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Ground Penetrating Radar for Railroad Track Substructure Evaluation

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Abstract

This report presents the results of the first three phases of a multiphase project to adapt Ground Penetrating Radar (GPR) to railroads for use in developing useful indices of substructure condition and performance. The report includes brief discussions of some basic GPR principles, as well as data processing and modeling techniques that are applicable to railroad surveys. The railway GPR equipment is mounted on a hi-rail vehicle and includes multiple sets of 1-GHz air-launched horn antennas suspended above the track that permit fast survey travel speeds and high resolution measurements to a depth of 3 to 6 ft (1 to 2m). The data from the multiple sets of antennas provide transverse and longitudinal measurements of the track substructure. The report presents example results from more than 200 miles (320 km) of surveys to demonstrate the capabilities and applicability of GPR to assess railway track substructure (ballast, subballast, and subgrade) conditions and to produce quantitative indices of railway track substructure condition for use in track substructure maintenance management efforts.

KEYWORDS: Railroad, substructure, Ground Penetrating Radar, track maintenance, ballast, subballast, subgrade, non-destructive testing.

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Preface

This report presents the results of Phases 1 through 3 of a multiphase project to develop Ground Penetrating Radar (GPR) for application in railway track substructure assessment. These completed phases have significantly advanced the state of the art of GPR data collection and interpretation in the railroad environment. The follow-on phases will use the identified strategies to develop robust automated data interpretation and to further investigate safety-compromising substructure track conditions.

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Summary

Ground Penetrating Radar (GPR) has been employed to assess railway track substructure (ballast, subballast, and subgrade) conditions and to produce quantitative indices of substructure condition for use in track maintenance management efforts. GPR involves transmitting radar pulses into the substructure and measuring return signals that have reflected off boundaries between substructure layers with different electromagnetic properties. This report demonstrates uses of GPR to produce images and quantitative indices of railroad track substructure condition quickly on a continuous non-destructive basis.

The GPR equipment that has been developed in this project is mounted on a hi-rail vehicle with clearance between the antennas and the track surface to permit continuous measurements to be made along the track from above the top-of-rail at normal vehicle speeds. Antennas are located at both ends of the ties, as well as in the center of the track, so the variations of conditions are measured laterally across and longitudinally along the track. The antenna configuration and surveying procedures have been optimized to account for the radar-scattering influence of ties and rail.

The GPR data are processed to correct for location variations and to produce uniformly spaced data. The data are also processed to remove unwanted background data, principally from effects of ties and rails. After processing, modeling techniques have been demonstrated to produce quantitative measures of substructure layer thickness and water content. Observations from inspection trenches excavated under the track have been used to gather soil properties and thickness information to compare with the radar measurements to validate the effectiveness of the technique.

Indices of track substructure condition have been developed based on the GPR data. This report presents some example indices that have been based on the longitudinal and lateral variation of substructure layers, and the extent of ballast pocket development. GPR provides a means to develop substructure indices based on layer contours, moisture contents in the different substructure layers, amount of fouling in the ballast and the rate of change of layer parameters.

More than 200 miles (320 km) of data were collected during this project at sites representing a variety of subsurface conditions to demonstrate and verify the radar techniques. The survey results show that the current GPR system is capable of observing substructure conditions, such as thickness of the ballast and subballast layers, variations in layer thickness and condition along and across the track, pockets of water, and soft subgrade. In addition, locations and depths of subsurface drainage pipes, trenches, and utilities can be identified. Further phases in the technology evolution include the complete automation of data processing and interpretation, and continued surveying to gain more experience in identifying safety-compromising substructure track conditions.

1. Introduction

Track substructure (ballast, subballast, and subgrade) conditions have an important influence in determining track performance, assessing the potential for service interruptions, and needing to reduce train speed. A significant part of a railroad's track maintenance budget is driven by the rate of deterioration of track geometry. Rough track is caused by movements in the substructure under repeated train loading. The performance is significantly affected by moisture accumulation and thickness of the roadbed layers (Selig and Waters, 1994). Thus the hidden and hard to monitor substructure conditions are important to railway track performance.

GPR has the ability to map key railroad track substructure conditions quickly on a continuous, top-of-rail, non-destructive basis (Olhoeft and Selig, 2002; Hyslip, et al., 2003). This report describes work in which GPR was used to observe substructure conditions, such as thickness of the ballast and subballast layers, variations in layer thickness and condition along and across the track, pockets of water, and soft subgrade. In addition, the GPR identifies locations and depths of subsurface drainage pipes, trenches, and utilities.

For this development project the GPR antennas were located between the rails, as well as at the ballast shoulders beyond the ends of the ties. The multiple-antenna configuration provided measurement of the transverse, as well as longitudinal variation of the track substructure. The radar equipment was mounted on a hi-rail vehicle, and surveys were conducted continuously at speeds ranging from less than 2 mph to more than 25 mph (3 to 40 km/hr). At 10 mph (16 km/hr) the radar resolution is a few inches horizontally (~7 cm) and a fraction of an inch vertically (< 1.0 cm), while depths of penetration of more than 6 feet (2 m) were achieved. Future GPR systems of this type are anticipated to be mounted on track geometry measurement vehicle (TGMV) for routine surveying during track geometry data collection.

The GPR system for railroad use described herein has been developed in phases. The first two phases used existing hardware to explore the capabilities of GPR for railway track and established appropriate apparatus and procedures for collecting and processing the radar data. The need for obtaining radar measurements at multiple positions across the track to portray the three-dimensional nature of the substructure was determined. The ability to model the radar data to determine estimates of water content of the substructure materials was demonstrated. A variety of radar images were produced in Phase 2 (FRA Contract No. DTFR53-01-P-00535) that illustrated the potential benefits of radar for determining track subsurface conditions.

Phase 3 (FRA Contract No. DTFR53-02-P-00263) also used available radar equipment mounted on a hi-rail vehicle. Multiple antenna configurations were established and optimum configurations were determined. Measurement procedures were defined and calibration procedures partly developed. Software was designed to process the radar data automatically. Existing GPR modeling techniques for calculating complex dielectric permittivity versus depth were demonstrated manually (Olhoeft, 1998, 2000). Effective

medium mixing models were used to bound bulk density and water content manually from the permittivity (Olhoeft et al., 2004). More than 200 miles (320 km) of data were collected at sites representing a variety of subsurface conditions to demonstrate and verify the radar techniques.

Follow-on phases have been planned to include installing the radar on hi-rail track TGMV and use it to collect radar images routinely and to provide automating the calculation of the depths, densities, and moisture contents of the substructure layers.

2. GPR

2.1 Applications

Since the early 1970s, GPR has been found to be useful in many areas of non-destructive subsurface investigations (Olhoeft and Smith, 2000). Highway examinations using radar have determined pavement layer thickness and deterioration, and extensive work has been performed for bridge deck and scour evaluations. In environmental surveys, GPR is useful in detecting underground storage tanks, buried drums, and debris, as well as detecting other contamination not visible from the surface. Archeological and forensic surveys have produced dramatic results. Radar has commonly been employed to detect reinforcing steel, post-tension members, and conduits within concrete structures and pavements, as well as identifying voids and loss of support beneath slabs. Geologic investigations have profiled bedrock and the water table, while hydrologic studies have examined lake, river, and subbottom features. GPR is also being used on railroad tracks to provide continuous measurement of the condition of track substructure layers and thereby provide information for maintenance and rehabilitation decision making. The most successful applications are those exploiting the ability of GPR to produce high-resolution images of the subsurface and to detect nonmetallic buried objects quickly, continuously, and do not require direct material surface contact.

2.2 Principles

The GPR method transmits pulses of radio energy into the subsurface and receives the returning pulses that have reflected off interfaces between materials with different electromagnetic properties. It is a pulse-echo technique using radio energy as depicted in the Figure 1. Antennas are moved across an area with a continuous series of radio pulses, producing a distorted cross-section of the subsurface. The distortion is a function of the geometry of the antenna position and orientation, as well as the velocity of the material properties in the subsurface. Correcting for these parameters removes the distortion to generate a true geometric cross-section image of the variations of electromagnetic properties in the subsurface.

The dielectric permittivity and electrical conductivity are mostly independent. For example, freshwater and saltwater have essentially the same dielectric permittivity (salt water is slightly lower); however, saltwater exhibits a much higher electrical conductivity than freshwater. GPR pulses travel at similar speeds through both types of water; however, in saltwater the energy is attenuated very quickly and does not penetrate deeply.

As shown in Figure 1, reflections of the GPR pulse occur at boundaries in the subsurface where changes occur in the material properties. Only a portion of the pulsed signal is reflected and the remaining part of the pulse travels across the interface to again be reflected back to the receiver from another interface boundary. The time the pulse takes to travel through the layer and back is controlled by the thickness and electromagnetic properties of the material. The travel time between upper and lower boundaries of a layer can be used to calculate the layer thickness employing a known velocity.

2.3 Data Processing

To achieve the desired information in the railroad environment from the radar, the collected data must be processed to:

1. Locate radar data position (e.g., tag the data with global positioning system (GPS) coordinates, such as World Geodetic System 1984).
2. Verify accuracy of location using such things as digital video and U.S. Geologic Survey (USGS) digital orthophoto quadrangle (DOQ) images.
3. Remove unwanted background and objects (e.g., the ties and rails).
4. Apply time-space and other filters to enhance desired image features.
5. Scale data plots for desired distance formats.

The steps of automatically processing GPR data from raw data with distortions to geometrically correct images are known and straightforward. In this project, the data acquisition process was standardized for uniform acquisition of GPR data (in terms of procedures, time and relative amplitude calibration, antenna geometry, and polarization) and location information. The location, or position, information was best accomplished using wide area augmentation system, differential global positioning system (WAAS DGPS). GPS, however, does not work everywhere, so backup positioning systems were provided. The data processing then easily becomes automatic to correct for distortions and common acquisition problems. With calibrated time and position, the GPR data can use diffraction hyperbola and other velocity determination estimates to scale vertical axis to produce geometrically correct image cross sections of the subsurface. This was demonstrated in Phase 2 of this project. Also in Phase 2, the GPR antennas were polarized and located to minimize the reflections from the rails.

Automation requires standardization, and the standardization of the data acquisition process required gaining experience by collecting data in the field, thus reducing problems that must be dealt with in later data processing. Examples would be how to

recognize and handle radio frequency interference problems caused by railroad communications and other sources appearing in the GPR data, how to acquire accurate location information where the GPS does not work (e.g., high radio frequency noise areas, tunnels), how to recognize and flag places where GPR does not work (i.e., no penetration through clay layers, metal, highly conductive salt zones, or from too much clutter), and other unanticipated issues.

Once GPR data are processed to geometrically correct image cross-sections of the track substructure, then image processing and texture, morphological or pattern recognition algorithms can be applied to automatically enhance, detect, and extract geometric features of interest. Examples of these features include detection and mapping of ballast and other layer thickness, location of abrupt thickness changes (such as a shear key), location of material changes (such as type of ballast), location of utilities (such as cable and pipe crossings), or location of drainage features.

2.4 Data Modeling

Modeling produces quantitative values for dielectric permittivity and depth. Once obtained, dielectric permittivity can subsequently be modeled into water content and density. Modeling requires radar system calibration for recorded signal time and absolute amplitude. Providing automatic modeling is desirable to derive dielectric properties and then extract density and water content information (Olhoeft and Smith, 2000). Once the absolute amplitude calibration procedure is available, the automatic modeling becomes straightforward and is currently performed automatically for concrete and asphalt highway surveys (Olhoeft, 2000). However, the railway situation is more complicated than highways. Highways have a flat, smooth, horizontal surface that is easily calibrated for absolute amplitude while railway ballast is coarse gravel with a slope and surface roughness comparable to the scale of the 1 GHz wavelength. Thus the smooth surface calibration assumptions and procedures do not work. An absolute amplitude calibration procedure using multiple antenna geometries, polarizations, and/or frequencies will be required to be developed to provide automatic modeling of railroad GPR data.

