255

National Cooperative Highway Research Program

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NCHRP Synthesis 255

Ground Penetrating Radar for Evaluating Subsurface Conditions for Transportation Facilities

A Synthesis of Highway Practice

Transportation Research Board
National Research Council

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Synthesis of Highway Practice 255

Ground Penetrating Radar for Evaluating Subsurface Conditions for Transportation Facilities

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Subject Areas
Pavement Design, Management, and Performance;
Soils, Geology, and Foundations; and
Materials and Construction

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communication and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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NOTICE

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration of the U.S. Department of Transportation.

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to state DOT geotechnical, bridge, and pavement engineers, engineering geologists, consultants involved with ground penetrating radar (GPR) investigations for state DOTs, and researchers. It describes the current state of the practice of using GPR for evaluating subsurface conditions for transportation facilities. This was accomplished by conducting a literature search and review and an extensive survey of U.S. and Canadian transportation agencies and practitioners, as well as limited international information collection. GPR is a noninvasive nondestructive tool used in transportation applications such as evaluation and characterization of pavement systems, soils, and environmental problems.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

This report of the Transportation Research Board presents information on the principles, equipment, logistics, applications, and limitations of GPR pertaining to transportation applications. Selected case studies for which ground truth information is available are presented. In addition, an extensive bibliography and glossary are provided as well as appending information about GPR manufacturers from their literature.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the research in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

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GROUND PENETRATING RADAR FOR EVALUATING SUBSURFACE CONDITIONS FOR TRANSPORTATION FACILITIES

SUMMARY

Transportation agencies need better methods for measuring the near-surface and subsurface conditions of their transportation facilities. Determining pavement thickness, detecting voids beneath pavements, and measuring the moisture content in pavement layers are examples of subsurface pavement conditions for which data are necessary. More efficient, expedient, and cost-effective ways to identify and evaluate these and other highway conditions are being sought. This is because limited knowledge of pavement conditions impacts maintenance and repair schedules and procedures. One promising technology for addressing these issues is ground penetrating radar (GPR).

GPR is a noninvasive and nondestructive tool that has been successful in some transportation applications, such as profiling asphalt pavement thickness and detecting air-filled voids. GPR is used for a variety of applications, including

- Mapping underground utilities,
- Profiling ice thickness,
- Bathymetric (depth measurement) surveys of fresh water lakes,
- Archaeological investigations,
- Shallow bedrock profiling,
- Measuring pavement thickness,
- Measuring pavement base and subbase thickness,
- Locating voids beneath pavements,
- Detecting bridge deck delamination,
- Mapping soil stratigraphy, and
- Characterizing environmental contamination.

Several additional applications include: determination of bridge approach compaction, bridge support river scour, and reinforcing bar mat existence, spacing, and topography.

The transportation community requires a better understanding of the applicability of GPR to their particular situations, including the constraints and limitations on the use of GPR technology. This synthesis summarizes information about GPR and its application for transportation facilities. The principles, equipment, logistics, applications, and limitations of GPR pertaining to transportation applications are addressed. The report is based on a review of the literature and on a survey of state and Canadian provincial transportation agencies. The survey provided information on the state of the practice and on GPR use at the project and network levels, identified emerging GPR technologies, and suggested areas for future research. Selected case studies for which ground truth information is available are presented.

Questionnaires were sent to 63 transportation agencies of which 51 responded. Of the respondents, 33 have experience with GPR. About 60 percent of those with GPR experience use contractors/consultants for GPR pavement investigations, while 11 agencies own GPR

equipment. Overall, agencies are satisfied with GPR results with more than 90 percent stating that they would use or will continue to use GPR.

The use of GPR for transportation applications holds much promise; however, more development needs to occur for the technology to be used by transportation engineers on a routine basis. Transportation agencies have tested GPR in a variety of situations and are learning about its advantages and limitations. Changing or altering their use of GPR or altering the state of the practice of GPR does not seem warranted at this time, since nothing was revealed during this study to suggest a superior practice. However, manufacturers and developers of GPR could evaluate and improve their hardware and software to better meet the needs of the highway engineer.

Research needs to be done to improve GPR equipment to produce more reliable and consistent results. Better software is needed for interpreting and displaying GPR results in a format meaningful to the pavement engineer. There is also a need for GPR performance-based specifications and measurement standards. Performance-based specifications are needed by the pavement engineer when specifying the purchase of GPR equipment. GPR users need these procedures and standards for acceptance testing and periodic calibration to detect equipment degradation. The pavement engineer wants and needs better technology for pavement management; manufacturers of relevant technology have an opportunity to fill that need.

CHAPTER ONE

INTRODUCTION

BACKGROUND

Transportation agencies need more efficient ways of identifying and evaluating the conditions of highway systems. This need is particularly critical when evaluating near-surface and subsurface highway conditions. The "unseen" deterioration of a pavement system impacts maintenance, repair schedules and procedures, and can lead to pavement failure. As an example, early detection and identification of subsurface cavities leads to effective remediation, such as filling the cavity. One promising technology for evaluating "below the surface" conditions of highway systems is ground penetrating radar (GPR). GPR is a noninvasive, nondestructive tool that has been used to map subsurface conditions in a wide variety of applications (*1–4*).

Radar, as popularly understood, was used during World War II to detect and track aircraft (*5*). However, the first radar specifically designed to penetrate the ground was developed at MIT's Lincoln Laboratory, Lexington, Massachusetts, in the late 1960s for the U.S. military to find shallow tunnels in Vietnam (*6*). In 1970, the first commercial company was established to manufacture and sell GPR equipment and services and the first GPR patent was issued in 1974 (*7*). Since the early 1970s, an extensive body of literature on GPR has been published, including reports specifically addressing various aspects of GPR use for evaluating transportation facilities. This synthesis includes many relevant reports and papers in the reference and bibliography sections; however, the selection is by no means exhaustive or complete. The intent is to provide the interested investigator with a starting point for further research on the subject. Many of the included references have their own extensive reference list. In the 1980s, Dr. Gary Olhoeft at the U.S. Geological Survey, for example, compiled a list of more than 1,000 GPR references. This bibliography was partially published in 1988 and is cited in the bibliography at the end of this report. Another source with up-to-date information is the World Wide Web (WWW), search words: Ground Penetrating Radar. For specific highway applications, the first WWW stop should be the Federal Highway Administration's SHRP (Strategic Highway Research Program) Information Clearinghouse (http://www.hend.com/shrp/shrp). This site contains links to the Transportation Research Board (TRB) bookstore (http://www.nas.edu/trbbooks/), which stocks copies of SHRP research reports.

The Federal Highway Administration (FHWA) initially conducted GPR research in the mid-1970s to investigate the feasibility of radar in tunnel applications (*8*). FHWA research then shifted to the use of GPR for detection of subsurface distress in bridge decks. A van-mounted GPR system was developed under a 1985 FHWA contract for additional GPR evaluation and testing. State highway agencies and universities used the van in their research efforts. The FHWA has been and is an important source of research and information on evaluating GPR for transportation facilities.

State departments of transportation (DOTs) have found GPR to be useful in providing continuous information, such as pavement thickness, that was previously only available as point measurements (cores) (*9–11*). Because GPR surveys are continuous profiles rather than discrete points, the GPR technique can provide much more information than previous methods. This synthesis report describes the theory, equipment, applications, and state of the practice of GPR technology for evaluating subsurface conditions for transportation facilities. The survey questionnaire sent to state and Canadian provincial transportation agencies to acquire information on GPR use at the project and network levels is reproduced in Appendix A. The responses are summarized in Appendix B.

GPR is a tool for investigating certain materials, such as asphalt, concrete, rock, fresh water, ice, and soil; however, radar will not penetrate electrically conductive materials, such as metal, sea water, or mineralogical clays. GPR is an "anomaly" detector, as such it will map changes in the ground or within materials due to contrasts in the electromagnetic properties of materials. For example, the boundary between an asphalt layer and the supporting base constitutes an electromagnetic impedance change. GPR maps that change into what is called "radar space." The GPR instrument detects but does not identify the anomaly. The task of identification is left to the human interpreter or some form of "ground truth," such as coring a hole. Those new to GPR may not realize that there are fundamental physical limitations independent of instrumentation. As an example, GPR exploration depth is not necessarily limited by instrumentation, but is primarily governed by the electromagnetic properties of the material itself. No amount of hardware improvement will overcome the fundamental physical limits. GPR is based on fundamental electromagnetic principles, which will be outlined shortly.

A key component of GPR methodology is knowing how and where the tool is useful and how to interpret the resultant anomaly map to provide useful information. GPR is effective in some situations and not in other situations and this distinction is not necessarily known before a project is undertaken. Much of the effectiveness of GPR technology is a function of the skill of the GPR operator and the skill of the data interpreter. Most GPR research is directed toward understanding and reporting the parameters under which GPR is an effective tool and, as a consequence, those situations where GPR is not an effective tool. This synthesis report provides some guidance to understanding the issues surrounding GPR and its effectiveness. The interested reader is encouraged to review the referenced literature, and to talk to the experts and GPR manufacturers.

Manufacturers of GPR equipment design and build their products to have the best available performance in order to stay competitive. Most equipment suppliers have been in business for several years and have developed a base of users. Choice of a particular manufacturer seems to be based on perceived performance and ease of operation, completeness of product offerings, level of after-sale support, and price. It is not the intent of this report to evaluate particular equipment or equipment manufacturers. However, a list of GPR equipment manufacturers known to market toward pavement applications is provided in Appendix C. It is not intended to encompass all GPR manufacturers, but should provide a representative listing.

PRINCIPLES OF OPERATION

Radar [RA(DIO) + D(ETECTING) + A(ND) + R(ANGING] is a well-established method of using radio waves to detect objects and determine their distance (range) from echoes they reflect. Ground penetrating radar (GPR) is a special kind of radar for the detection and location of buried artifacts and structures; radar as such does not identify or evaluate targets. Identification and evaluation are the responsibility of the operator/interpreter or possibly a computer. GPR is sometimes referred to as subsurface radar, impulse radar or ultra-wide band radar. The terms "impulse" and "ultra-wide band" indicate the transmission of radio energy over a large frequency band in contrast to more conventional pulse radars operating at a single frequency, which is turned on and off.

The primary components of a GPR system are illustrated in Figure 1. The antenna unit can be a single antenna that transmits and receives radar signals or separate antennas for transmission and reception. A two-antenna unit can be built into a single plastic case or be configured as two separate and separable units. There are advantages and disadvantages to each configuration that have to do with operational considerations and manufacturer preferences, not necessarily overall radar performance. However, the antennas should be lightweight and maneuverable so that they can be easily positioned over the area to be investigated.

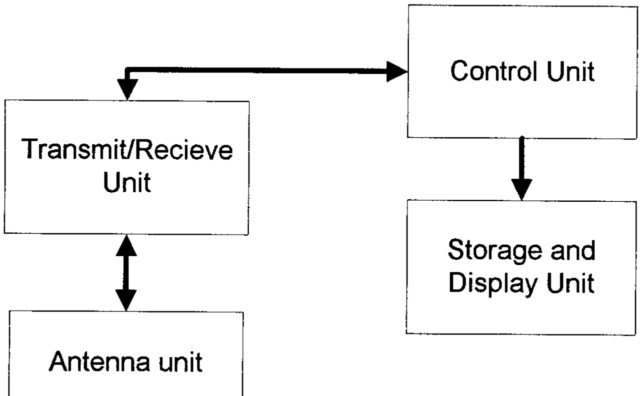

FIGURE 1 Major components of a GPR system.

