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New Ground Penetrating Radar Analysis Techniques for Ballast Assessment

Imad L. Al-Qadi, Roger Roberts, Erol Tutumluer,
Zhen Leng, and Xie Wei, UIUC Railroad Engineering Program

Summary

A field survey using ground penetrating radar (GPR) equipped with multiple sets of 2 gigahertz air-horn antennae was conducted at the Facility for Accelerated Service Testing (FAST), Transportation Technology Center (TTC), Pueblo, Colorado. Compared to ground truth excavation and ballast gradation analysis results, GPR can be an effective technique to assess railroad track ballast substructure condition.

This *Technology Digest* describes appropriate techniques to remove interference and reduce the strong clutter to obtain clear GPR data of the railroad substructure. A time-frequency method — short-time Fourier transform — is also introduced to extract ballast fouling condition at given depths.

GPR can overcome many of the limitations of traditional ballast assessment methods. It can provide an efficient, effective, and continuous way to assess railroad track substructure condition, especially the ballast layer. However, GPR systems face challenges during field surveys including high radio frequency interference from railroad communication systems and strong reflections from the rails.

Field trials were conducted using the High Tonnage Loop at FAST. GPR was used to determine the depths and characteristics of ballast layers in a heavy haul track. The results were verified by excavation of the track cross section in the test locations. The cross trenching analysis determined the fouling index of the ballast in 6-inch depth intervals. From this comparison, it was determined that GPR can distinguish ballast/sub-ballast interfaces, can determine ballast layer depths, and can determine the relative amount of fouling in ballast. GPR can also compare and rank various locations for ballast condition.

The survey was conducted by the University of Illinois–Urbana Railroad Engineering Program and Geophysical Survey Systems, Inc. under sponsorship by the Federal Railroad Administration and the Association of American Railroads Strategic Research Initiative on Technology Scanning.

INTRODUCTION

Railroad ballast is one the most critical components of the railroad track substructure. It supports and distributes rail vehicle loads, prevents track deformation, and facilitates the drainage of moisture away from the track structure. Over time, ballast can be fouled by the breakdown of ballast aggregate and/or the infiltration of fines, which undermine the functionality of ballast and adversely affect the structural capacity of track.

The traditional methods used to assess ballast condition are visual inspection and drilling and digging at discrete intervals along the track. However, visual inspection may not reveal internal flaws in the ballast/subballast layer, and drilling is time consuming and does not provide continuous information about track subsurface condition. Considering that significant subsurface variation may occur within short distances, a continuous and rapid measurement technique is needed. GPR is a method that can overcome many limitations associated with traditional inspection methods. However, the GPR system faces some challenges during field surveys such as high radio frequency (RF) interference from railroad communication and strong reflections from rails. This digest reports appropriate techniques to remove the interference and reduce the strong clutter from the rails to obtain clear GPR data of railroad substructure. In addition, a time-frequency method, short-time Fourier transform (STFT), is introduced as a tool that can be used to maximize the capabilities of GPR.

THEORETICAL BACKGROUND

Radar is used to obtain specific information about an object's location and size by measuring the characteristics of the electromagnetic (EM) fields scattered around the object. As the amount of information transmitted in a unit of time is proportional to the radar's bandwidth, expanding radar's frequency band can increase the system's capacity. The GPR method, which uses an ultra-wideband (UWB) signal, is based on sending EM waves into the ground using a transmitting antenna. A receiver antenna collects the reflected signal from the interfaces between the materials and scattering from heterogeneities having different EM properties within the materials.

To avoid antenna damage from the rough ballast surface and to improve data collection efficiency for ballast condition surveys, air-coupled horn antennae are preferred over ground-coupled antennae. Figure 1 shows the various paths of the received signal from ballast. The direct part (S1) represents the energy radiated directly from the transmitter to the receiver. The second part (S2) is the signal reflected from the surface of the ballast. The third part (S3) is the portion of the energy received from local scatterers in the ballast. If there is a clearly defined interface between the clean and fouled ballast or subballast, the fourth part of the signal (S4) will be received from the interface reflection. Using a low-frequency antenna, the signal S3 is weak because air voids are much smaller than the incident wavelength. For the same reason, the transition area between clean and fouled ballast may not be detected with a low-frequency antenna. Using a high-frequency antenna, such as 2 gigahertz (GHz), strong signals S3 and S4 can be used to extract ballast fouling information.