GPR data in this study were modeled by matching simulated radar pulses to the measured radar pulses. Figure 2 presents an example of full waveform modeling through to depth determination and validation by trenching (from Olhoeft et al., 2004). The bottom right-hand image in Figure 2 is raw, unprocessed GPR data. A single scan is selected from this data for modeling after digital video certifies the antenna field of view is clear. GRORADAR (Olhoeft, 1998) uses full waveform modeling to produce electromagnetic material properties, which turn time into depth. The modeling results were validated using the results from cross-trenches dug along the track, which are shown in the top portion of Figure 2.

The extracted radar information is then analyzed with other available information, such as assets, geometry, and work history to determine substructure conditions. The GPR data, location information, and digital video were integrated together with track features, milepost and offset, and track geometry data from TGMV using Optram, Inc.'s Right-of-Way Infrastructure Management (ORIM) database and viewer. This integrated view of conditions can then be used to define problem sites and to develop substructure indices that are referenced to location along the track in a track chart view. The output can be viewed in many ways, including GIS, track chart view, or exception report.

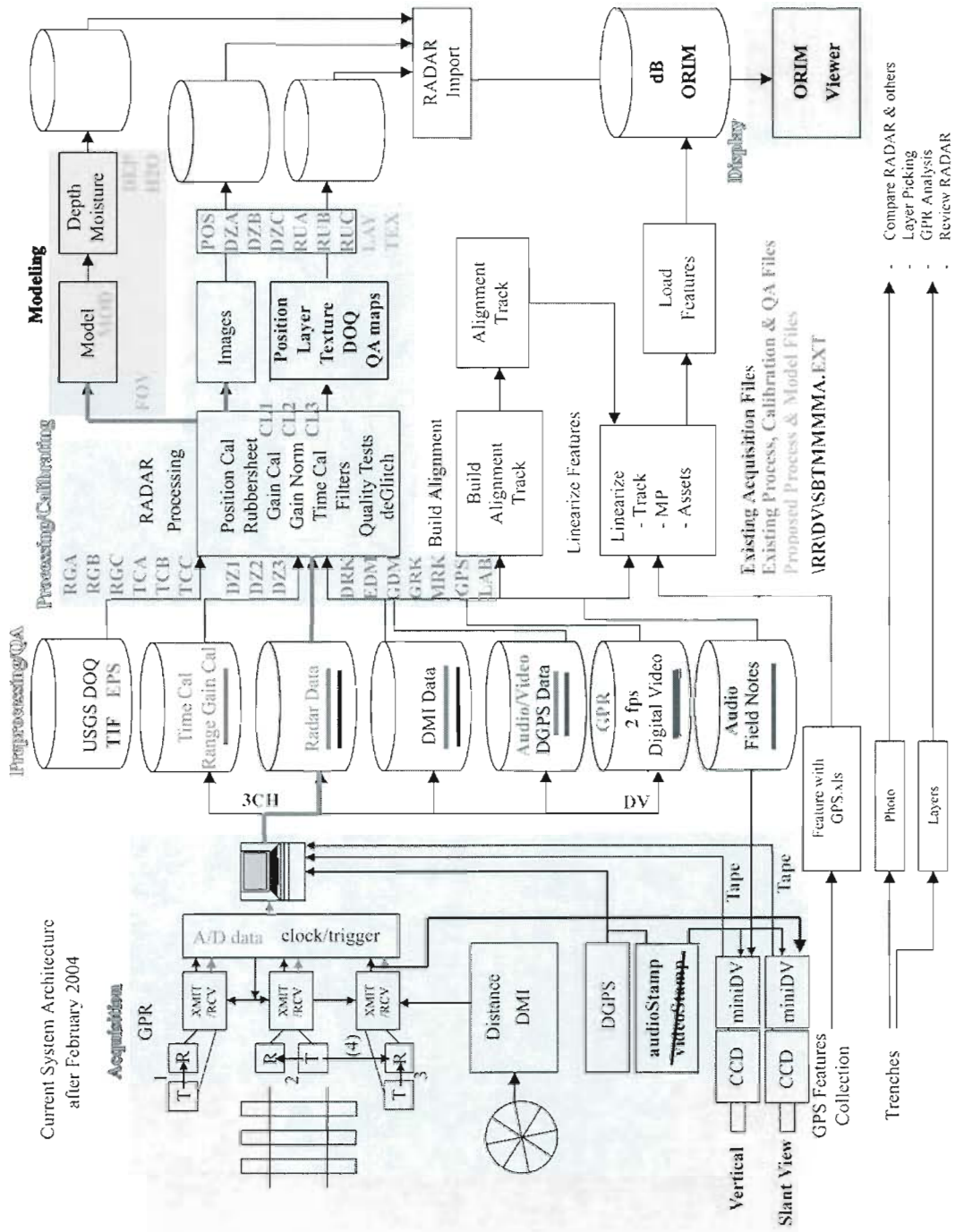


Figure 3. GPR System Flow Diagram.

23 24X

3. GPR for Railroad Applications

3.1 Railroad Substructure Investigation

Appropriate tools for field investigation of railway substructure problems include cross-trenches, cone penetrometer tests, test borings, characterization of track geometry data and deterioration trends, track stiffness measurements, and GPR (Selig, 1997; Hyslip and McCarthy, 2000). GPR surveying provides a continuous survey and characterization of the track substructure, quickly locating areas of potential trouble for further investigation or maintenance. GPR has the ability to provide a rapid, non-destructive measurement technique for evaluating these key substructure condition indicators (Olhoeft and Selig, 2002) and can be used to provide numerical data for development of substructure condition indices (Hyslip, et al., 2003).

Material and moisture variation within the track substructure causes distinct material differences that are easily recognized by GPR. Water possesses a high dielectric permittivity compared to the other materials typically found in the substructure and produces a strong effect on the GPR profiles. In an area where water has been trapped in the substructure, the dielectric permittivity is increased, resulting in increased two-way travel time and a stronger reflection than if it were drier. The texture of the radar record allows the relatively coarse-grained ballast layer to be recognizable from the comparatively finer-grained subballast layers, and the texture allows fouled ballast to be distinguished from clean. In the case of fouled ballast, the normal layering is disrupted by fine-grained materials in the otherwise coarse-grained matrix. By quantifying the GPR scattering pattern textures, determinations can be made regarding the amount of fouling in the ballast layer.

To verify and calibrate the railway GPR data, it is currently necessary to excavate cross-trenches (inspection trenches) in locations with key substructure conditions to correlate the actual conditions with the radar data. Figure 4 shows a typical GPR image example along a 500 ft (150 m) section of track. Figure 4 also shows photos of the cross-trenches that were excavated and logged for calibration of the GPR data. Depths to key substructure layers are measured in the cross-trenches and used with travel times from the radar data to determine average velocities. The velocities are used to calculate the material properties values, such as dielectric permittivity.

Once enough GPR data has been calibrated with inspection trench information, the need for inspection trenches will diminish from what is presently required. Eventually quick assessments of subsurface conditions over large distances will be made with minimal invasive cross-trenching.

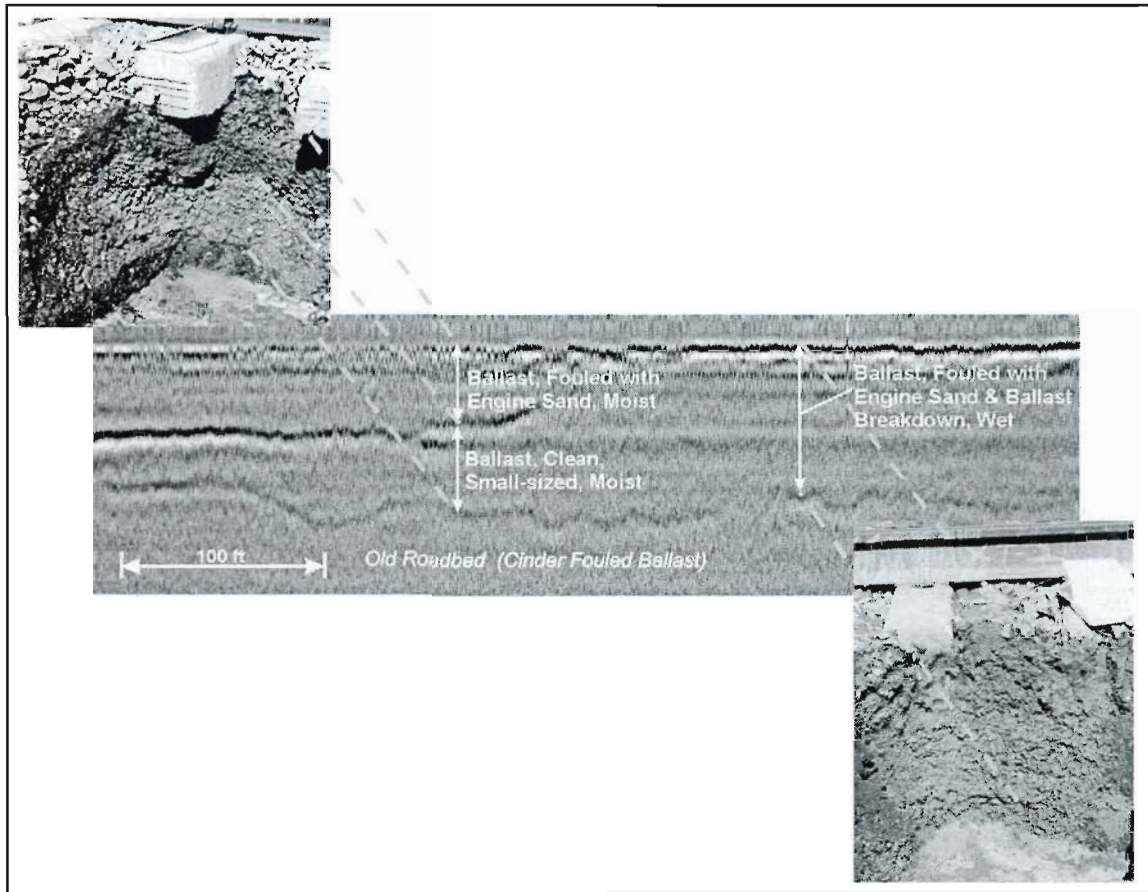


Figure 4. GPR Image Example with Cross-Trenches for Calibration.

3.2 Advantages and Limitations

Many advantages exist for the use of GPR on the railroads. Principally, GPR provides a rapid, non-destructive, top-of-rail measurement technique of substructure layer conditions with minimum interference to train operation. In this regard, GPR can be utilized as an effective tool for exposing the root cause of reoccurring poor geometry and unstable roadbed. GPR surveys can be collected on railroad tracks at vehicle travel speeds in excess of 25 mph (40 km/hr), and the use of multiple antennas can provide variations in substructure conditions across the track, which allows for this technique to be used on a network-level basis to provide indices of track quality for utilization in inspections to assess safety, maintenance, and operational constraints. The wide-area surveying ability also provides the means to define sections of track that have similar conditions and expected performance.

GPR provides the ability to measure layer thickness and, using the multiple antenna configuration, can determine the amount of deformation and non-uniformity of substructure layers. The lateral configuration of the substructure layers can attest to the root cause of substructure problems. The ability of GPR to measure layer thickness also

provides information on the adequacy of the substructure's strength to sustain traffic loads. By mapping the thickness of ballast and subballast layers, GPR can expose areas exhibiting subballast spreading, subgrade squeeze, subgrade attrition, and expansive clay problems. GPR can also detect trapped water from poor drainage and distinguish fouled ballast from clean ballast.

As with all subsurface investigation techniques, however, GPR does have some limitations. For instance, substructure layer boundaries may not be detectable to GPR under certain conditions, such as too little difference in electrical properties between the two adjoining layers or boundaries producing high reflections that mask radar signals from lower layers. The depth of radar penetration may be limited by such things as high moisture content or wet conditions, highly conductive (salty or clayey) soils, or highly metallic ballast components. GPR is also susceptible to interference from other radio sources, especially in urban environments, which can mask subsurface returns.

3.3 Equipment for Railroad Applications

Antennas are used to transmit and receive the radar pulses. The transmitting and receiving electronics are controlled by the GPR control unit, which also measures the time and amplitude of the returned signals. GPR antennas are designed to operate at various frequencies from tens of MHz to several GHz. The antenna's operating frequency must be considered for a given investigation. The antenna choice must take into account the trade-off that exists between resolution and depth of penetration. The higher the antenna frequency, the greater the resolution it exhibits; but higher frequency antennas have less depth of penetration compared to lower frequency antennas. Lower frequency antennas penetrate deeper than those at a higher frequency, but they have reduced resolution.

