Scattering Analysis of Railroad Ballast Using Ground Penetrating Radar

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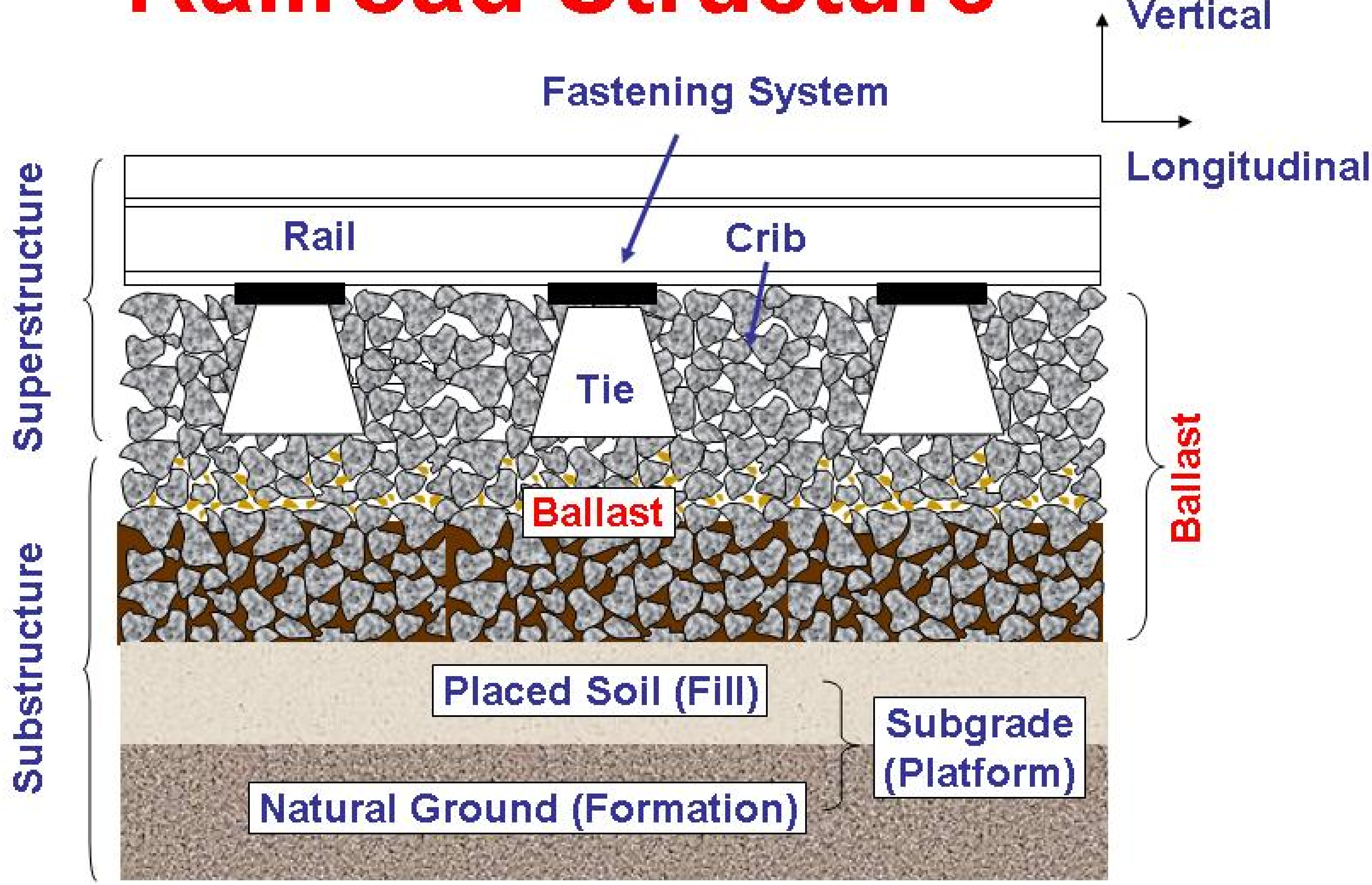
Outline

- Background
  - Railroad Ballast Characteristics
  - GPR Application in Railroad
- Objective
- GPR Data Collection and Processing
- Scattering Pattern Analysis
- Moisture Measurement Using Amplitude Envelope Method
- Summary