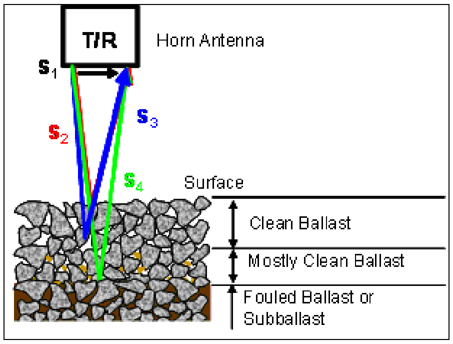


Figure 1. Paths of Electromagnetic Waves

DATA COLLECTION

GPR surveys were conducted at the Facility for Accelerated Service Testing, Transportation Technology Center, Pueblo, Colorado. Rapid field data collection was accomplished by suspending a 2 GHz air-coupled antennae above the rail on a high-rail vehicle (Figure 2). Data was collected at a speed of 12.4 mph. To reduce the influence of rails, the antennae should be at least 24 inches from the rails (6 inches from the edges of the ties). Multi-channel GPR equipment was used to identify railroad substructure characteristics. The antennae were oriented so that more energy was radiated in the direction parallel to the rails and less energy toward the sides. This effectively decreased the influence of rail reflections. Multiple GSSI SIR-20 antennae (developed by Geophysical Survey Systems, Inc.) were used for data collection.

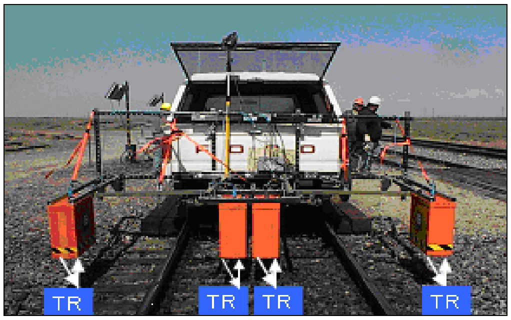


Figure 2. GPR Equipment Using Multiple 2 GHz Antennae

GPR Data Processing

Because of the UWB width of GPR receivers, GPR signals are susceptible to variable noise sources, such as cellular phone towers, cellular phones, radios, and any other EM devices emitting in the GPR bandwidth. To avoid these noises, GPR data is initially filtered in the frequency domain and then transferred back to the time domain. There are four basic types of filters: high pass, low pass, bandwidth, and notch filters. High-pass filters only allow the signals with frequencies higher than a preset frequency to pass; low-pass filters only allow the signals with frequencies lower than a certain cutoff frequency to pass; bandwidth filters allow the signals within a preset frequency range to pass; and notch filters block the signals within a certain frequency range.

Short-Time Fourier Transform

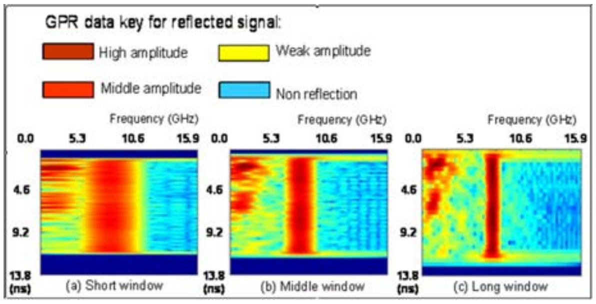
STFT is a time-frequency technique that may effectively track the frequency spectrum change with time. The information of frequency spectrum change with time is obtained using Equation 1:

$$STFT_x(t,\Omega) = \int_{-\infty}^{\infty} x(\tau)w(\tau - t)e^{-j\Omega\tau}d\tau \qquad (1)$$

where x is the reflected signal, t is the time variable, Ω is the radial frequency variable, and w is the window sequence.