A second consideration for antenna selection relates to how the antenna is deployed. The two basic categories of antennas are air-coupled (air-launched) and ground-coupled (Smith, 1995). Antennas that are air-coupled are designed to be used suspended above the ground surface, with an air gap. Ground-coupled antennas are designed to be in direct contact with the ground surface, with no air gap. Air-coupled antennas are particularly suited to railroad substructure applications since they are suspended above the ground and thereby allow high-speed measurement and clearance for turnouts, grade-crossings, wayside detection devices and trash.

For the railway GPR development discussed in this report, three sets of GSSI 4208 1GHz air-launched horn antenna pairs were used. These air-coupled antennas are designed to work from 12 to 24 inches (30 to 60 cm) above the ground surface. A pair of antennas is deployed outside each rail at the ends of the ties, and a third pair is positioned between the rails along the centerline of the track. The system uses antenna polarization to minimize interference clutter effects of the ties and running rails to produce a clearer image of the substructure conditions. The antennas are supported on an adjustable frame of high-strength fiberglass tubing that is mounted on a hi-rail vehicle, as shown in Figure 5.

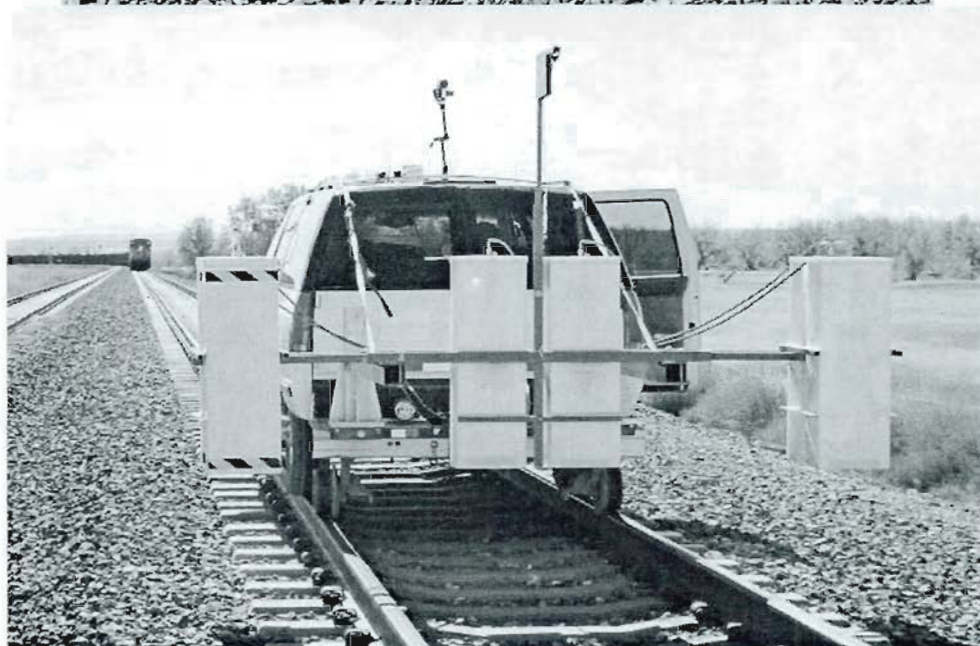
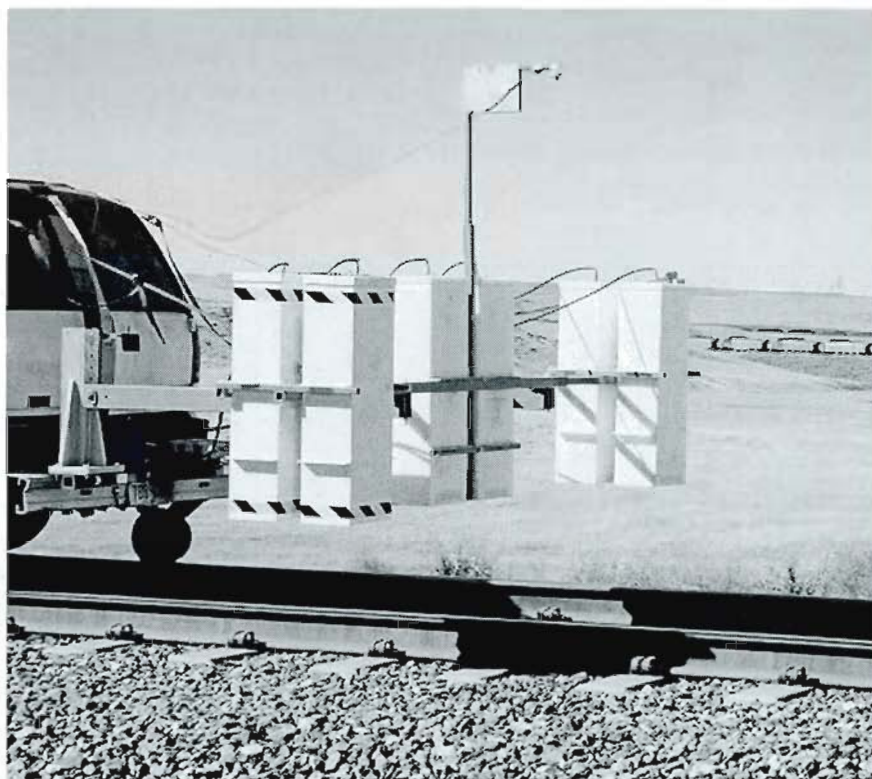


Figure 5. GPR Hi-Rail Setup with Three Pairs of 1-GHz Horn Antennas

The three antenna-pair arrangement permits three profiles to be collected at the same time as the pairs of antennas are moved along the track. This provides three continuous parallel longitudinal images along the track, providing information on the cross-track variability.

An accurate accounting of the locations of the GPR measurements is critical to an effective investigation. The system employs an integrated WAAS DGPS, a backup distance measuring instrument (DMI) synchronized with the vehicle transmission for where GPS signals are unavailable, and wide area as well as antenna field-of-view digital video systems. The DGPS can provide location information with accuracy error of less than 3 ft (1 m), but it can be adversely affected by bridges, tunnels, and radio frequency interference. The DMI provides continuous positioning information to supplement the DGPS data but with an accumulating error of about 0.2 percent. Digital video images of the track are collected to further refine location information through identification of fixed assets along the track. The location data are verified against 1-meter USGS aerial or satellite DOQ maps. Even with this redundancy, an instance occurred during this project where no positioning information was obtained due to a combination of high RF interference in a urban environment (a lightning storm and strong solar activity creating a geomagnetic storm) making DGPS worthless, the DMI slipped on rain slick rails, and a spider crawled into the digital video camera lens and blocked the view.

In addition to QA/QC of the antenna field of view and help in positioning, the digital video can also help to assess ties condition and other visual conditions along the track.

3.4 Project Surveys

As part of this multiple phase project to develop GPR for railroad use, over 230 miles (370 km) of track has been surveyed. In order to gather GPR experience on prevalent substructure conditions, the GPR testing first focused on the heavy haul coal lines in the western United States. Subsequent GPR surveys were performed in Mississippi and Arkansas, where chronic substructure problems were also prevalent and maintenance and repairs were imminent. Further tests were performed in North Dakota and along electrified urban commuter lines in New Jersey. Table 1 lists the general location, survey mileage, and general site conditions at locations surveyed during this project.

Table 1. List of GPR Surveys Performed During Project.

Location	Distance (miles/km)	Comments
Crawford, NE	10.4/16.6	Initial GPR–single antenna pair. Data processed and used for substructure assessment and remedial work planning.
Denver, CO	2.1/3.4	Equipment testing and development along this mainline track in urban environment.
Denver, CO	2.1/3.4	Equipment testing and development. Repeat survey at varying water content and freeze-thaw temperature.
Sheridan, WY	4.3/6.9	Data processed and used for substructure assessment and remedial work planning for a section of track with poor drainage and failing clay subgrade.
Lindenwold, NJ	19.0/30.4	Data collected, processed, interpreted, and used for substructure remediation planning for third-rail electrified transit line.
Pueblo, CO	2.0/3.2	Data processing and interpretation of ground-coupled antenna survey for concrete slabtrack. Report submitted to FRA. Air-coupled antenna data collected on TTCI's High Tonnage Loop.
Denver, CO	2.1/3.4	Equipment testing and development. Repeat survey at varying water content and freeze-thaw temperature.
Sheridan, WY	4.3/6.9	Return visit to previously surveyed problem site to note substructure changes.
Gillette, WY	37.0/59.2	Heavy-haul coal line with much coal fouled ballast. Data processing and interpretation are on hold.
Newcastle, WY	29.8/47.7	Heavy-haul coal line on highly plastic subgrade. Data processing and interpretation are on hold.
Ardmore, SD	15.0/24	Heavy-haul coal line on highly plastic subgrade. Eight miles processed and interpreted and used for substructure assessment.
Jonesboro, AK	23.8/38.1	Substructure survey for planning of line upgrade. Twelve of 17 files processed through uniform trace spacing.
Hillsboro, ND	47.7/76.2	Survey of track sections with reoccurring subgrade performance issues. Eight miles of automatic processing complete. Four miles of enhanced complete.
Grand Forks, ND	36.5/58.4	Data processing and interpretation are on hold.
Total	238.2/381.1	

3.5 Example Results

Figures 6 through 13 are example results from GPR surveys conducted on railroad tracks since 2001.

Figure 6 shows two GPR cross-section images that are from the same location, but opposite sides of the track. The sand zone shown in the top scan acts as a water pocket, and the trapped water in this pocket softens the surrounding clay subgrade causing track geometry deterioration. The shear key in the bottom image was a previous attempt to stabilize the soft subgrade by digging a drainage trench into the subgrade clay and filling it with ballast. The extent of the shear key is well-defined by the increase in ballast thickness and absence of the subballast layer.

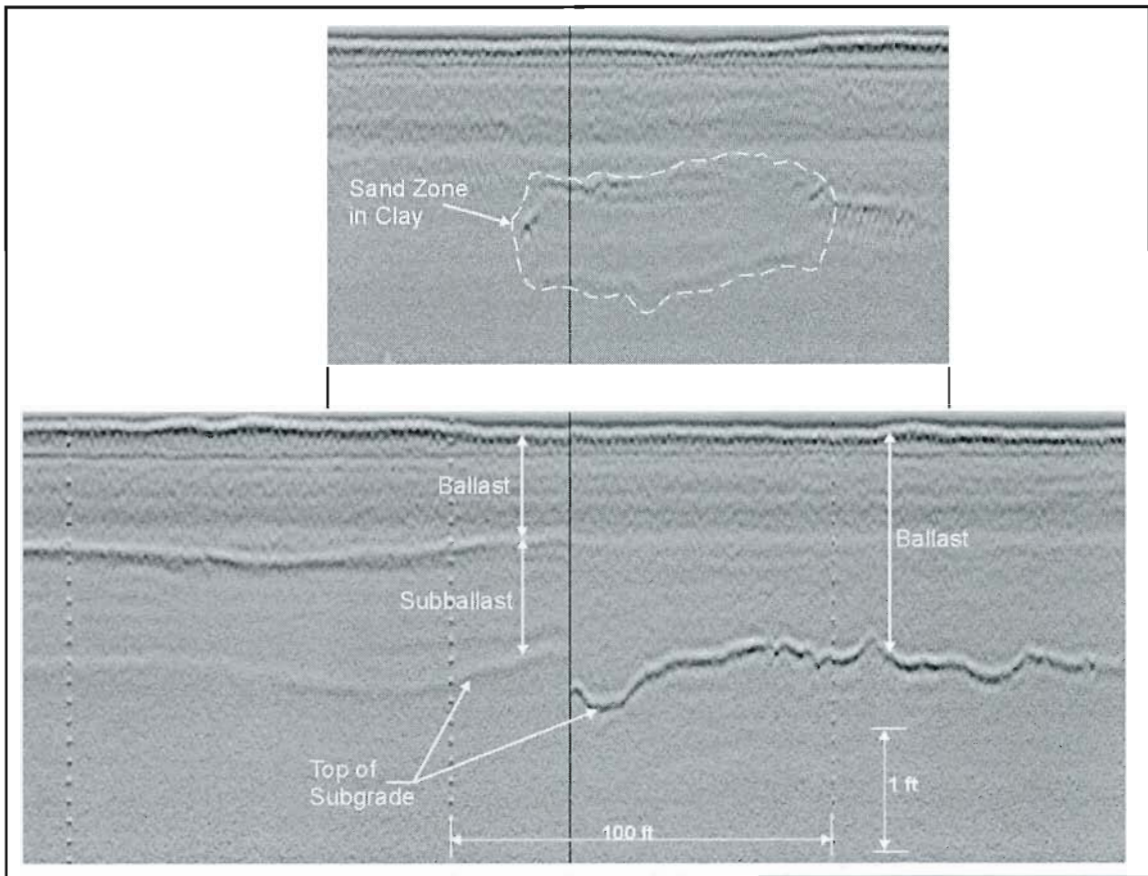


Figure 6. GPR Profiles Showing Sand Pocket and Shear Key.

