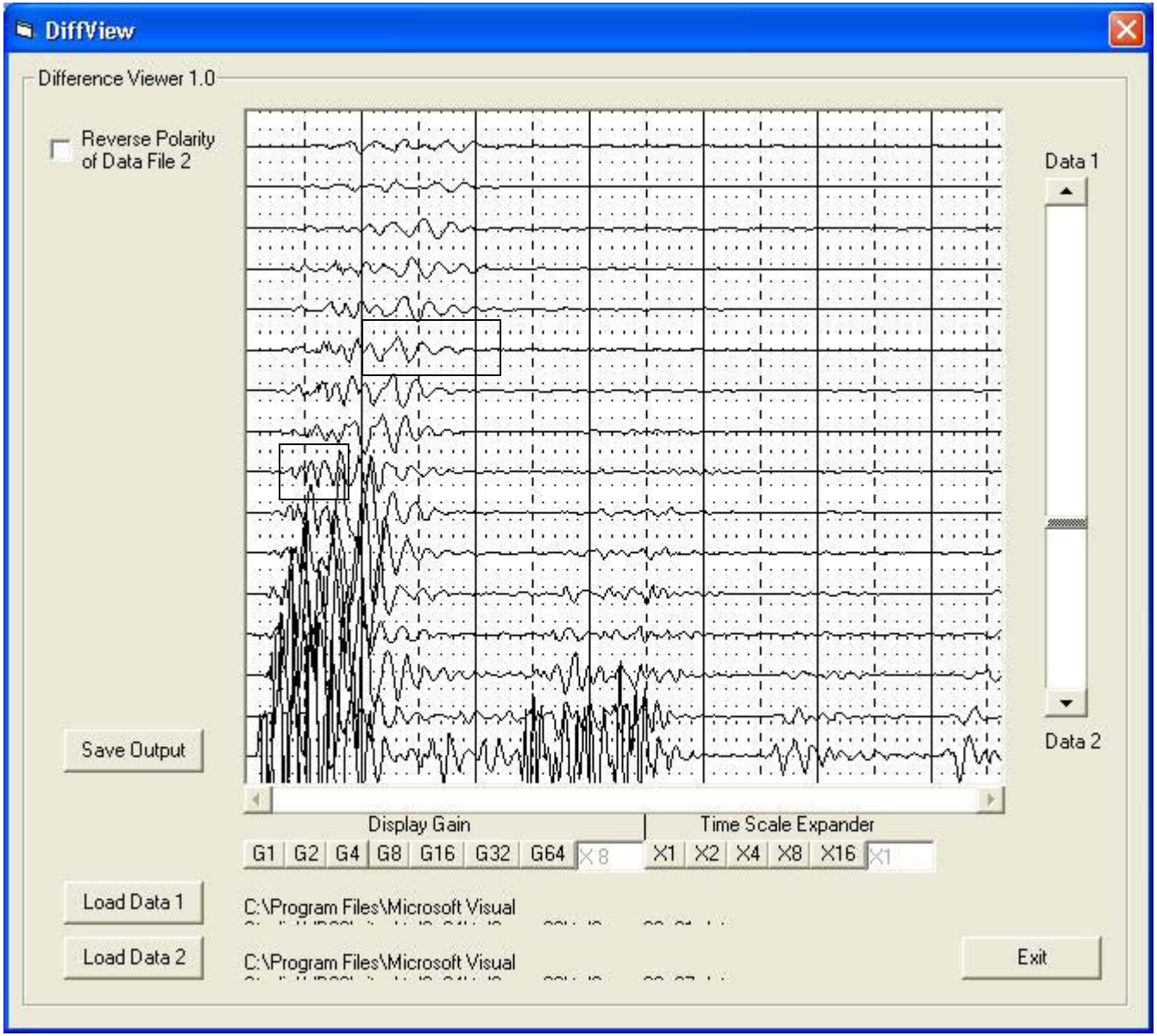
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Load Data 2
C:\Program Files\Microsoft Visual
Exit

Detailed examination of this data indicates that most of the uncertainty comes from source variability.

A new source is being designed.

Also, we will examine numerical techniques to equalize the source function in different traces.

(Note: The stacking of traces does not remove the effects of source differences because they are the same magnitude as the differences we are attempting to observe.)

The phase velocity perturbation at any point along the line is a cumulative function of phase velocity perturbations between the source and that point.