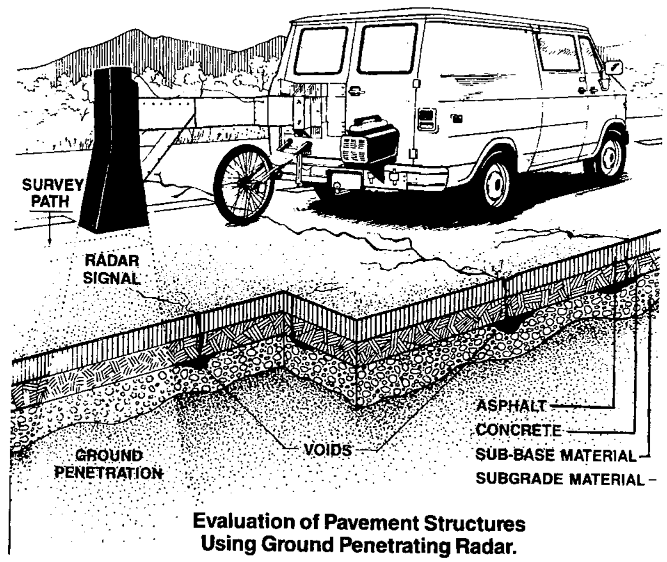

FIGURE 2 Illustrated example of a van-mounted GPR system. *(Courtesy of Pulse Radar, Inc.)*

GPR antennas are designed for either "air-coupled" or "ground-coupled" operation. In the air-coupled mode, the antennas are suspended about 250 mm above the surface for operation at highway speeds (up to about 80 km/h). Ground-coupled antennas rest on the ground surface for better signal penetration into the ground; however, survey speeds are generally limited to about 8 km/h. Antenna size is a function of the radar operating frequency, to be discussed later; in general, the higher the frequency, the smaller the antenna, the higher the resolution, and the smaller the depth of investigation.

The transmit/receive unit (Figure 1) consists of a transmitter for signal generation, a receiver for signal detection, and timing electronics for synchronizing the transmitter and receiver. The control unit is the operator interface that controls the overall operation of the radar system, sending the received data to the data storage and display unit. Typically for highway investigations, the GPR system is used in a van as illustrated in Figure 2. In the illustration, the antenna is an air-coupled, single transmit/receive antenna. A separate survey wheel is used for indexing the radar data. The GPR electronics are housed in the van.

Figure 3 shows another van-mounted GPR configuration for highway surveys. In this picture, four air-coupled antennas are seen suspended above the wheel tracks of the van. The two inline antennas on the left are separate transmit and receive units, while those on the right are another pair of separated transmit and receive antennas.

As depicted in Figures 2 and 3, GPR surveys are conducted near the pavement surface where radio waves are directed into the ground. Figure 4 illustrates signal transmission and reflection at several layers of a pavement section. When the radar signal encounters an interface between materials of different electromagnetic properties, part of the signal travels through the interface into the next layer and the rest of the signal is reflected back toward the surface. The amount of signal that is transmitted through the interface is a function of the

FIGURE 3 Major components of a GPR system.

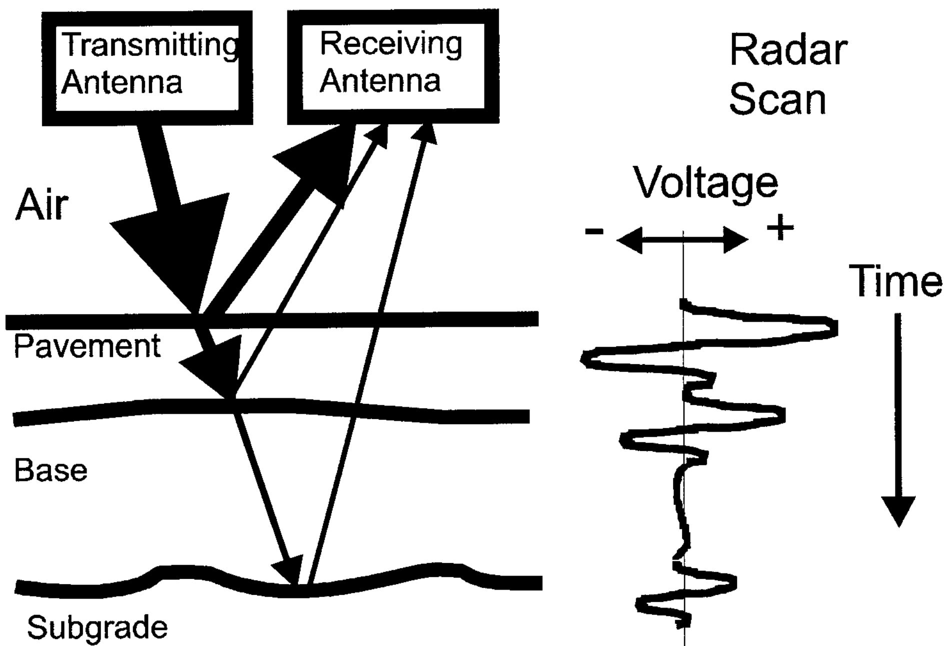

FIGURE 4 Transmission and reflection from the interfaces in a pavement section.

electromagnetic impedance contrast between the two materials comprising the boundary; the greater the difference in electromagnetic properties, the stronger the reflection back to the surface. For example, at a metal surface all the signal is reflected and none is transmitted through the metal surface.

At the radar control unit the reflected signals are represented by a waveform of voltage changes as a function of time (see Figure 4). These waveforms are the signals that are stored and displayed. One display technique is to graphically stack sequential waveforms to create a profile of horizontal distance over the pavement surface as a function of time, as shown in Figure 5. This profile is a depiction of impedance changes as a function of horizontal survey travel along the surface of the ground and radar signal travel-time into the ground, and thus, represents an anomaly map in radar space.

An example of the same GPR data in two different formats is shown in Figure 6. The upper radar profile is a series of "wiggle" plots, similar to the left-hand trace in Figure 5, and the lower profile is an intensity modulated image as in the right-hand profile of Figure 5. The hyperbolic patterns in the lower profile of Figure 6 represent reflections from five tanks buried to a depth of about one meter; only four of the tanks are shown in the upper wiggle plot. The other reflection patterns below the main tank reflectors are probably interference patterns and illustrate the complexity of radar images and the difficulties associated with interpreting these images. To reiterate,

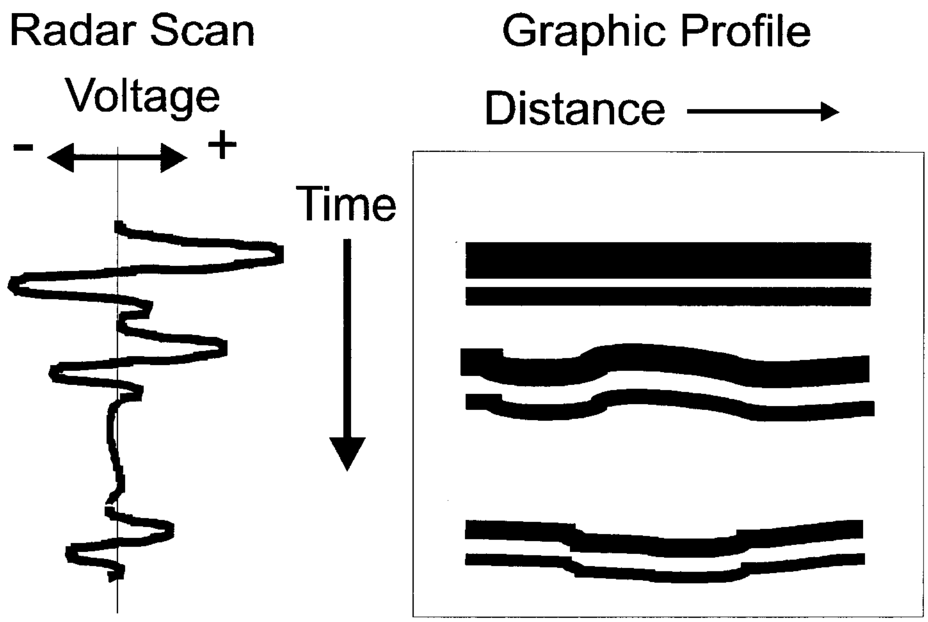

FIGURE 5 Radar scan and graphic profile that results from pavement section in Figure 4.

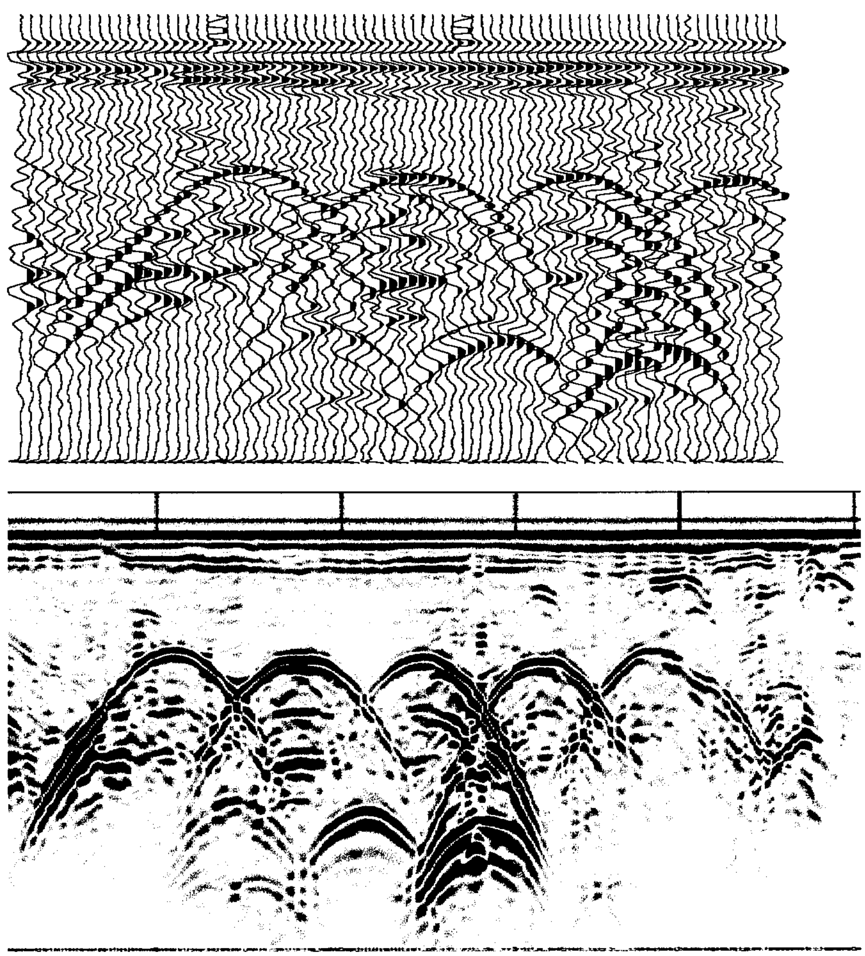

FIGURE 6 GPR profiles in two formats, a wiggle plot and an intensity plot. The dark hyperbolic patterns are from five metal tanks at a depth of about 1 meters, total depth of profile is about 3 meters. *(Courtesy of Geophysical Survey Systems, Inc.)*

GPR maps anomalies. Other insight is needed for identifying the anomalies, such as identifying the hyperbolic patterns as tanks in these profiles.

The time that GPR measures is the round-trip travel time of short nanosecond (ns) pulses. (A nanosecond is a billionth of a second, or the time it takes for a radar pulse to travel 300 mm in air.) Measured round-trip travel time data can be converted into thickness or depth information with knowledge of the velocity of propagation in the subsurface layer, as expressed in the formula:

$$d = v \times t/2 \qquad (1)$$

where

d = depth,
v = velocity, and
t = two-way time.

Velocity of propagation in materials is governed by the electromagnetic properties of the material (see following discussion on electromagnetic properties of materials). Velocity depends primarily on the dielectric properties of the material, signal speed is slowed down by the square root of the relative dielectric constant (see glossary for definitions):

$$v = c / \sqrt{\varepsilon_r} \qquad (2)$$

where

c = speed of light (300 mm/ns), and
ε_r = relative dielectric constant.

With the time-distance relationship defined, depth to various anomalies can be estimated if the dielectric constant is known, and likewise, if the depth to a particular target is known, then the dielectric constant can be calculated.

Amplitude of a reflected signal is a measure of the relationship between the relative dielectric constants at a boundary. This relationship is expressed as the reflection coefficient:

$$\rho = (\sqrt{\varepsilon_{r2}} - \sqrt{\varepsilon_{r1}}) / (\sqrt{\varepsilon_{r2}} + \sqrt{\varepsilon_{r1}}) \qquad (3)$$

where

ε_{r1} = relative dielectric constant of upper medium 1, and
ε_{r2} = relative dielectric constant of lower medium 2.