Figure 7 shows an example of the subsurface conditions at highway grade crossings, as detected by GPR. Trapped water immediately adjacent to the crossing is apparent by the high amplitude reflections. The decrease in GPR reflection amplitude progressing away from the crossing in the right side of Figure 7 correlates to decreasing water content of the subballast and subgrade. The strong reflection from the surface of the reinforced-concrete crossing planks momentarily reduced the signal amplitude from the subsurface layer compared to the open track.

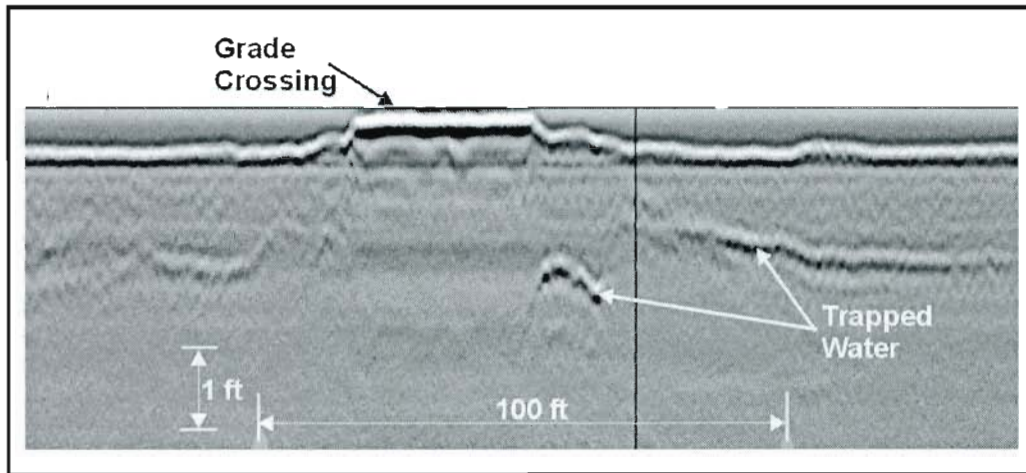


Figure 7. GPR Profile at Highway Grade Crossing.

The GPR profile in Figure 8 shows the access road along one side of the track. The variable thickness of the gravel surface layer is clearly shown. Also shown are drainage pipes from under the track installed in trenches dug into the road subgrade. The isolated reflections beneath the gravel roadbed at 10 ns are from drainage pipes at approximate depth of 2.1 ft (0.6 m). The breaks in the otherwise continuous reflection from the bottom of the roadbed correlate with the pipes below.

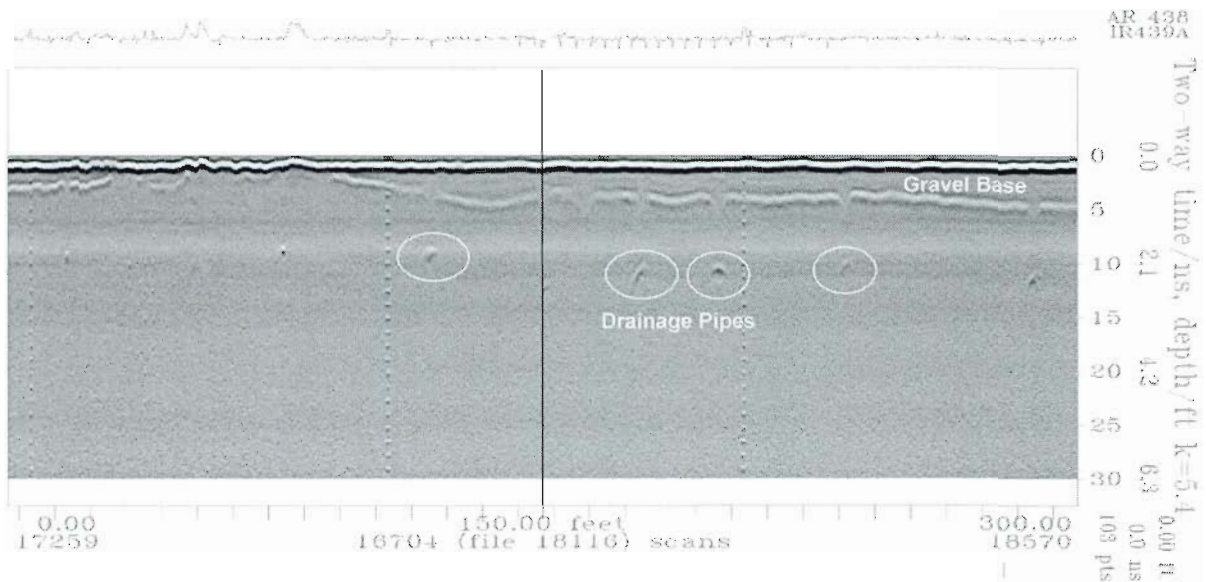


Figure 8. GPR Image of Access Road Along Track.

The scan in Figure 9 shows the varying thickness of ballast and subballast, which, in this example, is an indication of a problem associated with lateral subballast spreading on top of a clay subgrade. This spreading occurred because the clay surface softened to a toothpaste consistency from the presence of water and the repeated train loading caused the subballast to flow laterally.

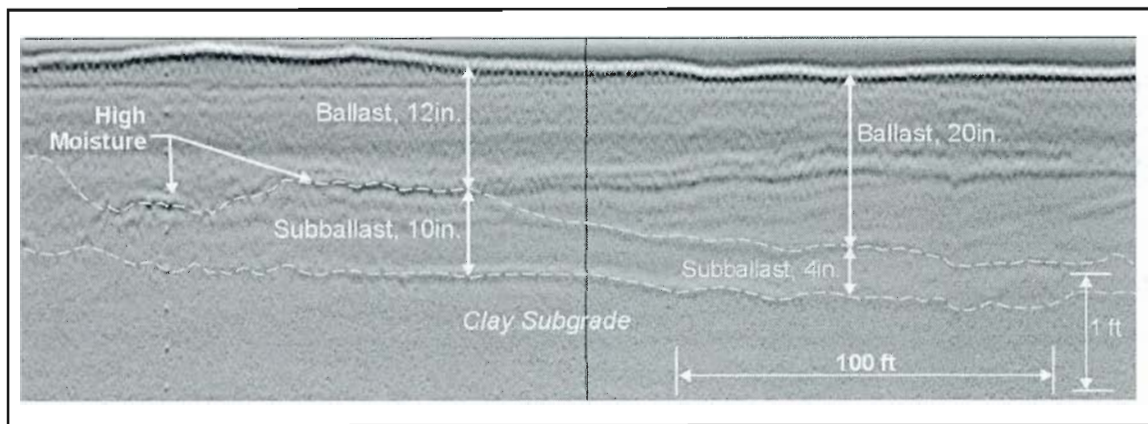


Figure 9. GPR Profile Showing Effects of Spreading Subballast.

The profile in Figure 10 shows ballast pockets that have developed in the embankment under the track. The ballast pockets are formed by failure of one side of the embankment, which bulged outward allowing the ballast to settle.

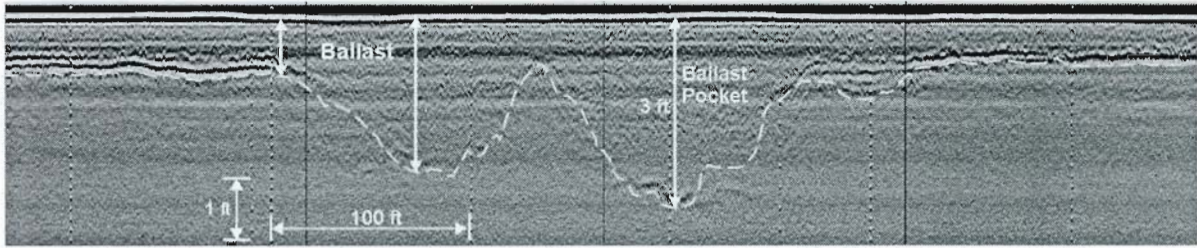


Figure 10. GPR Profile Showing Ballast Pockets.

Figure 11 shows a V-shaped ditch that was dug perpendicular to the track in the bottom image to drain trapped water from the track.

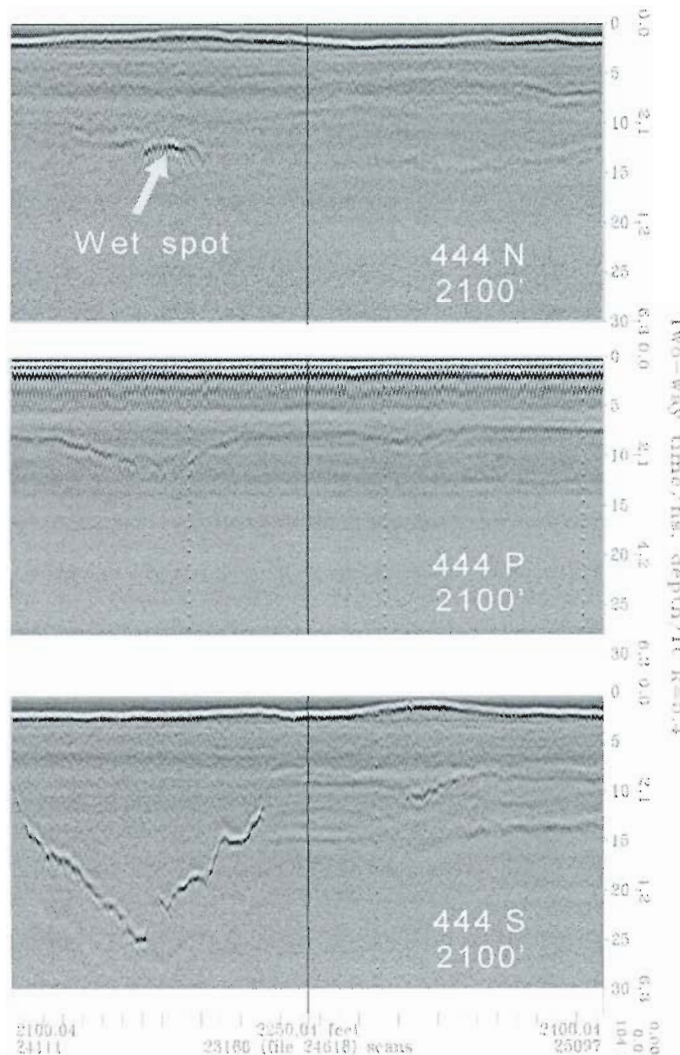


Figure 11. Comparison of Images on the Two Sides and the Center of the Track Substructure.

The top and bottom profiles in Figure 11 show data from outside the edge of ties (north and south side of track, respectively), while the middle profile shows data along the center of the track. The center image shows a greatly reduced ditch depth, and the top image shows a wet spot on the opposite side of the track from a deep V-drain. Using an estimated ballast dielectric permittivity from the radar travel time to the bottom of the V-shaped ditch, the ditch depth was estimated at 4.7 ft (1.4 m). The image of the bottom of the ditch is brighter than the ballast/subballast boundary, which indicated that the bottom of the ditch is wetter. The north side (top image in Figure 11) of the wet spot has the texture and periodicity corresponding to the tie spacing. Excavation of a similar image in another location showed this pattern to be caused by extrusion and fingering of the subgrade clays under the repeated loading of the passing trains. Figure 12 shows a larger, enhanced version of the bottom image in Figure 11.

