CIVIL ENGINEERING DEPARTMENT

State-of-the-Art Rapid Non-Destructive
Pavement Assessment: Ground Penetrating Radar (GPR)
in Monostatic Survey Mode

February 1999

Lanbo Liu, Assistant Professor
Department of Geology and Geophysics

JHR 99-267 Project 97-4

SCHOOL OF ENGINEERING
UNIVERSITY OF CONNECTICUT
STORRS, CONNECTICUT

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16. Abstract

A feasibility study on investigating state-of-the-art non-destructive pavement assessment using ground penetrating radar (GPR) has been conducted. We have found substantial advance in GPR antenna design over the last several years. The ultimate goal of all new designs is achieving higher transmission efficiency. The interpretation software mainly use the artificial neural network. In terms of survey method, in addition to the commonly used monostatic transmitter-receiver pairs, multiple transmitter-receiver pairs start to merge in the pavement assessment practice.

In addition to a literature search, substantial research was conducted in three aspects in the field of software development: (1) Radar wave propagation forward modeling using the finite difference pseudo spectral approach; (2) Signal processing using wavelet decomposition to extract instantaneous parameters; (3) Image reconstruction using backscattering diffraction tomography. All three topics find direct application in using GPR in rapid pavement assessment.

In future studies on using GPR for rapid pavement the following is suggested: (1) using horn antennas with stepped frequency in 1-5 GHz; (2) using software based upon neural network with association to wavelet transform to substantially reduce the amount of data involved, and (3) using a multiple transmitter-receiver array to get in situ velocities.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	mililitres	mL
gal	gallons	3.785	Litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
^0F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	^0C

* SI is the symbol for the International System of Measurement

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C+32	Fahrenheit temperature	°F

°F 32 98.6 212 °F
-40 0 40 80 120 180 200
-40 -20 0 20 40 60 80 100
°C 37 °C

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1. Introduction

The federal and state governments have spent millions of dollars each year to maintain the existing highways and roads (e.g., Table 1, the allocation of funds from FHWA to the state of Connecticut for the fiscal years 1992-95). To accurately assess the pavement and bridge condition and optimally maintain roads to their best condition, an efficient pavement assessment system and an up to date road condition database are essential. Moreover, according to the U.S. Department of Transportation (USDOT), more than 40% of the 578,000 highway bridges in the United States were either structurally deficient or functionally obsolete in 1990s (USDOT, Federal Highway Administration, Publication No. FHWA-PL-90-024). These conditions can limit bridge utility and, if not properly monitored and maintained, pose a safety threat to bridge users. An efficient and cost-effective pavement and bridge condition assessment system is of critical need.

Several technologies, including surficial video survey, infrared, acoustic sensing, etc. have been used in highway engineering practice. As an emerging new technology, ground penetrating radar (GPR) has gained only a certain degree of use in this field in the last decade or so. Advances in GPR-based detection and inspection systems have the potential of addressing critical national and international needs for reliable, cost-effective non-destructive test (NDT) of highways and bridges.

Emerging GPR technology has a natural application as a supplementary device for the road video survey, which has been widely used in road condition assessment in most states of the United States for a long time, GPR can be used to identify valuable parameters that cannot be obtained from a visual evaluation of the road surface, including pavement-layer thickness and, potentially, damaged or delaminated subsurface areas. In addition, pavement-layer thickness is a required testing (deflection and elastic properties). Moreover, it would be possible to obtain an improved characterization of the pavement structure by

Table 1. Allocation of Federal-Aid Highway Funds (FHWA) to the State of Connecticut (1992-95)

Index 1995	Total (Thousands of $)	Other (thousands of $) /1	Motor carrier safety assistance program (Thousands of $)	IVHS (Thousands of $)	Forest highways (Thousands of $)	Public lands (Thousands of $)
CT	42,236	1,278	978	427	0	0
Index 1995	Parkways and park roads (thousands of $)	Emergency relief (thousands of $)	Projects mandated by ISTEA (Thousands of $) /2	Discretionary Bridge Replacement & Rehabilitation (Thousands of $)	Discretionary Interstate 4 R (Thousands of $)	Discretionary Interstate (Thousands of $)
CT	0	1,943	14,610	8,000	15,000	0
Index 1994	Total (Thousands of $)	Other (thousands of $) /3	Motor carrier safety assistance program (Thousands of $)	IVHS (Thousands of $)	Forest highways (Thousands of $)	Public lands (Thousands of $)
CT	16,478	2,871	686	400	0	0
Index 1994	Parkways and park roads (Thousands of $)	Emergency relief (thousands of $)	Projects mandated by ISTEA (Thousands of $) /4	Discretionary Bridge Replacement & Rehabilitation (Thousands of $)	Discretionary Interstate 4-R (Thousands of $)	Discretionary Interstate (Thousands of $)
CT	0	0	14,609	0	2,088	0
Index 1993	1993 Total (Thousands of $)	1993 Other (thousands of $) /5	1993 Motor carrier safety assistance program (Thousands of $)	IVHS (Thousands of $)	1993 Forest highways (Thousands of $)	1993 Public lands(Thousands of $)
CT	22,880	18,351	864	234	0	0
Index 1993	1993 Parkways and park roads (Thousands of $)	1993 Emergency relief (thousands of $)	1993 Projects mandated by ISTEA (Thousands of $) /6	Discretionary Bridge Replacement & Rehabilitation (Thousands of $)	Discretionary Interstate 4-R (Thousands of $)	Discretionary Interstate (Thousands of $)
CT	0	2,617	14,805	9,794	12,917	0
Index 1992	1992 Total (Thousands of $)	1992 Other (thousands of $)	1992 Motor carrier safety assurance program (Thousands of $)	Business enterprise training (Thousands of $)	Transportation assistance program (Thousands of $)	1992 Projects mandated by ISTEA (Thousands of $) /7
CT	20,939	14,040	546	120	77	6,156
Index 1992	Forest highways (Thousands of $)	Public lands (thousands of $)	Parkways and park roads (Thousands of $)	Emergency relief (Thousands of $)		
CT	0	0	0	0		

Explanations of Table 1:

1 Includes Bridge Acceleration discretionary.

2 Projects identified in sections 1103 - 1108 of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991.

3 Includes Bridge Acceleration discretionary.

4 Projects identified in sections 1103 - 1108 of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991.

5 Includes Bridge Acceleration discretionary.

6 Projects identified in sections 1103 - 1108 of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991.

7 Projects identified in sections 1103 - 1108 of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991.

combining the data provided by such an NDT system with that supplied by impact testing (coring and sampling). Over the last decade, these potential benefits have promoted transportation agencies and private industry in North America, Europe, and some developing countries, to start incorporating GPR technology into pavement-assessment engineering practice. However, the most challenging part for using such a non-destructive test and assessment technology is, inevitably, the reduction of a huge amount of data into a form that is readily interpretable to highway engineers.

To solve this problem, automatic acquisition and interpretation of GPR data for pavement assessment has recently attracted tremendous attention and research efforts. As a preparation phase for future research on the application of GPR techniques for pavement and bridge assessment, the PI conducted a feasibility investigation on state-of-the-art use of ground penetrating radar to rapid pavement assessment. This study systematically acquired, summarized, and reviewed the latest developments in this research area. The performance, feasibility, and accessibility of different approaches developed in North America and other countries in the world have been evaluated and compared in terms of the hardware, software and survey methodology. Recommendations and justifications for the optimal approaches, as well as suggestions for future research topics based upon reviews of up-to-date information are provided at the end of this report. This study can be viewed as a compilation of valuable information to researchers in the Connecticut Department of Transportation (ConnDOT) and the University of Connecticut (UConn) to carry out future projects using GPR in rapid non-destructive pavement assessment.

Before its application to pavement assessment, GPR has been used in other areas of non-destructive testing and subsurface imaging. One successful instance is detecting the thickness of the ice layer in Antarctica. GPR is enjoying wider and wider applications in many geotechnical and civil engineering fields. The last decade has seen a rapid development in using GPR for pavement and bridge assessment. For example, among the 111 papers included in the proceedings of the 6th International Conference on GPR held in October 1996, which represents the wide applications of GPR in environmental engineering, geotechnical engineering, mining, geological sciences, water resources planning, archaeological detection, and planetary science, 16 papers, about 15% of the total number of papers included in the proceedings, are directly or indirectly related to concrete, aggregates, and asphalt-property and rapid pavement assessment; evidently, this is a substantial portion for GPR applications. For a practical and optimal highway pavement assessment, minimization or complete avoidance of traffic obstruction is essential. Realization of this goal depends on rapid and accurate acquisition and fast processing techniques. The monostatic GPR survey is therefore naturally the first choice for meeting this request.

The monostatic GPR survey is characterized by having the transmitting and receiving antennas moving and kept at a short separation while the survey is being conducted. The survey vehicle with monostatic GPR equipment can go as far as necessary, because the survey method sets no limit on the length of the profile. This is the fastest way to carry out

GPR surveys and is particularly suitable for pavement assessment along highways for engineering purposes.

Use of monostatic survey mode, nevertheless, leads to a small incident angle (the angle between the incident waves and the normal of the interface) of the transmitting radar signals, and the reflected rays project almost exclusively in the vertical direction. Consequently, limited data coverage in this mode makes subsurface imaging very awkward and the convergence of inversion very slow. To keep the advantages of the monostatic survey mode in its full scale and overcome its disadvantages, a comprehensive approach involving improvement of the hardware, software and survey methodology should be considered in an integrated manner. To acquire information on the latest developments for using GPR in pavement assessment, which will serve as the foundation for development in the future for research personnel of ConnDOT and UConn, Project 97-4 conducted the reconnaissance review of the state-of-the-art use of GPR for rapid non-destructive pavement and bridge deck assessment. The information resources in this study include journal publications, manufacturer manuals, technical reports, GPR conference proceedings, web pages, as well as tests and research conducted by the research group lead by the PI. The findings summarized in the following sections reflect an in-depth searching and compiling of all available literature to the PI.

As defined in the proposal, the task of this project is divided into 3 sub-tasks: (1) comparison and evaluation of hardware of different GPR systems; (2) comparison and evaluation of data processing algorithms; and (3) comparison and evaluation of survey methodologies. We have collected information on current research and field practice of applying GPR to pavement assessment in all the three aforementioned domains. This report emphasizes, however, the data processing part and includes a section of data processing research resulting from the PI's research group on the wavelet transform algorithm. Based upon findings of the latest development in GPR hardware, software and survey setup, the report also makes a recommendation for future development in GPR pavement assessment.

2. Ground Penetrating Radar (GPR) Data Acquisition Hardware

The GPR hardware consists of the transmitting-receiving antennas, timing system, power supply, analog/digital converter (A/D), and the data acquisition control unit. The hardware of a GPR unit should be evaluated as an integrated system. Based upon the criteria proposed by Texas Transportation Institute (TTI), the GPR International User's Group Committee suggested that the GPR hardware can be evaluated in terms of: (1) Noise to signal ratio; (2) signal stability; (3) travel time linearity; (4) long-term stability test; and (5) penetration depth test. First, let's describe the definitions of these parameters.

2.1 GPR System Evaluation Parameters

(a) Noise to Signal Ratio

The first parameter to be evaluated is the noise to signal ratio (N/S) with the definition of

$$N/S = A_n / A_s$$

As can be seen, the N/S ratio is reciprocal to the commonly used signal to noise ratio (S/N). The noise level A_n is defined as the maximum amplitude in one time trace. The signal level A_s is defined as the amplitude of the echo from a testing metal plate. The N/S ratio will be calculated on each of 100 waveforms and the average value will be taken as the N/S of the system. The noise to signal ratio test result for a GPR unit should be less than or equal to 5%, i.e.,

$N/S \leq 0.05$

(b) Signal Stability (Jitter)

Jitter refers to the short term variation in magnitude of a quantity from trace to trace, when the system is under static operation condition. For a GPR system, jitters can be used to quantify signal stability in two major parameters: the amplitude jitter and the time jitter. The amplitude jitter is defined as

$$J_{amp} = (A_{max} - A_{min})/A_{ave}$$

where A_{max} is the maximum amplitude of the metal plate reflection for all 100 traces and A_{min} the minimum amplitude of the reflection for all the 100 traces. A_{ave} is defined as the average trace amplitude of the 100 traces. The time jitter is defined as

$$J_{time} = (T_{max} - T_{min})/T_{win}$$

where T_{max} is the maximum elapse time between time zero to the arrival of the reflection echo for all 100 traces and T_{min} the minimum elapse time for all the 100 traces. T_{win} is length of the time window. Both the amplitude jitter and the time jitter should not exceed 1%, i.e.,

$$J_{amp} < 0.01, \; J_{time} < 0.01$$

(c) Traveltime Linearity

When conducting the test of traveltime linearity, the GPR antenna of transmitter/receiver pair is placed in the air at three different positions, aiming at a thick reflector. At these three different distances from the reflecting object the amplitude of the GPR echo falls about 15%, 30%, and 50% respectively. The segmental distances, travel times, and velocities are used to define the Variation in Velocity Factor

$$\delta v = \frac{|v_{32} - v_{21}|}{(v_{32} + v_{21})/2}$$

where the numerator is the absolute difference in velocity of the 2 segments, and the denominator is the average velocity. The inaccuracy in Pulse Velocity is given by

$$\delta c = \frac{|v_{31} - c|}{c}$$

where the numerator is the deviation of the measured velocity from c, the speed of light (electromagnetic wave velocity in vacuum). Both the Variation in Velocity Factor, δv, and the Inaccuracy in Pulse Velocity, δc, should be less than 5%.

