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## Data Analysis of Railroad Substructure Conditions using Ground Penetrating Radar

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### Summary

New findings from research conducted at the University of Illinois at Urbana-Champaign (UIUC) can be used to better assess railroad substructure condition using ground penetrating radar (GPR). Controlled laboratory testing was conducted to determine accurate ballast dielectric constants and to construct short-term Fourier transform (STFT) spectra of railroad ballast materials under various fouling and moisture conditions using collected GPR data. The laboratory testing resulted in several specific and significant findings regarding dielectric constants. For example:

- Limestone ballast has a greater dielectric constant than granite ballast at the same fouling level.
- At a dry fouling level of 0 to 50 percent, the dielectric constant ranges from 3.25 to 3.77 and 3.96 to 4.84 for granite and limestone ballast, respectively.
- The dielectric constants of ballast fouled by various percentages of dry clay can be predicted using linear relationships.
- A STFT color map can effectively detect fouling and water accumulations if the accurate dielectric constant is used.

These findings can be used to help maximize the use of GPR data as it is used to accurately assess ballast condition.

Two types of ballast — granite and limestone — were tested in the laboratory, and dry clay was used as the fouling material. Using 2 GHz antennae, GPR data was collected on clean ballast and on ballast at various fouling and moisture conditions. Then the dielectric constants of the two ballast materials fouled by various percentages of dry clay were calculated, and the STFT spectra of ballast GPR data was analyzed.

Previous research has shown GPR to be an efficient, effective, and continuous approach to assess railroad substructure conditions. However, GPR's assessment accuracy has been limited by unknown ballast dielectric constants and an unclear interface between clean and fouled ballast. Therefore, because ballast fouling in the railroad substructure is detrimental to track effectiveness and limits its structural capacity, a more accurate assessment method as facilitated with this study can ultimately improve the safety and performance of the rail system.

This work was conducted by the UIUC's Railroad Engineering Program under sponsorship by the Association of American Railroads Strategic Research Initiative on Technology Scanning.



**INTRODUCTION**

Railroad ballast plays an important role in supporting railcar loading, preventing track deformation, and providing drainage from the track structure. However, ballast fouled by degradation of aggregates or infiltration of fines undermines the ballast functionality and may result in damage to the rail system. Measuring the intact ballast thickness and early detection of fouled ballast can enhance the safety and performance of the track system, and the data can be used to optimize the life-cycle cost of the ballast system. The traditional ground truth (drilling or trenching) method, used to measure ballast thickness and evaluate its condition, is time consuming and does not provide a continuous measurement. GPR, however, is a nondestructive method that can efficiently, effectively, and continuously assess track substructure conditions.

Compared to uniformly graded clean ballast, fouled ballast has a finer, well-graded particle size with fewer air voids. Using GPR antennae for ballast surveys at high frequencies, such as 2 GHz, air voids in clean ballast and fouled ballast produce different scatter patterns. The presence of fine particles generates more energy attenuation. Because the scattering energy attenuation is dependent on frequency and transmission medium property, STFT is a feasible technique to track the frequency change and assess ballast fouling conditions over time. By using this technique, clean ballast can potentially be distinguished from fouled ballast using 2 GHz antennae. If accurate dielectric characteristics of ballast are used, the change of frequency spectrum over time can be transformed into variation within the ballast depth. Thus, STFT spectra can be built for field data calibration. This digest presents the results of laboratory measured dielectric constants and STFT analysis for clean and fouled ballast.

**DIELECTRIC CONSTANT CALCULATION**

When an electromagnetic (EM) wave is traveling within a medium, the wave propagation velocity can be calculated using Equation 1:

$$v = \frac{c}{\sqrt{\epsilon_r}} \tag{1}$$

where  $v$  is the wave propagation velocity,  $c$  is the speed of light in free space  $9.84 \times 10^8$  f/s ( $3 \times 10^8$  m/s), and  $\epsilon_r$  is the dielectric constant of the medium. For a layered system, the two-way travel time within the  $i^{\text{th}}$  layer can be measured by the GPR system. Knowing the EM velocity in the transverse medium yields the thickness of the layer using Equation 2:

