ESTIMATING HYDROGEOLOGIC PARAMETERS FROM RADAR DATA

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ABSTRACT

Radar reflections for a layered medium are dependant on the dielectric constants of the layers, which is closely linked to saturated porosity, and more loosely to hydraulic conductivity. Radar data have been obtained at a site where hydraulic conductivity has been measured in great detail. The radar cross section from the site clearly shows layering within the section, and it is tantalizing to predict that the hydraulic conductivities also persist along the bedding surfaces. The radar trace may be converted to a band limited pseudo−dielectric constant log by the same methods used to estimate an acoustic velocity log in seismic work. Thus, the resulting dielectric constant section can be converted to pseudo−porosity and pseudo−hydraulic conductivity displays. But, because of the limited bandwidth of the radar signal, it is tricky to invert the radar traces to yield dielectric constant and ultimately hydraulic conductivity. The main computations are 1. deconvolution with Seismic Unix routines and 2. conversion to dielectric constant including filtering to minimize numerical instabilities.

Keywords: radar, dielectric constant, hydrogeologic Parameters, Seismic Unix, Matlab

This research takes advantage of a site where hydraulic conductivity has been measured in great detail, the Macrodispersion Experiment (MADE) site in Columbus, Mississippi. Tereschuk (1998) acquired the data. Young and Tereschuk (1998) compared scale lengths of the radar data with the scale length of hydraulic conductivity, Young (1999) generated synthetic radar traces from the hydraulic conductivities . Adams, et al (1992) and Boggs et al (1992), present the geologic setting, the location of the hydraulic conductivity determinations and related hydrogeologic studies.

SIMPLE DIRECT TRACE INVERSION FOR DIELECTRIC CONSTANT

Linseth (1977) describes how to convert a seismic trace to acoustic impedance; the radar problem is directly analogous to the seismic problem, but the result for radar is the square root of the relative dielectric constant. From basic principles, it is known that the reflection coefficient sequence, RC_i, in a radar trace depends on the dielectric constants of the layers according to:

$$RC_i = (\varepsilon^{1/2}_{i+1} - \varepsilon^{1/2}_i)/(\varepsilon^{1/2}_{i+1} + \varepsilon^{1/2}_i) \quad (1)$$

where ε_i is the relative dielectric constant of the ith sample. The sampling can be either in time or depth. Equation 1 can be solved for the dielectric constant of layer i+1 as

$$\varepsilon^{1/2}_{i+1} = \varepsilon^{1/2}_i (1+RC_i)/(1-RC_i) \qquad (2)$$

Thus, to apply this to an entire radar trace, a starting dielectric constant must be provided for ε_1. A reasonable value for dielectric constant may be obtained from the average radar wave velocity known from a CDP measurement.

Radar data traces are not reflection coefficients; they are merely a time series representing antenna voltage convolved with the response of the recording system. Common radar processing that may be applied to make the radar traces resemble reflection coefficients are:

- "dewow" to compensate for transient polarization of the soil near the antennas
- trace gain adjustment to compensate for loss of amplitude due to spreading and absorption (SEC)
- deconvolution

Dewowing and compensation for spreading and absorption are carried out with software from Sensors and Software, Inc., the manufacturers of the radar. Deconvolution is carried out in Seismic Unix with a driver routine modified from Benz, 1999, using Weiner predictive filtering, e.g. Yilmaz (1987), Chapter 2. The value of using Seismic Unix is that it is free and it contains many common seismic waveform processing and display routines. It runs on Unix workstations or on PCs equipped with the Linux operating system. Deconvolution usually has two goals, forcing the wavelets into spikes to resemble reflection coefficients, and removing reverberation. The primary peak centered about zero lag in autocorrelation of the traces represents the autocorrelation of the wavelet. If there is reverberation present in the data, a secondary autocorrelation peak will be present at the reverberation time. Reverberation does not appear to be present in the radar data, as indicated by a lack of a secondary peak in the autocorrelation. The time occupied by the autocorrelation of the wavelet is used for the prediction lag and the time to before the first reverberation is used as the operator length. Short portions of the radar cross section are shown before and after deconvolution in Figures 1 parts a and b. The corresponding autocorrelation is shown in Figure 1 part c.

