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# Ground Penetrating Radar Evaluation and Implementation

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## Summary

Transportation Technology Center, Inc. (TTCI) has been working with the Federal Railroad Administration (FRA) and John A. Volpe National Transportation Systems Center (Volpe Center) on a project to determine the state-of-the-art of ground penetrating radar (GPR) technology for track substructure inspection. Phase 1 of the project was an evaluation of ballast inspection techniques performed at the Facility for Accelerated Service Testing (FAST) High Tonnage Loop (HTL) at the Transportation Technology Center near Pueblo, Colo. Six commercial GPR systems, labeled as systems 1–6, participated in the evaluation with required outputs of ballast fouling analysis, layer depth interpretation, and moisture content sensitivity. The outputs of the systems were compared to each other and to known conditions with the following results:

- Three proprietary methods (signal scattering, dielectric dispersion, and propagation analysis) were used to determine ballast fouling. The signal scattering (system 1 using 2 GHz antennas) and dielectric dispersion methods (systems 2–5 using 400 MHz antennas) produced generally similar results, reporting low percentages (6 percent or less) of the track as being highly fouled. However, the system 6 signal propagation method (using a 900 MHz antenna) indicated that 30 percent of the track was highly fouled and 44 percent was moderately fouled. The results of this evaluation indicated that the scattering and dielectric dispersion methods produced fouling results that were in agreement with known conditions. However, the propagation analysis did not produce results that were consistent with known conditions, because it significantly overstated the fouling condition.
- All GPR systems produced similar ballast layer depth interpretations, although variances of 6 to 9 inches in the reported primary layer thickness values were fairly common. The variances were due primarily to the assumed dielectric constant of the ballast used by the different systems. The evaluation results indicated that all systems were capable of producing reasonably accurate ballast layer thickness data.
- GPR signals are highly sensitive to the presence of moisture. Results of the moisture content sensitivity comparison showed that all systems were able to detect an increase in moisture as water was added to the ballast and changes in the moisture content as the water dispersed through the layer.

The evaluation approach was primarily a performance comparison of the ballast fouling and layer depth outputs of the different systems for FAST HTL Sections 25, 8, 7, 3, and 33. Systems participating in the evaluation included:

- 400 MHz, 900 MHz, 1 GHz, and 2 GHz time domain pulsed antennas from two different manufacturers.
- A frequency-domain antenna from a third manufacturer that transmits a sine wave of constant amplitude and stepwise frequency from 150 MHz to 2.5 GHz.



**INTRODUCTION**

The following *Technology Digest* presents the results of an evaluation of GPR technologies performed by Transportation Technology Center, Inc. at the Transportation Technology Center’s FAST HTL. The work was carried out as part of Federal Railroad Administration (FRA) Task Order 248, GPR Evaluation and Implementation, with additional funding provided by the Association of American Railroads’ Improved Track Substructure Strategic Research Initiative.

The objective of FRA Task Order 248 is to enhance the use of GPR as a railroad track substructure inspection technique with an objective evaluation of commercial GPR systems at the FAST HTL to establish the state-of-the-art for track inspection and development of guidelines for GPR implementation for track inspection.

A number of GPR systems participated in the evaluation, representing most of the current North American service providers. The focus of the evaluation was ballast condition assessment, specifically ballast fouling, layer depth, and moisture content.

**GPR Background**

GPR is a nondestructive geophysical inspection technique that is widely used to identify and visualize subsurface structural and material conditions. The basic technique is well documented in GPR literature and involves the transmission of radio frequency electromagnetic energy into the ground or other physical medium by a transmitting antenna. Some portion of the transmitted energy is reflected by contrasts in material dielectric permittivity and electrical conductivity that occur at material interfaces such as changes in soil layers, ground water surfaces, or manmade objects.

The amplitude and return time of signal reflections are captured by a receiver antenna as the transmitted wave penetrates the medium and as the antennas move along the surface. The recorded data is processed to produce an image (radargram) of the subsurface profile (see Figure 1) where the wave reflections are shown as functions of the wave travel time. The wave travel time is converted to penetration depth based on the wave velocity.