$$d_i = \frac{vt_i}{2} = \frac{ct_i}{2\sqrt{\epsilon_{r,i}}} \tag{2}$$

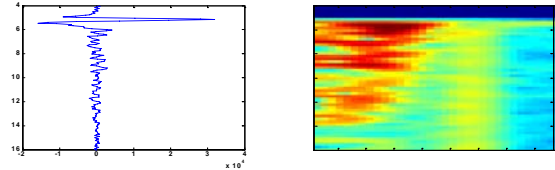
where  $d_i$  is the thickness of the  $i^{\text{th}}$  layer,  $t_i$  is the two-way travel time within the  $i^{\text{th}}$  layer, and  $\epsilon_{r,i}$  is the dielectric constant of the  $i^{\text{th}}$  layer. Likewise, if the layer thickness and the travel time within the layer are known, the dielectric constant can be calculated using Equation 3:

$$\epsilon_{r,i} = \left(\frac{ct_i}{2d_i}\right)^2 \tag{3}$$

STFT is a time-frequency technique that records data in both the time and frequency domains and effectively tracks the frequency spectrum change with time. The information on frequency spectrum change with time is obtained using Equation 4:

$$STFT(t, \Omega) = \int_t [x(\tau) \cdot w(\tau - t)] \cdot e^{-j\Omega\tau} d\tau \tag{4}$$

where  $x$  is the reflected signal,  $t$  is the time variable,  $\Omega$  is the radial frequency variable,  $w$  is the window function, and STFT is the energy at time  $t$  and frequency  $\Omega$ . Once STFT is calculated, it can be plotted against  $t$  and  $\Omega$ . For example, Figure 1B is the STFT spectrum for the time-domain signal in Figure 1A. In Figure 1B, the color red (dark shade in grey scale) represents high energy and blue (light shade in grey scale) represents low energy. If the dielectric constant of the medium is known, the time axis can be transformed to depth using Equation 2.



(A) GPR signal in time domain (B) GPR signal STFT spectrum

**Figure 1. STFT Spectrum Example**

To measure ballast dielectric constants in the laboratory, two 4.9 x 4.9 x 3.9 foot wooden boxes, as Figure 2 shows, were constructed. Each box has scales at the four corners to measure ballast thickness. Two types (limestone and granite) of ballast aggregates were evaluated. Dry clay was used as a fouling material. Fouling material encountered in the field might be different, thus the conclusions of this study are most applicable to cases where the fouling material is dry clay. This study used 2 GHz air-coupled antennae, and the following testing procedure was followed for each ballast type:

1. Place and compact 11.8 inches of clean, dry ballast in the box. Calculate ballast air void content and collect GPR data.
2. Apply dry clay into the ballast at four fouling levels: 10, 25, 40, and 50 percent of the air void volume. Vibrate the ballast with clay to permit clay penetration into the bottom. Collect GPR data for each fouling level.
3. Place and compact another 12-inch lift of clean dry ballast on top of the 12-inch lift of 50-percent fouled ballast and collect GPR data.
4. Place and compact 12 inches of clean dry ballast on top of the 24-inch lift of partially (25%) fouled ballast and collect GPR data.

Evenly spray water into the 36-inch depth of ballast at various levels: 10, 25, 40, and 50 percent by air void volume of the bottom 12-inch lift of clean ballast and collect GPR data at each moisture level.

At the maximum densities, the resultant clean ballast air void was 36.3 percent for granite and 37.8 percent for limestone. Before the fouling material was applied, both granite and limestone ballast were uniformly graded with an average aggregate size of 2.5 inches.



Figure 2. Wooden Box and 2 GHz Antennae Used for Ballast Testing

**LABORATORY TESTING RESULTS**

The dielectric constants of the two ballast materials fouled by various percentages of dry clay were calculated using Equation 3 and presented in Figure 3. The following findings were observed:

- Granite ballast has a smaller dielectric constant than limestone ballast at the same fouling level.
- The dielectric constant of bulk ballast increases with the fouling level increases.
- A strong linear relationship exists between ballast dielectric constant and fouling level for both ballast materials. For any fouling level between 0 and 50 percent, the equations shown in Figure 3 can be used to predict ballast dielectric constant.