(d) Long Term Stability

There are two measures for evaluating the long term stability of a GPR system: the Long Term Amplitude Variation (LAV) and the Long Term Time Window Shifting (LTS). These two variables are measured according to the following procedure:

(i) Turn the system on for two hours.

(ii) Allow the first 20 minutes for system stabilization, then start to measure the amplitude and arrival time of an echo from a reflecting metal plate.

(iii) Take measurements at one-minute interval for the full 120 minutes, so that 120 readings are obtained for both amplitude and arrival time.

The LAV is defined as

$$LAV = (A_{max} - A_{min})/A_{20}$$

where A_{max} and A_{min} are the maximum and minimum amplitude of the 100 readings between 20 minutes and 120 minutes, respectively. A_{20} is the amplitude measured after 20 minutes. The Long Term Amplitude Variation (LAV) should be less than 3%. The LTS is defined as

$$LTS = (T_{max} - T_{min})/T_{win}$$

where T_{max} and T_{min} are the maximum and minimum arrival time of the 100 readings between 20 minutes and 120 minutes, respectively. T_{win} is the length of the time window. The Long Term Time Window Shifting (LTS) should be less than 5%.

(e) Penetration Depth

The ratio of the amplitudes of the GPR echo from a metal plate, penetrating through pure water with a thickness of 2 wavelength of the electromagnetic (EM) wave in water and through air with a height of 1 wavelength in air, is defined as the Water Penetration Index (WPI)

$$WPI = A_{water}/A_{air}$$

The higher the penetration Index, the better the GPR's penetration power. The Water Penetration Index (WPI) should be greater than 25%.

As an real case example, a test set with the Geophysical Survey System Inc. (GSSI) GPR system using the 1 GHz air-launched antenna deploying the above procedures and criteria generated the following results (Scullion, et al, 1996):

(1) Noise/Signal Ratio	4.85% (<5%)
(2) Amplitude Stability	0.35% (<1%)
(3) Travel-Time Variation	1.02% (<2%)
(4) Long Term Stability	2.35% (<3%)
(5) Water Penetration Index	35.44% (>25%)

Testing results show that this particular set of the GSSI GPR system has met the specified quality control standard.

2.2 GPR Performance Evaluation in Practice

Instead of providing the information for evaluating the system, as described in the last sub-section, GPR pavement assessment service vendors provide some more practical parameters such as the error in thickness estimate, minimum layer thickness recognition, and scanning rate, among other less often used parameters. Table 2 lists these parameters for several different systems; they are relatively straightforward, easier to evaluate, and of direct interest to highway engineers.

It is apparent that GPR performance is not determined by the system alone; coupling of the system with different earth or engineered materials will also alter the performance level of a particular GPR unit substantially. Table 3 lists the electrical and electromagnetic parameters of some commonly encountered earth and engineering materials. The dielectric permittivity (ε), velocity (v), skin depth (δ) and the transition frequency (ω_t) are:

$$\varepsilon = \varepsilon_r \varepsilon_0$$

$$v = \frac{1}{\sqrt{\varepsilon \mu_0}} = \frac{1}{\sqrt{\varepsilon_r \varepsilon_0 \mu_0}} = \frac{c}{\sqrt{\varepsilon_r}}$$

$$\delta = \frac{2}{\sigma}\sqrt{\frac{\varepsilon}{\mu_0}}$$

$$\omega_t = \frac{\sigma}{\varepsilon}$$

The electromagnetic constants shown in the above formulas are the dielectric permittivity in free space, $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m (i.e., Farads/meter); and the magnetic permeability in free space, $\mu_0 = 4\pi \times 10^{-7}$ H/m (i.e., Henries/meter). The velocity is the

Table 2. Summarized information for fundamental parameters for different radar systems

GPR Systems	Central Frequency	Number of Antennas	Antenna Type	Error in thickness	Min. Layer Thickness	Scan Rate (traces/sec)	Survey Speed (km/hour)
GSSI SIR-10	2.5 & 1 GHz	two 1-GHz & one 2.5-GHz	horn	~ +/- 5 %			105
Swiss FLMTR	2.5 & 1 GHz	one 1-GHz & two 2.5-GHz	horn			50	50
Road Radar	2.5 & 1.1 GHz	one 1.1GHz & one 2.5-GHz	horn+ground coupling	+/- 5%	40 mm	every 0.015 - 200m in dist.	Max. 100
Pulse Radar /RODAR	2.5 GHz	one	horn		1/8" thick air filled voids		65/km

Table 3. Electromagnetic properties of some earth and engineered materials

Material	conductivity σ (miliS/m)	dielectric constant ε_r	dielectric permittivity ε (picoF/m)	elctromagn. velocity v (m/μs)	skin depth δ (m)	transition frequency ω_t (MHz)	reference
fresh water	12-50	81	735	33.3	95.1-22.8	16-68	Brewster & Annan (1994)
salt water	150	81	716	33.3	7.6	209	Daily, et al (1995)
air	$2.5x10^{-14}$	1.0	8.85	300.0	-	$0.28x10^{-11}$	
clay (dry)	1-10	10	88.5	94.9	141-14.1	11-113	Telford et al (1990)
clay (saturated)	100-1,000	7	62.0	113.4	0.98-0.1	161-1614	Ulrikesen (1982)
sand (dry)	0.001	4.5	39.8	141.4	63,412	$0.25x10^{-1}$	Patel (1993)
sand (saturated)	0.1	30	266	54.8	4,227	0.38	Ulrikesen (1982)
dry concrete		5.6	49.6	126.8			Matthews et al (1998)
dry soil	4	3.9	34.5	151.9	13.7	116	Wakita et al (1996)
wet soil (20%)	13	14.4	127.4	79.0	15.6	102	Wakita et al (1996)
granite (dry)	$1 x10^{-5}$	5	44.2	134.2	$7x10^{6}$	$0.23x10^{-3}$	Ulrikesen (1982)
granite (saturated)	$1 x10^{-1}$	7	62	113.4	7,045	1.6	Ulrikesen (1982)
Texas aggregates	0.0012	5.1	45.1	132.8	59,889	$0.27x10^{-1}$	Saarenketo at al (1996)
asphalt		6.8	60.2	115.0			Hugenschmidt et al (1996)
PCE	$5.6x10^{-9}$	2.3	20.4	197.8	$5.8x10^{9}$	$0.27x10^{-6}$	Brewster & Annan (1994)

speed at which the radar wave propagates in the media. The skin depth characterizes how deep a radar wave can penetrate the material before dead off. The transition frequency marks the lower threshold for proper functioning of the radar system in that particular kind of material. For example, for the Texas aggregates, the transition frequency is 0.027 MHz. It means that in the frequency range above 0.027 MHz, all electromagnetic signals behave as propagating waves, rather than diffusive EM fields. For radar systems with working frequency band above 10 MHz the transition frequency of aggregates is well below, so that the GPR is a superior detecting tool for aggregates. This is true for most engineered materials. GPR may encounter difficulty, however, when working in areas with rich clayey soils (with transition frequencies in the range of ten to hundreds of megahertz, also see Table 2).

2.3 New Developments in GPR Antenna Technology

The characteristics of the antenna is the critical segment in determining if a GPR system is superior in collecting high quality measurement data. We will put our emphasis on evaluating the performance of antennas. The transmitting-receiving antenna is the most critical hardware component to determine the performance of a GPR system. Basically, there are two types of antenna systems used in pavement assessment: the air-launched horn antenna and the ground coupled flat bow-tie antenna (Smith, 1995). From information gathered so far, we see that for rapid pavement assessment the most commonly used antenna is the horn antenna with a central frequency of 1 GHz and higher. Some systems also use a combination of air-launched horn antenna and ground coupled ones. Using the ground coupled antenna has no major impact to the survey speed; however, changing the worn-out sliding strips at a regular time period may increase the budget for survey expenses.

The GPR antenna differs from a radio communication antenna in that it is a short-pulse antenna, operating near the ground and characterizing signals in time domain. The desired antenna performance is to transmit and receive short duration time domain waveforms (on the order of a few nanoseconds). The duration of the signal impulse depends on the trade-off between the resolution and the penetration depth. The tail of the signal must be minimized to prevent masking of targets from the air-ground interface. To reduce the tail most GPR antennas are using resistive loading (Shlager et al, 1994). To minimize the influence of varying ground condition on the antenna, a new method is to elevate the feeding point of the antenna and embed dielectric materials between the antenna and the ground (de Jongh et al, 1998). To reduce the radiation of the GPR antenna into the upper halfspace into the sky, shielding has been used. The horn antennas are all shielded. High-frequency ground-coupled dipole antennas are usually shielded.

In terms of new antenna development, there are several newly proposed techniques that have emerged in recent years. Engineering material testing and pavement and bridge deck assessment have received special attention (Huston et al, 1998; de Jongh et al, 1998). Huston et al (1998) reported the design of the low impedance mismatch antenna (LIMA). This design reaches a higher radiation efficiency and greater penetrating depth by reducing the impedance mismatch at the antenna aperture. The flared and tapered plates provide a smooth impedance transition from antenna to the air. To reduce the resonance and tail in the time domain signal and increase the antenna-ground coupling efficiency, de Jongh (1998) conducted the comparison of radar signal transmitted-received with air-filled and dielectric material-filled horn antennas. As an alternative approach to us the time domain impulse signal, some researchers also use frequency domain continuous waveforms geared by the stepped frequency technique (Kong et al, 1998; Noon, 1996; Sato, et al, 1995; Stickley et al, 1998). Noon (1996) provided a comprehensive review of the GPR technique using the stepped frequency approach. The main advantage of the stepped frequency technique is that it is relatively easy with existing technologies to efficiently sample the received signals using low speed A/D converters at relatively low data rates. Kong et al (1998) designed a wide bandwidth stepped frequency radar system using a HP 8719 network analyzer. The response of the system remains flat in the frequency of 2.3 GHz to 5.3 GHz. A similar approach has been implemented in studies using the borehole radar (Sato, et al, 1995).

3. Ground Penetrating Radar (GPR) Data Processing Software

The GPR data processing and interpretation software is the actual tool for extracting, from the raw GPR data, the pavement and bridge information of interest to highway engineers. A typical GPR pavement assessment software package generates several parameters as the final products: (1) interface depth (thickness) profile; (2) velocity estimation (related to material property) in each layer; and (3) crack density (crack/meter) and anomalies (voids or rebars). Typical service work can generate data as much as 25-30 Mbytes/km for detailed roadway surveys. Without automated processing, data interpretation would not be possible for anything other than tiny projects. Automated interpretation also attains a level of consistency. The proprietary post-processing software also provides a myriad of data presentation formats that have been designed by road and bridge engineers. All system generated data is also produced in machine readable formats for direct import into commercial software packages. In this section we first evaluate the current status of GPR data processing software. Then we present a GPR pavement assessment data processing example from Road Radar. Finally we discuss some new developments in data processing algorithms.

3.1 Current Status of GPR Pavement Assessment Software

The data reduction and processing-interpretation software used in currently available GPR pavement assessment systems consists of two fundamental parts: data pre-processing and pattern recognition. In the data pre-processing part, the GPR raw data are reduced and analyzed to extract fundamental pavement layer information. The interpretation part deploys artificial intelligence such as the neural network algorithm for feature recognition (such as rebars and voids filled with water or air) and expert system (with the assistance of human operator) to top level feature classification.

Traditional time and frequency domain preprocessing operations are applied to the raw GPR data in the data pre-processing stage. The purpose of pre-processing is to determine the physical parameters (dielectric constant, the critical parameter to determine the radar wave velocity, and electric conductivity) for the road or bridge cross-section and produce interface reflection amplitude, continuity and thickness profiles for each layer in the structure. Actually a fair amount of road/bridge information could be extracted from only the preprocessing stage.

In the pattern recognition part, the neural network technique is a common approach to identify structural anomalies such as rebars in bridge decks or voids in road base. Neural networks have been used in many areas for classifying or simplifying complex data sets. In the field of NDT, neural networks have proven to be an effective means of interpreting the complex signals obtained from pulse-echo testing of concrete and other engineering materials. Several authors have reported using artificial neural networks to assist in the analysis of GPR data (Pratt and Sansalone, 1992; Molyneaux et al, 1995; Attoh-Okine, 1995; Shaw et al, 1998). Molyneaux et al (1995) investigated the ability of a three-layer network to classify A-scans according to the presence or absence of a rebar, to assign the bar (if present) into one of six depth categories and to categorize the diameter of the bar. Attoh-Okine (1995) found that a Kohonen network (self-organizing map) could be used to classify the substructures of various pavements from the Fourier transform of radar waveforms. Shaw et al (1998) described a data collection and extraction technique using the neural network topology and training algorithm. They compared the results from different approaches and found that results for radial basis function networks were a little better than using linear analysis. However, when using the multi-layer perceptron networks, the target recognition results were much better.