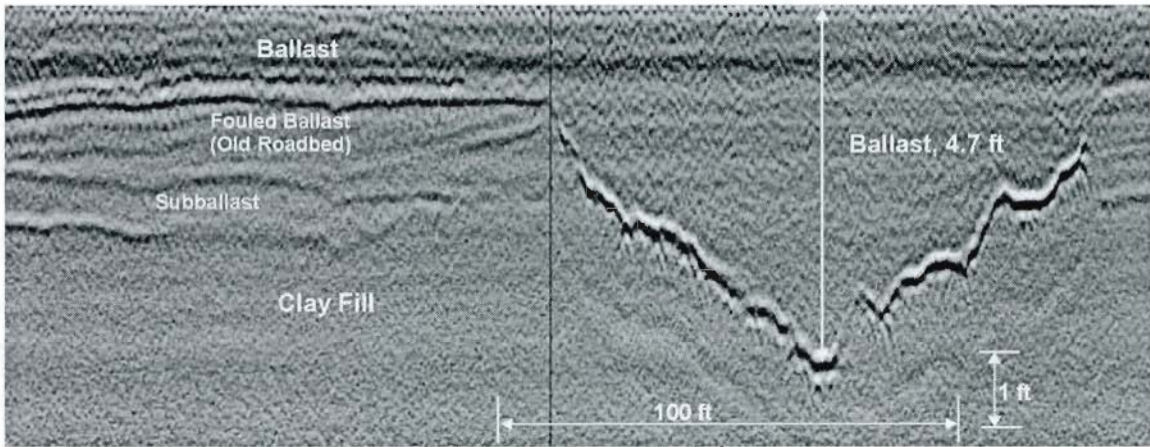


Figure 12. Deep V-Shaped Ballast Trench. Enhanced Closeup of Figure 11.

Figure 13 shows the variation in the ballast thickness at the two ends of the ties. The ballast layer becomes thin at the center of the image. The bottom of the ballast layer is above the bottom of the tie in the center of the lower image.

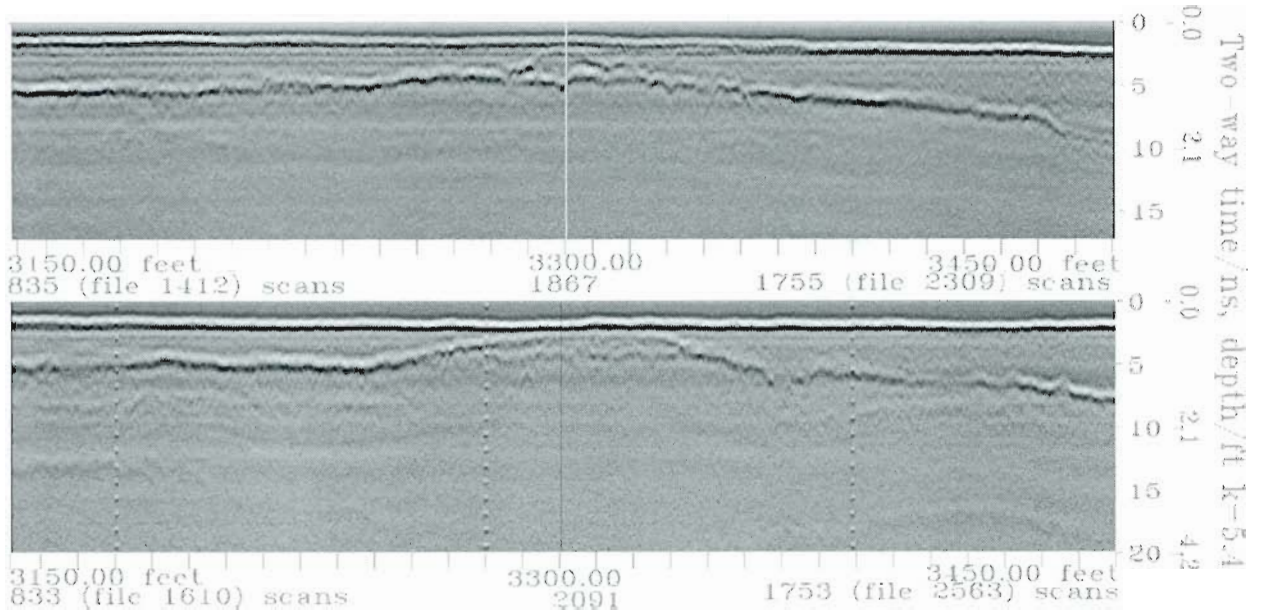


Figure 13. Reduced Ballast Layer Thickness.

4. Substructure Management Using GPR

4.1 Track Substructure Condition

Rough ballasted track is often caused by the poor condition of the track substructure (ballast, subballast, and subgrade) under repeated train loading. The author's experience has indicated that the majority of track substructure problems in the United States are associated with one or more of the following:

- Poor drainage of ballast, subballast, and subgrade, due primarily to:
 - Trapped water in ballast and subballast.
 - Layer depression in impermeable subgrade.
- Fouled ballast (causing rapid loss of surface after maintenance).
- Subgrade failure or deformation (from progressive shear or excessive plastic deformation).
- Subgrade attrition (due to lack of subballast).
- Subgrade excessive swelling and shrinking (expansive clays).
- Longitudinal variation of the condition and behavior of the track substructure.
- Transitions (causing loading and stiffness discontinuities).
- Unstable embankments.
- Inadequate amount of crib and shoulder ballast.
- Sinkholes (karst and mining regions).

Indicators of these substructure problems are manifest in terms of one or more of the following condition indicators of the ballast, subballast, and subgrade:

- Layer extent
- Water content
- Material Properties

The condition of the layers, in terms of thickness, lateral and longitudinal extent, deformation with time, attest to such problems as a subgrade failure and deformation, subgrade attrition, embankment instability, and sinkholes. The water content of the substructure indicates poor drainage and can also attest to poor subgrade. Information on material properties of the substructure can lead to conclusions on fouling condition, ballast, and soil type.

GPR has the ability to map most of these key condition indicators quickly with a continuous, top-of-rail survey. Table 2 presents the various substructure problems and the corresponding GPR information that can be measured for use in defining the extent and severity of the problems.

Table 2. Substructure Problems and Corresponding GPR Measurement.

Substructure Problem	GPR Information Based On
Poor drainage–trapped water	Intensity of GPR reflection and moisture contents of ballast/subballast layers.
Poor drainage – layer depression (bathtub)	Difference in depth to impermeable subgrade surface laterally across the track (i.e., lateral layer thickness variation).
Fouled ballast	GPR scattering pattern textures and permittivity of ballast layer.
Subgrade failure or deformation	Ratio of layer thickness and/or subgrade surface depth from middle to edge of tie. Also, moisture content and consistency of subgrade soil along with thickness of granular layer.
Subgrade attrition	Lack of subballast layer in combination with fine-grained fouling.
Subgrade excessive swelling and shrinking	Variation of clay subgrade surface. Also, moisture content and consistency of subgrade soil.
Longitudinal variation of the condition	Variation (roughness) of layer thickness, moisture content and composition.
Subballast moving laterally on thin clay surface	Change in layer thickness laterally across the track and presence of high moisture content layer.
Transitions	Rate of variation of the substructure layers along or across track of layer properties.
Unstable embankments	Typically, the present GPR system is not applicable due to shallow penetration (<2m). Some indication of shallow manifestation of layer deformation may be possible.
Inadequate crib and shoulder ballast	This can be performed without GPR by inspection of ballast surface (or by using the digital video acquired with the GPR).

4.2 Engineering Solutions

GPR can be used for investigation of specific chronic problem locations and provide information for diagnosing causes of problems at specific locations (e.g., ballast pockets, soft clay) and for development of engineering solutions. GPR is very complimentary to other investigation tools, such as cross-trenches and track stiffness measurements.

Figure 14 shows an example GPR survey result where GPR was used to investigate a chronic problem spot near a pair of road grade-crossings. Figure 14 shows a typical example of the subsurface conditions along three parallel longitudinal profiles at two road grade-crossings, as detected by GPR. Trapped water immediately adjacent to the crossings is apparent in the images. This water is trapped due to nonexistent lateral drainage out of the track. The low point on the relatively impervious subgrade surface is shown about 300 ft (100 m) to the left of the main road crossing. This information is useful for the design of an effective drainage system that will improve the subsurface condition and thereby solve a chronic maintenance problem. In this case, the GPR indicates that the trapped water can be drained longitudinally away from the crossings to a positive outlet point, as depicted on the bottom image in Figure 14.

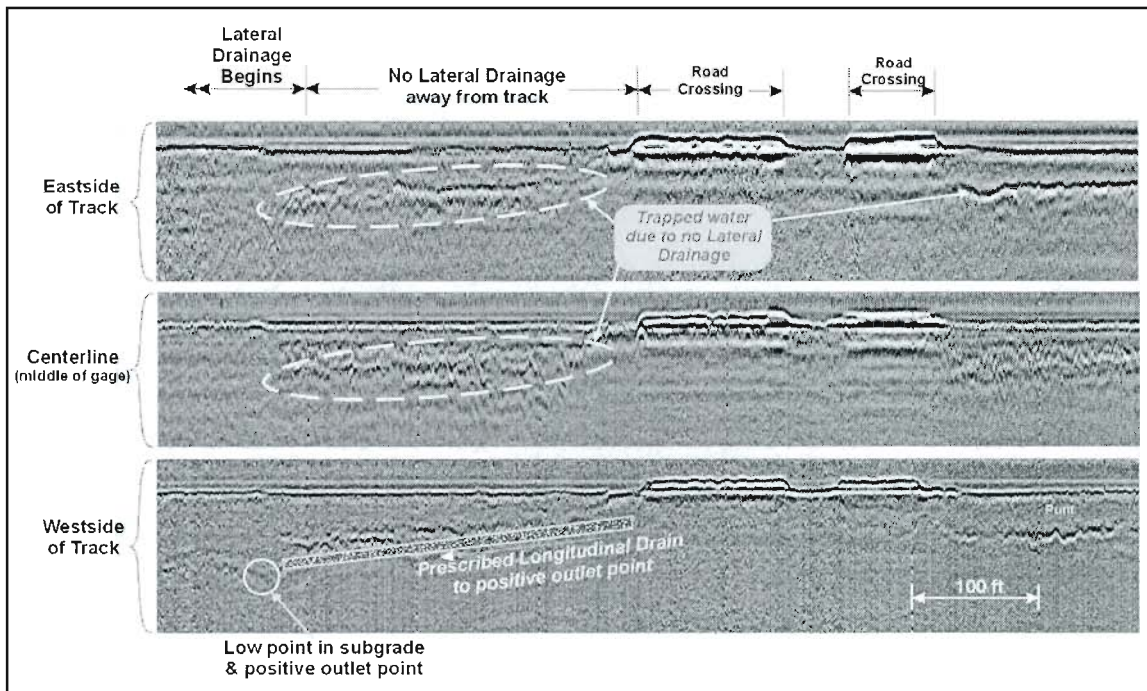


Figure 14. Three Parallel, Longitudinal GPR Images near Two Road-Crossings.

4.3 GPR Substructure Indices

The ability of GPR techniques to quickly collect quantitative information on track substructure will make it an invaluable tool for substructure maintenance management. GPR data is being used to develop indicators of substructure condition and performance for wide-area planning and allocation of resources.

General indices of track substructure condition can be based simply on the longitudinal and lateral variation of layers, water, and material properties. The longitudinal variation of substructure layers often results in track stiffness variations, which translates into rough track. Figure 15 presents an example of a general index based on longitudinal variation of layers.