Railroad Structure



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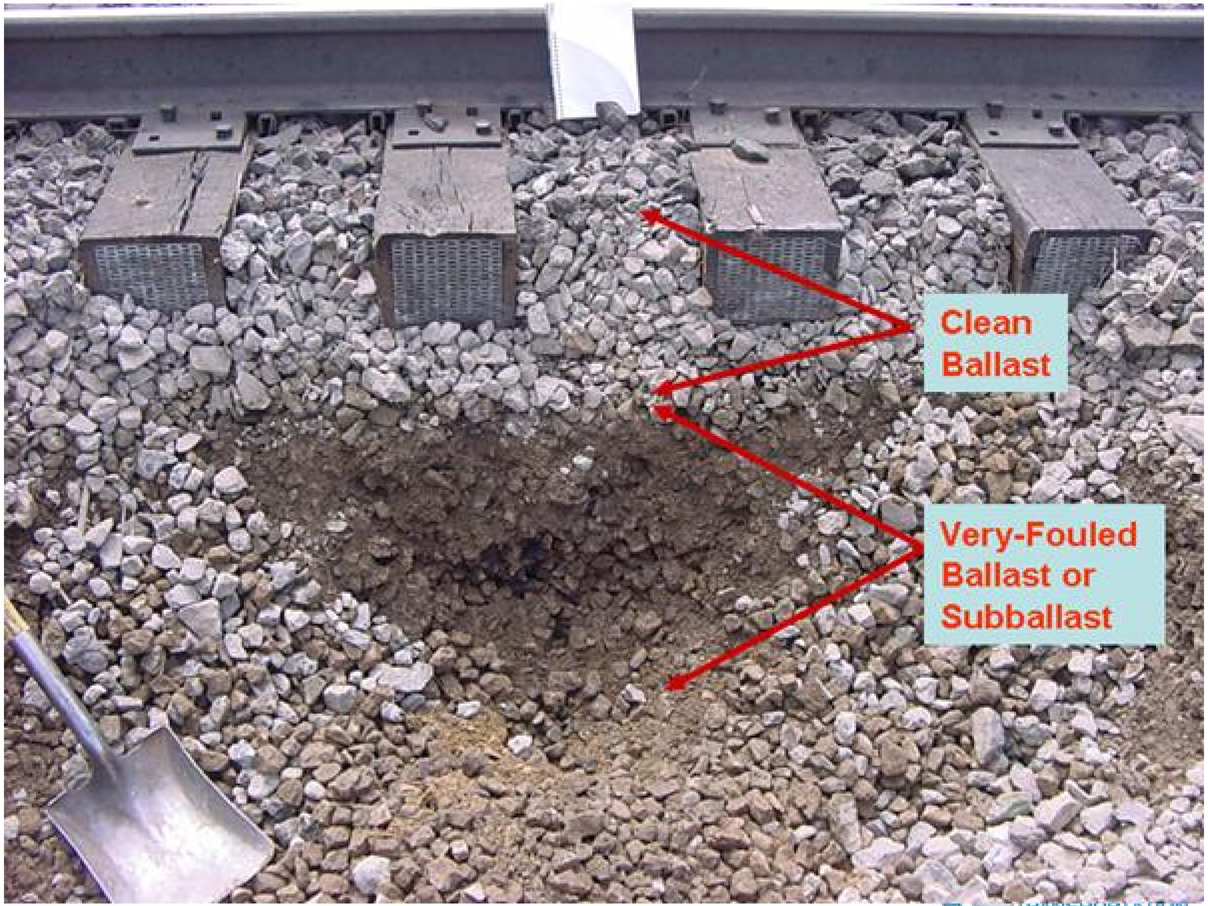
Ballast Functions

- Structural Support
  - Resist vertical, lateral, and longitudinal forces
  - Support sleepers
  - Reduce stress levels on subgrade
- Drainage
- Reduce frost problems
- Absorb noise

Ballast Fouling

Ballast fouling greatly influences its functions:

- Clean ballast: Uniformly-graded large aggregate having high air void content
- Fouled ballast: Fine materials fill air-void space



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Sources of Ballast Fouling (Selig et al. 1994)

- Ballast breakdown: 76%
- Infiltration from subballast: 13%
- Infiltration from ballast surface: 7%
- Subgrade Infiltration: 3%
- Sleeper wear: 1%

Railroad Ballast Assessment

- Traditional Selective Drilling Method:
  - Condition driven
  - Time consuming
  - Limited coverage
  - Train traffic disturbance
- GPR:
  - Nondestructive/ no disturbance to structure
  - Continuous
  - Rapid
  - High coverage
  - Very limited train traffic disturbance