To illustrate the data-processing flow in a GPR pavement assessment system, the next sub-section presents an example of the principle of GPR software used by Road Radar, Inc.

3.2 Example: GPR Pavement Assessment Software of Road Radar System

The automated data processing and interpretation software used by Road Radar, Inc. is sketched with block diagram in Figure 1. As mentioned before, most GPR pavement assessment software consists of pre-processing and interpretation. The raw data from the antennas first goes through the time-domain and frequency-domain analyzer to get the fundamental information of the signals. The feature of the Road Radar System pre-processing software which differs from other GPR processing is that it determines the layer velocity at each measurement point. The ability to measure the radar signal propagation velocity is necessary for accurate structural measurement. The measured velocity combined with the measured signal propagation time can then be used to determine the layer thickness or depth to an event. In this way it provides a high level of accuracy without the need for calibration cores.

After data pre-processing, a neural network based radar reflector recognition module reduces data density by approximately 90-95%. This is the major step to turn the data-rich, information-poor raw GPR data into data-slim, information-rich radar anomalies. The Road Radar System processing-interpretation software package was developed under a graphical user interface (GUI) environment. This graphical radar interpretation environment exploits a rule based expert system paradigm to allow a technical individual with limited radar experience to successfully process typical road data. On simplistic planar layer road structures, the system can perform automatic interpretation of the radar data. On more variable construction surveys, the system interprets consistent sections and defers to the operator for guidance at the transition points which typically represent construction joints or other discrete subsurface anomalies. The final output from the software are layer thickness,

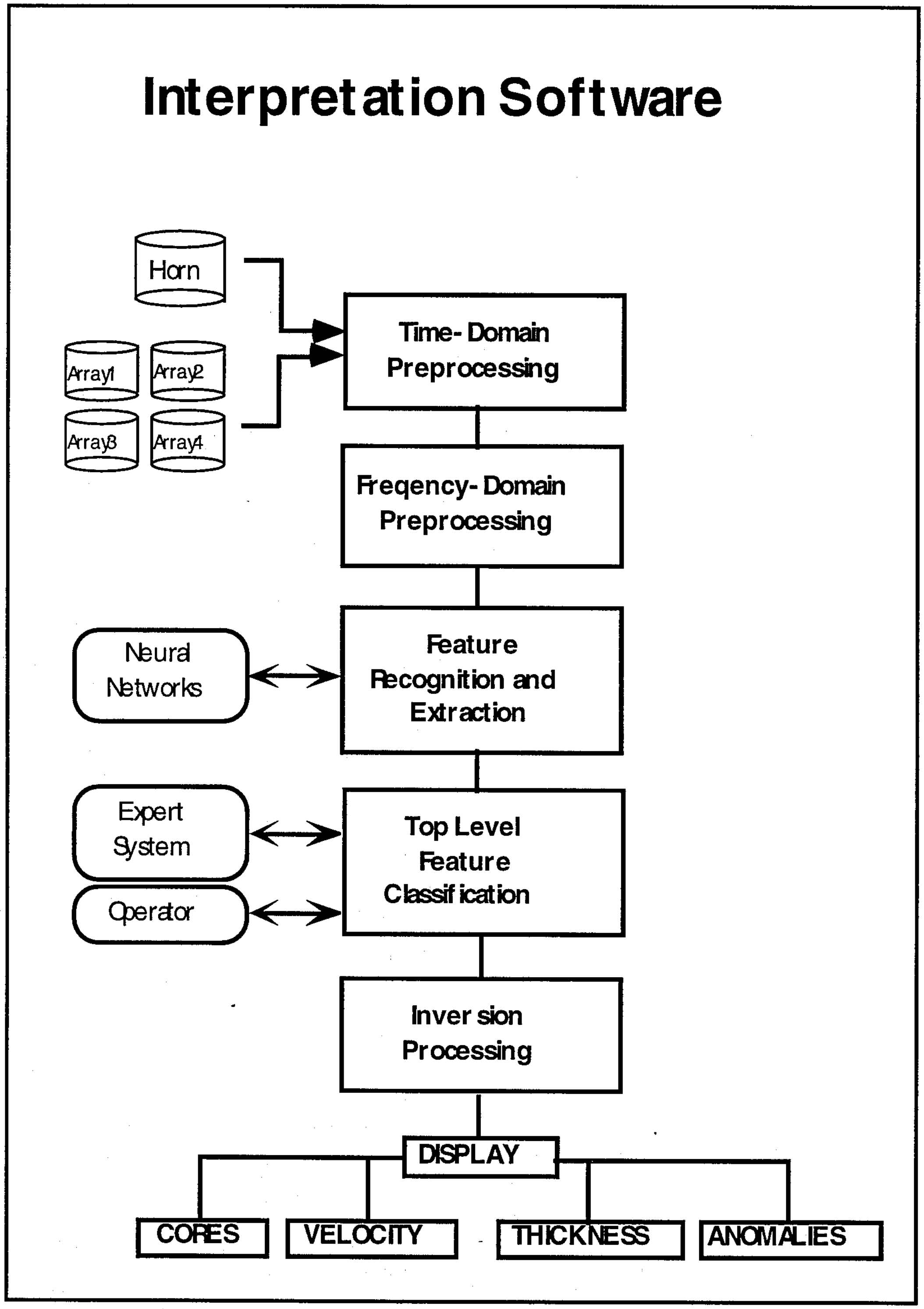


Figure 1. Flow chart of data processing software used by Road Radar System.

velocity in each layer, and distribution and interpretation of anomalies. A typical graphic profile output with interpretation will be shown in Section 4 - GPR Pavement Survey Methodology. Besides the above mentioned software from consulting firms, other commercially available GPR pavement assessment software includes PAVELAYER from Infrasense Inc. and ROADSEG from Texas Transportation Institute (TTI).

3.3 New Data Processing Software Algorithm

In recent years, more efficient and accurate GPR data processing algorithms have been proposed by different researchers. Among the new approaches, it is worth paying special attention to the interface tracking technology using multitarget probability density function (PDF).

Spagnolini (1997) proposed a layer-stripping algorithm to detect the depth to the interfaces and the EM velocity within layers. This approach has average accuracy, but is very efficient for processing a large quantity of data in a real-time mode. The layer thickness and dielectric permittivity of material in each layer are simultaneously solved by using an inverse scattering approach for monostatic GPR survey. The material parameter estimation is obtained from EM inversion by using the layer-stripping algorithm after echo detection. Multitarget detection estimates the time of delays (TODs) that pertain to the same interface. TODs are then mapped in depth by time to depth scaling, which is performed according to the permittivity values estimated from echo amplitudes. The estimation of interface TODs becomes the major issue to make the analysis of pavement thickness fully automatic. It is better to estimate TOD of interfaces after interface-detection instead of estimating TODs of isolated echoes after echo-detection. Lateral continuity of echoes that pertains to neighboring scans is exploited by tracking the detected echoes so as to reduce the probability of false alarms while preserving the continuity of interfaces. This approach is equivalent to the multitarget tracking (Bethel and Rahikka, 1987; Bethel and Paras, 1994) but in a monostatic mode. The lateral continuity of interfaces is explicitly assumed in model parameterization of the EM inversion. Thus, both EM inversion and interface detection are optimized to take into account lateral continuity of materials.

In the multi-interface detection algorithm, the first-order Markov model can be used to describe the lateral continuity by relating the *a priori* probability density function (PDF) of the *i*-th trace to the *a posteriori* PDF of trace (*i-1*)-th. This is obtained by assuming a Markov model for the interface generation process. The *a priori* PDFs for trace *i*-th are thus obtained from the *a posteriori* PDFs for trace (*i-1*)-th by using different transition probabilities for detection and tracking.

In summary, this method can be understood as a two-step approach. First, the interface is detected and echoes are spatially tracked, then the echoes that belong to the detected interface are moved from the data. More iterations are applied to the reduced set of data until a given threshold in the overall residual has been reached. The analysis results suggest that the optimum processing sequence in pavement assessment could be the use of the detection and tracking approach jointly with EM inversion (layer-stripping) for time to depth mapping of those interfaces tracked in time domain.

In Section 5, discussing the direction of data processing software development, we will describe the on-going research conducted by the PI's group on wavelet transform. Combination of the wavelet transform method and the neural network approach may lead to a new breakthrough in GPR data processing for pavement assessment.

4. GPR Pavement Survey Methodology

The purpose of a radar pavement survey is to provide pavement engineers with subsurface information for either project-level rehabilitation design or network-level work planning. The degree of information detail and survey spacing along the highway depends upon the particular requirements of the project engineers. The survey methodology varies when the GPR technique is used in different projects.

4.1 Objectives at the Network Level and the Project Level

At the network level, the objective of pavement assessment is to locate pavement segments and check expected performance. Another purpose is to gather enough information to estimate current and future budget for improvement and/or maintenance. At this level, the radar can be used to detect segment changes and can also be used in conjunction with other methods (e.g., the high-frequency seismic survey) of non-destructive evaluation of a pavement structure by measuring thickness of the layers at the point of testing to provide an overall thickness profile. Generally, GPR data is collected every 0.1 mile. At this sampling rate, the data acquisition and storage process will not place any limit to the speed of the survey vehicle. A survey along a single lane may be adequate at this level. The estimated cost for surveying at the network level is about $30-60/lane-mile.

At the project level, the object of GPR survey is to provide information in detail for the selected pavement management system project. Traditionally, this information has involved a review of structural and surface condition to determine the structure betterment required. For example, if the pavement has failed, then reconstruct; if some remaining life exists, then over-lay; if structurally sound, then functionally rehabilitate. GPR survey at this level is in a more detailed mode. Multiple passes may be needed in a problematic segment to provide lateral extent of subsurface events. Meanwhile, the sampling rate is much higher than surveys at the network level. Thus, the speed of the vehicle needs to be slower, and the cost of survey is higher than at the network level, it is about $100-300/lane-mile. To improve the efficiency of the survey at the project level and to increase the width of GPR signal coverage, a single transmitter with multiple receiver radar system has been proposed by a research group in the Lawrence Livermore National Laboratory. The sketch of this idea is shown in Figure 2 (Warhus et al 1993; Nelson 1994).

4.2 GPR Pavement Assessment Survey Methodology

There are different kinds of GPR antenna combinations in GPR pavement assessment practice (e.g., see Table 2). The simplest one is using the ground-coupled flat bow-tie antenna. Figure 3 shows an example by using the ground coupled bow-tie antenna (i.e., the GSSI 400 MHz antenna), made by the University of Nebraska-Lincoln. The GSSI SIR antenna system can provide GPR survey data in 4 channels; 2 in co-polarization setup and the other 2 in cross-polarization setup. Sato et al (1995) discussed the advantages for using the combined polarization antenna setup in boreholes.

Another type of antenna, the air launched horn antenna (Figure 2), is more commonly used in the pavement assessment practice. Examples of GPR pavement survey system using only the horn antenna include Pulse Radar, the GSSI SIR-10, etc. It has the advantage of no direct friction between the antenna and the surface, so that it won't place any constraint on the speed of the survey vehicle. Research conducted by Infrasense Inc. (Maser, 1997) in Minnesota using highway-speed horn antenna radar equipment and automated analysis software, can accurately measure asphalt thickness. To accurately measure concrete and base thickness, lower speed ground coupled equipment also must be used. In that project, researchers collected radar data for pavement layer thickness at 40 MN/ROAD research pavement sections in Minnesota to obtain accurate asphalt pavement layer thickness data on the sections. A blind comparison between radar asphalt thickness data and available cores shows an R-squared of 0.98. For concrete thickness, the R-square was 0.76. The report details results for base and subbase thickness and for the layer thicknesses of the four aggregate sections.