This expression allows the calculation of the dielectric constant of the surface pavement at the air/pavement boundary, since the relative dielectric constant of air is 1. For an air-coupled GPR system, a large metal plate on the surface is used to normalize the reflected signals, since the reflection coefficient is -1 for metal.

Knowledge of the propagation velocity of the various pavement materials and layers is not necessarily available before a survey starts. In practice, the propagation velocity needs to be measured using either: 1) normalized reflection amplitude using Equation 3, 2) multiple antennas in air, or 3) multiple antennas on the surface. Experience and theory indicate that the third method is the most accurate. Generally, a three-element array is used consisting of a transmitter and two receivers placed on the surface, offering a practical method for determining the signal velocity in the pavement layers at every sample point. The calculated velocity and signal travel-time are used to determine the thickness at each location.

ELECTROMAGNETIC PROPERTIES OF MATERIALS

Materials such as soil, rock, concrete, and water can be characterized by their electromagnetic (EM) properties. Velocity of propagation of an EM signal in materials is a function of the dielectric constant of the material mixture and is primarily governed by water content. Radar signal attenuation is controlled by the electrical conductivity of the material; clay soils are conductive, thus radar range is limited to about a meter. This is typical of mineralogical clay (e.g., montmorillonite), it may be possible to penetrate deeper in other clay types. Sandy soils are much less conductive and penetration depths are on the order of 30 meters. Table 1 provides examples of the electromagnetic properties of representative materials. In general, these EM properties are frequency dependent. The glossary at the end of the report explains many of these terms in detail. In Table 1, the unit used for electrical conductivity is milliSiemens/meter (mS/m).

Dielectric mixture theories (*13*) are used to calculate the complex dielectric constant of three- and four-phase soil mixtures for modeling the radar propagation response and interpreting measurement results. Mixing models take into account solid density (solid particle and air volume) and water volume.

FREQUENCY, RANGE, AND RESOLUTION

The range or depth to which GPR is effective is a function of several parameters, such as material conductivity and water content; transmitter pulse width (center frequency) and power output; antenna gain and efficiency; and receiver sensitivity. Target resolution is primarily a function of frequency.

The performance of ground penetrating radar is estimated from the following radar range equation. Maximum radar range is a function of radar system parameters, target parameters, and the electromagnetic properties of the materials being probed. Soil conditions govern the attenuation and velocity of the radar signal. The radar range equation appropriate for GPR is:

$$Q = 10 \log \left[\frac{P_{min}}{P_t} \right] = 10 \log \left(\frac{E_t E_r G_t G_r v_m^2 \, g e^{-4\alpha R} \sigma}{64\pi^3 f^2 R^4} \right) \qquad (4)$$

TABLE 1

TYPICAL ELECTROMAGNETIC PROPERTIES ELECTED MATERIALS AT 100 MHZ (12)

Material	Relative Dielectric Constant, ε_r	Electrical Conductivity (mS/m)	Velocity (m/ns), v	Attenuation (dB/m), A
Air	1	0	0.30	0
Fresh Water	81	0.05	0.033	0.1
Sea Water	80	$3x10^4$	0.015	10^3
Dry Sand	3–5	0.01	0.15	0.01
Saturated Sand	20–30	0.1–1.0	0.06	0.03–0.3
Silts	5–30	1–100	0.07	1–100
Clays	5–40	2–1000	0.06	1–300
Limestone	4–8	0.5–2	1.12	0.4–1
Granite	4–6	0.01–1	0.13	0.01–1
Bituminous Concrete	3–6	0.5–1.5	0.12	0.05–0.5
Concrete (cured)	6–11	1–3	10	0.5–1.5

where Q is the system performance factor in decibels (dB) and the various components are:

System dependent:

P_{min} = minimum detectable power,
P_t = transmitter output power to antenna,
E_t and E_r = antenna efficiency,
G_t and G_r = antenna gain, and
f = frequency of operation.

Media dependent:

v_m = velocity of propagation in medium,
α = attenuation coefficient of medium, and
e = natural logarithm.

Target dependent:

g = back scatter gain of target, and
σ = target scattering cross-section area.

Range dependent:

R = distance to target from antenna.

Commercially available GPR systems advertise Q values from about -100 dB to -150 dB, the lower value is without computer processing while the larger value (-150) is with processing. Antenna efficiency and antenna gain are influenced by the type of material and the coupling of the antenna to the material.

Figure 7 is a plot of maximum radar range as a function of frequency for three different target types—smooth plane reflector, a rough plane reflector, and a point scatterer. As frequency of operation decreases, the maximum range increases for plane reflectors, such as boundaries between soil and bedrock or dry and wet soil. For point targets, such as boulders or metal drums, maximum range increases with frequency because the target radar cross-section is larger at the higher frequencies. However, at even higher frequencies, the target is no longer a point scatterer and its response approaches a plane reflector.

Figure 8 shows the influence of soil conductivity on maximum radar range at three frequencies for a rough plane reflector. Note that low conductivity sands are much more transparent than clays. Water content is not as important as the conductivity of the water. Penetration depth is roughly the same for moist sand and saturated sand as long as the conductivity is the same.

GPR resolution is dependent on the radar operating frequency and material dielectric constant. For example, Figure 9 is a plot of the resolvable minimum layer thickness as a function of frequency and the dielectric constant of the layer. For a particular dielectric constant of a layer of material, higher operating frequencies resolve thinner layers. As an example, for a dielectric constant of nine, the approximate minimum resolvable thickness is 500 mm at 100 MHz and 200 mm at 300 MHz. Keep in mind that measuring these thicknesses with GPR requires a recognizable reflection from both the top and bottom of the layer.

GPR EQUIPMENT

Current GPR equipment used in highway and other transportation applications evolved over the last 25 years. Since short-pulse transmitters and sampling receivers are used in all these GPR systems, much of the effort has been directed toward antenna design and fabrication. The two distinct approaches are ground-coupled and air-coupled antennas. As the term suggests, ground-coupled antennas operate at the pavement surface, the advantage being deeper penetration, however, highway speeds are generally limited to about 8 km/h. Applications include mapping bedrock and soil layers, and detecting pipes, buried drums, and subsurface contamination. Antennas are available with center frequencies ranging from 50 MHz to 2.5 GHz, providing a wide range of penetration depths and resolutions.

Air-coupled antennas have a horn shape, are mounted about 250 mm above the pavement, and can operate at highway

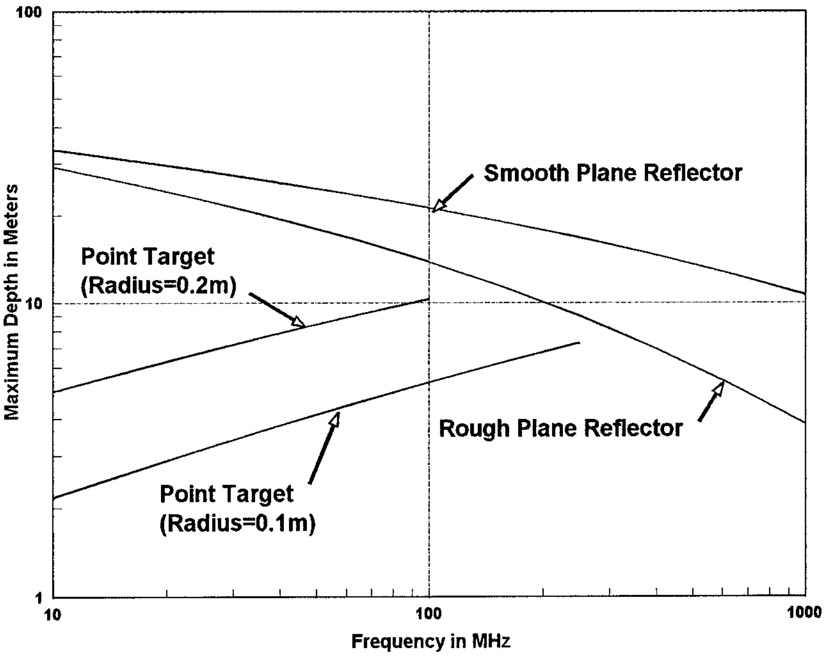

FIGURE 7 Maximum radar range for three target types (Q = -110 dB, dielectric constant = 6, and conductivity = 0.001 S/m. *(R.M. Morey, ARA, Inc.)*

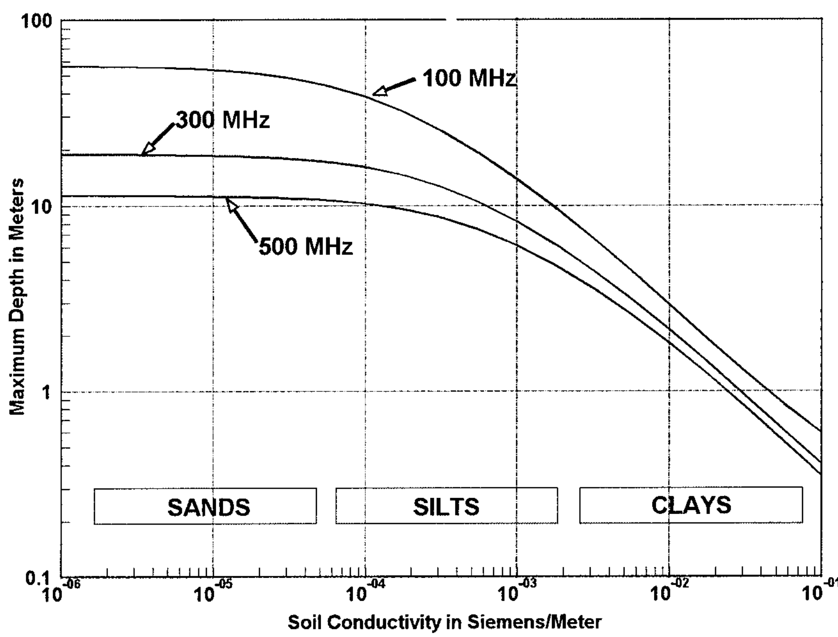

FIGURE 8 Radar range to a rough plane reflector, such as bedrock. The soil types are general designations. (Q = -110 dB and dielectric constant = 6.) *(R.M. Morey, ARA, Inc.)*

speeds. Horn antennas are more suitable for pavement thickness and bridge deck applications, for which quantitative, near-surface results are required. Thickness resolution of about 10 mm is obtainable; however, penetration depth is limited to about 0.6 m. Antennas are available with center frequencies ranging from 1 GHz to 2.5 GHz.

GPR systems typically collect vertical radar "scans" at a rate of up to 100 scans per second, allowing data acquisition rates at driving speeds. For example, using 100 scans/second, a survey conducted at 70 km/h would produce about 5 scans per meter. The radar data are digitized during a survey and recorded on digital tape or hard disk.