GPR Background

- Ground Penetrating Radar (GPR) is a special kind of radar
- Purpose of using GPR:
  - Detect target buried in dielectric medium
  - Estimate their depth
- GPR applications: geophysics, archeology, law enforcement, civil engineering (structure, transportation – pavement, railroad)

GPR Application for Railroads

- Ground-coupled antenna may produce ringing when h> λ /8
  - Strong surface reflection
  - For 900MHz, $\lambda/8 = 42 < 70$mm (size of ballast)
- Air-coupled antenna can be used in order to avoid obstacles
  - Strong echoes produced by rails may mask weak signals from ballast
  - Several data processing techniques may be used

Dielectric Characteristics of Ballast

Dielectric constants of quartzite ballast

Railroad Ballast	Dielectric Constant
Dry, Clean Ballast	3.0
Wet, Clean Ballast (5% water)	3.5
Dry, Spent Ballast	4.3
Wet, Spent Ballast (5% water)	7.8
Saturated, Spent Ballast	38.5

– *Effect of moisture on fouled ballast is much greater than on clean ballast*

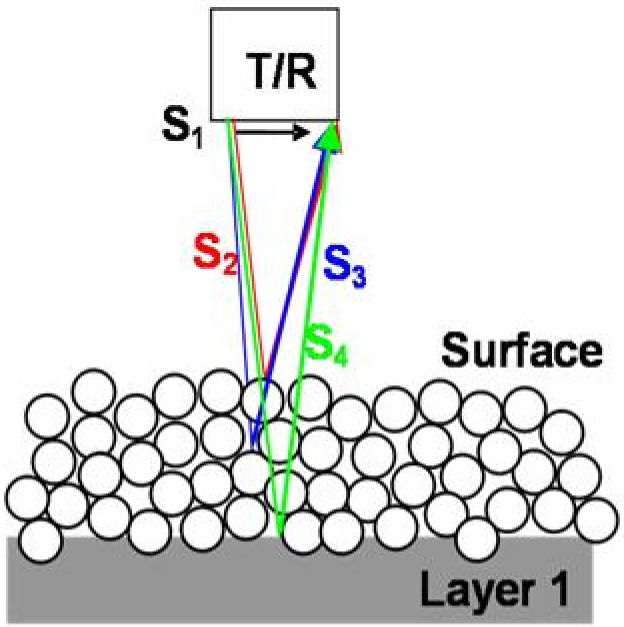
Objective

- Assess railroad ballast condition using GPR:
  - Estimate ballast thickness
  - Detect ballast fouling
  - Analyze the influence of ballast fouling on drainage capability