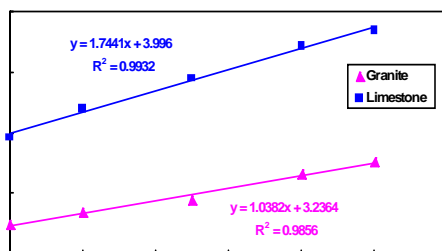


Figure 3. Dielectric Constants of Ballast Fouled by Various Percentages of Dry Clay

Figure 4 shows the measured bulk dielectric constants of ballast with 13-percent fouling material at various moisture contents. Shown is that as the moisture content increases, the bulk dielectric constant of ballast increases significantly. There is a strong linear relationship between the dielectric constant and moisture content. When the moisture content by volume of air void increases from 0 to 15 percent, the increases of dielectric constants are from 3.9 to 9.1 and from 4.2 to 10.5 for granite and limestone, respectively.

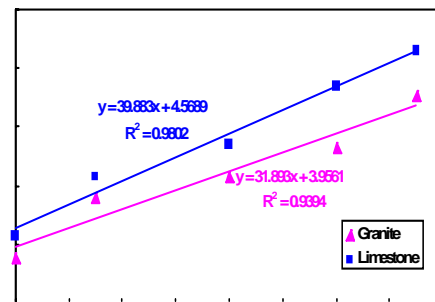


Figure 4. Dielectric Constants of Ballast Fouled at Various Moisture Contents

Using Equation 4, the STFT spectra of GPR data were calculated and plotted for ballast at various fouling and moisture levels. The laboratory predicted dielectric constants were used to estimate fouling depth. Several cases are presented here to demonstrate the validity of the STFT analysis technique for this type of GPR data. Figure 5 shows STFT spectrum for a 36-inch depth of dry clean ballast. It is clear that frequency energy attenuates gradually. However, in Figure 6, which presents STFT spectrum for a 24-inch depth of dry clean ballast on top of 12 inches of 50-percent fouled ballast, a sudden energy drop can be observed around 26 inches. This indicates that the 10-inch depth of ballast at the bottom is fouled. The dry clay, which was applied to fill 50 percent of the 12-inch depth of clean ballast air void volume, actually filled 10 inches instead of filling 100 percent of 6 inches. This was considered reasonable as the air voids were 60 percent filled. For the same ballast shown in Figure 5, when 50-percent water by the air void volume of the 12-inch depth of ballast was applied, the STFT spectrum in Figure 7 was obtained. Compared to the STFT spectrum in Figure 6, high-energy area was observed at the bottom of the ballast. This high-energy area indicates water accumulation at this location that resulted in strong signal reflection.

In summary, in the STFT spectrum for clean ballast, the frequency energy (red and yellow area) gradually attenuates. When there's significant fouling occurring, there will be a sudden energy drop (sudden color change from red/yellow to blue) in the STFT spectrum. And when there's water accumulating, concentrated strong energy area (red area) will show up in the STFT spectrum, since the water causes strong reflection to the GPR signal.

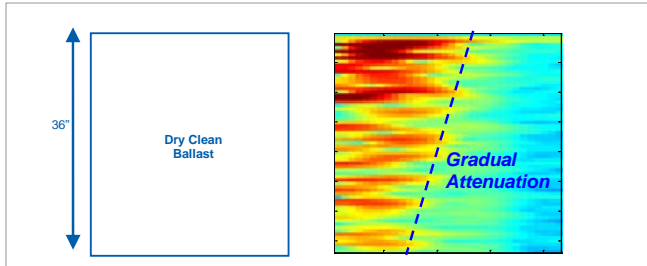


Figure 5. STFT Spectrum for 36 inches (Dry Clean Ballast)

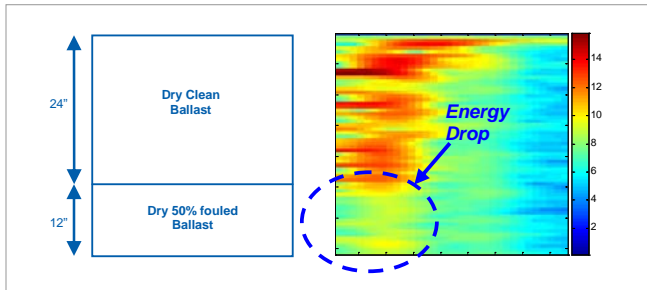


Figure 6. STFT Spectrum for 24 inches Dry Clean Ballast on Top of 12 inches of Dry 50% Fouled Ballast

