An Automated System for Rail Transit Infrastructure Inspection

Final Report

Under Cooperative Agreement
No. RITARS-12-H-UML

Report Submitted to: U.S. Department of Transportation
Office of the Assistant Secretary for Research and Technology

Report Submitted on: March 29, 2015
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ACKNOWLEDGMENTS

The authors would like to thank the U.S. Department of Transportation’s Office of the Assistant Secretary for Research and Technology (USDOT/OST-R) for providing financial support to this project. Also, the authors would like to thank all project technical advisory members for providing invaluable comments to ensure that this project moved forward in the right direction. Additionally, we would like to thank MBTA and Metro St. Louis for allowing us to test the developed system on their passenger rail systems and for their employees’ assistance. Last but not least, The PI is extremely grateful to Colvins Truck Rental in Waltham Massachusetts. Without their permission and assistance to modify their hi-rail SUV, it would be impossible for us to complete the field data collection as scheduled.
EXECUTIVE SUMMARY

This project applied commercial remote sensing and spatial information (CRS&SI) technologies such as Ground Penetrating Radar (GPR), laser, GIS, and GPS to passenger rail inspections. An integrated rail inspection system that can be mounted on hi-rail vehicles has been developed. This integrated system consisted of four major components: GPR subsystem, laser subsystem, track dynamic model subsystem, and a web-GIS based Decision Support System (DSS). The GPR subsystem was designed to identify track subsurface problems such as fouled ballast and suspicious underground objects. It was developed using a set of home-made horn antennas; the laser subsystem was for detecting surface track defects such as missing fasteners and cross ties, large cracks in cross ties, and wide rail gauge. It was developed based on a commercial laser product called LCMS; the track dynamic model was developed to identify a critical track structure problem called hanging tie using spectrum analysis. The main instrument for this subsystem was a 3-axial accelerometer; and the web-GIS based DSS was developed using ArcGIS for Server and Microsoft SQL Server. Its purpose was mainly to manage and visualize the results generated by the previous three subsystems.

The first three subsystems were integrated and mounted on a hi-rail SUV. This automated and operational system was then tested at both Massachusetts Bay Transportation Authority (MBTA) and Metro St. Louis. The team also developed algorithms for processing the GPR, laser, and track dynamic model data. These algorithms include a 2D entropy method for GPR data analysis and a 3D template matching method for identifying missing fasteners. Among them, the laser algorithms have already been commercialized by Pavemetrics as LRAIL. The data collected from MBTA and Metro St. Louis was processed by these algorithms and fed into the DSS. In addition to popular GIS tools for visualizing, querying, and editing spatial and attribute data, the project team developed a mobile App to facilitate field asset inspections.

Rail transit agencies in the United States rely heavily on visual observation for their weekly track inspections. This manual method is time-consuming, costly, and cannot effectively identify subsurface safety hazards. The project team reached out to several major rail transit agencies in the United States and demonstrated the developed product. These demonstrations generated substantial interest among these stakeholders. With the aging rail infrastructure, this developed system is expected to substantially benefit the rail transit industry by improving the track inspection efficiency, accuracy, and safety of both the rail transit systems and track workers. During the course of this project, the team identified additional interesting and innovative ideas. Some of them have been successfully implemented such as the mobile App. These ideas are also discussed throughout this report.
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CHAPTER 3
GPR HARDWARE AND SOFTWARE
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The GPR subsystem consists of hardware and software systems. In this chapter, the focus is on the hardware system and the associated control software development. Some radar data processing algorithms are also presented at the end. In the next chapter, a more detailed discussion on the radar data processing algorithms is provided.

3.1. GPR Hardware Development

3.1.1. System Architecture

As shown in Figure 23, the GPR hardware consists of five important functional units: (1) RF (radio frequency) transmitter, (2) ultra-wideband (UWB) antennas, (3) data acquisition comprising high-speed real-time digitizer, high-speed data transmission, and storage unit, (4) multi-core computer, and (5) FPGA digital controller along with a wheel encoder.

![Figure 23 High-speed UWB GPR system.](image)

The RF transmitter comprises of an UWB pulse generator that generates high-amplitude Gaussian pulses with the pulse repetition frequency (PRF) determined by the FPGA. The high-speed digitizer comprises of a 10-bit 8-GHz real-time sampling ADC and a high throughput data transmission unit connected to a computer via PCIe connection. The computer streams the data from the digitizer and tags the data with header details. The wheel encoder measures the scan distance via quadrature pulses generated based on distance travelled. The FPGA receives the pulses from the wheel encoder to perform travel distance triggered scans. The distance information is transmitted to the computer for creating the data headers. The UWB antennas in this GPR system are compact and have good impedance matching over a wide bandwidth for
effective signal transmission and reception. Some selected key specifications of this GPR system are summarized in Table 2. In the rest of this section, the designs of selected key functional units are elaborated.