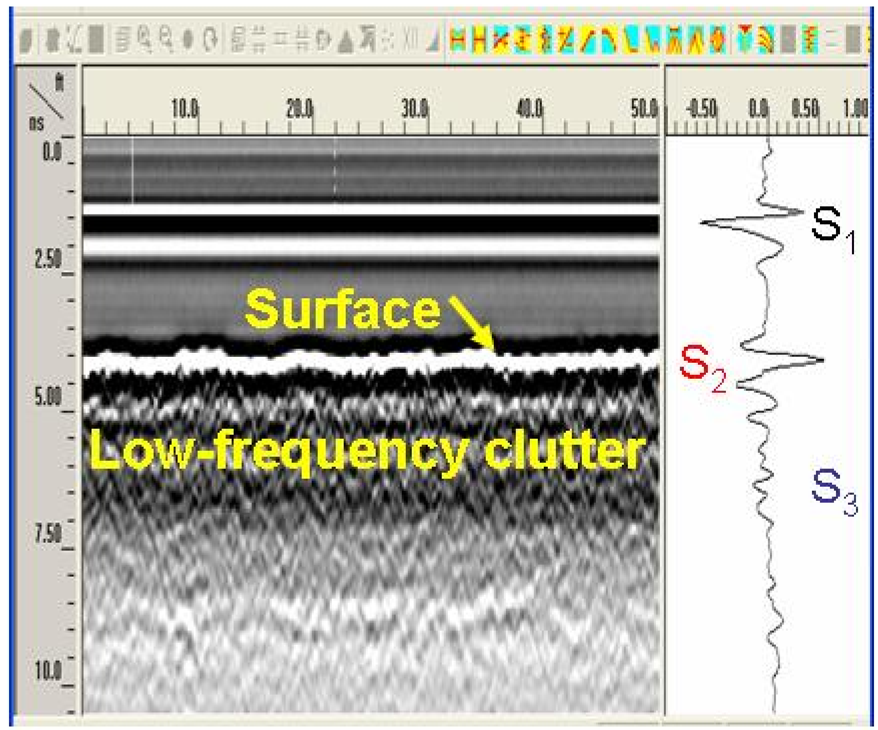
GPR Data Collection on Railroad

- Equipment
  - SIR-20 control unit,
  - Three bistatic 1 and 2 GHz air-coupled horn antennae were used to collect continuous parallel longitudinal scans
  - DMI was used to trigger GPR acquisition
  - Digital camera was used to identify railroad surface
- Data collection location
  - Outer and center antennae were mounted at least 600 mm from rails

Raw GPR Data of Ballast



Different Paths of Reflected Signal



Raw GPR data

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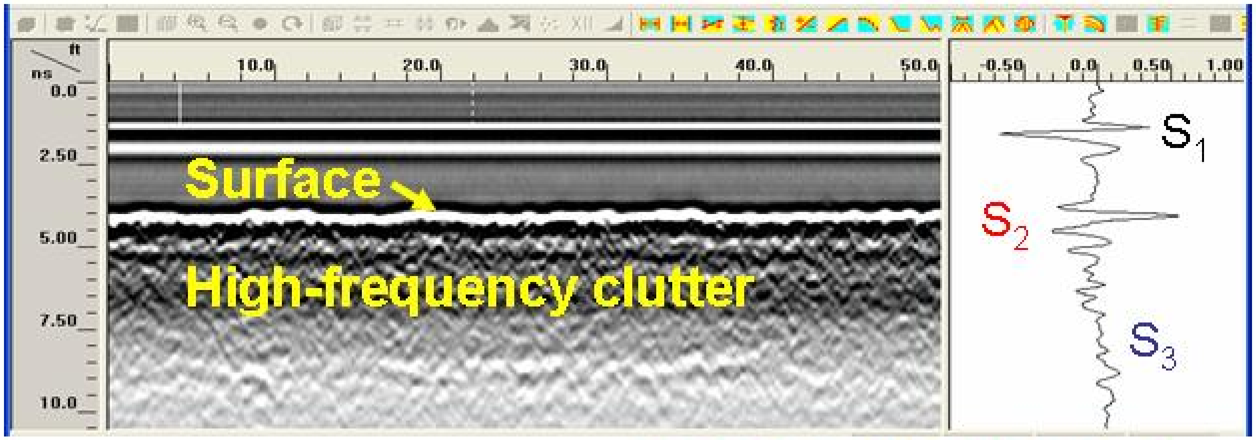
GPR Data Processing

- To remove the strong clutter bands from rails and produce clear image:
  - Surface reflection was corrected
  - Vertical band-pass FIR filter was used to remove noise
  - Horizontal band-pass filter was implemented to remove clutter from rails
  - Gain was applied to account for energy attenuation