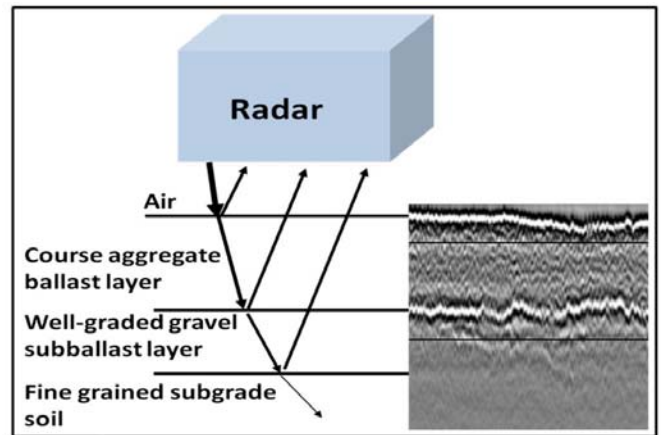
Wave velocity (V) is determined by the dielectric permittivity of the material it is passing through and is calculated using Equation 1:<sup>1</sup>

$$V = c/\epsilon^{0.5} \tag{1}$$

where c is the speed of light (11.8 inches/nanosecond) and ε is the material dielectric constant (i.e., the ratio of a material dielectric permittivity to the permittivity of air, which is 1).

Dielectric constants for geological materials vary from less than 10 for dry materials to 10–30 for moist materials. The dielectric constant of water is 80; therefore, a change in moisture content at an interface can have a significant effect on the wave velocity and will produce a strong signal reflection.

Attenuation of the transmitted wave is governed by material conductivity. Increasing conductivity increases the attenuation, thereby reducing the wave penetration depth.



**Figure 1. Example of Processed GPR Image Showing Boundaries in the Track Substructure**

Assessment of the track subsurface condition requires interpretation of the processed image. Commercial track inspection systems have developed proprietary software to interpret the GPR signals for specific output parameters, including:

- Ballast layer thicknesses
- Degree of ballast fouling
- Moisture
- Subgrade deformation

In addition to the software results, the final output usually relies on some amount of operator involvement to interpret the data.

**TRACK APPLICATION OF GPR**

GPR inspection of the track substructure is usually focused on the ballast layer condition in terms of fouling and layer thickness and possibly moisture retention. Ballast assessment can be a challenge for GPR, because the material is not particularly homogenous and may have variable dielectric and conductive material properties. Moisture content within the layer can also vary, which can affect interpretation of the GPR data.

**Layer Thickness**

Layer thickness (D) is calculated from the two way travel time of the wave (t) using Equation 2:<sup>1</sup>

$$D = ct/2\epsilon^{0.5} \tag{2}$$

It is clear that the precision of the thickness calculation is dependent on the dielectric constant ε value that is used. In Figure 2, the calculated layer thickness is plotted against a range of ballast material dielectric constants for wave travel times of 5, 15, and 30 nanoseconds. The increasing ε values in Figure 2 represent increased fouling and/or moisture in the ballast.

Figure 2 indicates that the longer the time travel, i.e., increasing layer thickness, the more sensitive the thickness calculation is to the assumed  $\epsilon$  value. For travel times of 15 nanoseconds or less, the use of  $\epsilon$  values between 4 and 7 that may be considered to be typical of many ballast conditions should produce reasonably accurate and consistent layer thickness data. However, for deep ballast layers, such as ballast pockets or locations where the track grade has been raised using ballast to avoid flood water, the assumed  $\epsilon$  becomes more critical. Issues surrounding GPR determination of ballast thickness and fouling are briefly discussed in the following two subsections.