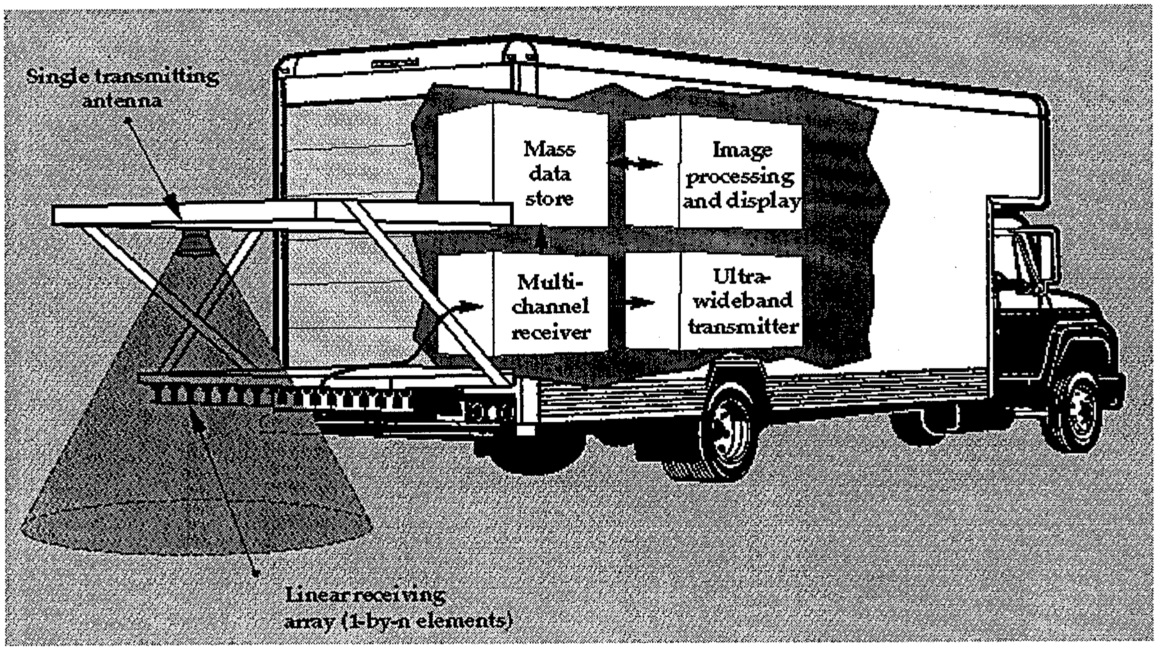


Figure 2. The Ground Penetrating and Imaging Radar (GPIR) truck proposed by the Lawrence Livermore National Laboratory.

Figure 3. The GPR van of University of Nebraska at Lincoln with GSSI system.

Besides using single type antennas for pavement assessment, some systems use a combination of the air-launched horn antenna and the ground coupled bow-tie antenna. For example, the Road Radar System uses a 2.5 GHz air-launched horn antenna and a 1 GHz ground-coupled array antenna, combined with a video logging camera. The technically superior hybrid radar hardware comprises one half of the total Road Radar System. Meanwhile, the post-processing software environment completes the system. The hardware setup of the Road Radar System is shown in Figure 4. A comprehensive graphical signal processing environment combines time and frequency domain techniques with rule-based expert systems and neural network based pattern recognition to automate the radar data interpretation process.

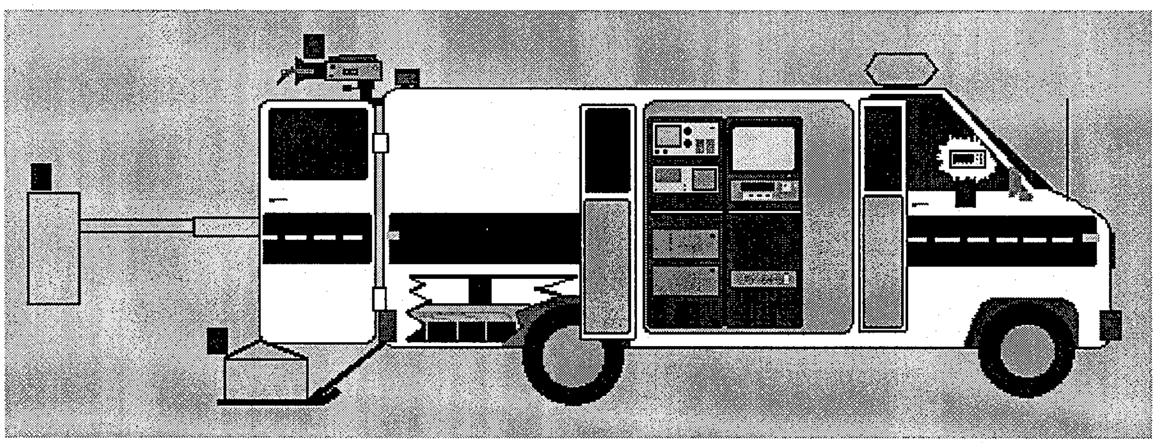


Figure 4. Road Radar data acquisition system components. (1) 2.5 GHz air-launched horn antenna; (2) video logging camera; (3) 1 GHz ground-coupled array antenna; (4) Radar system control and data acquisition; (5) Distance measuring instrument; (6) RF electronics.

The output formats produced by Road Radar may be client specified. Standard formats include the continuous multiple layer thickness profiles and raw radar data annotated with identified features such as: cracks, voids, structure changes. Other data can also be included such as: deflection measurement at specific locations and underground infrastructure. Tabular presentation of thickness of each layer at client selected intervals includes means and standard deviations. A piece of GPR survey profile output is shown in Figure 5.

The following list summarizes survey-methodology issues.

(i) Project scope (network level, project level);

(ii) Antenna type (surface contact antenna, air-launched horn antenna);

(iii) Frequency of GPR signal (all above 1 GHz).

Clients can specify either a network-level or project-level survey. The speed of the survey vehicle depends on data sampling rate (spacing). High sampling rate (at the project level) places a limit on the survey speed. The frequency range currently used in practice is 1-5 GHz. Air-launched horn antenna is the favored kind of antenna in GPR pavement assessment survey. Combination of the air-launched antenna and the ground coupled dipole antenna may yield more subsurface information, with a bit higher budget for ground-coupling antenna maintenance (changing the worn-out sliding strips).

4.3 New Developments in Multi-Channel Acquisition

Although the ground penetrating radar has been used in the simple monostatic mode for a number of years in geotechnical and transportation applications, the use of a single-channel setup has not allowed the considerable benefits possible with multi-channel acquisition. The past couple of years, however, have seen new developments in multi-channel acquisitions in GPR road surveys.

Peacock [1997] of Geotechnica LTD in UK proposed and implemented a new GPR acquisition hardware system using the multi-channel idea. This multi-channel radar system uses eight transmitter/receiver pairs in a closely coupled configuration as a single antenna with full digital control and data acquisition. The antenna is entirely controlled by a high-

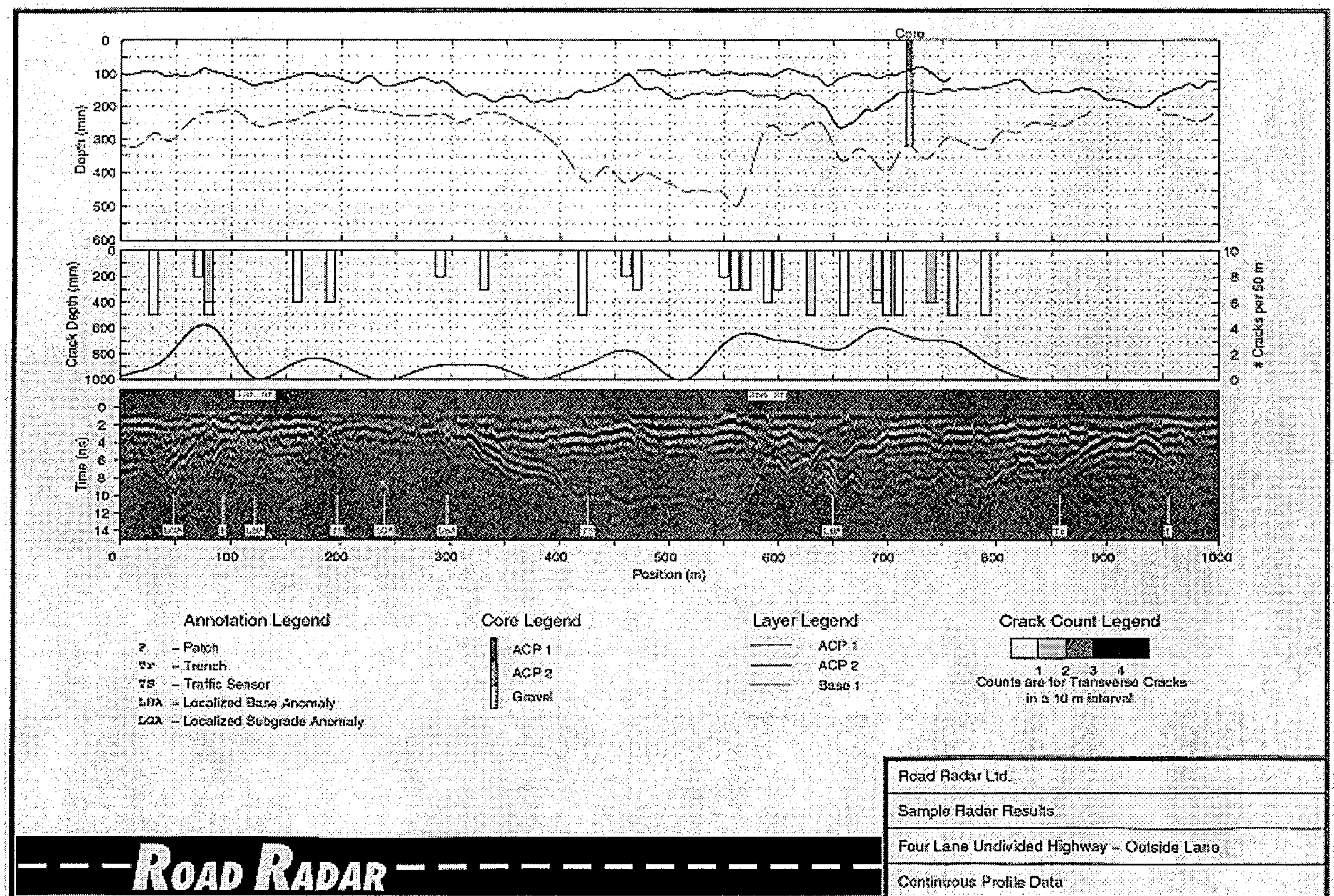


Figure 5. An example of Road Radar survey results.

speed microprocessor which connects other antennae to an acquisition computer on a 1 Mbyte/sec SDLC network link. The network protocol permits a maximum of 255 antennae to link together on a drop-down bus topology. The functionality of one antenna is shown in Figure 6.

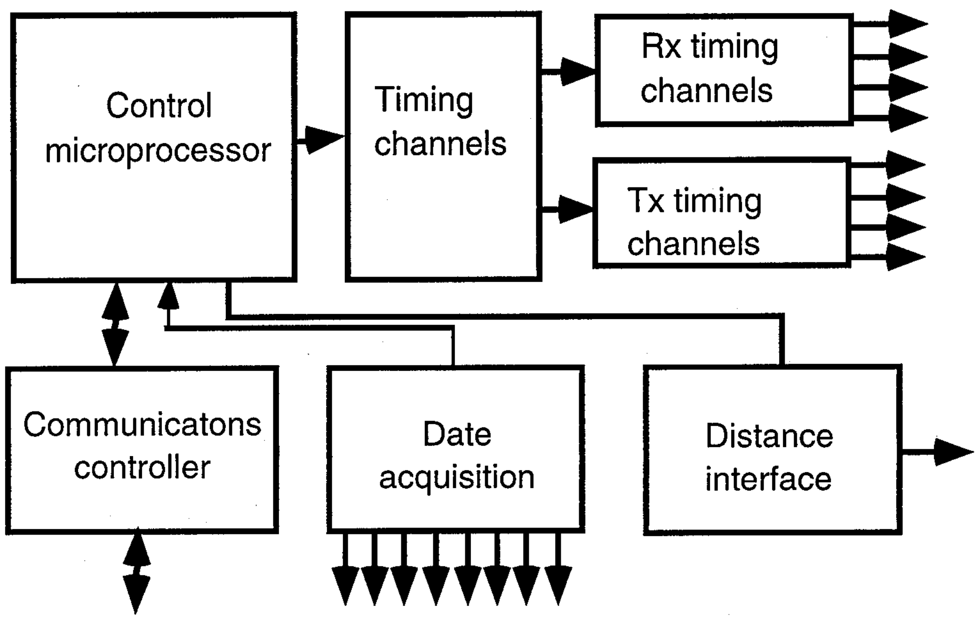


Figure 6. GPR Data acquisition functional schematic sketch proposed by Geotechnica (Peacock, 1998).

The use of a multi-channel system permits a major improvement in the quality of GPR. Such an improvement is attributed to the high power of the transmitters and the ability of velocity-based stacking to attenuate reverberation and focus the overall antenna response to a common reflection point. Inclusion of the velocity data promises depth information in the final cross sections and allows the use of migration techniques, which, for many years, have constituted the single most important data-processing technology used in exploration seismology.

5. GPR Data Processing Research Carried Out By the PI: Wavelet Transform

During the fiscal year of 1997-98, besides the feasibility study via literature search defined in Project JHRAC 97-4, the PI also devoted a substantial portion of his time to the study of GPR data-processing algorithms. Among the advancements in this area, he found that the technique of wavelet transform may be an optimal candidate for improving data-processing and -interpretation software packages, and would lend itself as an excellent topic for follow-up studies on GPR pavement assessment in the future.

5.1 Introduction of the Wavelet Transform

In recent years the digital signal processing technique of wavelet transform has been very successfully applied in a number of scientific and engineering fields. The advantage of the wavelet transform technique is that it can combine reduction, compression, denoising, time-frequency analysis, and feature recognition for the same data set. The vast quantity of data generated by a road survey poses severe limits to survey speed and length. Any technique with potential to compress large data sets without loss of information is worth further investigation. Besides processing the GPR data, this technique can also be used in data processing and compression of other pavement assessment methods that involve a large amount of data such as the video camera survey.