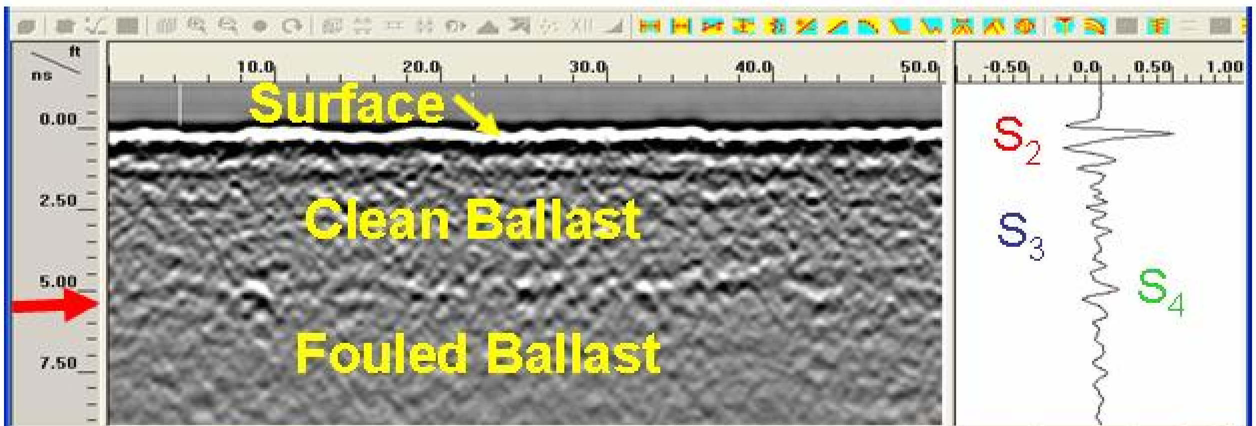
Processed GPR Data

First pulse from surface and subsequent small pulses are mainly from scattering

Raw GPR data



Processed GPR data



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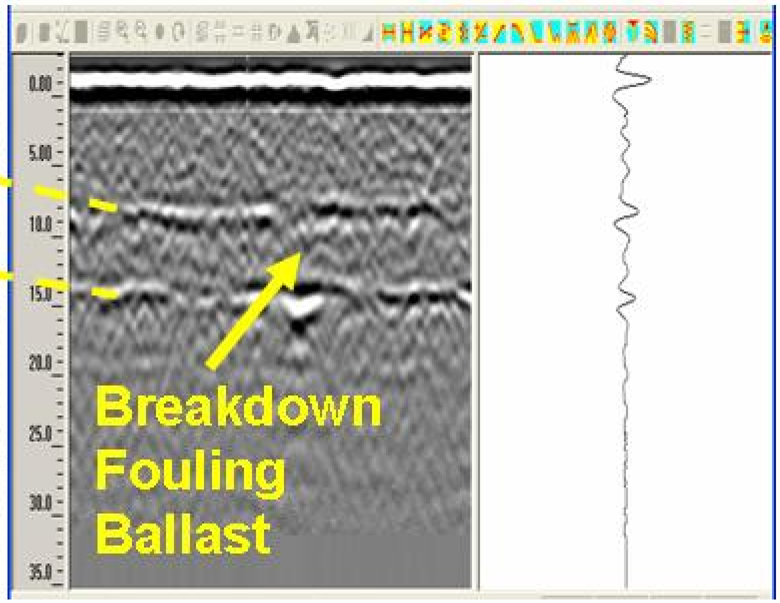
Ballast Breakdown

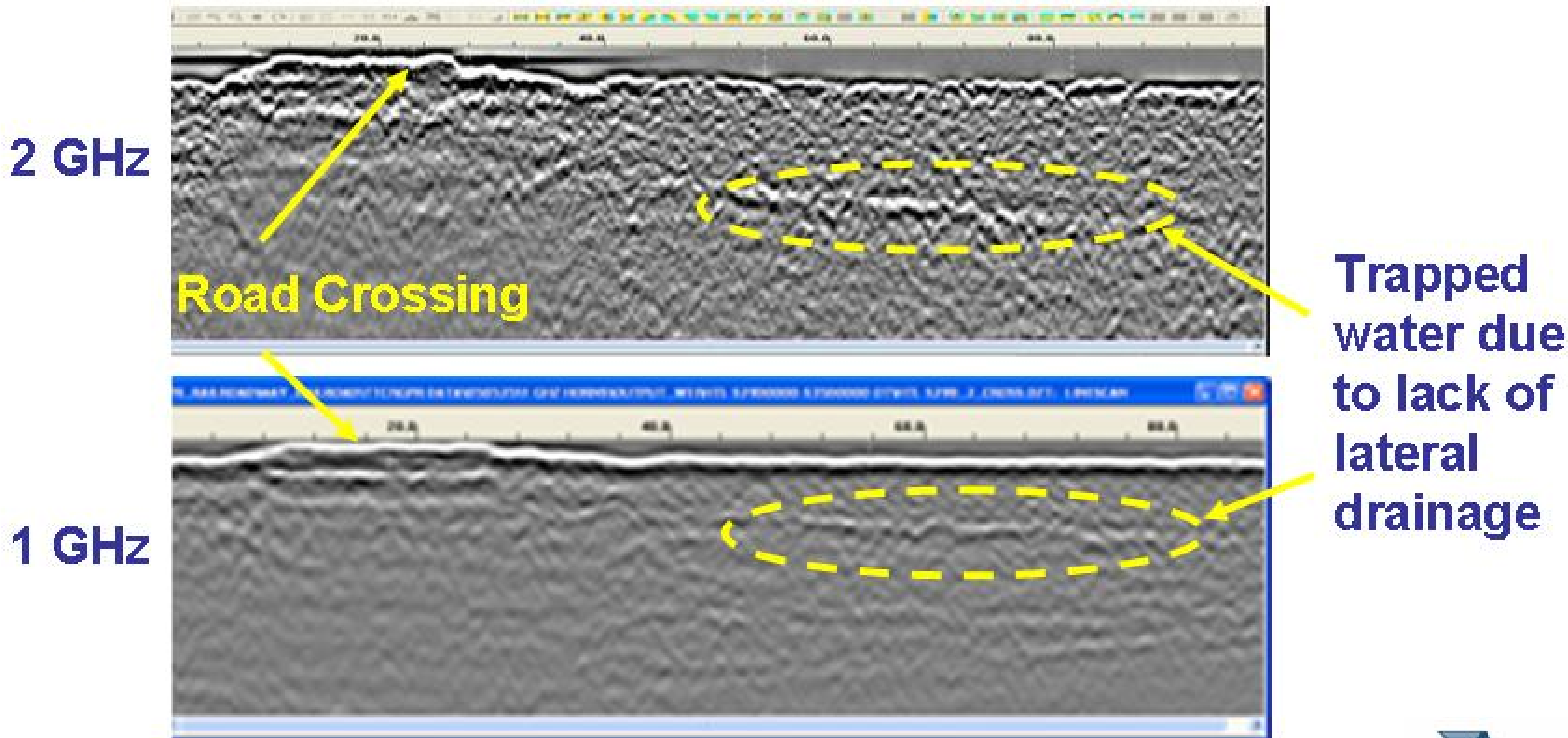
In clean ballast, the penetration depth of 2-GHz antenna is about 600mm, much greater than the sleeper's height, 150mm