Before implementing the STFT, horizontal band-pass filters are used to remove the low-frequency clutter from rail and some of the noise. Then, a time-zero adjustment is used to shift the data and locate the surface pulse at time zero. Since the surface reflection pulse has high energy that can overwhelm the frequency spectrum analysis of the following weak signal scattered from ballast, it is set to zero before implementing the STFT to avoid its influence. In the STFT, the Hamming Window Sequence is used to extract the local frequency spectrum. The length of window is important because it affects the relative resolutions in time and frequency domains. In addition, considering that the 2-GHz GPR data from ballast is a random signal, the horizontal low-pass filter is used to smooth the variation in the longitudinal direction, and the filter length is chosen to be the tie interval.

Figure 3 shows a STFT example. In each figure, the x-axis represents the frequency and the y-axis represents the two-way travel time. The energy range from high to low is represented by the hot to cold colors, respectively. The left bright area represents the energy of the GPR signal, and the right bright band with the central frequency at approximately 7.5 GHz represents the energy from external RF interference. It appears that the STFT technique is a powerful method to separate the energy of the external noise from valuable information, if the noise frequency band is far from the dominant frequency of GPR signals and the noise source is synchronous with the transmit rate of the GPR system. The blue areas at the bottom of the figures are generated by the time-zero offset, and the blue areas at the top of the figures are generated by setting the surface pulse to zero. Comparing the results with various window lengths, we can observe that frequency resolution is better with a long window; while a short window can improve time resolution. The window length for Figure 3b balances time and frequency resolutions, so it will be used in the following data processing.



(a) Short window (b) Middle window (c) Long window

Figure 3. STFT Results Using Various Window Lengths for the Scan with Contaminating Radio Frequency Noise

Radio-Frequency Interference Removal

One of the challenges an air-coupled GPR system faces during field surveys is the high RF noise environment from railroad communications. Usually a band-pass filter is used to clean the RF noise if the frequencies of external signals are far from the dominant frequency of the GPR antennae. However, if the frequency bands of some RF noise are located in the UWB frequency band of the GPR signal, the band-pass filter may not be effective.

Considering that communication signals are usually narrow band, a database of RF frequency bands can be built. Then notch filters can be used to remove the RF noise. Figure 4a shows the STFT results of GPR data with radio frequency noise. Figure 4b shows the result for the same GPR data after implementing the notch filter. Comparing the two figures, the notch filter is shown to be effective in reducing the influence of RF interference. These results also demonstrate the immunity of UWB radar to synchronous external narrowband EM radiation effects and noise. After removing the RF noise, the filtered data can be used to predict the substructure condition using the STFT technique.

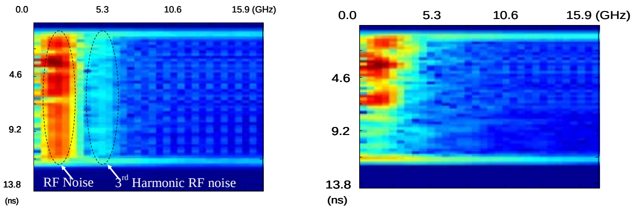


Figure 4. STFT Results with RF Noise Using 2GHz Antennae

Analysis of Field Results

To validate the use of GPR for ballast condition assessment, ground-truth data was collected at TTC during the summer of 2007. Samples were collected at 6-inch depth intervals. Moisture content and aggregate gradation analyses were conducted on the collected samples. The fouling index, F_I, was used to measure ballast fouling condition:

$$F_I = P_4 + P_{200} \qquad (2)$$

where P_4 is the weight percentage of particles passing through a No.4 (.187 in) sieve, and P_{200} is the percentage of fine particles passing through a No. 200 (0.003 in) sieve. A value less that 10 percent is considered clean ballast. If the percentage is 10-20 percent, ballast is moderately fouled. If the percentage is greater than 20 percent, the ballast is considered significantly fouled.