Table 2 UWB air-coupled impulse GPR system specifications

<table>
<thead>
<tr>
<th>Key Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical sampling rate</td>
<td>8 GHz</td>
</tr>
<tr>
<td>Vertical sampling window</td>
<td>40 ns</td>
</tr>
<tr>
<td>Pulse repetition frequency</td>
<td>0 to 30 kHz</td>
</tr>
<tr>
<td>Horizontal resolution</td>
<td>Up to 1 cm at 100 km/h survey speed</td>
</tr>
<tr>
<td>Signal bandwidth</td>
<td>600 MHz to 2 GHz (1 GHz central frequency)</td>
</tr>
<tr>
<td>Penetrating capability</td>
<td>Up to 1 meter</td>
</tr>
</tbody>
</table>

3.1.2. UWB Pulse Generator

A UWB Gaussian pulse is generated using a microstrip delay line, a Schottky diode, and a step-recovery diode (SRD) connected in series or parallel to the delay line. Pulse generators with SRD connected in series with a microstrip delay line generates pulses with low ringing. But the output amplitude of the pulses is smaller and requires power amplification before being transmitted via the antennas. Pulse generators with shunt-connected SRDs produce higher amplitude pulses that are prone to higher level of ringing. However, by placing the pulse forming network (comprising the delay line and Schottky diode) in the input stage of the SRD, the level of ringing can be reduced drastically. Using a transistor switching circuit and a power transistor operating in saturation region to drive the SRD, negative Gaussian pulses with 23V peak-to-peak amplitude can be generated over a wide range of pulse repetition frequency.

The circuit diagram of the UWB Gaussian pulse generator is presented in Figure 24. It comprises of four parts: (1) Op-amp to amplify the digital clock from an FPGA, (2) Edge triggered timing circuit, (3) BJT driver circuit to generate a negative driving pulse, and (4) Gaussian pulse generator using a SRD.

![Figure 24 UWB Gaussian pulse generator with shunt-connected SRD.](image)
The first part of the circuit consists of a current feedback operational amplifier, THS3091, to amplify the clock signal from an FPGA. The timing control circuit ensures that irrespective of the PRF of the FPGA clock signal, a negative pulse with defined width is provided to the driver stage. The UWB Gaussian pulse is generated using the combination of a step-recovery diode (SRD), a Schottky diode, and a delay line. In steady state, the Schottky diode is reversely biased and the SRD is forward biased by a small bias voltage Vbias (~1.25 V). When the negative pulse is applied from the driver circuit, the effective voltage (Vbias-Vneg) reversely biases the SRD and forward biases the Schottky diode. Due to the presence of the intrinsic layer, the SRD continues forward conduction for short time duration. When the charges are depleted, the SRD turns off instantaneously and generates a very sharp transition edge in the order of 10s of picoseconds. Also, the SRD offers very high impedance which reflects the signal away from the SRD in two directions, one towards the output and the other one back towards the input stage. Since the Schottky is forward biased and effectively grounded, the signal that travels via the delay line to the Schottky diode is reflected back to the output with opposite polarity. The two signals combine and produce a UWB negative Gaussian pulse.

The width of the UWB pulse is determined by the signal propagation delay across the delay line. The filter capacitor, \( C_f \), transmits only the UWB pulse signal while blocks the driver signal and eliminates the low frequency noise. The waveform measured in a DSO (digital sampling oscilloscope) after 20 dB attenuator (factor of 10) is shown as the pulse generator component in Figure 25. The PCB (printed circuit board) implementation of this GPR pulse generation circuit is shown in Figure 26.

![Figure 25](image)

**Figure 25** Output waveform of the Gaussian pulse generator measurement upon 20 dB attenuation.
3.1.3. UWB Antenna

The UWB antenna in a GPR system needs to have good impedance matching to minimize the internal reflections and to smooth the transition of the circuit impedance. The objective is to maximize power transmission. In this project, the GPR system is equipped with a novel Good Impedance Match Antenna (GIMA).