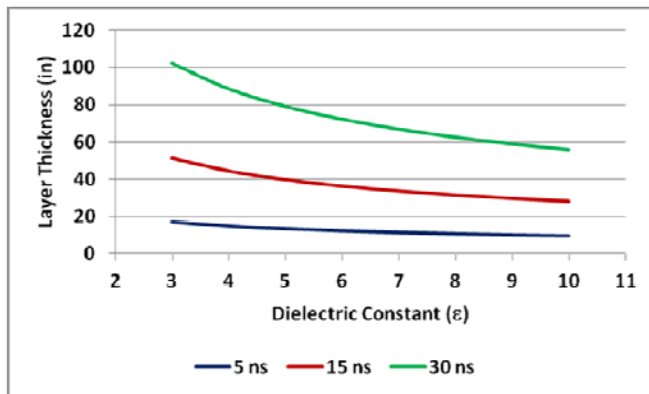


Figure 2. Sensitivity of the Thickness Calculation to Travel Time and Ballast Material Dielectric Constants

### Ballast Fouling Analysis

Given the amount of resources that railroads devote to ballast maintenance, the detrimental effect that fouled ballast can have on overall track performance, and the inability to effectively measure fouling by other methods, assessment of the fouling condition is arguably the most important application of GPR for track inspection, but it is also the most difficult.

The nonhomogenous nature of the ballast layer and the top-to-bottom fouling variation makes the layer interface reflection of the GPR signal an impractical method for fouling determination. Methods that have been developed to quantify ballast fouling include signal scattering analysis, dielectric dispersion analysis, and signal propagation analysis. These methods were used in the FAST HTL evaluation and are briefly described as follows:

- Signal scattering. Scattering occurs when the transmitted wavelength is roughly the same as the perimeters of interparticle air voids in clean ballast. Scattering decreases as the ballast becomes fouled. Research indicates the wavelength of a 2 GHz signal is adequate to sense changes in typical ballast gradations.<sup>2</sup>
- Dielectric dispersion. The recorded time domain data is converted to the frequency-domain and a frequency spectrum is produced. Clean ballast has less dielectric dispersion, resulting in more area under the frequency spectrum than fouled ballast. The dispersion method has been developed for the 400 MHz signals.

- Signal propagation analysis. Propagation analysis relies on the effect of changing dielectric permittivity in the ballast. Fouled ballast has higher permittivity and slower velocity.

### FAST HTL Evaluation

Table 1 describes the systems participating in the evaluation and producing final results. The mix of antenna types, antenna manufacturers, engineering teams, and geophysics providers included:

- 400 MHz, 900 MHz, 1 GHz and 2 GHz time domain pulsed antennas from two different manufacturers.
- A stepped-frequency continuous-wave (SFCW) frequency-domain antenna from a third manufacturer with 31 transmitter-receiver dipoles spaced about 4 inches apart. The SFCW system transmits a sine wave of constant amplitude and stepwise frequency variation.
- Two engineering teams supplied hi-rail vehicles, antenna mounting hardware, and ancillary equipment such as wheel distance measuring encoders, video recorders, and GPS capability.
- Three geophysics groups interpreted, analyzed, and reported the data.

Table 1. GPR Systems Description

System	Antenna Description	Fouling Analysis
1	Time domain pulsed radar, 400 MHz used for layer depth mapping and 2 GHz used for ballast fouling	Scattering
2	Time domain pulsed radar, 1 GHz	Dielectric dispersion
3	Time domain pulsed radar, 400 MHz antenna manufacturer 1	Dielectric dispersion
4	Time domain pulsed radar, 400 MHz antenna manufacturer 2	Dielectric dispersion
5	SFCW radar manufacturer 3, 150 MHz to 2.5 GHz frequency range, air coupled	Dielectric dispersion
6	Time domain pulsed radar, 400-MHz and 900 MHz antenna manufacturer 2, ground coupled	Propagation analysis

The evaluation approach was primarily a head-to-head comparison of the ballast fouling and layer depth outputs of the different systems for the relevant FAST HTL Sections 25, 8, 7, 3, and 33.

Subjective descriptions of relative ballast conditions for the purposes of this study were set as 4, clean; 3, moderately clean; 2, moderately fouled; and 1, highly fouled. These categories represent conditions in the top 16 to 20 inches of the ballast measured from the top of tie, in ballast intended to be composed of crushed rock. There was no attempt in this study to relate the ballast conditions found by GPR to their ability to economically maintain track geometry under train loads.