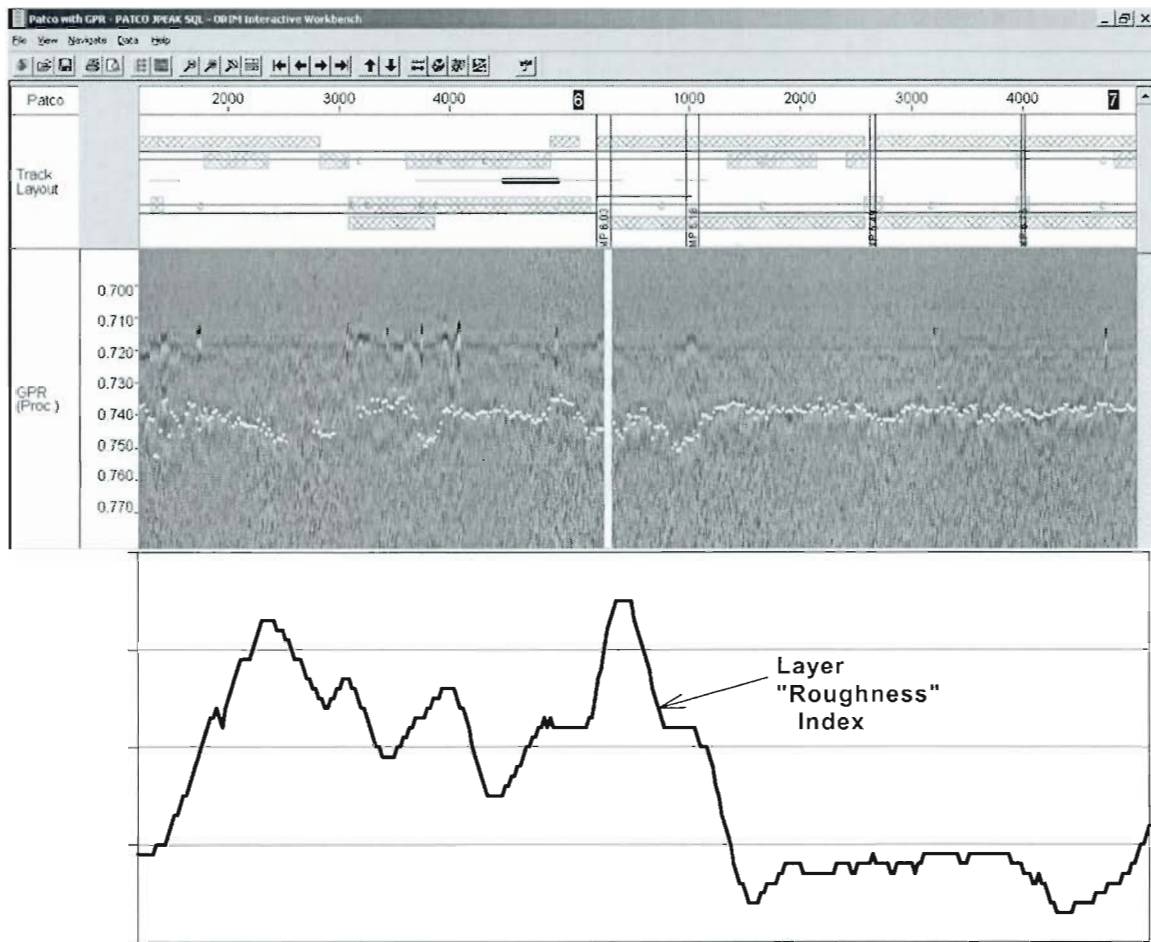


Figure 15. Example of Layer-Based Index of Longitudinal Layer Variation.

The GPR image in Figure 15 is an almost 2-mile (3.2-km) section of track. The distance to the bottom of the granular layer was manually digitized (shown as white points on the

GPR gray-scale image). These data were then converted to a continuous index representing layer variation. The Layer Roughness Index in Figure 15 is simply calculated as the moving standard deviation of the digitized bottom of the granular layer over an average moving-window. This index is shown on the bottom plot in Figure 15. The index is high on the left side of the plot where the subgrade surface elevation is variable. The index is low on the right side of the plot where the subgrade surface is relatively uniform.

A general index based on moisture content can be determined in the same manner. Eventually, once the modeling development work is further along, the variation in ballast layer fouling can be quantified in much the same way.

In Figure 16 an example of a more specific index, based on layer detection, is subgrade layer depth variation for ballast pockets. Figure 20 presents an explanation of the derivation of this index.

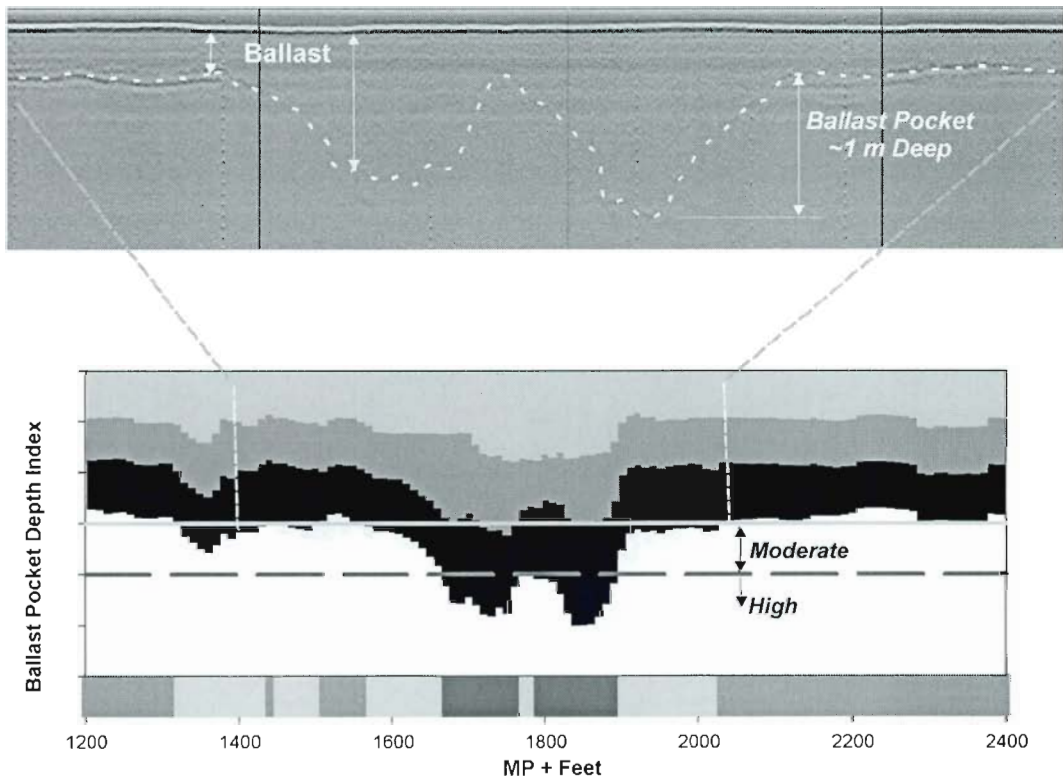


Figure 16. Subsurface Index Based on Ballast Pocket Condition.

Other specific indices can be developed based on the lateral variation of layers. For instance, the lateral variation of the subgrade surface across the track is indicative of poor drainage due to bathtub condition and subgrade failure or deformation. Figure 17 shows

a typical track cross-section with deforming subgrade. The arrow dimensions indicate the GPR antenna locations.

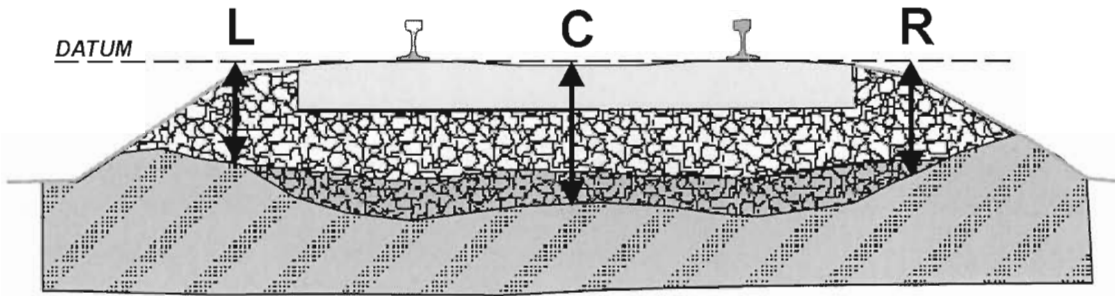


Figure 17 Typical Track Cross-Section with Subgrade Deformation.

Figure 18 shows actual longitudinal scans for approximately 1000 ft (300 m) of track. The distance from the datum to the top of the subgrade surface is indicated by the white arrows. Locations A and B are where the subgrade soil has deformed upwards, creating a situation similar to that shown in Figure 17.

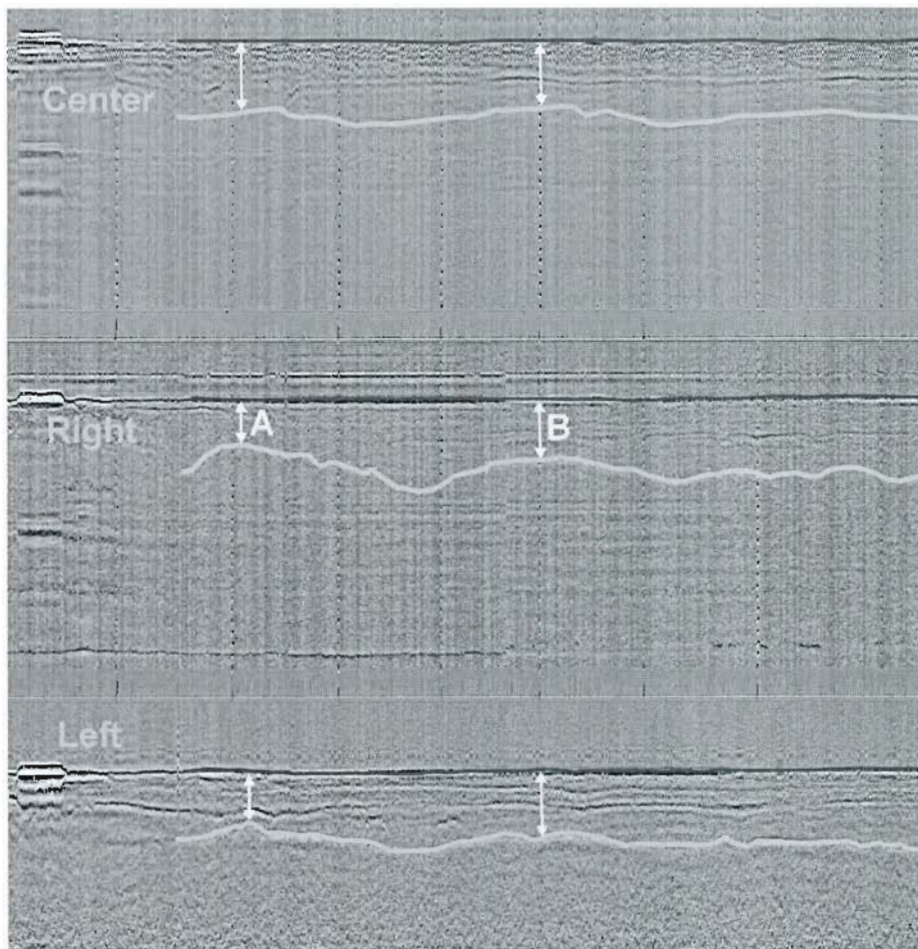


Figure 18. Three Parallel GPR Profiles Showing Subgrade Deformation.

One approach to developing meaningful substructure indices based on GPR requires matching the information from the GPR measurements to known characteristics of different types of substructure problems and then quantifying the GPR data to depict these characteristics. Figure 19 shows an example of this approach.