Figure 5 shows the ground-truth images for three cases. The corresponding aggregate gradations are shown in Table 1. For case 1, ballast is relatively clean until 30 inches. Then, ballast becomes significantly fouled at 30-36 inches. For case 2, ballast is relatively clean until 24 inches and significantly fouled after that. In addition, ballast in case 2 is moderately fouled at 12-18 inches, corresponding to the blurred ballast-subballast interface in Figure 5b. For case 3, ballast is clean until 6 inches. Ballast becomes significantly fouled at 12-18 inches, which may result from ballast breakdown fouling. Case 3 has the worst fouling condition at a depth of 12-18 inches. The ballast from 18-30 inches is in a relatively good condition, which may provide a relatively good drainage capability. The ballast-subballast interface is clear, as shown in the ground-truth image in Figure 5c.


(a) Case 1 (b) Case 2 (c) Case 3

Figure 5. Ground-Truth Trench Images

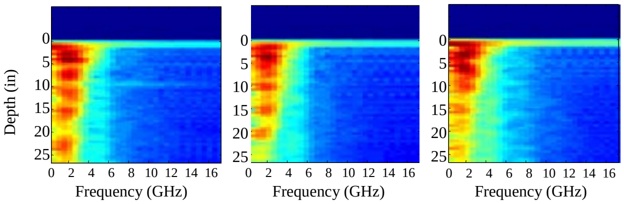
Table 1. Comparison of Ballast Gradations for Cases 1-3

Depth (in.)	0-6	6-12	12-18	18-24	24-30	30-36	36-42
F_l of Case 1 (%)	1.9	4.2	2.7	2.8	9.3	30.9	soil
F_l of Case 2 (%)	0.5	7.4	10.1	5.2	23.0	58.9	68.8
F_l of Case 3 (%)	0.6	14.7	23.5	11.1	18.2	26.4	84.1

Figure 6 presents the STFT images for the three cases. For case 1, the energy attenuation is slow until about 24 inches, which is around the penetration limitation of the 2 GHz antennae. For materials with certain dielectrics, a higher antenna frequency leads to a lower penetration depth. As the ballast layer thickness is greater than the penetration limitation of 2 GHz antenna, data from low-frequency antenna is needed to analyze ballast at greater depth, as well as subballast and subgrade conditions. For case 2, the energy attenuation is slow up to 21.7 inches; then it attenuates rapidly. For case 3, the first energy drop occurs at 6 inches. This drop is not very evident, indicating the ballast is moderately fouled. The second energy drop appears at 12 inches, which is relatively clear, indicating significantly fouled ballast.

Considering the field samples were collected at 6 inch intervals, the variation between the GPR data and the results from the ground-truth trenches and ballast gradation analysis is acceptable. By comparing the STFT images in Figure 6 with the ground-truth data in Figure 5 and Table 1, the following observations are made:

- The ballast layer in case 1 is in better condition than cases 2 and 3.
- The moderately fouled ballast at 24-30 inches in case 2 matches the energy attenuation at the bottom of the STFT image in Figure 6b (color change from hot to cold) and the excavation shown in Figure 5b.
- The high-frequency energy attenuation at 6-18 inches in case 3 suggests greater ballast fouling compared to cases 1 and 2. These observations from the STFT images match the gradation results in Table 1.
- For cases 1 and 3, slow energy attenuation was observed at the bottom of STFT images. This indicates relatively good ballast condition at 18-36 inches and a clear ballast-subballast interface. These results match the ground-truth trench observations and ballast gradation analysis.
- In general, ballast-subballast interface is beyond the penetration limitation of the 2 GHz antennae. Further information on deep substructure condition can be assessed using low-frequency antennae, such as 500 MHz.



(a) Case 1 (b) Case 2 (c) Case 3

Figure 6. STFT Images

CONCLUSIONS AND RECOMMENDATIONS

Considering that one of the challenges of using an air-coupled GPR system during a field survey is a high RF environment from railroad communications, a notch filter can be used to automatically remove the narrowband interference. The STFT, a time-frequency method, can effectively track the change of energy and frequency spectrum over depth. To validate this method for railroad substructure condition assessment, a GPR survey was conducted and field samples were collected at TTC. The STFT images match the ground-truth data and this digest shows that 2 GHz antennae have the capability to detect fouling in railroad ballast.

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