The overall GPR design philosophy is largely applications-oriented, where the design details depend on the target type and intervening earth medium. Depth of penetration is a function of radar operating frequency and pavement and soil

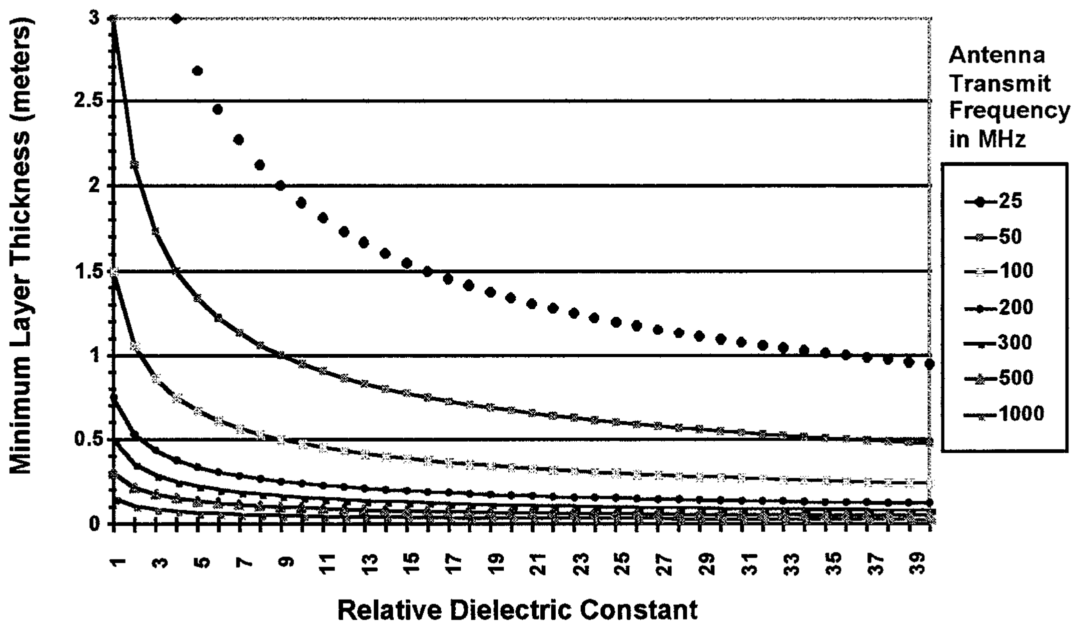

FIGURE 9 Resolution as a function of operating frequency. *(Courtesy of Geophysical Survey Systems, Inc.)*

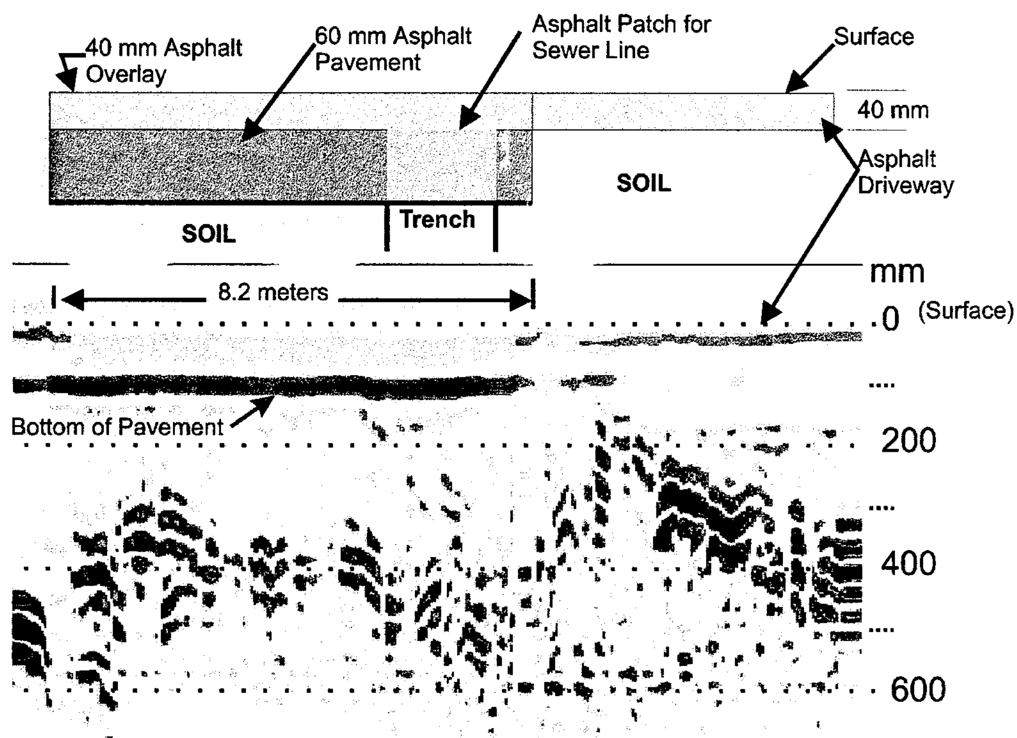

FIGURE 10 Typical GPR pavement profile with pavement cross-section. *(R.M. Morey, ARA, Inc.)*

characteristics—lower frequencies penetrate deeper while higher frequencies offer higher resolution. Therefore, GPR techniques bring into play the interrelationship between electromagnetics, soil science, pavement materials, geophysics, signal processing, interpretation, and display.

GPR systems operate over the frequency range of 50 MHz to 2.5 GHz. For pavement applications, the best results are obtained with antenna frequencies in the 500 MHz to 2.5 GHz range. A major requirement of pavement system evaluation is to be able to resolve layers as thin as 50 mm. A GPR center frequency of about 2.5 GHz is required to resolve 50 mm layers reliably in pavements. However, at 2.5 GHz depth of penetration is limited. A lower center frequency of about 900 to 1000 MHz is necessary for reliably profiling thick surface layers and base and subbase layers. Generally, two separate GPR antenna systems are necessary to perform a complete pavement survey, e.g., one operating at 2.5 GHz and one at 900 MHz.

Interpretation of GPR Data

Radar data are generally analyzed from a graphical presentation of horizontal surface location (x-axis) versus signal travel time (y-axis). Analysis seeks to relate arrival patterns from different reflectors to depths and horizontal surface location. Figure 10 is an example of a GPR pavement profile with the pavement cross-section showing various features. The time scale (y-axis) has been converted into a depth scale. Note the dark band at 100 mm representing the reflection at the asphalt/soil boundary. The undulating reflection between 200 and 400 mm is the boundary between fill material and the original ground surface.

Experienced interpreters are generally needed for analysis of GPR data. Manufacturers of today's GPR equipment are implementing signal processing techniques, software algorithms and display formats that show GPR data in more visually comprehensible pictures; however, experience is still required for useful interpretations. Advances are being made in the processing of data and the development of numerical models for the semi-automatic and automatic interpretation of radar waveforms (*14–18*). These processing techniques are allowing the processing of large quantities of data, with the eventual goal of real-time analysis

CHAPTER TWO

APPLICATIONS AND OPERATIONAL CONSIDERATIONS

GPR has been used for a variety of infrastructure and pavement applications, including

- Measuring pavement thickness,
- Measuring base and subbase thickness,
- Locating voids beneath pavements,
- Detecting delamination,
- Detecting excess moisture, and
- Mapping underground utilities.

PAVEMENT THICKNESS

Existing pavement layer thickness measurement methods include coring and test pit excavations. These direct methods are time consuming and expensive and only provide information at the test location. Using GPR to determine pavement layer thickness is one of the more successful applications of GPR. The American Society for Testing and Materials (ASTM) Standard D 4748–87 (*19*) presents detailed procedures for determining the thickness of newly built pavements and overlays using GPR. Continuous, calibrated GPR profiles ensure that the thickness is as specified. For older pavements, GPR profiles provide structural and inventory information.

Pavement thickness evaluation is based on the measurement of the time difference between layer reflections and the velocity of propagation within the layers. The reflections from the interfaces must be strong enough to be interpreted and tracked for reasonably consistent results. For an example, the reflection from the bottom of a reinforced concrete slab may be too weak to identify. Experience has shown that GPR works well on flexible pavements but may be less effective on rigid pavements.

Propagation velocity (a function of dielectric constant) can be approximated from published results (see Table 1) or calibrated from a known core thickness. Manufacturers are solving the complexity of measuring thickness of pavements with the use of multiple receiving antennas; the received time difference to the two antennas is used to compute signal velocity, thus producing real time output of pavement layer thickness.

Despite limitations associated with weak signals and velocity uncertainty, the advantages of determining thickness with GPR are considerable. It is reported (*8*) that layer thickness to a depth of 0.6 m can be measured to an accuracy of ±6 mm. In contrast, the standard deviation of core thickness measurements is about 6 mm for portland cement concrete (PCC) and can vary from 5 to 19 mm for bituminous concrete. An advantage of GPR is that it is nondestructive and can provide close to 100 percent coverage. Coupled with an effective coring program, GPR is demonstrating the accuracy and precision with which continuous pavement layer thicknesses can be determined (*11, 20–22*).

SUBGRADE SURVEYS

Subgrade surveys and site investigations with GPR can be classified into the following areas *(23):*

- For new road alignment investigations, GPR surveys can determine the soil types and their boundaries, estimate the depth to bedrock, and evaluate the ground water level and frost susceptibility. GPR data can direct other site investigations, such as drilling, to optimize the use of these traditional methods. GPR data can also be used for comparing alternative highway routes.
- For highway bridge site investigations, GPR has been used to map the bottom topography of fresh water rivers and lakes and to estimate the quality of underwater sediments. In addition, it can be used to detect underground springs, caves, and old mine tunnels.
- For road-strengthening projects and constructing a new road alignment alongside an old roadway, GPR surveys provide valuable information on the geological structure of the subgrade and on previous construction activity. GPR results are used to focus sampling and other traditional investigation methods on sites that are most relevant to road design.

STRUCTURES

Practical application of GPR in the evaluation of bridge decks shows that GPR technology, when integrated with existing technologies, produces a complete and fairly accurate assessment of bridge decks (*24–28*). GPR is an excellent tool for locating changes in pavement structure because these substructure changes show up clearly in the graphic display of the radar data (*18*).

Moisture within asphalt and base layers can lead to "stripping" in the asphalt. Stripping is a moisture related mechanism by which the bond between the asphalt and aggregate is broken, leaving an unstable low-density layer in the asphalt. GPR is sensitive to the presence of water (*10*) especially areas of excess water; therefore, GPR can provide highway agencies with a tool for preventive maintenance when excess moisture is a problem. For example, the Texas Transportation Institute has conducted several GPR surveys to identify the presence of stripping within existing pavements (*23*).

Dowels in jointed concrete are important for load transfer from slab to slab, and for minimizing stresses to the concrete. Detecting misaligned dowel bars is of interest for quality control of dowel placement. The depth and spacing of dowels using GPR coupled with graphic analysis techniques has been demonstrated (*29*).

Flowing water can erode streambeds around bridge foundations, causing scour holes that can threaten the stability and safety of bridges (*30*). At several sites throughout the United States, GPR surveys were performed during normal flow conditions to determine the thickness of infilled material in scour holes. The interpretation of some of the GPR records was verified by probing the streambed around the piers or by collecting core samples.

VOIDS BENEATH PAVEMENTS

The nondestructive mapping of voids under concrete pavement is of interest to pavement engineers because of the loss of pavement support. Voids often develop because of consolidation, subsidence, and erosion of the supporting material. Generally, voids occur beneath joints where water enters the soil and, aided by the pumping action of traffic, carries out the fine materials. The first published study demonstrating the feasibility of using GPR to locate and measure voids beneath pavements showed GPR to be capable of locating voids to within ± 150 mm (*31*).

Other studies have also shown that GPR has the capability to detect air- and water-filled voids (*3,32,33*). Recent improvements in equipment and data interpretation techniques have enabled the detection of voids as small as 3 mm (*34,35*). Under some conditions, the volume of the void can be estimated to determine the quantity of grout needed to fill the void for pavement stabilization. GPR can be useful not only in locating voids before stabilizing a pavement, but also for checking on the effectiveness of complete stabilization (*36*).

DELAMINATION DETECTION

Delaminations in concrete bridge decks are a major maintenance problem. Separation of the concrete from rebars is caused by the forces resulting from corrosion. A study of GPR as a network-level tool to quickly assess the general condition of bridge decks evaluated GPR's capabilities to detect delamination (*37*). Bridge decks were inspected at a speed of 65 km/h without closing the decks to traffic. Results of the evaluation were encouraging, as distressed areas with longitudinal dimensions of 0.6 m or more could be detected.

Five New England states sponsored a research project that led to further development and verification of GPR for bridge deck evaluation (*38,39*). The program involved both network-level surveys to assess general conditions and project-level surveys to detail unsound areas. The study focused on asphalt-overlaid bridge decks where the subsurface distress included freeze-thaw damage as well as delamination. Comparisons of GPR results with coring methods showed GPR predictions of deck deterioration were within ± 4.4 percent of the actual proportion of deck deterioration.

ENVIRONMENTAL ISSUES

GPR is routinely used for detection of buried objects and is especially effective in locating buried tanks, drums, and pipes. Continuing studies are being made (*40–42*) to determine if GPR is feasible for detecting and defining the extent of contaminated soil or ground water due to a toxic spill. GPR studies of kerosene-saturated sand above the water table indicated distinct reflections from the contaminated boundary (*43*). Also, GPR has been used to delineate a gasoline plume at the site of a former gasoline station (*44*).