Wavelet transform methods found their origin as an analysis tool for examining scattering of seismic waves. In the last few years, it has been proven that they are useful and popular in many fields. Wavelet analyses can characterize temporal or spatial behavior of geophysical signals. They can filter and enhance data, as well as remove unwanted signals. In addition, they can be used to detect specific events in the compressed data.

The key advantage of the wavelet transform over the conventional Fourier transform is its capability of localizing the target information in both the time and frequency domain simultaneously. The wavelet transform distinguishes itself from the Short Time Fourier Transform for time-frequency analysis in that it has a zoom-in and zoom-out capability. Thus, the approach is suitable for time-frequency analysis of radar signals. Application capability of the wavelet transform depends on the selection of the wavelet functions. The popularly developed wavelet functions are orthonormal and compactly supported, but they do not have a finite impulse response and linear phase. In using radar for non-destructive assessment, the orthonormality of this kind of wavelet functions is undesirable, especially when subsequent complex processing is required. The non-orthogonal wavelet transform algorithm avoids phase distortion problems, hence provides a better choice for GPR applications. In seismic studies it was applied to remove coherent noises. The signals reconstructed by using the wavelet transform show significant improvement in the signal to noise ratio.

Another advantage of the wavelet transform is that there exist proven, fully-developed algorithms capable of achieving compression ratios in excess of 100:1 in the processing of seismic reflection data, which is very similar to the processing of GPR data. Although the compression algorithm is "lossy", in the sense that it introduces noise into the final reconstituted data set, the compression noise leads to no observable loss of geophysical information at compression ratios substantially greater than 100:1. The compression algorithm employs the wavelet transform to characterize data on the basis of a number of subbands having different temporal and spatial frequency content. The coherency and redundancy of multidimensional seismic datasets permit efficient quantization of the data by each wavelet-transform subband, such that a very small number of bits per data sample will accurately represent the data. The ability to compress data by such large factors leads to the possibility of storing entire field datasets onto the hard disk of the on-vehicle computer or transmitting entire field datasets from a survey vehicle directly to a processing center nearly in real time.

5.2 Research on Wavelet Transform and Testing Data Collection

The PI presented a paper to the 7th International Conference on GPR in Lawrence, Kansas in May, 1998 on using the wavelet transform in environmental application (Liu and Oristaglio, 1998). In this paper the authors presented a method for imaging subsurface features by calculation of the instantaneous parameters of GPR time traces. Figure 7 shows a GPR profile acquired over a subsurface gasoline contaminant plume. Wavelet analysis for time trace at the location outside of the plume (Figure 8a) is significantly different from that within the plume (Figure 8b). Extraction of the instantaneous phase through the use of the wavelet analysis may allow identification of the interfaces between asphalt, base and subbase in pavement assessment.

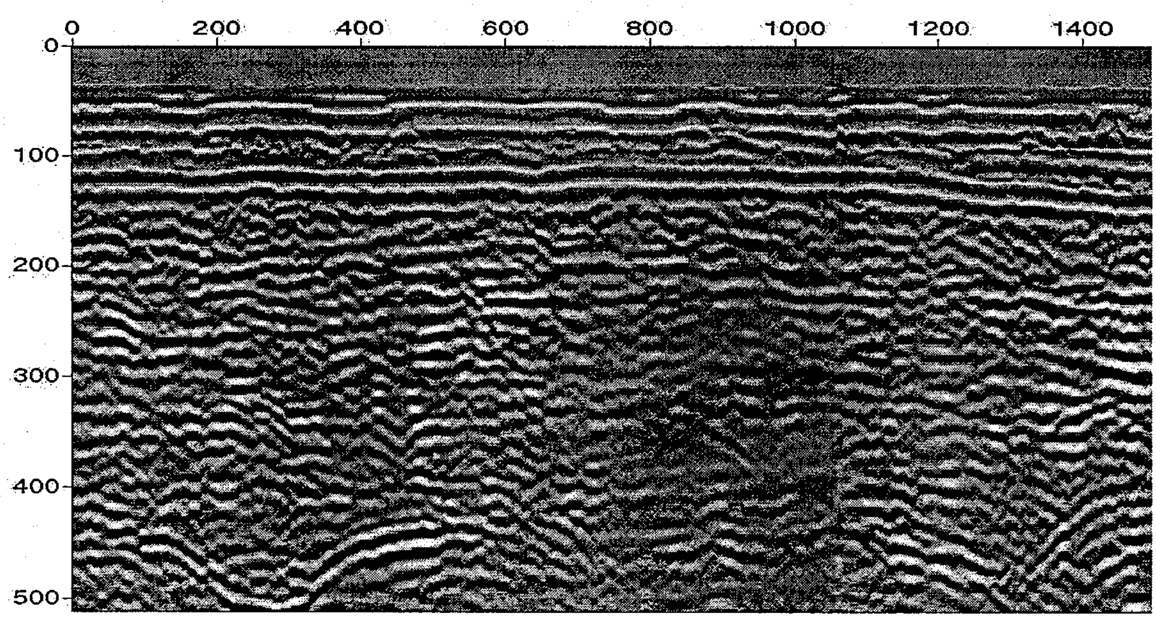
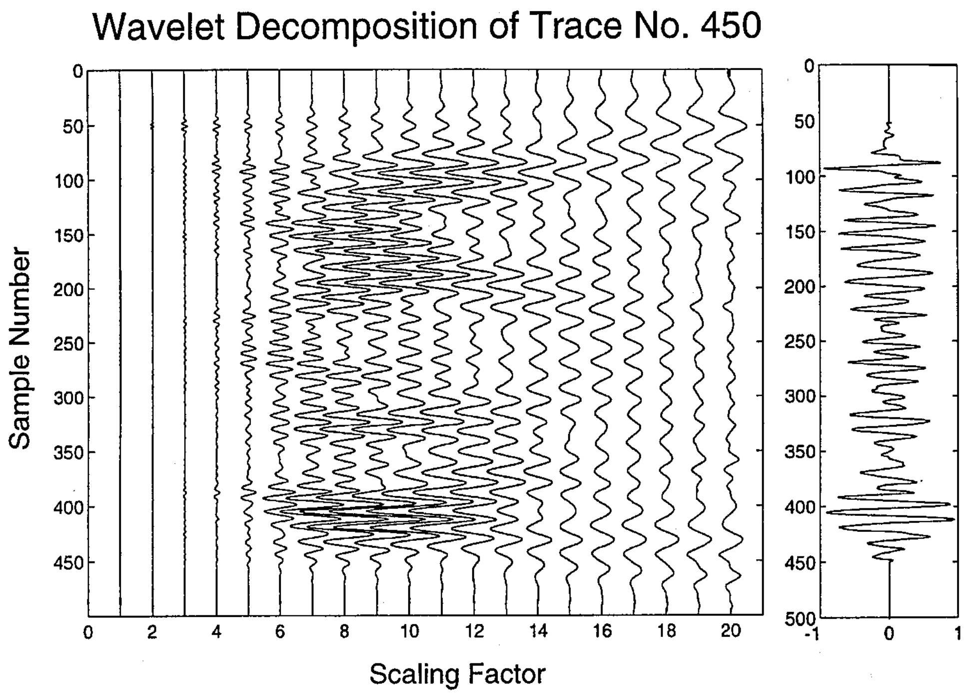
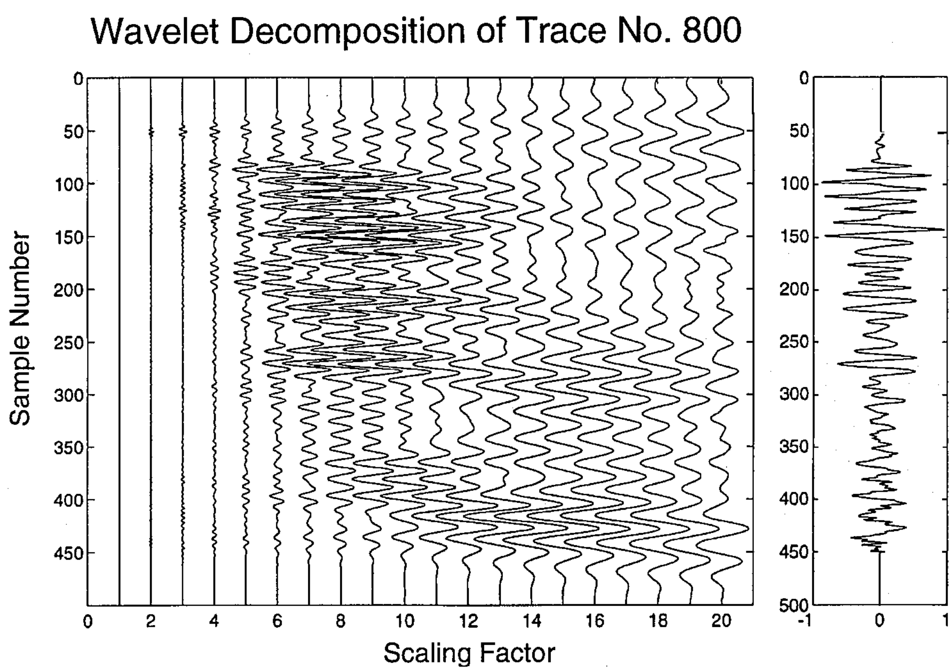


Figure 7. A GPR profile collected at the former Wurtsmith Air Force Base in Michigan, courtesy from W.A. Sauck. The central frequency of the antenna is 100 MHz. The total scan length in travel time is 400 nanosecond, consisting of 512 samples in each trace. A total number of 1,576 traces scanned 300 feet in horizontal distance (oriented with west to the left) on the surface in an approximately east-west direction.



(a)



(b)

Figure 8. Wavelet decomposition for 2 time traces in the GPR shown in Figure 7. Trace No. 450 (shown as (a)) is acquired at a position outside of the plume on the surface. The position on surface to acquire trace No. 800 (shown in (b)) is directly above the plume.

The PI's group also collected a test dataset over asphalt pavement using the 1 GHz RAMAC/Radar system. In the profile we can clearly identify the base of the asphalt layer. This is only a test dataset using ground-coupled bow-tie antennae, but it is encouraging that by just such a simple test, we do see the main features of pavement structures. This test dataset was collected on the Depot Campus of the University of Connecticut and is shown below as Figure 9. From the profile it is clear that the interface between the asphalt layer and the base is different between the far right at the profile from the rest. The reason is not known at this stage; more direct ground-truth information is needed to verify the existence of this anomaly.

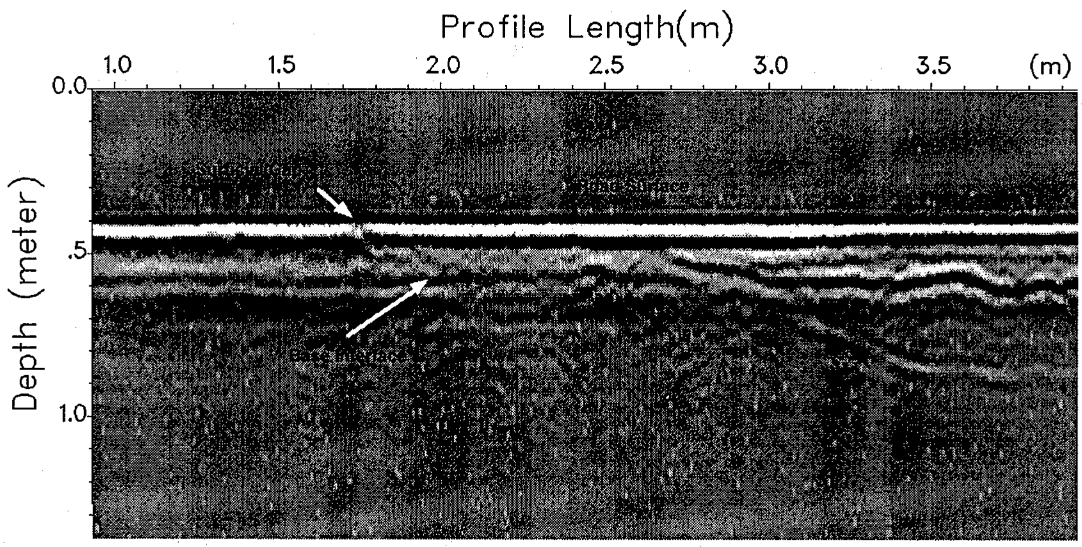


Figure 9. GPR profile along the asphalt paved path in front of the Coventry Cottage, Depot Campus, Storrs, CT. The GPR system is the RAMAC/RADAR by MALA Geoscience, Inc. using 1 GHz antenna.

6. Conclusions and Suggestions

As a summary of previous sections, the PI highlights the following conclusions and makes a number of suggestions, in accordance with the findings, to the Joint Highway Research Advisory Council (JHRAC) and ConnDOT.

(1) The GPR survey is close to mature to be considered as a major non-destructive testing technology in highway pavement assessment.

(2) In terms of GPR hardware, there are mainly two types of antenna to be used in practice: the air-launched horn antenna and the ground coupled bow-tie dipole antenna.