Breakdown ballast under sleepers

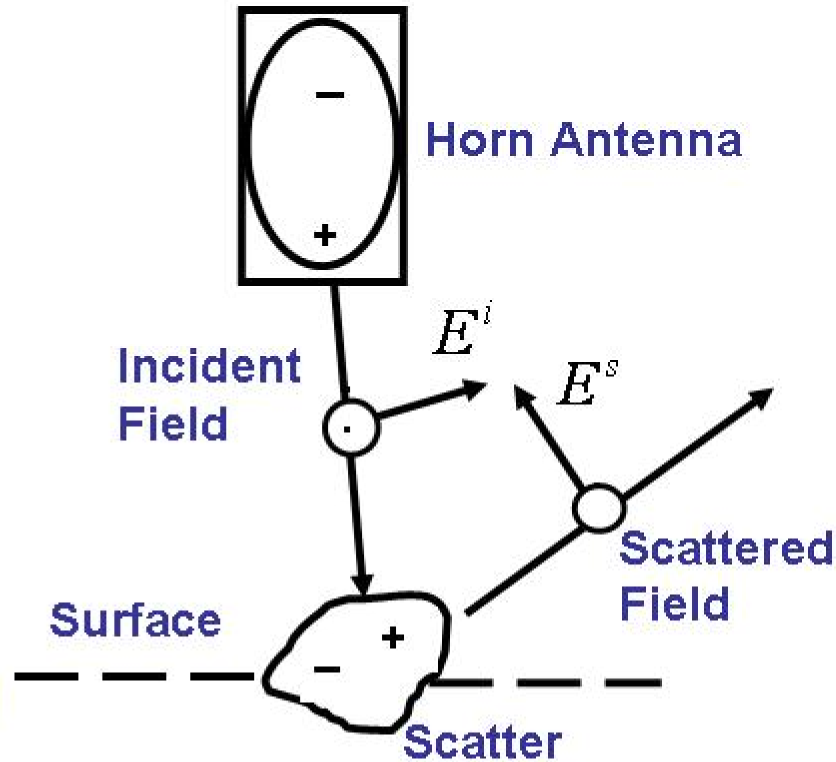
Trapped Water Detection

- 2-GHz antenna is more sensitive to scattering pattern change than the 1-GHz antenna



Scattering Pattern Analysis

- **Pavement Materials:**
  - Scattering response is weak (**homogenous material**)
  - Reflected pulse has similar shape as incident signal
- **Railroad Ballast:**
  - Scattering response is dominant (**heterogeneousity** is high)
  - Reflected pulse shape is influenced by size of scatter



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GPR Frequency Selection

Frequency → air void → ballast fouling

	Ground Coupled Antenna						Air Antenna	
f (MHz)	100	200	400	500	600	900	1000	2000
	(low frequency)						(high freq)	