Chlorinated organic solvents belong to a class of groundwater contaminants commonly referred to as dense nonaqueous phase liquids or DNAPLs. These liquids are more dense than water, are immiscible in water, and will migrate downwards through the water table. A GPR experiment proved successful in mapping and monitoring a DNAPL release into a sandy aquifer (*45*). GPR reflections were observed from the DNAPL pooling on successively deeper low-permeability horizons. Others have demonstrated an increase in radar reflectivity at a bedrock boundary due to saturation of fractures by creosote (*46*).

APPROPRIATE GPR SYSTEMS

Several manufacturers of GPR systems are listed with a brief description of their capabilities in Appendix C. The listing does not encompass all manufacturers of GPR equipment, but does include information on companies known to market toward pavement applications for which product information could be obtained. The list represents the best information available at the time the report was written. Other suppliers might exist and any omissions were inadvertent. Geophysical Survey Systems, Inc. and Sensors & Software, Inc. primarily sell equipment and will demonstrate their GPR systems. Road Radar, Ltd. and Penetradar Corp. provide a service with their GPR equipment, while Pulse Radar, Inc. will sell equipment but also promotes a service to the pavement engineering community.

Software

Equipment manufacturers support their hardware with software packages, including data processing, analysis, and display applications for GPR data. Software is not available from the service-only providers.

Logistics

Operational considerations tend to be site specific, including survey procedures, permits, safety requirements, speed of survey, survey coverage, traffic disruption, weather and seasonal influences, crew size, and survey vehicles. Generally, a grid system or location marks are set up to index the GPR data as a survey is proceeding. The antenna location information is recorded with the data so that the interpreted results are correlated with survey surface features. Survey speed for ground-coupled antennas is generally about 8 km/h and for air-coupled antennas up to about 80 km/h. The survey coverage is a continuous line directly under the antenna. Surveys can be conducted at any time except during rain or when the surface is wet; wet surface conditions affect antenna coupling into the ground. Surface snow and ice are not a problem from the GPR performance perspective; however, field operations may be affected. A GPR survey crew is generally two people: an operator and a driver. Survey vehicles can be a car or a van; the GPR equipment is not very big, the antennas are the largest unit and their size depends on the operating frequency. Various GPR operating procedures for highway surveys, including ground-truth methods and results, are outlined in the literature (e.g., *20, 22, 47, 48)*.

Interference

Interference to GPR operation includes radio and TV transmissions and above-ground reflectors, such as vehicles, guardrails, trees, power lines, and bridges. The antennas can pick up radio frequency interference; however, this does not seem to be a serious problem for GPR operation. Radar reflections from above-ground reflectors is a problem when interpreting the data, since these unwanted targets can mask subsurface information.

Limitations

GPR equipment, when well designed and manufactured, operates from known radar and electromagnetic principles. Much research has been devoted to understanding where and how well GPR does work, and to publishing those results, not as limitations but as operational constraints. The major concerns of GPR system users/operators and their clients are depth of penetration and target resolution. How deep can I "see" to profile reliably and how accurately can I determine layer thickness, void size, dowel misalignment, etc.?

Depth of penetration, or radar range, is primarily a function of material electrical conductivity. Clays are more conductive than sands and therefore, penetration is limited to centimeters in clays. Radar operating frequency also determines penetration depth—lower frequencies penetrate deeper. However, operating frequency also determines the resolving power of the radar; higher frequencies are needed for accurate range and target resolution. This is why manufacturers offer a range of antennas, operating from about 20 MHz to 2.5 GHz. GPR limitations are partly caused by improper use of the equipment, poor selection of antennas, lack of understanding of radar principles, and unskilled data interpretation.

Ground Truth

Ground truth methods include drilling and coring holes and digging test pits. Information on ground truth methods is available in the literature (*20,22,48–50*).

ACCURACY

Researchers have reported that the accuracy of thickness calculations using appropriate data analysis software has been ± 7.5 percent for the asphalt and ± 12 percent for the base layers (*18*). Layers within the asphalt, and the thickness of new overlays can also be detected. While the layer thicknesses can be calculated with a relatively high degree of accuracy, the determination of layer material type has been more qualitative and subjective. Recently, a numerical classification scheme has been developed for determining base material type from the dielectric constants calculated from the radar data (*51*). Depending on how well the velocity of propagation is known or calibrated, depth accuracy to targets and interfaces is about 10 percent.

COSTS AND PERSONNEL REQUIREMENTS

Costs associated with GPR hardware, equipment and software, equipment rental, and data processing can be obtained from the listed manufacturers (Appendix C). GPR systems sell from between $30,000 and $90,000. Equipment rental costs vary between $300 to $800 per day. Commercial GPR survey services will perform surveys and provide interpreted results for $1,000 to $3,000 per day. Personnel requirements include at least a two-person crew at the field-technician level and a trained, experienced radar data interpreter. Equipment manufacturers will provide the training needed to operate their equipment and analyze the data.

CHAPTER THREE

REVIEW OF HIGHWAY AGENCY PRACTICES

Sixty-three questionnaires were sent to the 50 states, Puerto Rico, the District of Columbia, and 11 Canadian transportation agencies. Of the 51 responses received, 33 agencies reported experience with GPR. Eleven of these agencies report performing or sponsoring research and development in GPR. A summary of the responses can be found in Appendix B.

GPR EQUIPMENT BEING USED

The majority of the respondents use contractors or consultants for pavement analysis; only 11 of the 33 agencies with GRP experience own GPR equipment. Four equipment manufacturers are mentioned: Geophysical Survey Systems, Inc., Penetradar Corp., Pulse Radar, Inc., and Road Radar, Ltd.

Factors Influencing Equipment Selection

Evaluation of the comments, where given, suggested several factors that influenced equipment selection:

- Type of application,
- Proximity of equipment manufacturer and/or experienced resources, and
- Costs of equipment, training personnel, and mobilization.

Applications

The most common GPR applications reported were pavement layer thickness (24 agencies), void detection (22 agencies), and bridge deck delamination (16 agencies); followed by delamination detection (11 agencies), depth to steel dowels (8 agencies), base layer thickness (8 agencies), buried objects (8 agencies), depth to bedrock (8 agencies), asphalt stripping (7 agencies), and bridge support scour (6 agencies). Additional information is provided in the Question 3 Tables, Appendix B.

The majority of the agencies use GPR for void detection, pavement layer thickness measurement, and bridge deck delamination, while validating GPR data with coring, boring, and chain-drag methods. Of the various applications, GPR seems to be most successful for pavement layer thickness measurements, while agencies report less than satisfactory results with void detection and questionable results locating areas of asphalt stripping. The reports were mixed regarding effectiveness of GPR for bridge deck delamination studies.

Specific Applications

Comments on specific applications listed the following advantages and disadvantages of GPR:

Pavement Layer Thickness	Void Detection	Bridge Deck Assessment	Asphalt Stripping
Pro:			
Surface layers as thin as 30 mm and depth of 0.6 to 0.9 m are being measured	Voids as thin as 6 mm are being detected.	Debonding, delamination, scaling and distintegration are being detected.	GRP demonstrated to be effective; detecting stripping in asphalt layers.
Con:			
Layers must have different dielectric properties to show up on radar	Large voids and water-filled voids in saturated soil are difficult to detect		Stripping layers extremely variable and offer wide range of dielectric contrasts.

State of the Practice

Agencies are using GPR as an additional means to analyze road and bridge conditions where nondestructive methods are needed or where any other method would be too costly. The agencies indicated that traditional methods are used in combination with GPR to calibrate and substantiate GPR results.

Only a few of the agencies are attempting more sophisticated uses of GPR, such as determining base layer moisture and the attendant asphalt stripping. These agencies use a combination of consultants and university researchers on research projects rather than for general production surveys.

Generally, dual antennas that are vehicle-mounted over the wheel paths are standard practice. Commercial GPR equipment used to collect data is mounted inside the vehicle and an operator continuously monitors the incoming data and watches to see that the equipment is functioning correctly. Real time annotation and data analysis have not been mentioned as having found their way into general practice.

GPR data are collected at near highway speeds at the rate of approximately one sample per meter. Indexing the data using mile marker locations, fixed survey marks, Global Positioning Satellite receivers and various other tactics enables users to locate (and hence re-locate) data records with surface features. No conformable standard for initial calibration of GPR instrumentation has arisen from the combined users. Crew sizes vary, though a minimum of two people is a consistent figure being reported. Productivity for the survey crew also varies widely from 320 to 480 km/day to 16 km/day depending on nature of the application.

GPR data interpretation has taken several weeks to several months to complete and report. No standard or adequate visual interface to display or report data seems to have emerged. A review of the various papers and reports from agencies and consultants shows that reported GPR results are often cryptic and inconclusive.

About 60 percent of state transportation agencies using GPR prefer to contract with consultants rather than purchase their own equipment and train their personnel. Since this survey was addressed to state transportation agencies, information was not collected from consultants as to their state of the practice and effectiveness in using GPR.

Results

Overall, agencies are satisfied with GPR results—more than 90 percent stated that they would use or continue to use GPR. Little information was reported concerning calibration or formal quality assurance procedures and methods. With the majority of GPR equipment owned by consultants, state agencies have little control over quality assurance of GPR data gathering or interpretation other than overseeing ground truth measurements to use for GPR validation.

Problems

Highest on the list from the responding agencies is the problem of subjective interpretation of GPR data, with resultant inconsistencies with ground truth data. It was also noted that different consultants using different equipment would report different results over the same test areas.

Future Needs

Rapid and objective GPR data analysis is the first priority. Essential to this analysis is determining the dielectric constants for the materials being investigated, since the dielectric constant determines the velocity at which the radar energy passes through the materials. Velocity of propagation, in turn, is used to calculate the depth and thickness of these materials. Also moisture content, one of the leading precursors to pavement failure, is directly tied with dielectric constant of these pavement materials.

The need for rugged, portable, lightweight instrumentation, with low power consumption, high accuracy and resolution, was noted. Ease of use by technical staff, especially on site in less than ideal and nighttime conditions was mentioned. Equipment costs and optimizing survey procedures and practices, which influence total project costs, were commented on several times.

CHAPTER FOUR

CASE STUDIES AND EMERGING TECHNOLOGIES

CASE STUDIES

Three case studies are selected for presentation. Selection is some what arbitrary except that the locations are geographically diverse (Connecticut, Kansas, and Manitoba), cover several different years (1989, 1992, and 1995), and used three different manufacturers GPR equipment (GSSI, Pulse Radar, Inc., and Road Radar Ltd.; see Appendix C).

Connecticut *(52)*

The Connecticut Department of Transportation retained FGA Services, Inc., who in turn hired Donohue & Associates, Inc., (now Rust Engineering) to perform a pavement evaluation study, conduct a GPR investigation, and recommend a rehabilitation approach for about 38 km of Interstate 84 between Vernon, Connecticut and the Massachusetts state line. The continuously reinforced concrete pavement was experiencing excessive pavement distress and required a high level of maintenance. The predominant surface distresses observed were punchouts, deteriorated asphalt patches, pumping, deteriorated outer lane/shoulder joints, and deteriorated construction joints.

A GPR survey was conducted to locate voids beneath the I-84 pavement during May and June, 1989. Tests performed on multiple layer pavement sections, with total thicknesses of about 0.5 m, indicated that the radar returns were too weak to reliably detect voids. Therefore, the GPR survey was confined to the 200-mm thick pavement sections. A GSSI SIR System 8 was used for the GPR survey. The equipment was housed in a van with the ground-coupled antennas mounted in front of the van—an antenna in each of the wheel paths. A preliminary analysis of the GPR data was used to select 20 coring locations for GPR ground truth and calibration.

The reported results state that:

- 140 km of highway were scanned using the dual antennas for a total of 280 km of highway profile data,
- The GPR survey identified 852 m of void areas, representing approximately 0.3 percent of the area surveyed.
- The voids identified in the GPR data were assigned the letters "S", "M" or "L", depending on the interpreted vertical dimension of the void signature and the ground-truth cores. Void thicknesses ranged from about 6 mm to greater than 25 mm. These results are tabulated in the report *(52)*.
- The punchout locations noted during the visual inspection corresponded very closely with the void locations identified during the GPR survey.