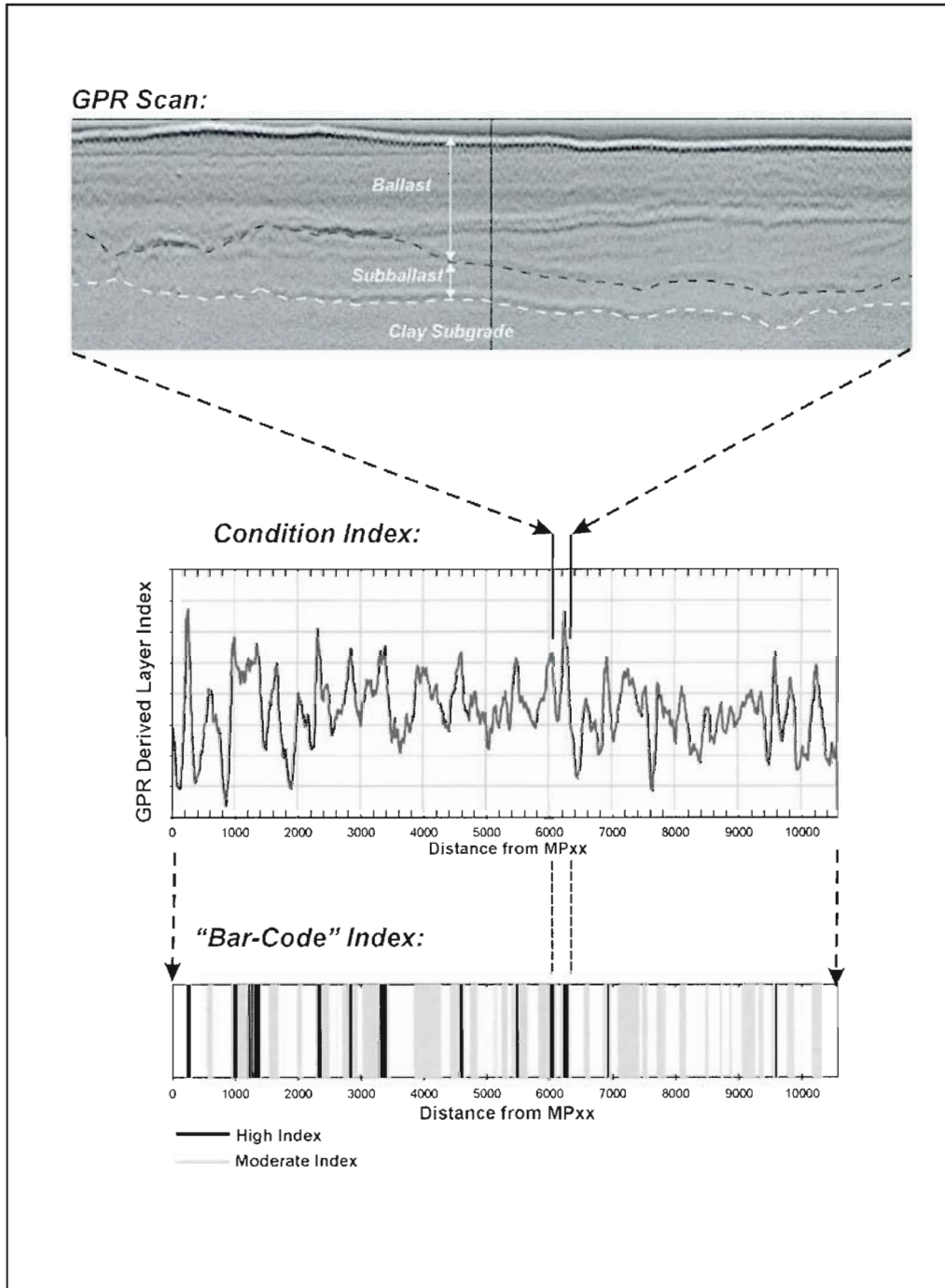


Figure 19. Subsurface Index Based on Thinning Subballast.

Figure 19 shows a GPR scan with varying thickness of ballast and subballast which, in this example, are an indication of a problem associated with lateral subballast spreading

on top of a clay subgrade (like Figure 9). The problem with the spreading subballast shown in Figure 19 was prevalent throughout a 2-mile section of track. GPR data were used to develop an index based on the relative thickness of the ballast and subballast layers. The GPR Derived Layer Index in the middle of Figure 19 is the highest when the subballast is thinnest and the ballast is correspondingly thickest. Conversely, the layer index is low when the subballast and ballast are near their nominal thickness of approximately 10 inches and 12 inches, respectively. The index is shown as a continuous trace on the middle plot in Figure 18 and as a bar-code image in the bottom plot. The bar-code image is derived by applying thresholds to the continuous layer index plot and is a convenient way to view the extent of the problem for a particular section of track. The dark bands in the bar-code image indicate areas where the subballast has thinned considerably, and similarly, the lighter banding indicates less thinning. Remedial work was planned based on the condition of the track as depicted by the bar-coded image.

Figure 20 depicts an example of a Ballast Pocket Index showing three parallel longitudinal GPR profiles indicating ballast pockets that have developed in an embankment under the influence of heavy axle load traffic. A ballast pocket is formed by the greater load-induced settlement of the subgrade surface directly under the track. As downward infiltrating water ponds in the depression that is created, the fill continues to soften and further deformation occurs. As the track settles due to the fill deformation, additional ballast is added and tamped under the ties to raise the track, resulting in a thick ballast pocket. A common, simple remedy to minimize the continued development of the ballast pocket is to drain the ballast pocket with a cross drain (essentially a ballast filled trench) excavated perpendicular to the track. GPR can delineate the bottom of the pockets to ensure that lateral drainage is put at the most effective location (i.e., at the lowest point of the ballast pocket).

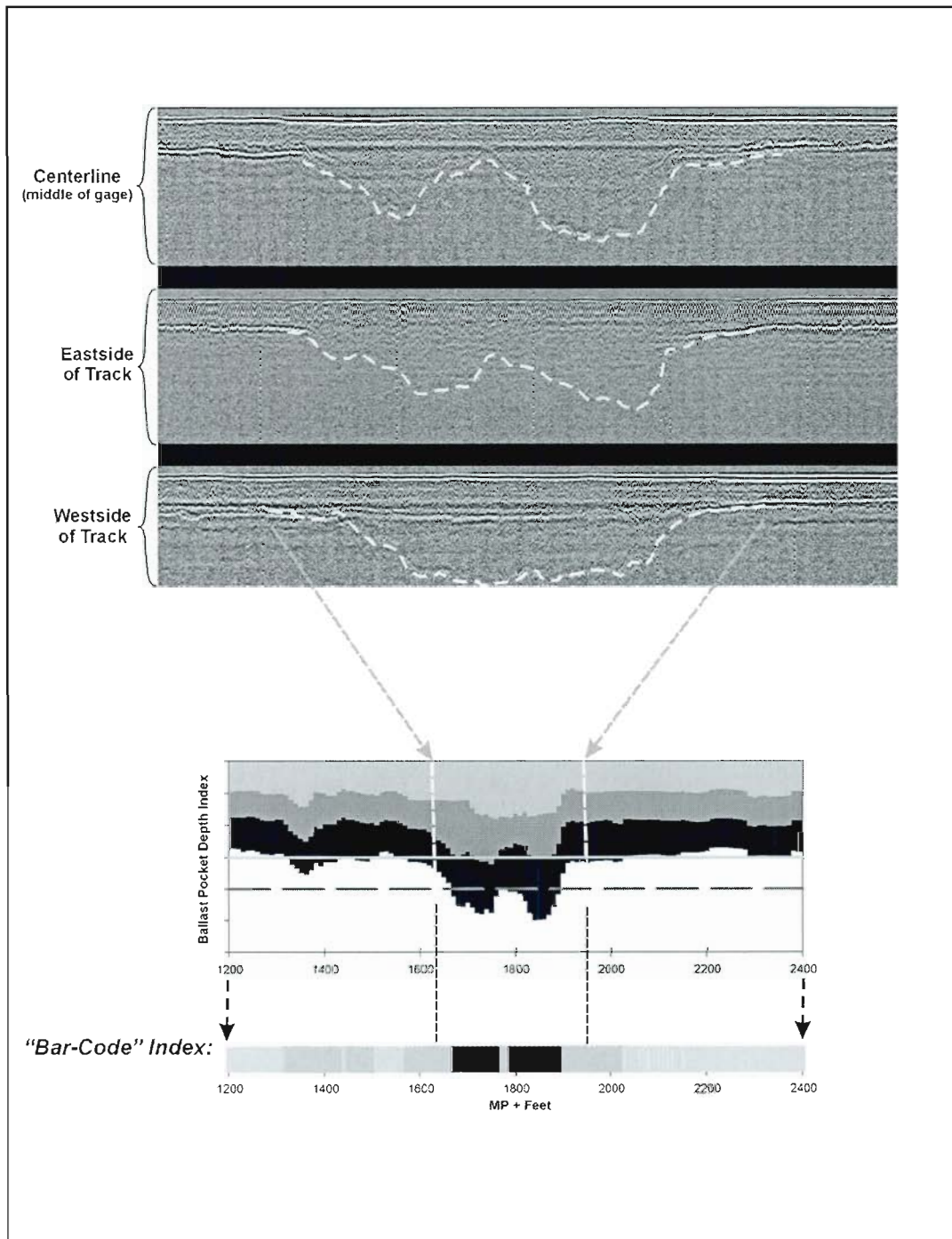


Figure 20. Subsurface Index Based on Depth of Ballast Pocket.

The banded image in the bottom of Figure 20 shows the depths of the subgrade surface added together to accentuate the areas with the ballast pocket condition. Thresholds applied to the Ballast Pocket Depth Index plot (middle of Figure 20) yields the color coded bar scale plot in Figure 20. The bar-code depicts the worst areas (deep ballast pockets) with dark banding and good areas with white.

To get the greatest benefit from the GPR, the radar information must be integrated with other information such as track geometry, track asset features, track stiffness measurements, maintenance records, and geo-environmental information. The geo-environmental information includes geology, terrain, depositional environment, clay type, (expansive versus non expansive, dispersive versus flocculated) drainage characteristics, and climate factors. This integration can result in a holistic Substructure Maintenance Management (SuMM) program through which correct decisions on maintenance and capital improvements can be made. The ORIM™ system has been used to help correlate the substructure characteristics derived from GPR with these other condition indicators. Geographical information systems tools and linearized, track-chart based tools, such as ORIM, allow the viewing of the relationship of GPR to track condition and features, as well as visualizing substructure effect on geometry trends and maintenance effort.

Another example of a BP Index condition index based on GPR information is depicted in the ORIM screen grab in Figure 21. Figure 21 shows an integrated image showing two parallel longitudinal GPR profiles along a 1.5 mile (2.4 km) section of heavy-tonnage freight mainline. The images, shown with the digitized layer boundaries, indicate ballast pockets that have developed in an embankment under the influence of heavy axle load traffic. A Ballast Pocket Index was derived to indicate where the ballast pocket condition has developed. Figure 21 shows the Ballast Pocket Index matched with the track layout and track geometry data, and review of Figure 21 reveals that many of the geometry rough spots are being driven by the ballast pocket problem. A common remedy to minimize the continued development of the ballast pocket is to drain the ballast pocket with a cross drain (essentially a ballast-filled trench) excavated perpendicular to the track. GPR can delineate the bottom of the pockets to ensure that lateral drainage is put at the most effective location (i.e., at the lowest point of the ballast pocket).