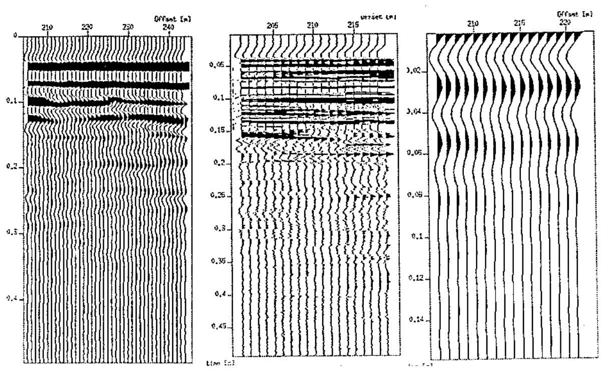

Figure 1. Steps in deconvolution (left to right)
a. selected radar traces before deconvolution. For all panels, the vertical dimension is time in microseconds and
the horizontal dimension is trace number.
b. selected radar traces after deconvolution
c. autocorrelation of radar traces before deconvolution

The prediction lag was 40 microseconds and the operator lag was 150 microseconds. It is clear in Figure 1 b that the wavelets in the radar traces have become more like spikes.

The equations presented above are valid for data of infinite bandwidth. Linseth argues that the seismic trace is band limited. The low frequency, long wavelength information is missing, thus to reconstuct a realistic synthetic sonic log it is necessary to obtain and mix in the long wavelength velocity data from a sonic log from a nearby existing well. The same arguments apply for radar. For this paper, the long wavelength information is from CDP radar data obtained for velocity determination. Three prominent reflections were used to determine velocity; they yielded a nearly constant value of .067 m/ns (Tereschuk, 1998), or a relative dielectric constant of about 20. Thus the low frequency component of velocity or dielectric constant for the radar traces is approximately constant. The only "mixing" that was done on the radar trace was to assign the first term in the computed dielectric constant trace to the mean dielectric constant found from the analysis of the CDP data.

PRACTICAL MATTERS

The major effort in the work presented here was actually in the practical matters discussed in this section.
The major computational steps are:

- converting radar files to Seismic Unix format
- carrying out the deconvolution
- reading the Seismic Unix file into Matlab
- computing, conditioning and displaying the dielectric constants