There were no statements in the report about the correlation of coring results with the interpreted GPR data, except to imply that where the GPR indicated a void, ground-truth coring found a void.

Kansas *(53)*

The main objective of this study was to assess the applicability of GPR thickness profiling technology to KDOT's pavement evaluation and management program, at both the network and project levels. To meet this objective, it was necessary to establish the capabilities of radar technology for accurately generating continuous pavement profiles for asphalt overlaying a variety of base conditions. Testing consisted of collecting radar data on in-service pavements and correlating the predictions from the radar data with direct measurements. The project included test site selection, radar data collection, analysis of radar waveforms, selection of direct measurement locations, collection of direct samples, and correlation between radar data and the direct measurement.

GPR data were collected by INFRASENSE, Inc. of Cambridge, Massachusetts, using a van-mounted air-coupled horn antenna system provided and operated by Pulse Radar, Inc. of Houston, Texas. Based on analysis of the radar data, areas were identified for direct sampling. Extraction of direct samples was carried out jointly by KDOT and the University of Kansas. Radar data were collected at moderate speeds of about 30 km/h, continuously digitized, and stored on the hard drive of a PC computer. The radar data were subsequently analyzed by INFRASENSE using its PAVLAYER customized software for radar pavement applications. Asphalt pavement thickness and base layer thickness were automatically calculated and continuous thickness profile plots were evaluated and compared to the direct sampling measurements.

Direct sampling consisted of taking 100-mm diameter cores through the pavement, photographically documenting the cores, and recording layer thickness to an accuracy of about 3 mm. Data from 73 cores taken at 11 sites showed that the radar predictions were within 10 percent of the core data. The asphalt thicknesses encountered in this study ranged from 51 mm to 64 mm. The authors considered the results to be excellent, showing that GPR, when properly used, represents an effective alternative to coring in a variety of flexible pavement engineering and management applications.

The Kansas case study report states that the cost of a radar pavement survey, including data analysis and reporting, ranges from $30 to $435/lane km. This depends on the number of km that can be surveyed per project, the number of km that can be surveyed per field day, and the level of detail of data analysis. Costs included site mobilization (approximately $3,000), survey labor and equipment ($2,000/day), data analysis ($56/km for project level analysis) and report preparation

($1,500). For example, a one-lane survey involving three projects, each 16 km in length, would take one survey day and cost about $190/lane km. This cost is similar to what KDOT currently spends for project level coring. However, KDOT realizes two significant benefits: 1) No lane closures, which increases safety and reduces costs; and 2) Continuous data at spacing as close as 1.5 m.

The radar results showed an ability to characterize the variability of the pavement thickness over potential project sections; true thickness and its variation is very important. For example, project decisions consider amounts of cold milling because the closer the milling gets to the bottom of the existing layer, the more construction related problems are encountered.

Manitoba, Canada *(20)*

The Manitoba Department of Highways and Transportation's Materials and Research Branch participated in a pavement layer thickness determination project with Road Radar Ltd. of Edmonton, Alberta. The Road Radar System was used during October 1994 at the Brokenhead River SPS-5 Pavement Test Site situated 60 km east of Winnipeg. The objective of the project was to evaluate the accuracy and repeatability of the GPR system pertaining to layer thickness determination. Ground-truth coring took place after the results of the radar survey were submitted to the Materials and Research Branch. The SPS-5 test site consists of nine separate test cells 152-m in length that vary in pavement thicknesses from approximately 100 to 250 mm.

Road Radar Ltd. conducted the survey at a speed of 10 km/h from their radar van using a ground-coupled antenna and an air-coupled antenna. Data were transferred from the van to a work station for processing using proprietary software to automatically interpret and report the radar results. Coring by the Materials and Research Branch took place during January of 1995.

Analysis of the radar data was compared with thickness data obtained by coring. The average accuracy was found to be 9 percent with a standard deviation of 14 mm. Specific results indicated that the radar:

- Did not identify the lifts within the asphalt layer or the milled asphalt layer,
- Did distinguish the difference between the virgin and recycled asphalt mixes,
- Did have an accuracy of between 10 and 30 mm on pavement layers ranging between 100 and 250 mm in thickness,
- Produced an average error of 9 percent based on the absolute difference between the radar results and the core thickness, and
- Demonstrated a standard deviation of approximately 14 mm on thicknesses from 100 to 250 mm.

EMERGING GPR TECHNOLOGIES

New GPR developments, which have the potential for advancing the state of the art in the assessment of transportation facilities, will most likely be centered on incremental improvements in hardware and software. The underlying hardware technology has matured. Manufacturers are repackaging their hardware to make it smaller, lighter, and more user friendly. Software developers are evaluating methods to improve data interpretation and display using analysis techniques from other disciplines, such as seismic and medical. Advances in computer technology will provide better and less expensive processing power for GPR interpretation; however, routine "automatic" interpretation of GPR data is still a distant prospect, except for asphalt thickness, which is done now.

One development that does bear watching, although still in the laboratory, is Synthetic Aperture Radar (SAR). SAR is a method of data collection and processing that employs scanning a GPR antenna, under computer control, in such a way as to create a synthetic aperture. The purpose of the synthetic aperture is to more tightly focus the radar beam, allowing the creation of clearer subsurface images. This technique is under development for transportation facilities at Lawrence Livermore National Laboratory *(26, 54)*. Software has been developed to convert the data into 2-D and 3-D images. Lab tests have been carried out on test slabs with rebars and artificial embedded defects (3 mm Styrofoam). The ability to detect and image these inclusions has been verified in the lab. Field studies have not yet been reported.

A recently published report *(55)* demonstrates the value of performing numerical simulation of GPR data before collecting real data, simulating both the measurements and the processing. This provides input into the survey design and an indication of the best possible results that can be expected under ideal conditions. Survey design for both data acquisition and processing can be optimized using simulation methods, especially for complicated structures such as bridge decks. In the report, both 2-D and 3-D GPR data were collected over a bridge deck before and after resurfacing with a layer of reinforced concrete. Numerical simulation of the 2-D data showed the best results that could be expected for these experiments. These synthetic examples demonstrated that it is possible to obtain high quality results with an appropriate combination of data acquisition and processing.

Commercial companies, such as Geophysical Survey Systems, Inc., Road Radar Ltd., Sensors and Software, Inc., and Pulse Radar Corp., are working to refine and improve their products and services; however, they are reluctant to discuss any details. Universities, such as, Ohio State University, Colorado School of Mines, University of Kansas, Texas A&M University, and others, do have some limited ongoing research and development on hardware and software. Most of the university work is funded by government agencies, such as the U.S. Air Force and the U.S. Army, for specific applications such as mine detection.

Examples of state highway agencies that are sponsoring recent GPR development and evaluation are the Florida Department of Transportation and the Texas Department of Transportation. Both agencies have purchased GPR equipment and are supported by the Texas Transportation Institute in specifying the GPR equipment.

CHAPTER FIVE

CONCLUSIONS

Ground penetrating radar technology has been used for about 25 years for a variety of applications, including pavement studies. The initial pavement applications involved research studies to understand the effectiveness of GPR to pavement problems, such as thickness determination, void detection, and bridge deck delamination. These studies used existing or modified GPR equipment available from commercial GPR developers or from university research groups. Eventually, companies were formed to assemble GPR hardware and provide services specifically for pavement inspection. This equipment, along with proprietary software, was tested and evaluated by the Federal Highway Administration and a few state highway agencies. Test results were encouraging and additional research was funded to better quantify and improve the technology for pavements and other transportation facilities.

GPR does "work." The issues are how well does it work and under what conditions. According to well-known electromagnetic principles, radio waves will penetrate solid materials such as soils, rocks, and asphalt. However, radio waves do not penetrate far through these materials. The strength of radio waves decreases exponentially and they soon become undetectable in these energy-absorbing materials. A misconception is that GPR is limited by the instrumentation. Exploration depth is primarily governed by the material itself and no amount of instrumentation improvement will overcome the fundamental physical limits.

The results from the survey of state DOTs and Canadian transportation agencies suggest that many agencies have tried GPR over the last decade and found it worked well for some situations and not well for other situations. GPR is not used on a routine basis by DOTs, even for relatively simple applications, such as pavement thickness profiling; however, Florida DOT reported that it has a GPR system dedicated to pavement layer thickness measurement. Evidence is available to suggest that the capabilities of current GPR systems are as follows:

- Asphalt layer thickness determination: GPR results are used to estimate thickness to within 10 percent and thicknesses of up to 0.5 m are accurately measured.
- Base thickness determination: thicknesses are estimated, provided there is a dielectric contrast between the base and subgrade.
- Concrete thickness determination: depth constraints and accuracy are not yet well defined. This is because portland cement concrete (PCC) attenuates GPR signals more than asphalt, concrete properties change as the cement hydrates, slabs that contain reinforcing steel make interpretation more difficult, and the dielectric contrast between the PCC and base may not be adequate for reflection detection.
- Void detection: GPR has detected air-filled voids as thin as 6 mm, while the detection of water-filled voids is more problematic. GPR is an anomaly detector, which means that validation cores are necessary.

Methods, techniques, and software for consistently and reliably interpreting GPR data are needed. Software is available for automatic data interpretation of asphalt pavement thickness. Software packages for other applications, such as mapping rebars and voids, are in development.

More development needs to occur for GPR to be used by transportation engineers on a routine basis. Future research includes improving GPR equipment to produce more reliable and consistent results, coupled with better software for interpreting and displaying results in a format meaningful to the pavement engineer. The pavement engineer wants and needs better technology for pavement management; manufacturers of relevant technology have an opportunity to fill that need.

There is a need within the pavement community for GPR performance-based specifications and measurement standards. Agreed upon performance-based specifications are needed by the pavement engineer when specifying the purchase of GPR equipment. Equipment manufacturers need measurement procedures and standards against which to qualify their GPR equipment. GPR users need these procedures and standards for acceptance testing and periodic calibration to detect equipment degradation. Similar performance-based specifications and measurement standards are needed for GPR software. Furthermore, an independent testing organization could be established to write the standards and perform acceptance testing and calibration for the pavement community. The Materials Division of the Texas Transportation Institute (TTI) has developed performance specifications and test procedures for GPR systems using 1 GHz horn antennas. TTI has also tested a number of systems against their performance specifications for clients. In addition, TTI is developing GPR training programs for the pavement community.

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GLOSSARY

Amplitude—The magnitude of a quantity, such as the voltage, current, or power of a signal. *Peak-to-peak* amplitude is the difference between the maximum positive and maximum negative amplitude.

Angle of incidence—Angle at which the wavefronts of a radar wave strike the ground or a target.

Antenna gain—(See Gain).

Antenna radiation pattern—A plot of the intensity of the radiation received at a given radial distance from an antenna versus angle relative to a given reference axis. The pattern typically consists of a *mainlobe*, into which the radiated power is primarily concentrated, and a series of progressively weaker *sidelobes*.

Antenna—A metallic apparatus for sending or receiving electromagnetic waves.

Aperture—Literally, an opening. In the case of an antenna, the area normal to the axis of the antenna's mainlobe, over which the radiation is distributed. An antenna's gain increases in proportion to the area of the aperture in square wavelengths.

Backscatter—Portion of a radar's transmitted energy that is intercepted by a target or other object and reflected (scattered) back to the radar's direction.

Bandwidth—(1) The width of the band of frequencies passed by a filter. (2) The band of frequencies occupied by the central lobe of the spectrum of an alternating current signal. Bandwidth is usually defined so that it includes most but not all of the signal power. Generally, it includes the portion lying between the points at which the power has dropped to half that at the center of the band.

Beamwidth—The angular width of a slice through the mainlobe of the radiation pattern of an antenna in the horizontal, vertical, or other plane. May be measured between the nulls on either side of the mainlobe or, more generally, between points where the gain has dropped to some arbitrarily selected fraction of that at the center of the lobe, typically the half-power (-3 dB) points.

Boresight line—The pointing direction of a radar antenna. This may be the central axis of the antenna's mainlobe.