(3) In terms of GPR data processing software, the neural network analysis is the major tool used in identifying subsurface events.

(4) In survey methodology, the GPR survey employs a different approach for jobs at the network level and the project level. The surveys conducted at the network level tend to be a reconnaissance, with low associated cost. The surveys at the project level are for detailed subsurface features, and thus more costly.

(5) During the last several years, there has been significant progress in the areas of hardware, software, and survey methodology development.

In the future, when ConnDOT plans to use GPR for rapid pavement assessment, the PI has the following suggestions:

(1) The horn antenna with stepped frequency in 1 - 5 GHz should be the at the top of the list in terms of hardware.

(2) Using software based upon neural network with association of wavelet transform to substantially reduce the amount of data involved.

(3) GPR surveys may still be in monostatic mode, but use the multiple transmitter-receiver array to get in situ velocities.

(4) Upon purchasing or evaluating GPR systems, request information on the system parameters mentioned in Section 2 from potential vendors. The PI is willing to help on conducting a thorough system check and evaluation using the criteria discussed in Section 2.

List of References

Attoh-Okine, N., 1995, Use of artificial neural networks in ground penetrating radar applications in pavement evaluation and assessment, Proceedings of International Symposium on Non-Destructive Testing in Civil engineering, pp. 93-99.

Bethel, R., and R. Rahikka, 1987, An optimum first-order time delay tracker, IEEE Trans. Aerospace and Electronic Systems, Vol. AES-23, No. 6, pp. 718-725.

Bethel, R., and G. Paras, 1994, A PDF multitarget tracker, IEEE Trans. Aerospace and Electronic Systems, Vol. AES-30, No. 2, pp. 386-403.

Brewster, M. L., and A. P. Annan, 1994, Ground-penetrating radar monitoring of a controlled DNAPL release: 200 MHz radar, Geophysics, Vol. 59, pp. 1211-1221.

Daily, W., and A. Ramirez, 1995, Electrical resistance tomography during in-situ trichloroethelene remediation at the Savanah River site, J. Appl. Geophys., Vol. 33, pp. 239-249.

Hugenschmidt, J., M. Partl, H. de Witte, and C. Uri, 1996, GPR inspection of a mountain motoway-a case study, Proceedings of the 6th International Conference on Ground Penetrating Radar, pp. 365-370.

Huston, D., K. Maser, J. Hu, W. Weedon, and C. Adam, 1998, Bridge deck evaluation with ground penetrating radar, Proceedings of the 7th International Conference on Ground Penetrating Radar, pp. 595-599.

de Jongh, R., A. Yarovoy, L. Ligthart, I. Kaploun, and A. Schukin, 1998, Design and analysis of new GPR antenna concepts, Proceedings of the 7th International Conference on Ground Penetrating Radar, pp. 81-86.

Kong, F.-N., H. Westerdahl, and L. Gelius, 1998, A very wide bandwidth step frequency GPR for testing concrete re-bars, Proceedings of the 7th International Conference on Ground Penetrating Radar, pp. 455-460.

Kung, K-J. S., and Lu, Z-B., 1993, Using ground-penetrating radar to detect layers of discontinuous dielectric constant, Soil Sci. Soc. Am. J., Vol. 57, pp. 335-340.

Liu, L. and M. Oristaglio, 1998, GPR signal analysis: instantaneous parameter estimation using the wavelet transform, Proceedings of the 7th International Conference on Ground Penetrating Radar (GPR '98), pp. 219-223.

Maser, K. R., 1994, Ground penetrating radar survey of pavement thickness on MN/ROAD sections, INFRASENSE, Inc. Report No. MN/RC-95/06 to Minnesota Department of Transportation, Office of Minnesota Road Research.

Mathews, S., A. Goodier, and S. Massey, 1998, Permittivity measurements and analytical dielectric modeling of plain structural concretes, Proceedings of the 7th International Conference on Ground Penetrating Radar, pp. 363-368.

Mesher, D.E., C.B. Dawley, J.L. Davis, and J.R. Rossiter, 1995, Evaluation of a New Ground Penetrating Radar Technology to Quantify Pavement Structures, Presented at the 74th Annual Meeting of the Transportation Research Board, Washington, D.C.

Mesher, D.E., C.B. Dawley, and B. Pulles, 1996, A comprehensive radar hardware, interpretation software and survey methodology paradigm for bridge deck assessment, Proceedings of the 6th International Conference on Ground Penetrating Radar, pp. 353-358.

Mesher, D.E., 1992, Artificial Intelligence Applied to Bridge Deck Radar Interpretation, Ph.D dissertation, McMaster University, Hamilton, Ontario, Canada.

Mesher, D.E., and W.F.S. Poehlman, 1992, Interpretation of pulsed radar backscatter waveforms using a knowledge based system, presentation at AIENG'92: Applications of Artificial Intelligence in Engineering, University of Waterloo, Ontario, Canada, July 14-17, 1992.

Mesher, D.E., and W.F.S. Poehlman, 1988, Impulse Radar Ground Profiling System, Presented at Telecommunication Research Institute of Ontario (TRIO) Expert System Group Report, McMaster University.

Molyneaux, T. S. Millard, J. Bungey, and J. Zhou, 1995, Radar assessment of structural concrete using neural network, Non-Destructive Testing and Evaluation International, Vol. 28, No. 5, pp. 281-288.

Nelson, S.D., 1994, Electromagnetic Modeling for Target-Rich Embedded Environments, Engineering Research, Development, and Technology, Lawrence Livermore National Laboratory, Livermore, California, UCRL-53868-93.

Noon, D., 1996, Stepped-frequency radar design and signal processing enhances ground penetrating radar performance, PhD Thesis, University of Queensland, Australia.

Noon, D., G. Stickley, and D. Longstaff, 1996, A frequency independent characterization of GPR penetration and resolution performance, Proceedings of the 6th International Conference on Ground Penetrating Radar, pp. 329-334.

Pagnoni, T., 1996, An automated radar system for non destructive testing of bridge and highway pavements, Proceedings of the 6th International Conference on Ground Penetrating Radar, pp. 359-364.

Patel, D. L., 1993, Desert Storm soil properties and mine detectors, Technical Report to Unite State Army, USA-BRDEC-TR//2537, 80 pp.

Peacock, J. H., 1997, Dynamically phased radar: a new technique for geotechnical investigations, SEG Expanded Abstracts, pp. 753-756.

Pratt, D., and M. Sansalone, 1992, Impact-echo signal interpretation using artificial intelligence, ACI Materials Journal, Vol. 89, No. 2 pp. 178-187.

Saarenketo, T. and P. Roimela, 1998, Ground penetrating radar technique in asphalt pavement density quality control, Proceedings of the 7th International Conference on Ground Penetrating Radar, pp. 461-465.

Saarenketo, T. and T. Scullion, 1996, Laboratory and GPR tests to evaluate electrical and mechanical properties of Texas and Finnish base course aggregates, Proceedings of the 6th International Conference on Ground Penetrating Radar, pp. 477-482.

Sato, M., T. Ohkubo, and H. Niitsuma, 1995, Cross-polarization borehole radar measurements with a slot antenna, J. Appl. Geophys., Vol. 33, pp. 53-61.

Scullion, T., C. H. Lau, and T. Saarenketo, 1996, Performance specifications of ground penetrating radar, Proceedings of the 6th International Conference on Ground Penetrating Radar, pp. 341-346.

Shaw, M., T. Molyneaux, S. Millard, J. Bungey, and M. Taylor, Automatic analysis of GPR scans on concrete structures, Proceedings of the 7th International Conference on Ground Penetrating Radar, pp. 449-453.

Shlager, K. L. et. al., 1994, Optimization of bow-tie antennas for pulse radiation, IEEE Transactions on Antenna and Propagation, Vol. AP-39, pp 410-413.

Simone, A., U. Spagnolini, G. Gentili, and V. Rampa, 1998, Electromagnetic inversion and interface tracking: system calibration and application, Proceedings of the 7th International Conference on Ground Penetrating Radar, pp. 607-612.

Smith, S. S., 1995, Detecting pavement deterioration with subsurface interface radar, Sensors, pp. 29-40.

Spagnolini, U., 1996, Joint approach of EM inversion and multi-layer detection/tracking for pavement profiling, Proceedings of the 6th International Conference on Ground Penetrating Radar, pp. 235-240.

Spagnolini, U., 1997, Permittivity measurements of multilayered media with monostatic pulse radar, IEEE Trans. Geosci. and Remote Sensing, Vol. 35, No. 2, pp. 454-463.

Spagnolini, U., and V. Rampa, 1998, Multitarget detection/tracking for monostatic ground penetrating radar: application to pavement profiling, submitted to IEEE Trans. Geosci. and Remote Sensing.

Stickley, G., D. Noon, D., M. Chernniakov, and D. Longstaff, 1998, Current development status of a gated stepped-frequency GPR, Proc. 7th Int. Conf. GPR, pp. 311-315.

Telford, W. M., L. P. Geldart, and R. E. Sheriff, 1990, Applied Geophysics, 2nd edition, Cambridge University Press, 770 pp., Cambridge, UK.

Ulriksen, C., 1982, Application of impulse radar to civil engineering, PhD Thesis, Department of Engineering Geology, Lund University of Technology.

U.S. Department of Transportation, Federal Highway Administration, 1990, Our Nations Highways: Selected Facts and Figures, Publ. No. FHWA-PL-90-024.

Wakita, Y., and Y. Yamaguchi, 1996, Estimation of the soil permittivity and conductivity by a GPR antenna, Proceedings of the 6th International Conference on Ground Penetrating Radar, pp. 123-127, Sendai, Japan, Sept. 30-Oct. 3, 1996.

Warhus, J.P., J.M. Hernandez, S.D. Nelson, E.M. Johansson, and H.Lee, 1993, Ground Penetrating, Imaging Radar for Bridge Inspection, Engineering Research, Development, and Technology, Lawrence Livermore National Laboratory, Livermore, California, UCRL-53868-92.

Appendix I: Publications by the PI and his students on GPR applications

Buursink, M., The application of ground penetrating radar (GPR) to the characterization of fractures in crystalline bedrock, *MS thesis*, 163 pp. Department of Geology and Geophysics, University of Connecticut, May, 1998.

Liu, L., The ground penetrating radar (GPR) survey at the future site of the Lebanon Historical Society Museum, Connecticut, Report to the Archaeology Research Specialists, Inc. 19pp, 1996.

Liu, L., State-of-the-art rapid non-destructive pavement assessment: Ground penetrating radar (GPR) in monostatic mode, Report to the Joint Highway Research Advisory Council, Connecticut Department of Transportation, 1998.

Liu, L., T. M. Habashy, and M. L. Oristaglio, Imaging the shape of a two-dimensional cylindrical inclusion near a plane surface by electromagnetic wave scattering, in the *Proceedings of the Progress in Electromagnetics Research Symposium (PIERS '97),* Cambridge, Massachusetts, July 7-11, p. 40, 1997.

Liu, L. J. W. Lane, and Y. Quan, Radar attenuation tomography using the centroid frequency down-shift method, *Journal of Applied Geophysics,* Vol. 40, No. 1-3, pp. 105-116, 1998.

Liu, L. and M. Oristaglio, GPR signal analysis: instantaneous parameter estimation using the wavelet transform, *Proceedings of the 7th International Conference on Ground Penetrating Radar (GPR '98),* pp. 219-223, Lawrence, Kansas, May 27-30, 1998.

Liu, L., and Y. Quan, GPR wave attenuation tomography using the frequency shift method, in the *Proceedings of the 6th International Conference on Ground Penetrating Radar,* pp. 335-340, Sendai, Japan, Sept. 30-Oct. 3, 1996.

Liu, L., and Y. Quan, GPR attenuation tomography for detecting DNALs, in the *DNAPL Conference Technical Papers,* Paper IV, Manchester, CT, Oct. 23, 1996.

Liu, L., and Y. Quan, GPR attenuation tomography for detecting DNALs, in the *Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP '97),* pp. 241-251, Reno, Nevada, March 23-26, 1997.

Liu, L., C. Zhou, F. P. Haeni, and J. W. Lane, GPR attenuation tomography using frequency shift method: Consideration of non-linear frequency dependence of attenuation, *SEG Expanded Abstracts, SEG 67th Annual Meeting*, pp. 442-445, Dallas, Texas, November 2-7, 1997.

Liu, L., C. Zhou, and L. Xiao, Imaging the interior of the Nathan Hale Monument in Coventry, Connecticut by GPR attenuation tomography, in the *Proceedings of the 7th International Conference on Ground Penetrating Radar (GPR '98),* pp. 775-778, Lawrence, Kansas, May 27-30, 1998.

Liu, L., C. Zhou, and L. Xiao, Imaging the interior of the Nathan Hale Monument in Coventry, Connecticut by radar tomography, *Journal of Applied Geophysics,* 1999. (submitted)

Xiao, L., L. Liu, and V. Cormier, Three-dimensional finite-difference time-domain solution to Maxwell's equations using pseudo-spectral method, *Proceedings of the 7th International Conference on Ground Penetrating Radar (GPR '98),* pp. 585-589, Lawrence, Kansas, May 27-30, 1998.