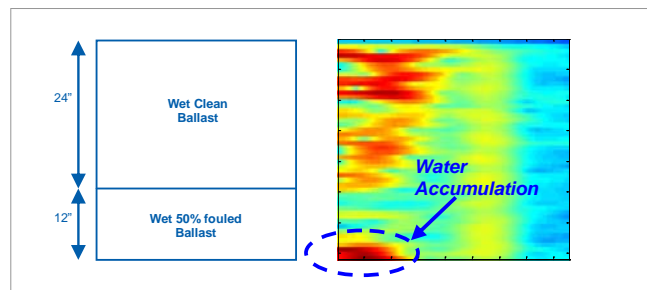


Figure 7. STFT Spectrum for 24-inch Wet Clean Ballast on Top of 12-inch Wet 50% Fouled Ballast

## CONCLUSIONS

The dielectric constants of two types of ballast were determined in a laboratory study. In addition, STFT spectra of ballast GPR data at various fouling and moisture conditions were analyzed. The conclusions are as follows:

- Limestone ballast has greater dielectric constant than granite ballast at the same fouling level.
- At a dry clay fouling level of 0 to 50 percent, the dielectric constant ranges from 3.25 to 3.77 and 3.96 to 4.84, for granite and limestone ballast, respectively.
- Dielectric constants of ballast fouled by various percentages of dry clay can be predicted using linear relationships.
- Moisture can significantly increase the dielectric constant of ballast. There is a positive linear relationship between the bulk ballast dielectric constant and moisture content.
- A STFT color-map can effectively detect fouling and water accumulation locations when an accurate dielectric constant is used.

## RECOMMENDATIONS

Although the GPR method has shown many advantages compared to the traditional drilling method in ballast condition assessment, it is important to recognize its limits so that the benefits of this technique will not be oversold. Detecting ballast fouling using the STFT method is based on the assumption that the collected GPR data is clean and without significant noise. However, during the field data collection, many sources (e.g., rails, ties, and radio signals) generate noises, which may mask ballast information in the GPR data. Therefore, while GPR equipment should be properly set up during data collection, efforts are needed to further improve the GPR data filtering and data analysis techniques. To maximize the outcome of assessing ballast fouling using GPR, an appropriate procedure must be followed, and guidelines for this procedure should be developed to assist railroad engineers in effectively using this nondestructive testing tool.

## ACKNOWLEDGEMENTS

The Association of American Railroads Technology Scanning Program sponsored this work. The authors gratefully acknowledge the assistance of Jim Meister and the research project panel for their invaluable input during the study.

## REFERENCES

1. Roberts, R. et al. June 19-22, 2006. "Advances in Railroad Ballast Evaluation Using 2 GHz Horn Antenna," *Proceedings 11th International Conference on Ground Penetrating Radar*, (in CD) Columbus, Ohio.
2. Al-Qadi, I. L., W. Xie, and R. Roberts. Jan. 21-25, 2007. "Flaw Quantification of Railroad Ballast: A New Analysis Approach of Ground Penetrating Radar's Reflection Data," 86th TRB Annual Meetings, Paper No. 07-2273, Washington D.C.
3. Al-Qadi, I. L., W. Xie, and R. Roberts. 2008. "Scattering Analysis of Railroad Ballast Using Ground Penetrating Radar," *Journal of Nondestructive Testing and Evaluation*, Vol. 41, No. 6, pp. 441-447.
4. Xie, W. et al. Jan. 13-17, 2008. "Development of a Time-Frequency Approach to Quantify Railroad Ballast Fouling Condition Using UWB GPR Data," 87th TRB Annual Meetings, Paper No. 08-1846, Washington, D.C.
5. Al-Qadi, I. L., W. Xie, and R. Roberts. Oct. 2008. "Time-Frequency Approach for Ground Penetrating Radar Data Analysis to Assess Railroad Ballast Condition," *Journal of Research in Nondestructive Evaluation*, Vol. 19, No. 4, pp. 219-237.
6. Lahouar, S. Oct. 2003. "Development of Data Analysis Algorithms for Interpretation of Ground Penetrating Radar Data," Ph.D. dissertation. Virginia Polytechnic Institute and State University, Blacksburg, VA, 239 p.
7. Oppenheim, A. V., R. W. Schaffer, and J. R. Buck. 2005. *Discrete-time Signal Processing*, Pearson Prentice Hall.

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