Capacitor—A device consisting essentially of two surfaces separated by an insulating material (*dielectric*) such as air, paper, plastic film, etc. A capacitor stores electrical energy, blocks the flow of direct current, and permits the flow of alternating current to a degree proportional to the capacitance of the capacitor and the frequency of the current.

Clutter—Unwanted radar returns or radar reflections from the surrounding environment, both within the ground and above the ground. As an example, these unwanted reflections can be tree branches or tree roots.

Complex number—A number having both a real and an imaginary part, the latter being a number multiplied by the square root of -1, commonly represented by the letters "i" or "j".

Conductivity—One of the three constitutive parameters (conductivity, permittivity, and permeability) that describe the electromagnetic properties of a material. Conduction currents are currents due to the movement of "free" charges. Conductivity is a measure of the response of these free charges to an imposed electric field. Also, a measure of how easily charge can flow through a material.

Continuous-wave (CW) radar—A radar that transmits continuously and simultaneously listens for the reflected echoes.

Current—A flow of electrical charge. Generally, the charge is conveyed by free electrons, though it may also be conveyed by ions (atoms with one or more electrons removed).

Decibel (dB)—A logarithmic unit used to express power ratios. Decibels are also used to express the absolute values of certain quantities whose values may vary over a wide range, such as power, radar cross section, and antenna pattern. In this case the decibel values express the quantity in ratio to a given reference value.

Detection—The process of determining the presence of a target, or a signal.

Dielectric constant—The ratio of the capacitance with an insulating material between the plates of a capacitor to the capacitance with air insulation is called the dielectric constant of that insulating material. The material itself is called a dielectric. Therefore, air has a dielectric constant of 1, while other materials have higher values.

Diffraction—The phenomenon that causes light passing through a small hole to spread and be surrounded by progressively weaker rings of light. The same phenomenon is what causes the beam of a directional antenna to spread and be surrounded by sidelobes.

Dipole—A simple antenna consisting of a straight conductor, half a wavelength long.

Directivity—Ability of an antenna to concentrate the transmitted energy in a given direction and to emphasize the returns received from that direction.

Dynamic range—The spread between (1) the minimum amount that the input to a circuit or system must change to produce a discernible change in the output, and (2) the maximum peak-to-peak input that a circuit or system can handle without saturating.

Echoes—Radar returns received from a given object. Some people apply the term exclusively to target returns, thereby differentiating them from clutter.

Electric field—Field or force produced by an electric charge of a changing magnetic field. Has both a direction and a magnitude. May be visualized as the force exerted on a tiny charged particle.

Electromagnetic wave—Wave that is propagated by the mutual interaction of electric and magnetic fields. Radiant heat, light, and radio waves are electromagnetic waves.

Far field—Electromagnetic radiation from an antenna observed at a sufficiently great range that the lines of sight to the observer from all points on the antenna are essentially parallel.

Frequency domain—Mathematical realm in which the amplitudes of signals are expressed as functions of frequency rather than time. The spectrum of a time varying signal is obtained by translating the expression for the signal from the time domain to the frequency domain.

Frequency—Number of cycles per second that a pure unmodulated sine wave completes per second.

Gain—(1) In reference to a circuit or system, the ratio of the output to the input. (2) In reference to an antenna, the ratio of (a) the field strength (or power) of the radiation in a given direction to (b) the field strength (or power) of the radiation that would be produced in that direction if the same input power were applied to a hypothetical isotropic antenna, i.e., one that radiates equally in all directions. If losses in the antenna are not included in the measurement or calculation of the gain, it is referred to as *directivity gain.*

Gigahertz (GHz)—A unit of frequency: 1 GHz=1000 MHz.

Hertz—A unit of frequency: 1 hertz=1 cycle per second.

Isotropic radiator—An antenna that radiates equally in all directions. The imaginary source of the radiation used as a reference for the gain of a directional antenna.

Jitter—Small, rapid, perhaps random, fluctuations about an intended or average value.

Magnetic field—Field or force to which magnetic materials (e.g., iron) and permanent or electromagnets respond. May also be produced in space by a changing electric field. Has both magnitude and direction.

Mainlobe—The central lobe of a directional antenna's radiation pattern.

Megahertz (MHz)—A unit of frequency: 1 MHz =1,000,000 hertz.

Microsecond—A unit of time: 1 microsecond = 10^{-3} second.

Nanosecond—A unit of time: 1 nanosecond = 10^{10-9} second.

Noise—Unwanted, usually random, electrical or electromagnetic energy that interferes with the detection of wanted signals. The term is also applied to any unwanted random variations in the measured value of any quantity.

Permeability—One of the three constitutive parameters (conductivity, permittivity, and permeability) that describe the electromagnetic properties of a material. Permeability is a measure of the magnetic polarization of a material. Magnetic polarization does not vary in most materials and it is adequate to assume a value of that of free space or 1.

Permittivity—One of the three constitutive parameters (conductivity, permittivity, and permeability) that describe the electromagnetic properties of a material. Displacement currents are currents due to the movement of "bound" charges. Permittivity is a measure of the response of bound charges to an electric field or the polarizability of a material. Sometimes used interchangeably with *dielectric constant.*

Phase—Degree of coincidence in time between a repetitive signal, such as a sine wave, and a reference signal having the same frequency.

Phase shift—A change in the phase of a signal. It may either be deliberately introduced or be the result of natural causes, e.g., the reflection from a metal surface.

Polarization—The orientation of the electric and magnetic fields of an electromagnetic wave, such as a radar wave. In free space, these fields are perpendicular to each other and to the direction of propagation. By convention, the polarization of the wave is the direction of the electric field.

Power density—Power of a radio wave per unit of area normal to the direction of propagation.

Power—The rate of flow of energy, commonly expressed in watts.

PRF—Pulse repetition frequency: the number of pulses per second transmitted by a pulsed radar.

Propagation—The outward spreading (travel) of an electromagnetic wave (radio wave).

Pulse radar—A radar that transmits its radio waves in pulses and listens for the echoes during the periods between transmissions. Generally, ground penetrating radars are pulse radars.

Radar cross section—A factor relating the power of the radio waves that a radar target scatters back in the direction of the radar to the power density on the radar's transmitted waves at the target's range. Takes account of the cross-sectional area of the target as viewed by the radar, the target's reflectivity, and its directivity.

Radar signature—Identifying features or patterns in the returns a radar receives from targets of a given type.

Radiation (electromagnetic)—Energy in the form of an electromagnetic wave emitted by an antenna or a conductor in which free electrons are accelerated. Light and radio waves are electromagnetic radiation; they differ only in wavelength.

Radiation pattern—(See Antenna radiation pattern.)

Range time—The time a radar pulse takes to reach a target and return.

Range—The radial distance from a radar to a target or other object.

Receiver—The portion of a radar system that detects, amplifies, and filters the radio frequency signals (returns) received by the antenna and translates them to a lower frequency range for display and storage.

Reflection—(1) The process of re-radiating an incident radio wave. Reflection that is mirror-like is called *specular*. Reflection that is not is called *scattering*. (2) In an electrical circuit or transmission line, the return of a fraction of an incoming signal to its source when the impedance of two circuits, a transmission line and its load, etc. are not matched.

Reflectivity—The degree to which an object reflects incident radio wave.

Resistivity—The reciprocal of *conductivity*. High resistivity materials impede the flow of current.

Resolution distance—The minimum distance by which two objects may be separated and still be individually resolved by a given radar. It is commonly expressed as *azimuth resolution distance* (the minimum angular resolution distance) and *range resolution distance*.

Round-trip transit time—The time that a radio wave takes to reach a target or other object and return to the radar. (Equals twice the range divided by the radio wave velocity in the surrounding medium.)

Scatter—(1) To re-radiate the incident radiation in many different directions. (2) The radio waves scattered by a target or other object that is illuminated by a radar.

Signal processor—A digital or analog subsystem that sorts the radar returns by range, filters out noise and clutter, performs automatic target detection, etc.

Signal—(1) The term applied to the desired return from almost any object of interest (target) as opposed to noise or clutter. (2) The term applied to any electrical current or voltage that conveys desired information.

Signal-to-noise ratio—Ratio of the power (or energy) of a received signal to the power (or energy) of the accompanying noise.

Spectrum—Distribution of the power or energy of a signal over the range of possible frequencies; is commonly represented by a plot of amplitude versus frequency. If the amplitude is a voltage, a plot of the square of the amplitude is the power spectrum; the area under the power spectrum corresponds to the signal's energy.

Specular reflection—Mirror-like reflection occurring when an electromagnetic wave strikes a flat surface, the irregularities (roughness) in which are small compared to the wavelength of the incident wave.

Synthetic array (aperture) radar (SAR)—A high-resolution ground mapping technique in which advantage is taken of the forward motion of a coherent pulsed radar to synthesize the equivalent of a very long array antenna from the radar returns received. Another way of looking at SAR is that it increases the angular resolution of the radar antenna.

Thermal noise—A random voltage appearing across a conductor as a result of the thermal agitation of free electrons in the conductor. The noise power is proportional to the absolute temperature of the conductor.

Time domain—Mathematical realm in which the amplitude of signals is expressed as a function of time.

Transmitter—The basic functional element of a radar that generates the pulsed (or continuous wave) radio frequency signal that is radiated by the antenna.

Waveform—The overall form of the radio waves radiated by a pulsed radar. Includes the following characteristics: pulse amplitude, pulse width, and pulse repetition frequency (PRF).

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APPENDIX A

Agency Questionnaire

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Project 20-5, Topic 26-08

Ground Penetrating Radar (GPR) for Evaluating Subsurface Conditions for Transportation Facilities

QUESTIONNAIRE

Name of Respondent: ____________________

Title: ____________________

Agency: ____________________

Address: ____________________

Telephone: ____________________ Fax: ____________________

INSTRUCTIONS

We are collecting information about **ground penetrating radar** (GPR) and its application for transportation facilities; the results of this survey will be included in a NCHRP synthesis report. GPR is a non-invasive, nondestructive tool that is used in transportation applications, such as, evaluation and characterization of pavement systems, soils, and environmental problems. The synthesis will cover the principles, equipment, logistics, applications, and limitations of GPR pertaining to transportation applications. A survey of states and Canadian provinces is being conducted to obtain information on the **state-of-the-practice** and **GPR use** at the project and network levels; thus, the purpose of this questionnaire.

This questionnaire should be filled out by staff who have responsibility for pavement systems and environmental issues at agency facilities as well as information and/or experience with GPR. Our objective is to examine current practices in the use of GPR techniques for evaluating subsurface conditions in relation to transportation facilities.

Please answer as many of the following questions as possible. Please also provide copies of any supporting data or reports. Please send your completed questionnaire and supporting documentation to:

Rexford Morey
17 Sunland Drive
Hudson, NH 03051
Tel. 603-595-4714

If you have any questions, please call Mr. Morey or Mr. Stephen Maher, TRB Program Officer, at 202-334-3242.

I. Does your agency have experience with ground penetrating radar (GPR)? yes / no (If no, go to question 21.)

(If yes, please circle all appropriate letters a-d, and include comments if necessary.)

A. Currently own the equipment ____________________

B. Currently contract for services ____________________

C. Currently rent the equipment ____________________

D. Have past experience with GPR ____________________

II. What GPR equipment is your agency using?

Manufacturer____________________

Manufacturer____________________

III. Indicate (by checkmark) if GPR has been (or is being) used by your agency for any of the following applications. Also list other equipment (or technologies) currently used by your agency for those applications.

	GPR	Other Equipment/Technologies
Pavement layer thickness	____	____________
Void detection	____	____________
Delamination detection	____	____________
Depth of steel dowels	____	____________
Asphalt stripping	____	____________
Base layer thickness	____	____________
Base Moisture	____	____________
Depth to bedrock	____	____________
Water table location	____	____________
Buried objects (utilities)	____	____________
Subsurface ice	____	____________
Bridge deck delamination	____	____________
Bridge support scour	____	____________
Archaeological sites	____	____________
Others, list:		
____________	____	____________
____________	____	____________
____________	____	____________

IV. Are there environmental applications for which your agency uses GPR?

	GPR	Other Equipment/Technologies
Road salt distribution in soil	____	____________________
Tank and drum location	____	____________________
Plume detection (i.e. gasoline)____	____________________	
Others, list:		
________________	____	____________________
________________	____	____________________

Comments:

V. Are there other applications for which your agency uses GPR? Comments:

VI. Are you satisfied with the GPR results? yes / no / both

If yes, in what applications? Comments:

If no, in what applications? Comments:

VII. Is GPR cost effective? yes / no / both / don't know

If yes, in what applications? Comments:

VIII. If no, in what applications? Comments:

Other comments:

IX. Would your agency use GPR again? yes / probably not

Why?