Zhou, C., and L. Liu, Multi-frequency radar diffraction tomography using quasi-linear approximation, *Proceedings of the 7th International Conference on Ground Penetrating Radar (GPR '98),* pp. 303-307, Lawrence, Kansas, May 27-30, 1998.

Appendix II: Information on GPR Equipment Venders and GPR pavement assessment and bridge deck inspection vendors

Road Radar Inc.

14535-118 Avenue

Edmonton, Alberta

Canada, T5L 2M7

email: mesher@rrl.com

web: http://www.rrl.com/

Ground Penetrating Imaging Radar (GPIR)

Lawrence Livermore National Lab

Defense Sciences Engineering Division

and Laser Engineering Division

web: http://www-dsed.llnl.gov/documents

Geotechnica Ltd.

Unit 20, Applins Farm, Farrington

Blandford, Dorset DT11 8RA, UK

phone: 01747 812104

fax: 01747 812204

e-mail: peack@geotechnica.demon.co.uk

MALA GeoScience

Skolgatan 11,

S-930 70 Mala, Sweden

phone: 46-953-107-10

fax: 46-953-102-25

e-mail: geoscience@malags.se

Geophysics GPR International Inc.

2545, Delorimier Street

Longeuil, Québec J4K 3P7

Canada

phone: 514-679-2400

fax: 514-521-4128

e-mail: gprmtl@citenet.net

http://www.geophysicsgpr.com/index.htm

Geophysical Survey Systems, Inc.

13 Klein Drive,

P. O. Box 97

North Salem, N.H. 03073-0097

phone: 800-524-3011

phone: 603-893-1109

fax: 603-889-3984

e-mai: gssisales@aol.com

web: http://www.geophysical.com

Sensor & Software, Inc.

1091 Brevik Place,

Mississauga, ON

L4W 3R7 Canada

905-624-8909 (phone)

905-624-9365 (fax)

Infrasense, Inc.

14 Kensington Road

Arlington, MA 02174

phone: 617-648-0440

fax: 617-648-1778

e-mail: info@infrasense.com

web: http://www.infrasense.com

Pulse Radar, Inc.

10665 Richmond, Suite 170

Houston, Texas, 77042

phone: 713-977-0557

fax:713-977-2159

Annan, A P., 1996, Transmission dispersion and GPR, Jour. Environ. & Engineer. Geophysics, Vol. 0, pp. 125-136.

Annan, A. P., J. L. Davis, and D. Gendzwill, 1988, Radar sounding in potash mines, Saskatchewan, Canada, Geophysics, Vol. 53, pp. 1556-1564.

Attoh-Okine, N., 1995, Use of artificial neural networks in ground penetrating radar applications in pavement evaluation and assessment, Proceedings of International Symposium on Non-Destructive Testing in Civil engineering, pp. 93-99.

Balanis, C. A., 1989, Advanced Engineering Electromagnetics, 981 pp. John Wiley & Sons, New York.

Bano, M., 1996, Constant dielectric losses of ground penetrating radar waves, Geophys. J. Int., Vol. 124, pp. 279-288.

Baysal, E., D. D. Kosloff, and J. W. C. Sherwood, 1983, Reverse time migration, Geophysics, Vol. 48, pp. 1514-1524.

Beres, M. Jr., and F. P. Haeni, 1991, Application of ground-penetrating radar methods in hydrogeologic studies, Ground Water, Vol. 29, pp. 375-386.

Bethel, R., and R. Rahikka, 1987, An optimum first-order time delay tracker, IEEE Trans. Aerospace and Electronic Systems, Vol. AES-23, No. 6, pp. 718-725.

Bethel, R., and G. Paras, 1994, A PDF multitarget tracker, IEEE Trans. Aerospace and Electronic Systems, Vol. AES-30, No. 2, pp. 386-403.

Black, K., and P. Kopac, 1992, The application of ground-penetrating radar in highway engineering, Public Roads, Vol. 56, no. 3, pp. 96-103.

Brewster, M. L., and A. P. Annan, 1994, Ground-penetrating radar monitoring of a controlled DNAPL release: 200 MHz radar, Geophysics, Vol. 59, pp. 1211-1221.

Brewster. M.L., A.P. Annan, J.P. Greenhouse, B.H. Kueper, G.R. Olhoeft, J.D. Redman, and K.A. Sander, 1995, Observed migration of a controlled DNAPL release by geophysical methods, Ground Water, Vol. 33, pp. 977-987.

Brzostowski, M. and G. McMechan, 1992, 3-D tomographic imaging of near-surface seismic velocity and attenuation, Geophysics, Vol. 57, pp. 396-403.

Cai, J., and G. A. McMechan, 1995, Ray-based synthesis of bistatic ground-penetrating radar profiles, Geophysics, Vol. 60, pp. 87-96.

Casper, D. A., and K-J. S. Kung, 1993, Testing a two-dimensional, seismic migration routine on ground-penetrating radar simulations, Presented at the 2nd Government Workshop on Ground-Penetrating Radar, U.S. EPA.

Cheng, D. K, 1983, Field and wave electromagnetics, Addison-Wesley Publ. Co., pp. 317-322.

Chung, T., C. R. Carter, T. Masliwec, and D. Manning, 1994, Impulse radar evaluation of concrete, asphalt, and waterproofing membrane, IEEE Transactions on Aerospace and Electronic Systems, Vol. 30, No.2, pp. 404-414.

Collins, M. E., and J. A. Doolittle, 1987, Using ground-penetrating radar to study soil microvariability, Soil Sci. Soc. Am. J., Vol. 51, pp. 491-493.

Daily, W., and A. Ramirez, 1995, Electrical resistance tomography during in-situ trichloroethelene remediation at the Savanah River site, J. Appl. Geophys., Vol. 33, pp. 239-249.

Daniels, J. J., R. Roberts, and M. Vendl, 1995, Ground penetrating radar for the detection of liquid contaminants, J. Appl. Geophys., Vol. 33, pp. 195-207.

Daniels, J., 1988, Locating caves, tunnels and mines, The Leading Edge, Vol. 7, no. 3, pp. 32-37.

Davis, J. L., and A. P. Annan, 1989, Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy, Geophys. Prosp., Vol. 37, pp. 531-551.

Davis, J.L., C.B. Dawley, D.E. Mesher and J.R. Rossiter, 1994, Quantitative Measurement of Pavement Structures Using Radar, Presented at the 5th International Conference on Ground Penetrating Radar, June 12-16, 1994.

Dawley, C.B., and D.E. Mesher, 1994, Characterization of Multi-Layer Pavement Structures Using a New GPR Technology, Presented at the Innovative Design and Construction Session of the 1994 International Road Federation Conference and Exposition, Calgary, Alberta.

Endres, A., and R. Knight, 1991, The effects of pore-scale fluid distribution on the physical properties of partially saturated sandstones, Jour. Appl. Phys., Vol. 69, pp. 1091-1098.

Endres, A., and J.D. Redman, 1996, Modeling the electrical properties of porous rocks and soils containing immiscible contaminants, Jour. Environ. & Engineer. Geophys., Vol. 0, pp. 105-112.

Feng, S., and P.N. Sen, 1985, Geometrical model of conductive and dielectric properties of partially saturated rocks, Jour. Appl. Phys., Vol. 58, pp. 3236-3243.

Fisher, E., G. A. McMechan, and A. P. Annan, 1992a, Acquisition and processing of wide-aperture ground-penetrating radar data, Geophysics, Vol. 57, pp. 495-504.

Fisher, E., G. A. McMechan, A. P. Annan, and S. W. Cosway, 1992b, Examples of reverse-time migration of single-channel ground-penetrating radar profiles, Geophysics, Vol. 57, pp. 577-586.

Gazdag, J., 1981, Modeling of the acoustic wave equation with transform methods, Geophysics, Vol. 46, pp. 854-859.

Goodman, D., 1994, Ground-penetrating radar simulation in engineering and archaeology, Geophysics, Vol. 59, pp. 224-232.

Greenhouse J., M. Brewster, G. Schneider, D. Redman, P. Annan, G. Olhoeft, J. Lucius, and A. Mazzella, 1993, Geophysics and solvents: the Borden experiment, The Leading Edge, Vol. 12, No. 4, pp. 261-267.

Greenhouse, J. P., 1992, Environmental geophysics, SEG Annual Meeting Expanded Technical Program Abstracts With Biographies, Vol. 62, pp. 606-609.

Greeuw, G., J.W. de Feijter, and A. Kathage, 1992, Field and laboratory tests on line scatterers. Proceedings of the 4th International Conference on GPR, pp. 111-118.

Grumman, D.L., and J. J. Daniels, 1996, Experiments on the detection of organic contaminants in the vadose zone, Jour. Environ. & Engineer. Geophys., Vol. 0, pp. 31-38.

Johnston, D.H., 1981, Attenuation: A state-of-art summary, Seismic Wave Attenuation. In: M. N. Toksoz and D. H. Johnston (Editors), Geophysics reprint series, No. 2.

Joncsher, A. K., 1977, The 'universal' dielectric response, Nature, Vol. 267, pp. 673-679.

Joncsher, A. K., 1978, Low-frequency dispersion in carrier-dominant dielectrics, Philos. Mag. B., Vol. 38, pp. 587-601.

Kjartansson, E., 1979, Constant *Q*–wave propagation and attenuation, J. Geophys. Res., Vol. 84, pp. 4137–4748.

Hammond, W. R., and Sprenke, K. F., 1991, Radar detection of subglacial sulfides, Geophysics, Vol. 56, pp. 870-873.

Harrington, R. F., 1961, Time-harmonic electromagnetic fields: McGraw-Hill Book Co., pp. 1-12.

Hohmann, G. W., 1987, Numerical modeling for electromagnetic methods of geophysics, in M. N. Nabighian, Ed., Electromagnetic methods in applied geophysics-theory, Vol. 1, Soc. Expl. Geophys., pp. 313-363.

Hugenschmidt, J., M. Partl, H. de Witte, and C. Uri, 1996, GPR inspection of a mountain motoway-a case study, Proceedings of the 6th International Conference on Ground Penetrating Radar, pp. 365-370, Sendai, Japan, Sept. 30-Oct. 3, 1996.

Huston, D., K. Maser, J. Hu, W. Weedon, and C. Adam, 1998, Bridge deck evaluation with ground penetrating radar, Proceedings of the 7th International Conference on Ground Penetrating Radar, pp. 595-599.

de Jongh, R., A. Yarovoy, L. Ligthart, I. Kaploun, and A. Schukin, 1998, Design and analysis of new GPR antenna concepts, Proceedings of the 7th International Conference on Ground Penetrating Radar, pp. 81-86.

Ju, S-H., and K-J. S. Kung, 1993, Finite element simulation of funnel flow and overall flow property induced by multiple soil layers, J. Environ. Qual., Vol. 22, pp. 432-442.

Kong, F.-N., H. Westerdahl, and L. Gelius, 1998, A very wide bandwidth step frequency GPR for testing concrete re-bars, Proceedings of the 7th International Conference on Ground Penetrating Radar, pp. 455-460.

Kosloff, D. D., and E. Baysal, 1982, Forward modeling by a Fourier method, Geophysics, Vol. 47, pp. 1402-1412.

Kung, K-J. S., and Lu, Z-B., 1993, Using ground-penetrating radar to detect layers of discontinuous dielectric constant, Soil Sci. Soc. Am. J., Vol. 57, pp. 335-340.

Kuo, J. T., and V-H. Cho, 1980, Transient time-domain electromagnetics, Geophysics, Vol. 45, pp. 271-291.

Johansson, E.M., and J.E. Mast, 1994, Imaging Algorithms for Synthetic Aperture Ultra-Wide band Radar, Engineering Research, Development, and Technology, Lawrence Livermore National Laboratory, Livermore, California, UCRL-53868-93.

Lockner, D. A., and J. D. Byerlee, 1985, Complex resistivity measurements of confined rock, J. Geophys. Res., Vol. 90, pp. 7837-7847.

Maser, K. R., 1994, Ground penetrating radar survey of pavement thickness on MN/ROAD sections, INFRASENSE, Inc. Report No. MN/RC-95/06 to Minnesota Department of Transportation, Office of Minnesota Road Research.

Mathews, S., A. Goodier, and S. Massey, 1998, Permittivity measurements and analytical dielectric modeling of plain structural concretes, Proceedings of the 7th International Conference on Ground Penetrating Radar, pp. 363-368.

McCann, D. M., P. D. Jackson, and P. J. Fenning, 1988, Comparison of the seismic and ground probing radar methods in geological surveying, IEE Proc. Part F, Vol. 135, pp. 380-390.

Mesher, D.E., C.B. Dawley, J.L. Davis, and J.R. Rossiter, 1995, Evaluation of a New Ground Penetrating Radar Technology to Quantify Pavement Structures, Presented at the 74th Annual Meeting of the Transportation Research Board, Washington, D.C.

Mesher, D.E., C.B. Dawley, and B. Pulles, 1996, A comprehensive radar hardware, interpretation software and survey methodology paradigm for bridge deck assessment, Proceedings of the 6th International Conference on Ground Penetrating Radar, pp. 353-358.