The travel time, t, of a phase at given frequency traveling from a reference or reference position, x_r, to the observed position at distance, x, under the condition that the phase velocity is a function of distance can be expressed as:

$$t = \frac{\phi(\omega, x) - \phi_{ref}(\omega, x)}{\omega} = \int_{x_r}^{x} \frac{dx}{c(\omega, x)}$$

A similar equation can be written for the travel time, *t*`, for a phase in a perturbed velocity structure. Expressing the perturbed velocity as, $c(\omega,x)+\Delta c(\omega,x)$, that time is given as,

$$t' = \int_{x_r}^{x} \frac{dx}{c(\omega, x) + \Delta c(\omega, x)}$$

The difference in these two times is then measured directly by the difference in the phase spectra of the arrivals and the difference in the integrals.

$$\frac{\Delta\phi(\omega,x)}{\omega} = \int_{x_r}^{x} \frac{\Delta c(\omega,x)dx}{c(\omega,x)(c(\omega,x)+\Delta c(\omega,x))}$$

In this application, $\Delta c(\omega,x)$ is small and will vary about zero when compared to a relatively large and positive value for $c(\omega,x)$ and, thus, we can use the mean value theorem to pull $c(\omega,x)$ out of the integral. The equation we have to solve at each frequency is thus,

$$\frac{\Delta\phi(\omega,x)}{\omega} = \frac{1}{\bar{c}(\omega)^2}\int_{x_r}^{x} \Delta c(\omega,x)dx \qquad (7)$$

Equation (7) is solved either by differentiating the observed phase differences or by a numerical approximation to the integral.

The Fourier transform of the difference of two traces with identical sources and recording sites will give an estimate of the phase shift caused by the anomalous velocity. To show this, the Fourier transform of the difference, *d(t)*, of two traces, *a(t)* and *b(t)*, can be written as,

$$d(t) = \sum_{\omega} |A(\omega)| e^{i(\phi + \Delta\phi/2)} e^{i\omega t} + |B(\omega)| e^{i(\phi - \Delta\phi/2)} e^{i\omega t} \qquad (8)$$

where ϕ is the average phase shift. The real part of equation (8) can be written in terms of the sum and difference in the amplitude spectra as,

$$d(t) = \sum_{\omega} (|A| - |B|) Cos(\omega t + \phi) Cos(\Delta\phi/2) + (|A| + |B|) Sin(\omega t + \phi) Sin(\Delta\phi/2)$$

under condition of minimum difference in the amplitude spectra of the two traces, the phase shift is approximated by,

$$\Delta\phi \approx 2\,Sin^{-1}\left(\frac{|D(\omega)|}{|A(\omega)|+|B(\omega)|}\right) \qquad (9)$$

These phase differences are then used to solve for perturbations in phase velocity in equation (7).

Plans

1) The next task will consist of developing a more consistent source to facilitate comparison of traces.

2) Additional test sites will be located. We are particularly interested in test sites with shallow pumping of fluids in or out of shallow soil.

3) With the new data we will develop and refine the programs for differential interpretation.

4) The resolution of the differential technique will be examined as a function of depth and generalized properties of soils and unconsolidated rocks.

Desired test sites

Characteristics of an ideal test site.

1. Accessible and relatively flat surface over affected area.
2. Depth of target area shallower than 5 meters.
3. Water pressure changed significantly in transients.
4. Affected area about 25% of seismic line length.
5. Room for a seismic line up to 60 meters in length

Greater depth sensitivity would require a larger seismic source. Objective is to trace fluid path in shallow sediments when the fluids are forced through the sediments, as in a flushing operation.

Questions:

1) What are some possible applications for the PNNL site?

I have added my answer to this question in the example section.

2) What is the resolution of the differential surface-wave method in comparison to other geophysical methods.

The resolution of the differential surface-wave method of analysis should be better than, or at least as good as the direct seismic wave interpretation using the same seismometer and source configuration. The reason for this is that the differential method cancels out the seismic response related to the more complex structures that make direct seismic interpretation difficult.

The resolution as a function of depth of the surface wave inversion is roughly equivalent to that of DC resistivity. The DC resistivity resolution with depth is proportional to the spread length, just as the surface wave resolution is proportional to wavelength.

GPR will give more detail for very shallow features, but penetration can be degraded by low resistivity. Hence, in many typical areas, differential surface wave analysis would expect to see deeper structures, but with resolution decreased in proportion to depth.

High-frequency seismic reflection requires significantly greater field effort and has difficulty resolving structure in the extreme inhomogeneity of shallow soil. Where it works, the resolution is better, but shallow seismic reflection does not give information on changes in the shear-wave velocity.