- Low frequency may detect "clear" discontinuities in dielectric constant; but may not detect changes in air void volume

Detect Changes in Scattering Pattern

Air void volume in clean ballast is about 30%

$$D^N = \frac{2a\pi}{\lambda} = \frac{70 \times 30\% \times \pi}{\lambda} \qquad \lambda = \frac{c}{f \cdot \sqrt{\varepsilon_r}}$$

Normalized dimensions for different frequencies

F (MHz)	100	200	400	500	600	900	1000	2000
λ (mm)	1500	750	375	300	250	166	150	75
D^N	0.04	0.09	0.18	0.22	0.26	0.4	0.44	0.88

Note: Scattering response is dominant response as D^N close to unity.

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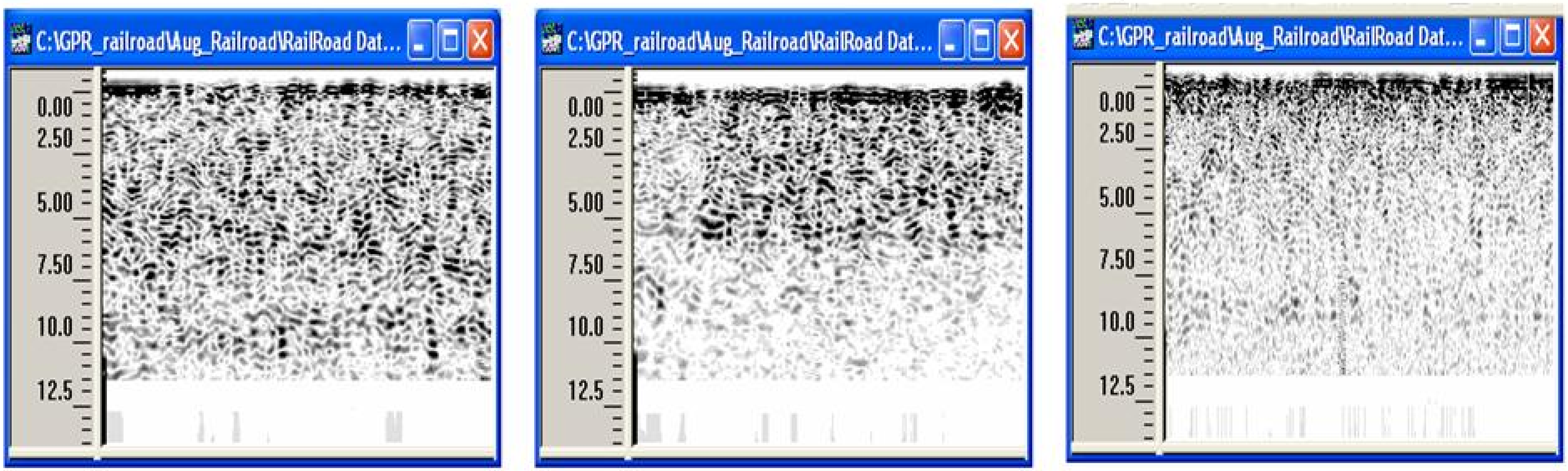
Scattering Pattern of Ballast under Various Conditions

Air void ⟷ Ballast fouling index



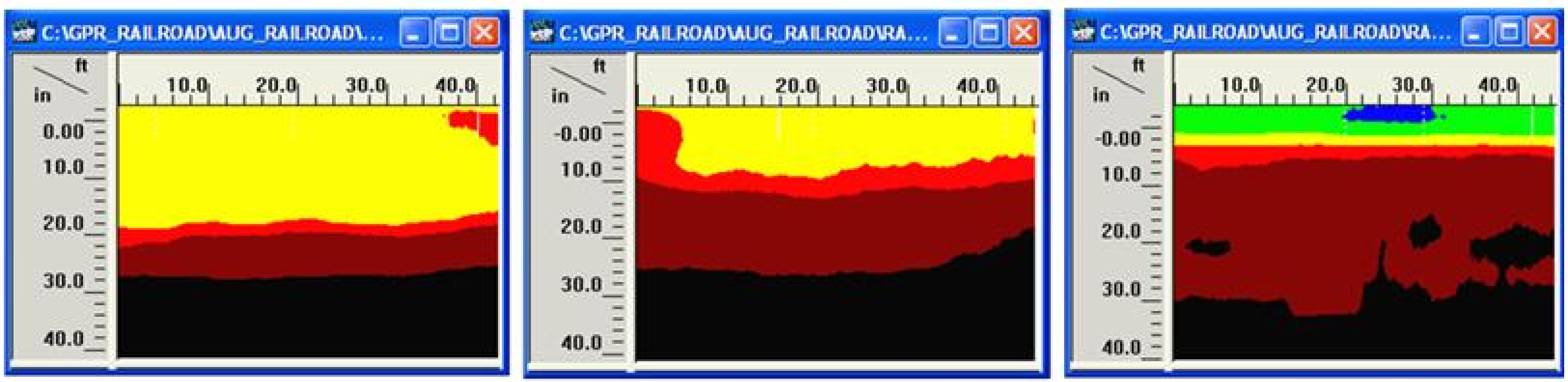
(a) Clean ballast (b) Moderately fouled ballast (c) Fouled ballast