X. How does your agency calibrate the GPR equipment? (Please submit any manuals or calibration reports.)

XI. How does your agency control the location of the GPR antenna and index the GPR data to the site being surveyed? (Survey points, pole locations, lane markers?)

XII. What size crews are used for GPR surveys (if appropriate, by application)?

XIII. What is the crew productivity (by application; in miles/day, area surveyed, etc.)?

XIV. Does your agency have a quality assurance procedure to monitor the information collected? yes / no

If yes, please briefly describe the procedures. (Please submit any manuals.)

XV. Does your agency use other pavement information with GPR results for better PMS decision-making?

A. Coring ______

B. Drilling ______

C. Test pits ______

D. Other______

XVI. What GPR software or data analysis procedures does your agency use?

XVII. Please comment on GPR improvements you recommend:

A. Hardware:______

B. Operations:______

C. Procedures:______

D. Software:______

E. Costs:______

F. Specifications:______

G. Other:______

XVIII. Do you have any GPR case studies, either positive or negative? yes / no If yes, please return report copies with this questionnaire.

XIX. Has your agency performed or sponsored any research or development in GPR? yes / no If yes, please briefly describe these efforts and enclose copies of any reports.

XX. Is your agency performing or sponsoring any research or development in GPR? yes / no If yes, please briefly describe these efforts and enclose any descriptive information.

XXI. What research do you feel will help in improving GPR and/or its state-of-the-practice?

GPR:______

State-of-the-practice:

XXII. Additional comments, suggestions and recommendations.

APPENDIX B

Summary of Survey Responses

Question 1. Does your agency have experience with ground penetrating radar (GPR)?

Yes: 33		Currently own the equipment:	11
No: 18		Currently contract for services:	15
		Currently rent the equipment:	1
		Have past experience with GPR	19

Question 2. What GPR equipment is your agency using?

Responses: 25	Manufacturer	GSSI:	7
		Road Radar:	7
		Penetradar:	4
		Sensors & Software:	2

Question 3. Table

Pavement Layer Thickness	Void Detection	Bridge Deck Delamination	Delamination Detection	Depth of Steel Dowels	Base Layer Thickness
Using GPR: 24	Using GPR: 22	Using GPR: 16	Using GPR: 11	Using GPR: 8	Using GPR: 8
Other Technologies	Other Technologies	Other Technologies	Other Technologies	Other Technologies	Other Technologies
Coring: 16	Coring: 2	Coring: 4	Coring: 3	Coring: 3	Coring: 4
Boring: 3	Boring: 3	Boring: 0	Boring: 2	Pachometer: 5	Boring: 2
Others: 2	Chain Drag: 2	Chain Drag: 7	Chain Drag: 6	Others: 3	Other: 1
	Others: 2	Others: 13	Others: 5		
Buried objects utilities	**Depth to Bedrock**	**Asphalt Stripping**	**Bridge Support Scour**	**Water Table Location**	**Archaeological Sites**
Using GPR: 8	Using GPR:8	Using GPR: 7	Using GPR: 6	Using GPR: 3	Using GPR: 2
Other Technologies	Other Technologies	Other Technologies	Other Technologies	Other Technologies	Other Technologies
Coring: NA	Boring: 6	Coring: 5	Others: 10	Boring: 6	Excavation: 4
Others: 6	Seismic: 1	Boring: 2	Others: 3		
Base Moisture	**Subsurface Ice**				
Using GPR: 2	Using GPR: 1				
Other Technologies	Other Technologies				
Coring: 2	Drilling				
Boring: 6					
Seismic: 1					
Other: 1					

The following table is an example tabulation of agency responses. Included are the responses to the first part of Question 1 and to GPR use in Question 3 for the first six categories

U.S.	Q1	Layer Thickness	Void Detection	Bridge Deck Delamination	Delamination Detection	Dowels	Base Thickness
Alabama	N						
Alaska.	N						
Arizona	N						
Arkansas	Y	X	X	X			
California	Y	X	X	X	X		
Connecticut	Y	X	X				X

U.S.	Q1	Layer Thickness	Void Detection	Bridge Deck Delamination	Delamination Detection	Dowels	Base Thickness
District of Columbia	N						
Florida	Y	X	X				X
Georgia	Y	X	X			X	
Hawaii	N						
Idaho	Y	X	X	X	X	X	X
Illinois	Y			X			
Indiana	Y						
Iowa	N						
Kansas	Y	X		X			
Kentucky	N						
Louisiana	Y	X					
Maine	N						
Maryland	Y	X	X				
Massachusetts	Y	X	X`	X	X	X	
Michigan	N						
Minnesota	Y	X					
Mississippi	Y		X				
Missouri	Y	X	X	X	X		
Montana	N	X					
Nebraska	N						
Nevada	Y						
New Hampshire	Y	X		X	X		
New Jersey	Y	X	X	X	X		
New Mexico	N						
New York	Y		X	X	X		
North Carolina	Y	X	X				
North Dakota	N						
Ohio	N						
Oklahoma	N						
Pennsylvania	N						
Rhode Island	Y		X	X			
South Carolina	Y		X				
Tennessee	Y		X				
Texas	Y	X	X			X	X
Utah	N						
Virginia	Y		X	X	X		
West Virginia	Y	X	X	X	X		
Wisconsin	Y	X	X		X	X	
Wyoming	Y	X	X	X	X	X	X
CANADA							
Alberta	Y	X		X			X
British Columbia	Y	X		X		X	X
Manitoba	Y	X	X				
Newfoundland	N						
Saskatchewan	Y	X					
Yukon	Y					X	
TOTAL		24	22	16	11	8	8

Question 4. Are there environmental applications for which your agency uses GPR?

Application:		GPR: Other Equipment Technologies:
Road salt distribution	0	Coring/Sampling
Tank and drum location	5	Metal Detector, Electrical, Excavation
Plume Detection (i.e., gasoline)	1	Core/Sampling
Others:	0	

Comments: none

Question 5. Are there other applications for which your agency uses GPR?

Bridge abutment thickness, Geological Survey

Question 6. Are you satisfied with GPR results?

If Yes: 15 Application:

Pavement thickness	9
Void detection	3
Underground tanks	3
Base thickness	2
Steel dowel location	2
Bridge overlay/scour	5

Both: 10 (responding)

If No: 13 Application:

Subgrade moisture	2
Void detection	3
Asphalt stripping	2
Others	3

Question 7. Is GPR cost effective:

Yes: 8 No: 2 Both: 8 Don't Know: 14

If Yes, what applications?:

Pavement studies	4
Bridge deck delamination	3
Bridge scour	2
Other	3

If No: what applications?:

Question 8. Would your agency use GPR again?

Yes: 27 Probably not: 2 Why: *(no firm responses)*

Question 9. How does your agency calibrate the GPR equipment?

Responses 10:

Metal plate/Air	2
Use coring to verify	3
Electronic means	2

Question 10. How does your agency control the location of the GPR antenna and index the GPR data to the site being surveyed?

Responses: 14

Global Positioning System	2
Survey Points	5
Mile Marks	6

Question 11. What crew size used for GPR surveys?
Responses 10: Average calculated as 2 crew persons.

Question 12. What is the crew productivity?
Responses: 4 *Varied widely depending on application*

Question 13. Does your agency have a quality assurance procedure to monitor the information collected? Yes: 4 (respondents)

Question 14. Does your agency use other pavement information with GPR for better PMS decision-making?

Coring: 15 Test pits: 2

Drilling: 7 Other: Visual, FWD, Roughness

Question 15. What GPR software or data analysis procedure does your agency use?

GSSI	2	PENETRADAR	1
RADAN (GSSI)	1	INFRASENSE	1
DECAR	1	PULSERADAR	1

Question 16. Please comment on GPR improvements you recommend.

Hardware: Higher speeds, better resolution

Operations:

Procedures:

Software: Automated data analysis

Costs:

Specifications:

Question 17. Do you have any GPR case studies either positive or negative?

Yes: 12 (respondents)

Question 18. Has your agency performed or sponsored any research or development in GPR?

Yes: 8 (respondents)

Question 19. Is your agency performing or sponsoring any research or development in GPR?

Yes: (11 respondents)

Question 20. What research do you feel will help in improving GPR and/or its state-of-the-practice:

Responses: 7 *The responses centered around user friendly software, better resolution and accuracy and procedural information such as antenna vs. resolution information.*

Question 21. Additional comments or suggestions.

The few comments which were submitted reflect the overall concerns described in the body of the survey.

APPENDIX C

GPR Manufacturers

Following is information about GPR manufacturers from their literature:

Geophysical Survey Systems, Inc. (GSSI)
North Salem, New Hampshire

Using fast sampling rates, GSSI SIR-10H can collect data at 65 mph with data points at every 3 ft, run up to 4 antenna pairs and computer process this data in real-time. Depths to several hundred feet or resolution of pavement layers 1 to 2 inches thick can be made depending on the antenna, radar frequency and procedural application. Specialized antennas for locating small voids, large cracks, reinforcing and base layer problems under or within jointed concrete or asphalt pavements and identification of deterioration of bridge decks are available.

GSSI provides several specialized software packages to run on PC's and offers a host of software tools to analyze, filter, compress and display large amounts of data taken over miles of pavement studies. One software package offered by GSSI will process continuous radar records, determining pavement layer thickness and depth to base, producing numerical ASCII or MS-EXCEL files.

Road Radar Ltd.
Edmonton, Alberta, Canada

Road Radar Ltd. provides highway inspection services using their proprietary Road Radar System. The Road Radar System has been designed specifically to meet the needs of road and bridge engineers. The system uses a patent pending approach to determine radar signal velocity for calculating layer thickness. Therefore, the system calibrates itself for changes in materials and/or changes in electrical properties within materials.

The Road Radar System consists of a hybrid antenna system. An air-launched antenna mounted above the pavement measures thin layers (i.e. 50 mm) and a surface-coupled antenna, in direct contact with the pavement surface, determines radar signal velocity and measures deeper layers (i.e. 2 m).

Penetradar Corp.
Niagara Falls, New York

Penetradar Corp. manufactures proprietary GPR systems which they use to provide inspection services for bridge decks and pavements. These GPR systems are mounted on vehicles for highway inspections at highway speeds and can also be configured for man-portable operation. Applications include determining bridge deck delamination, measuring pavement layer thickness, detecting subsurface moisture accumulation, and locating and measuring voids beneath pavement.

Pulse Radar, Inc.
Houston, Texas

Pulse Radar, Inc. was incorporated to provide a system to analyze subsurface pavement structures using short pulse, non-contact, ground penetrating radar. Pulse Radar provides the pavement community with a diagnostic tool for pavement evaluation, including subsurface profiles of pavement structure and techniques for interpreting profiles to determine the in-service condition of pavement structures. Pulse Radar's antennas are air-coupled horns, generally suspended from the front or back of a van. The company sells GPR equipment and provides highway inspection services.

Sensors & Software, Inc.
Mississauga, Ontario, Canada

Sensors & Software, Inc. manufactures and sells Ground Penetrating Radar systems, providing instruments, software, training and rentals. The pulseEKKO 1000 GPR with a 1200 MHz antenna and odometer wheel mounted to the back of a vehicle can be used for road and pavement surveys. The pulseEKKO 1000 GPR is also used for pipe and cable detection; finding rebar; road bed and shallow stratigraphy; archaeological investigations; building structure integrity; and nondestructive testing. The 1200 MHz antenna operates in the ground-coupled mode. Sensors & Software can provide GPR processing software for filtering, modeling and migration, topographic compensation, and wiggle-trace and color display.