A reader wishing to carry out similar computations is encouraged to become as familiar as possible with Seismic Unix from online material such as Stockwell (2002) and Benz (1999). The radar files, originally in Sensors and Software .dt1 format, were read by Seismic Unix with the dt1tosu command with a line such as:

```
dt1tosu< L1S.DT1 > l1a.su dt=1.6 swap=1
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The first option (dt=1.6) sets the sample rate equal to 1.6. The correct units are microseconds but Seismic Unix treats them as milliseconds. The second option (swap=1) instructs dt1tosu to swap the bytes of the input record. This is necessary because SU is being run on a Sun (Unix) workstation, and the radar data were acquired on a laptop PC. The byte order for 16 bit integer data is opposite for the two computer systems. The deconvolution is carried out with the script from page 85 of Benz (1999), with the file name and sample rate changed. The script calls the Seismic Unix command "supef" (Weiner prediction error filter). The .su format data are read into Matlab as binary data with the command "fread". The format is specified as "float".

If Equation 2 is used alone to convert the trace to reflection coefficients, a numerical instability results. The computed values drift with increasing time to an unrealistically high or low value, and the small fluctuations which should represent band limited dielectric constant are not visible in the trace. There are two likely causes of this instability. The traces contain a high amplitude wavelet which is the direct wave from the transmitter to the receiver. There is minimal geological information in this wavelet, and its time of arrival corresponds to the onset of the numerical instability. Also, because each new value for the reflection coefficient in Equation 2 is directly proportional to the previous value, an opportunity arises for numerical instability if, for example, the mean of the trace is not zero. To reduce the effects of these two likely causes of numerical drift, two operations were carried out on the data. The original radar trace was windowed with a trapezoidal function to reduce the direct wave before Equation 2 was applied. After Equation 2 was applied, the trace was high−pass filtered with a one−pole Butterworth filter with corner frequency at .01 of the Nyquist frequency (0.31 MHz). This frequency is well below the nominal 50 MHz center frequency of the antennas removes the drift and thus has no effect on the main energy of the signal.

A sample deconvolved radar trace and bandlimited dielectric constant trace are presented in Figure 2.

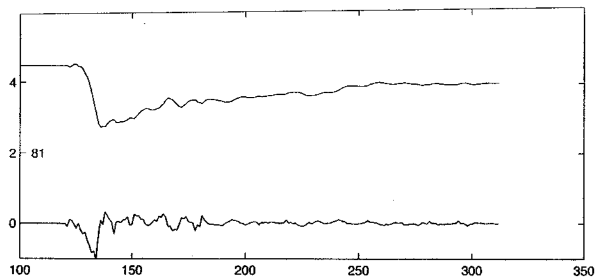

Figure 2. Sample deconvolved radar trace (bottom) and computed bandlimited dielectric constant trace (top) the units of the dielectric constant trace are actually square root of relative dielectric constant. The horizontal axis is in units of data points. The sample interval is 1.6 nanoseconds.

It would be desirable to test an assortment of operator lengths and lags, to adjust the deconvolution operator for the best appearance of the final cross section, but the work here is a first pass test of concept; experimentation with tuning the autocorrelation may be done later.

RESULTS AND CONCLUSION

Figure 3. presents the final cross section of radar converted to dielectric constant. Figure 4. presents the cross section of observed hydraulic conductivity. The converted radar section could be further scaled or adjusted to a best force fit to hydraulic conductivity. For the present, a direct relationship is assumed, that is, greater dielectric constant corresponds to greater porosity which corresponds to greater hydraulic conductivity.

The most conspicuous feature in the Figure 3 is a upward concave band of high over low dielectric in the left two−thirds of the cross section constant (dark grey over lighter in the monochrome version, blue over red in the color version). This region corresponds to a topographic low, and region of high over low values in the hydraulic conductivity cross section.

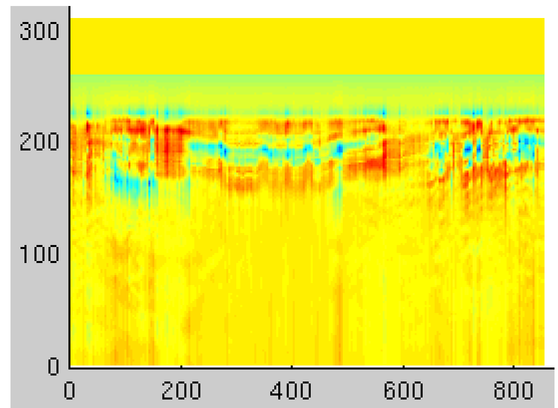

Figure 3. Dielectric constant cross section computed from deconvolved radar traces. Blue represents a dielectric constant of 16 and red respresents a dielectric constant of −1.5. The units of the vertical axis are samples,with zero at the top, the units of the horizontal axis are traces at a sample interval of 0.25 m/trace. The total horizontal distance is 213 meters.

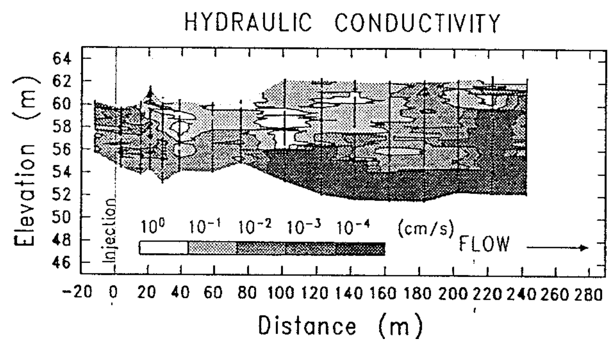

Figure 4. Observed hydraulic conductivity cross section (Boggs, 1992). The radar cross section extends from 27 to 240 m on the horizontal scale of this figure. Figures 3 and 4 have been printed to the same scale.

The form of the bedding visible in the original and converted radar data is consistent with the cross section of a stream bed. This region is identified as a meander channel from its surface expression. The high dielectric constants continue discontinuously to the right (south) end of the cross section. The discontinuity in the dielectric constants determined from radar is abrupt and is interpreted as some irregularity in the data rather than geologic origin.The discontinuity is possibly related to poor coupling between the antenna and the soil, but time does not allow a re−examination of the data to find the cause.

The radar data have been converted to an estimate of dielectric constant, aided by the knowledge of the mean radar wave velocity from CDP sounding. The dielectric constant is most closely related to hydraulic property of porosity. The cross section of estimated dielectric constant show high values in a zone known to have high hydraulic conductivity. The calibration or force fitting of the radar data to hydraulic conductivity has not yet been pursued.

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