Ballast exhibiting various scattering pattern (2-GHz)

Scattering Amplitude Envelope Approach (Roberts *et al*, 2006)

- The Hilbert transform is used to obtain the amplitude envelope of reflected signal
- Very low amplitude envelope and sudden change in slope of amplitude envelope indicate a change in ballast condition.

Clean Ballast
Fouled Ballast
Slightly Fouled Ballast
Moderately Fouled Ballast



(a) Clean ballast (b) Moderately fouled ballast (c) Fouled ballast

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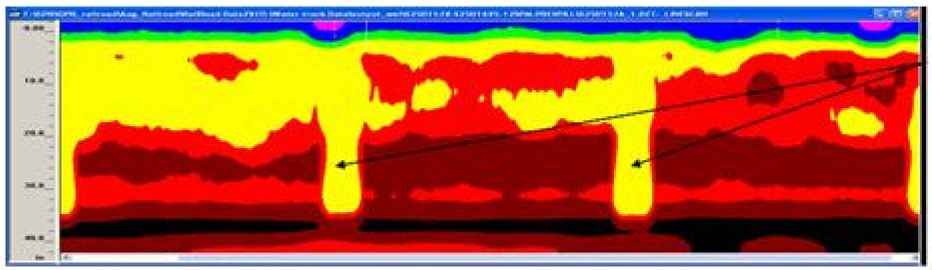
Moisture Measurement

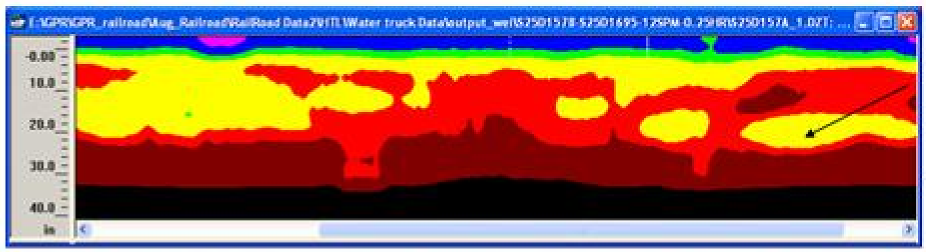
- Clean ballast allows water to flow through easily
- For slightly fouled ballast, fine particles partially block air void and influence drainage capability

Before Spray



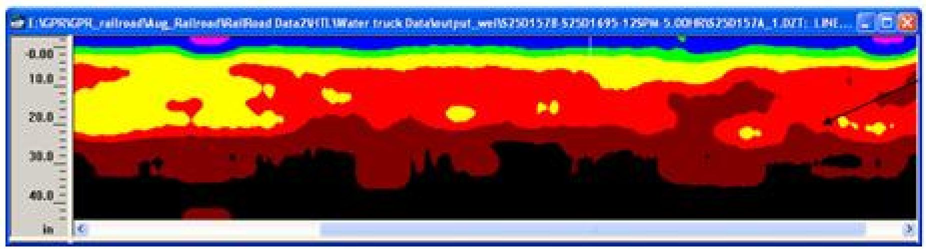
RF noise

0.25hr after spray



Significant Saturation contrast

5hr after spray



Diminished saturation contrast

Summary

- Fouled ballast generates different GPR **scattering patterns** compared to that of clean ballast
- **2-GHz** antenna is sensitive to scattering pattern change
- **Combination of direct scattering pattern analysis and amplitude envelope approach** may provide more information about ballast fouling and trapped water
- GPR proved to be an **effective approach** to detect ballast fouling

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Thank You!