Results of the ballast fouling comparison are summarized as follows:

- System 2 track center fouling data was not submitted due to noise issues.
- Systems 1, 3, 4, and 5 all showed 6 percent or less of the track center being highly fouled. Differences in these systems were found in the interpretation of clean, moderately clean, and moderately fouled conditions.
  - System 1 showed 67 percent of the track as clean, 20 percent as moderately clean, and 13 percent as fouled.
  - Systems 3 and 4 both showed about 90 percent of the track as clean, 7–11 percent as moderately clean, and less than 2 percent as fouled.
  - System 5 showed 34 percent of the track as clean, 49 percent as moderately clean, and 17 percent as fouled.
- System 6 results were substantially different than the other systems. System 6 interpreted the HTL ballast condition as being primarily fouled as opposed to the primarily clean or moderately clean interpretation of the other systems.

Gradation analysis of ballast samples taken in Section 25 was in general agreement with the fouling data from all systems except system 6. All samples taken at four locations within the section produced gradation curves conforming to AREMA size numbers 4 and 24 ballast,<sup>3</sup> indicating the ballast at the locations was clean.

All systems, with two notable discrepancies, produced similar ballast layer thickness interpretations.

- The first discrepancy was at the end of Section 03 where systems 1, 5, and 6 indicated an increase or no change in the track center and outside shoulder ballast thickness, whereas systems 2, 3, and 4 showed a substantial decrease in thickness. Field checks of the ballast depths did not support the reported reduced thickness.
- The second discrepancy occurred in Section 33 where systems 1, 2, 3, and 4 all indicated a 6–9-inch decrease in thickness, which was not seen by systems 5 and 6.

A moisture sensitivity test performed in Section 33 confirmed the well established ability for GPR to sense relative changes in moisture. A survey was taken before and after water was artificially added to the track over a distance of about 50 feet using a fire truck. All systems were able to

distinguish the increase in moisture added to the track and were also able to determine that the water was draining by a change in the moisture profile depth.

**CONCLUSIONS**

A comparison of ballast fouling and layer thickness interpretation is summarized in Figure 3. In general, the system using signal propagation analysis produced significantly different ballast fouling results compared to the scattering and dielectric dispersion fouling analysis methods. The ballast layer thickness and moisture results were less varied between systems; however, discrepancies in layer thickness results were noted.

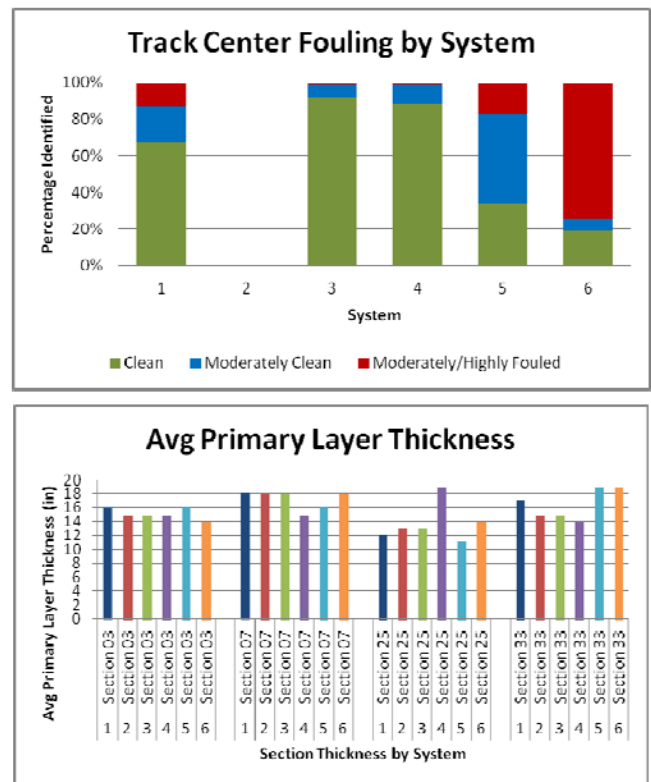


Figure 3. GPR System Output Comparison

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