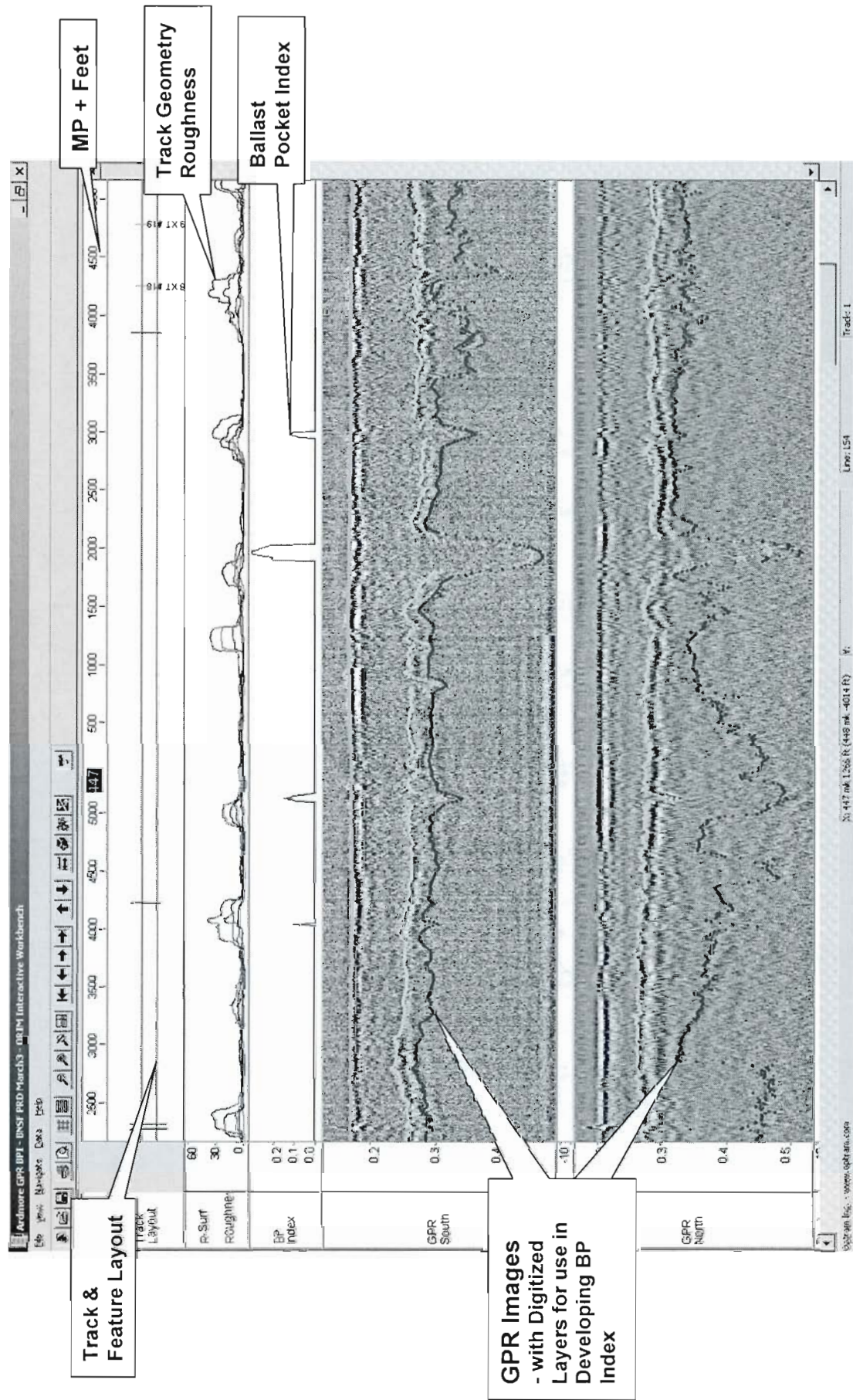


Figure 21. Integrated View of Track Layout, GPR Image, Ballast Pocket Index and Track Geometry Roughness.

These are a few examples of the track substructure indices currently being developed. These simple indices will be refined to include weighting factors, combined with other information, such as geometry and climate data. Indices can also be developed based on changes in layer and water over time.

In general, indices can be based on processed data without modeling. Indices can also be based on processed and modeled data. These indices would incorporate calculated water content and other parameters, and could be used to develop more accurate composite indices. Both of these types of indices possibilities are being considered.

Automated measurement and analysis techniques are being developed to produce quantitative indices of track substructure condition that will enable improved cost effectiveness of maintenance planning, increased safety, and reduced train service interruptions. These indices will be based on such things as layer contours, moisture content in the different substructure layers, amount of fouling material in the ballast, and rate-of-change of layer parameters.

5. Conclusions

The following are conclusions regarding the present development status and the use of GPR in the railroad environment. These conclusion have been determined as part of this project.

- 1) GPR rapidly and non-destructively provides continuous, top-of-rail measurements of substructure layer configuration and conditions.
- 2) Recording GPR data at three transverse locations across the track (both edges and centerline) provides useful profiles of the track substructure that show variations in conditions and depths along and across the track. Simultaneous recording at multiple transverse locations reduces track occupancy needs and provides precise correlation of the collected data streams.
- 3) GPR can provide quantified information on the thickness, as well as lateral and longitudinal extent of substructure layers, as an indication of track performance. GPR can obtain information on the adequacy of ballast and subballast thickness and the presence and extent of deforming subgrade, as well as the variability of substructure conditions longitudinally along the track.
- 4) GPR can determine the presence of trapped water in the substructure as high amplitude reflections, as well as moisture content of substructure layers through modeling.
- 5) GPR is capable of identifying locations and depths of subsurface drainage pipes, trenches, and utilities.
- 6) GPR is useful for site-specific engineering investigations to determine the root cause of specific problems and to develop engineering solutions at specific locations.
- 7) GPR can be used to develop substructure condition indices. The condition indices are needed to enable GPR to play a role in network-level planning and allocation of a railroad's maintenance and capital resources. For network-level planning, the GPR information can be correlated with other measurements, such as track geometry, features, track stiffness, and maintenance records to get complete understanding of the track performance.
- 8) It is imperative to use air-coupled GPR antennas in railroad applications to provide the necessary clearance to conduct railroad surveys at normal vehicle speeds. The air-coupled GPR antennas that were used in this project are designed to operate above the ground surface with a gap of at least 18 inches (0.5m).

6. Recommendations

The continued development of GPR for railroad application should focus on automation of data processing and interpretation to provide fast, automated investigation of track substructure conditions. The continued development of absolute calibration procedures will produce the ability to quantify the moisture content of various substructure layers. In addition, methods are currently being developed to determine the fouling condition of the ballast by extracting statistical scattering textures from the GPR images. Follow-on phases have been planned to include installing the radar on hi-rail TGMVs and use it to collect radar images routinely and to provide automating the calculation of the depths, densities, and moisture contents of the substructure layers.

Key components of follow-on work are:

- 1) Increasing the rate of radar data acquisition.
 - Requires the purchase of existing, off-the-shelf hardware components.
- 2) Completion of GPR data calibration and processing automation (including location).
 - Calibration requires using multiple antenna geometries, polarizations, and/or frequencies. This requires purchase of additional hardware, software development, and field testing.
 - Processing automation requires standardization of the data acquisition process and therefore requires gaining experience by collecting data in a wide variety of field conditions (both environmental and subsurface), thereby encountering unforeseen conditions or problems that affect the data collection process. Processing is presently automatic for the conditions already encountered.
- 3) Completion of automation of GPR data modeling to density and water content.
 - Requires the completion of the calibration and processing automation.
 - Once automatic processing and calibration are complete, then the GPR data can be automatically modeled with known and proven full waveform modeling techniques. These techniques are presently used in highway applications where the calibration automation is more straightforward.

- 4) Completion of GPR data textural analysis processing to fouling index automation.
 - Requires further correlation of known textural analysis techniques on the data with ballast fouling condition obtained from field investigations.
- 5) Automate QA/QC processing.
 - Requires standardization and automation of current manual process.
- 6) Improve data management and archival storage systems.
 - Requires applying known, robust information management techniques.
- 7) Automate layer detection and definition.
 - The existing GRORADAR software used in this project has this capability and must be fully automated.
- 8) Improve accuracy and reliability of position location system.
 - Requires the purchase and integration of inertial guidance instrumentation with existing hardware components.

7. References

Hyslip, J.P., Smith, S.S., Olhoeft, G.R., and Selig, E.T. (2003). "Assessment of Railway Track Substructure Conditions Using Ground Penetrating Radar." Proceedings of the 2003 Annual Conference of the American Railway Engineering and Maintenance-of-Way Association (AREMA), Chicago, October.

Hyslip, J.P. and McCarthy, B.M. (2000). "Substructure Investigation and Remediation for High Tonnage Freight Line." Proceedings of the 2003 Annual Conference of the American Railway Engineering and Maintenance-of-Way Association (AREMA), Dallas, TX, September.

Olhoeft, G.R., (2000). "Maximizing the Information Return from Ground Penetrating Radar." Journal of Applied Geophysics, v. 43/2-4, p. 175-187.

Olhoeft, G.R. (1998). "GRORADAR™: Acquisition, Processing, Modeling, and Display of Ground Penetrating Radar Data: Ver. 4.0." Software distributed on CD-ROM at GPR98, 7th International Conference On Ground Penetrating Radar, University of Kansas, Lawrence, KS, May.

Olhoeft, G.R. and Selig, E.T. (2002). "Ground Penetrating Radar Evaluation of Railroad Track Substructure Conditions." Proceedings of GPR2002, the 9th International Conference on Ground Penetrating Radar, Santa Barbara, CA, S.K. Koppenjan and H. Lee, eds., Proceedings of SPIE vol. 4758, pp. 48-53, April.

Olhoeft, G.R., Smith III, S., Hyslip, J.P. and Selig, E.T. (2004). "GPR in Railroad Investigations." Proceedings of GPR2004, the 10th International Conference On Ground Penetrating Radar, 21-24, Delft, The Netherlands, p.635-638, June.

Olhoeft, G.R. and Smith III, S.S. (2000). "Automated Processing and Modeling of GPR Data for Pavement Thickness and Properties." Proceedings of GPR2000, the 8th International Conference on Ground Penetrating Radar, Gold Coast, Australia, D.A. Noon, G.F. Stickley, and D. Longstaff, eds., SPIE vol. 4084, p.188-193, May.

Selig, E.T. (1997). "Substructure Maintenance Management". Proceedings 6th International Heavy Haul Railway Conference, International Heavy Haul Association, Cape Town, South Africa, April.

Selig, E.T. and Waters, J.M. (1994). Track Geotechnology and Substructure Management. Thomas Telford Ltd., London.

Smith III, S.S. (1995). "Detecting Pavement Deterioration with Subsurface Interface Radar." Sensors, vol.12, no. 9, p.29-40.

8. Bibliography

For more information, reference can be made to the following publications, most of which were written during the project.

FRA Research Results, RR02-03 (2002). "Ground Penetrating Radar for Railway Track Substructure Investigation". U.S. Department of Transportation, Federal Railroad Administration, September 2002.

Selig, E.T., Hyslip, J.P., Olhoeft, G.R., and Smith, S. (2004). "Ground Penetrating Radar for Track Substructure Evaluation, Phase 1-3," Report to BNSF Railroad and Federal Railroad Administration. March 1, 2004.

Selig, E.T., Hyslip, J.P., Olhoeft, G.R., and Smith, S. (2003). "Ground Penetrating Radar for Track Substructure Condition Assessment". *Proceedings of Implementation of Heavy Haul Technology for Network Efficiency*, Dallas, TX, May, p. 6.27-6.33.

Smith, S. (2005). "As-Built Survey of Slab Track Using Ground Penetrating Radar at Transportation Technology Center, Pueblo, CO". Federal Railroad Administration, Contract Number DTFR-53-02-P-00263.

Sussmann, T.R., Hyslip, J.P., and Selig, E.T. (2003). "Railway Tracks Condition Indicators from Ground Penetrating Radar". *NDT&E International*, 36, 157-167.

Sussmann, T.R., O'Hara, K.R., and Selig, E.T. (2002). "Development of Material Properties for Railway Application of Ground Penetrating Radar," *Proceedings of GPR2002, the 9th International Conference on Ground Penetrating Radar*, Santa Barbara, CA, pp.42-47.

Sussmann, T.R., O'Hara, K.R., Kutrubes, D., Heyns, F.J., and Selig, E.T. (2001). "Development of Ground Penetrating Radar For Railway Infrastructure Condition Detection," *Proceedings of the 2001 Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP)*, Denver, CO, March.

Sussmann, T.R., Heyns, F.J., and Selig, E.T. (1999). "Characterization of Track Substructure Performance". *Recent Advances in the Characterization of Pavement Geomaterials*, Geotechnical Special Publication No. 89, ASCE.

9. Acronyms

DMI	distance measuring instrument
DOQ	digital orthophoto quadrangles
GPR	Ground Penetrating Radar
GPS	global positioning system
ORIM	Optram, Inc.'s Right-of-way Infrastructure Management
SuMM	Substructure Maintenance Management
TGMV	track geometry measurement vehicle
USGS	United States Geological Survey
WAAS DGPS	wide area augmentation system, differential global positioning system