Mesher, D.E., 1992, Artificial Intelligence Applied to Bridge Deck Radar Interpretation, Ph.D dissertation, McMaster University, Hamilton, Ontario, Canada.

Mesher, D.E., and W.F.S. Poehlman, 1992, Interpretation of pulsed radar backscatter waveforms using a knowledge based system, presentation at AIENG'92: Applications of Artificial Intelligence in Engineering, University of Waterloo, Ontario, Canada, July 14-17, 1992.

Mesher, D.E., and W.F.S. Poehlman, 1988, Impulse Radar Ground Profiling System, Presented at Telecommunication Research Institute of Ontario (TRIO) Expert System Group Report, McMaster University.

Molyneaux, T. S. Millard, J. Bungey, and J. Zhou, 1995, Radar assessment of structural concrete using neural network, Non-Destructive Testing and Evaluation International, Vol. 28, No. 5, pp. 281-288.

Nelson, S.D., 1994, Electromagnetic Modeling for Target-Rich Embedded Environments, Engineering Research, Development, and Technology, Lawrence Livermore National Laboratory, Livermore, California, UCRL-53868-93.

Noon, D., 1996, Stepped-frequency radar design and signal processing enhances ground penetrating radar performance, PhD Thesis, University of Queensland, Australia.

Noon, D., G. Stickley, and D. Longstaff, 1996, A frequency independent characterization of GPR penetration and resolution performance, Proceedings of the 6th International Conference on Ground Penetrating Radar, pp. 329-334.

Olhoeft, G. R., 1986, Direct detection of hydrocarbon and organic chemicals with ground-penetrating radar and complex resistivity: Proc., NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater - Prevention, Detection and Restoration, Natl. Water Well Assoc., pp. 284-305.

Pagnoni, T., 1996, An automated radar system for non destructive testing of bridge and highway pavements, Proceedings of the 6th International Conference on Ground Penetrating Radar, pp. 359-364.

Peacock, J. H., 1997, Dynamically phased radar: a new technique for geotechnical investigations, SEG Expanded Abstracts, pp. 753-756.

Powers, M. H., 1995, Dispersive Ground Penetrating Radar Modeling In 2d. PhD Thesis, Colorado School of Mines, Golden, CO, USA.

Patel, D. L., 1993, Desert Storm soil properties and mine detectors, Technical Report to Unite State Army, USA-BRDEC-TR//2537, 80 pp.

Pratt, D., and M. Sansalone, 1992, Impact-echo signal interpretation using artificial intelligence, ACI Materials Journal, Vol. 89, No. 2 pp. 178-187.

Quan, Y., and J.M. Harris, 1997, Seismic attenuation tomography using the frequency shift method, Geophysics, Vol. 62, pp. 895-905.

Roberts, R. L., and J. J. Daniels, 1997, Modeling near-field GPR in three dimensions using the FDTD method, Geophysics, Vol. 62, pp. 1114-1126.

Roberts, R. L., and D. Petroy, 1996, Semi-automatic processing of GPR data collected over pavement, Proceedings of the 6th International Conference on Ground Penetrating Radar, pp. 347-352.

Saarenketo, T. and P. Roimela, 1998, Ground penetrating radar technique in asphalt pavement density quality control, Proceedings of the 7th International Conference on Ground Penetrating Radar, pp. 461-465.

Saarenketo, T. and T. Scullion, 1996, Laboratory and GPR tests to evaluate electrical and mechanical properties of Texas and Finnish base course aggregates, Proceedings of the 6th International Conference on Ground Penetrating Radar, pp. 477-482.

Sato, M., T. Ohkubo, and H. Niitsuma, 1995, Cross-polarization borehole radar measurements with a slot antenna, J. Appl. Geophys., Vol. 33, pp. 53-61.

Sato, M., and R. Thierbach, 1991, Analysis of a borehole radar in cross-hole mode, IEEE Transactions On Geoscience And Remote Sensing, Vol. 29, No. 6, pp. 899-904.

Scullion, T., C. H. Lau, and T. Saarenketo, 1996, Performance specifications of ground penetrating radar, Proceedings of the 6th International Conference on Ground Penetrating Radar, pp. 341-346.

Sen, P.N., C. Scala, and M.H. Cohen, 1981, A self-similar model for sedimentary rocks with application to the dielectric constant of fused glass beads, Geophysics, Vol. 46, pp. 781-795.

Shaw, M., T. Molyneaux, S. Millard, J. Bungey, and M. Taylor, Automatic analysis of GPR scans on concrete structures, Proceedings of the 7th International Conference on Ground Penetrating Radar, pp. 449-453.

Sheriff, R. E., and L. P. Geldart, 1995, Exploration Seismology, 592 pp, Cambridge University Press.

Shlager, K. L. et. al., 1994, Optimization of bow-tie antennas for pulse radiation, IEEE Transactions on Antenna and Propagation, Vol. AP-39, pp 410-413.

Simone, A., U. Spagnolini, G. Gentili, and V. Rampa, 1998, Electromagnetic inversion and interface tracking: system calibration and application, Proceedings of the 7th International Conference on Ground Penetrating Radar, pp. 607-612.

Smith, S. S., 1995, Detecting pavement deterioration with subsurface interface radar, Sensors, pp. 29-40.

Sokolnikoff, I. F., and R. M. Redheffer, 1966, Mathematics of physics and modern engineering, McGraw-Hill Book Co., pp. 485-487.

Spagnolini, U., 1996, Joint approach of EM inversion and multi-layer detection/tracking for pavement profiling, Proceedings of the 6th International Conference on Ground Penetrating Radar, pp. 235-240.

Spagnolini, U., 1997, Permittivity measurements of multilayered media with monostatic pulse radar, IEEE Trans. Geosci. and Remote Sensing, Vol. 35, No. 2, pp. 454-463.

Spagnolini, U., and V. Rampa, 1997, Multitarget detection/tracking for monostatic ground penetrating radar: application to pavement profiling, submitted to IEEE Trans. Geosci. and Remonte Sensing.

Stickley, G., D. Noon, D., M. Chernniakov, and D. Longstaff, 1998, Current development status of a gated stepped-frequency GPR, Proc. 7th Int. Conf. GPR, pp. 311-315.

Stutzman, W. L., and G. A. Thiele, 1981, Antenna theory and design, John Wiley & Sons, Inc., pp. 260-305.

Telford, W. M., L. P. Geldart, and R. E. Sheriff, 1990, Applied Geophysics, 2nd edition, Cambridge University Press, 770 pp., Cambridge, UK.

Turner, G., 1994, Subsurface radar propagation deconvolution, Geophysics, Vol. 59, pp. 215-223.

Turner, G., and A. F. Siggins, 1994, Constant Q attenuation of subsurface radar, Geophysics, Vol. 59, pp. 1192-1200.

Ulriksen, C., 1982, Application of impulse radar to civil engineering, PhD Thesis, Department of Engineering Geology, Lund University of Technology.

U.S. Department of Transportation, Federal Highway Administration, 1990, Our Nations Highways: Selected Facts and Figures, Publ. No. FHWA-PL-90-024.

Wakita, Y., and Y. Yamaguchi, 1996, Estimation of the soil permittivity and conductivity by a GPR antenna, Proceedings of the 6th International Conference on Ground Penetrating Radar, pp. 123-127, Sendai, Japan, Sept. 30-Oct. 3, 1996.

Warhus, J.P., J.M. Hernandez, S.D. Nelson, E.M. Johansson, and H. Lee, 1993, Ground Penetrating, Imaging Radar for Bridge Inspection, Engineering Research, Development, and Technology, Lawrence Livermore National Laboratory, Livermore, California, UCRL-53868-92.

Weil, G. J., R. J. Graf, and L. M. Forister, 1994, Investigations of hazardous waste sites using thermal IR and ground penetrating radar, Photo. Eng. Rem. Sen., Vol. 60, pp. 990-1005.

Yilmaz, O., 1987, Seismic data processing, Society of Exploration Geophysicists.

Young, R.A., and J. Sun, 1996, 3D ground penetrating radar imaging of a shallow aquifer at Hill Air Force Base, Utah, Jour. Environ. & Engineer. Geophys., Vol. 1, pp. 97-108.

Zucca, J.J., L.J. Hutchings, and P.W. Kasameyer, 1994, Seismic velocity and attenuation structure of the Geysers geothermal field, California, Geothermics, Vol. 23, pp. 111-126.

Appendix IV: A Glossary of Technical terms

Air-launched horn antenna

A type of GPR radar antenna that uses a horn-shaped aperture and is suspended at a certain height from the ground surface.

Borehole radar

A radar system specially designed for using in the boreholes. The major difference between the borehole radar and the surface GPR is that the antenna of borehole radar is designed in a cylindrical shape for lowering down to the borehole.

Dielectric permittivity and dielectric constant

The dielectric permittivity, along with electric conductivity, and magnetic permeability, describes the electromagnetic properties of a material. The dielectric permittivity can be expressed as a combination of the dielectric permittivity of free space (vacuum), ε_o, and a relative factor, the dielectric constant, ε_r, i.e.,

$$\varepsilon = \varepsilon_r \varepsilon_o$$

The dielectric permittivity of free space is merely a constant in the unit of farads/m. The dielectric constant is a dimensionless number and varies from 1 (air) to 81 (water) in accordance with the dielectric property of the media.

Electric conductivity

The property determines the efficiency of the electric current conducting in the medium. It is reciprocal to the commonly used resistivity.

Electromagnetic impedance

The electromagnetic impedance is defined as the square root of the ratio of the magnetic permeability and the dielectric permittivity. Using a simple formula it is

$$Z = \sqrt{\frac{\mu}{\varepsilon}}$$

where Z is the impedance, μ the magnetic permeability, and ε the dielectric permittivity. The contrast of impedances of two adjacent media determines the feature of reflection and transmission of the electromagnetic waves.

Electromagnetic (EM) wave velocity

The speed at which the electromagnetic waves propagate. The electromagnetic wave velocity in the air is close to the light speed in vacuum (~300,000 km/sec). In earth media, the electromagnetic wave velocity is about one third of the light speed. The dielectric permittivity and the magnetic permeability of a medium determine the EM wave velocity in it.

Expert system

A computer software package that integrates human experts' knowledge and experiences in certain field and generates an 'opinion' similar to a human expert would give. Such a system is a combination of interactive database and data processing software. A computerized medical diagnostics package may be the best example of such an expert system.

Fourier Transform

A mathematical operation that conducts mapping signals between two associated domains. The most frequently domains used in engineering problems are the time domain and frequency domain. The Fourier transform could also be performed in space domain and wave number domain.

Ground-coupled antenna

The GPR antenna that has placed near the surface of the earth for transmitting and receiving signals. The spacing between the ground-coupled antenna and the surface is between zero to a couple of centimeters.

Magnetic permeability

The material property describes the magnetic strength is the magnetic permeability (in units of henries/meter). Similar to the dielectric permittivity, the magnetic permeability μ can also be expressed by a dimensionless factor, μ_r, and the magnetic permeability of free space (vacuum), μ_o, i.e.,

$$\mu = \mu_r \mu_o$$

For most non-magnetic materials the relative permeabilities are always close to unity.

Monostatic GPR

GPR surveys using the set up that the transmitting- and the receiving- antenna are kept with a constant, short spacing.

Multi-target tracking

Data processing techniques that tracing multiple features in the time domain scans in the GPR records.

Neural networks

A mathematical algorithm that simulates the reactions of human neural system to external signal input. Neural network technique can be used as an artificial intelligence pattern recognition of targets existing in the digital signals. First, the networks need to be trained to recognize certain patterns, then they can be used in pattern recognition practice.

Radar wave velocity

See Electromagnetic wave velocity.

Transition frequency

The frequency at which the behavior of the electromagnetic signals varies between diffusive fields and propagating waves. If the frequency of the electromagnetic signal is lower than the transition frequency, it is essentially a kind of diffusive field. If the signal frequency is higher than the transition frequency, it behaves like a wave. The transition frequency is intrinsically determined by the electromagnetic properties of the medium in which the radar signal is transmitting and receiving. Specific, the transition frequency is defined as the ratio of the electric conductivity and the dielectric permittivity. Using a simple equation it is

$$\omega_t = \frac{\sigma}{\varepsilon}$$

where ω_t is the transition (angular) frequency, σ is the conductivity, and ε the dielectric permittivity. To make the radar work properly, it has to assure that the frequency used higher than the transition frequency of the medium.

Wavelet transform (WT)

A new kind of integration transform developed just in the last couple of decades. It terms of the function of mapping signals from one domain (e.g., time) to another domain (e.g., frequency), it is very similar to the Fourier Transform (FT), for which engineers and scientists are more familiar with and use more frequently. Nevertheless, one major difference and advantage the wavelet transform (WT) over FT is that it is capable to locate the frequency content features in time domain, or vice versa. In contrast, FT of a time domain signal can only tell the frequency content in general, but is unable to tell the frequency content variations with respect to time. Another important advantage is that after WT decomposition, one can keeps the useful information and greatly eliminates constituents that are irrelevant or noisy. So, WT is also a great tool in data reduction.