Project Title: The Use of Radar Methods to Determine Moisture Content in the Vadose Zone
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Research Group: This research project currently involves two graduate students (James Irving, Stephen Moysey) and one research scientist (Paulette Tercier).

Research Objective

Moisture content is a critical parameter affecting both liquid-phase and vapor-phase contaminant transport in the vadose zone. The objective of our three-year research project is to determine the optimal way to use of radar methods - both surface and borehole - as a non-invasive means of determining *in situ* moisture content. In our research we focus on two specific aspects of the link between radar images and moisture content. The first question we address is: Can we use a measure of the dielectric constant of a volume of the subsurface to determine the moisture content of that volume? The second question we address is: Can we use the radar data to characterize the spatial variability in moisture content?

Research Progress and Implications

This report describes the progress that has been made in the second year of our 3-year research project. Both of our defined research questions require, as a starting point, a well-focused radar image of the subsurface. Over the past year, we have developed an effective methodology for the estimation and correction of wavelet dispersion in ground penetrating radar (GPR) data. Wavelet dispersion results from the frequency-dependent attenuation of electromagnetic (EM) waves and causes a characteristic "blurriness" in the GPR image that increases with depth. Correcting for wavelet dispersion allows us to obtain the highest resolution radar images possible and is a necessary step for the determination of subsurface electrical properties.

In examining attenuation versus frequency curves for a wide range of geological materials, we have found that, over the bandwidth of a GPR pulse, the attenuation can be reasonably approximated by a linear function of frequency. As a result, wavelet dispersion in these materials can be adequately described using a single parameter, Q*, related to the slope of the linear region. To estimate subsurface Q* from GPR data, we have developed a technique that builds on the frequency shift method of Quan and Harris (1997). We compute Q* from the downshift in the dominant frequency of the radar signal with time using a relatively new time-frequency analysis tool called the S-transform (Stockwell et al., 1996). Once Q* has been obtained, we correct for wavelet dispersion in GPR data by inverse Q filtering. Our filtering algorithm, which we developed using a Bayesian approach to inversion, allows for the recovery of absorption-free models that are both sparsely distributed and temporally correlated. In the first year of this project we had tested a similar methodology using the wavelet transform. We have found that the S-transform is superior for Q* estimation because it yields a true measure of frequency, rather than scale, and it avoids the challenge of choosing a mother wavelet function for the analysis.

The construction of rock physics models for relating measured dielectric constant and water content has been another focus of our research over the past year. One of the central objectives in this aspect of our research is to develop a reliable means of quantifying the uncertainty in the estimates of water content that arise due to the heterogeneous nature of the subsurface, sampled materials. Our recent work has included the development of a methodology for making unbiased estimates of water content given directionally dependent measurements of dielectric constant when a random field can describe soil water retention properties.

Much of our research effort over the past year has focused on the use of radar images to obtain information about the spatial variability in moisture content. We have developed Matlab code that can be used for geostatistical analysis of GPR images and outcrop photographs. This analysis uses a spectral method allowing for the fast computation of the autocorrelation function from which we then calculate the experimental semivariogram. Correlation lengths are determined from the experimental semivariogram using Varfit, a modeling program which we have also developed. We used this method to analyze GPR data collected at Hanford in May 2001, and found excellent agreement between the correlation length determined for the radar image and that determined for moisture content, based on neutron probe data; the variograms from both data sets, over the same length scale, are best fit with a correlation length of 7 m. The encouraging results from this field test, carried out in collaboration with Eugene Freeman of PNNL, suggest that the spatial variability captured in a radar image contains useful information about spatial variability in moisture content. We have also used this spectral method to compare the correlation structure of digital photographs of outcrops as the resolution of the image is varied. This work, which is ongoing, allows us to investigate the scale-dependent nature of heterogeneity in natural systems.

Quan, Y. and Harris, J.M, 1997, Geophysics, 62:895-905.
Stockwell, R.G., Mansinha, L., and Lowe, R.P., 1996, IEEE Transactions on Signal Processing, 44:998-1001.

Planned Activities

In the time period June-August 2001 we will conduct cliff face experiments where we will obtain GPR data and digital photographs of the same 2-D section. The GPR data will be acquired along the top of the cliff at three frequencies, 50MHz, 100 MHz and 200 MHz. Digital photographs of the cliff face will be taken using an Olympus C3000 digital camera after the face has been excavated back to the location of the GPR line. Both the GPR data and the digital photographs will be analyzed using spectral methods to investigate the way in which the scale-dependent heterogeneity in the cliff face is recorded in, and can be extracted from, the radar image. Other field work in July and August will include the collection of surface and borehole radar data. These data will be the basis for investigating, over the next year, the use of borehole radar data to (i) better process surface-based GPR data, and (ii) constrain the inversion of surface-based GPR data for the recovery of subsurface electrical properties.

Over the next year we will continue the rock physics part of this project by evaluating the impact of non-uniform distributions of water (caused by flow) on our interpretations. We will also use the collected field data and build on the work involved with the inversion of GPR data to consider the impact of the measurement scale of GPR on our ability to extract reliable estimates of water content from radar data.

Information Access: (Publications related to this research)

Rea, J., and Knight, R., Geostatistical analysis of ground penetrating radar data: A means of describing spatial variation in the subsurface, Water Resources Research, 34, 329-339, 1998.
Tercier, P., Knight, R., and Jol, H. , A comparison of the correlation structure in GPR images of deltaic and barrier spit depositional environments, Geophysics, 65, 1142-1153, 2000.

Irving, J. and Knight, R., Estimation and correction of wavelet dispersion in GPR data, In: GPR 2000, Proceedings of the Eighth International Conference on Ground Penetrating Radar, Gold Coast, Australia, p. 123-129, 2000.

Knight, R., Ground Penetrating Radar for Environmental Applications, Annual Review of Earth and Planetary Sciences, 29, 229-255, 2001.