Figure 27 Drawing of UWB horn antenna (where $\mu = 13^\prime$, $\beta = 6^\prime$, $r = 150^\prime$, $a = 60$ mm, $b = 60$ mm, and $l = 180$ mm).
As shown in Figure 27, the GIMA is modeled as a waveguide with two metal conductors of varying width and separated by an insulator. The variation in impedance is achieved by smooth variation of the width of the metal plates and the separation gap (\( \beta \)) between them. The rolled edges of the metal plates are to minimize edge diffraction. Figure 27 shows the shape and the key dimensions of the GIMA. The antenna return loss S11 plot is shown in Figure 28. It can be seen that the GIMA return loss is less than -10 dB from 500 MHz to 6 GHz, which attests to its high-quality impedance matching across a wide frequency band. The hardware implementation of the GIMA is shown in Figure 29.

![Figure 28 Reflection loss of the UWB horn antenna from 30 MHz to 6 GHz.](image)

3.1.4. High Speed Digitizer Configuration

The digitizer used in this system is a 10-bit real-time sampling ADC (analog to digital converter) (Agilent Acqiris U1065A module) with a sampling rate of 8 GSa/s. Most existing commercial GPRs use equivalent sampling technique where only one or a set of data points are acquired from a single pulse. In order to reconstruct the entire pulse, a number of repetitive pulses are used. Therefore, to obtain good horizontal resolution, the pulse repetition frequency
should be in the order of MHz. For our GPR system, by employing the single-shot full-waveform sampling digitizer, high range resolutions can be obtained with low repetition frequencies even at high travel speeds.

At 8 GSa/s sampling rate, the digitizer rapidly accumulates large volumes of data. Such data volumes and rates are difficult to manage with ordinary read and write operations. A solution was proposed to configure the digitizer into the Simultaneous Acquisition and Readout (SAR) mode. In SAR mode, the internal memory of the digitizer is divided into three banks as shown in Figure 30. Each bank is further divided into 333 segments to hold data samples from one pulse in each segment.

![Figure 30 Digitizer configured in SAR mode.](image)

The SAR mode allows simultaneous data writing and reading in the digitizer memory. In other words, the stored data can be read out from one memory bank while the new incoming acquisition data can be written into another available memory bank. The bottleneck in this configuration is the transfer of data from the digitizer to computer memory. To address this issue, a parallel processing algorithm is used to speed up the reading process. A quad-core processor reads data from the digitizer using a high-speed PCI-Express bus, adds header information to the data, and writes the data in computer’s hard disk. The header information comprises of the data from the wheel encoder to measure travel distance, system time stamp, and channel tag. Using the SAR configuration, a seamless signal acquisition, data transfer, and storage is successfully achieved for a pulse repetition frequency of up to 40 kHz.

### 3.2. User Interface and Software Development

#### 3.2.1. Control Program & User Interface

The Graphical User Interface (GUI) of the control program for our GPR system is developed using NI LabVIEW. The GUI is shown in Figure 31. Using this GUI, users can configure the following GPR system parameters:
• Storage Path – The directory where the .tdms file (GPR data) is saved;
• Delay Time – The trigger delay time is used to adjust the GPR signal to appear in the middle of the sampling window;
• Trigger Number – It specifies for how many trigger pulses received, the digitizer is triggered to collect data once; and
• Pulse Number – In each data collection cycle, the number of GPR traces to be saved in hard disk.

Under normal GPR working condition, the “Error” panel should show no errors if the digitizer is successfully calibrated; the “DEPP EN” panel should display 1 if the FPGA module works properly; and the GPR data is saved as .tdms files in hard disk.

3.2.2. Large Data Stream Display

During GPR scanning, a large amount of data can be accumulated very quickly. The analysis below illustrates the developed GPR data acquisition module specifications.

• Pulse repetition frequency: 30 KHz;
• Each A-scan trace: 320 samples;
• Each sampling data size: 2 bytes (16 bits);
The size of each A-scan trace: 2 bytes × 320 samples/trace = 640 bytes;
For one hour (60 minutes) of GPR scanning, the total amount of acquired data is: 30 KHz × 640 bytes/trace × 3600 seconds = 69.12 GB.

If the GPR is mounted on a vehicle that travels at 30 mph, it means about 70 GB data is collected every 30 miles. To save such a huge data set in a single file and process it directly is very challenging. Therefore, we choose to divide the large data set into small segments so that signal processing can be conducted on each segment separately. Moreover, dynamic segmentation is introduced that renders users the ability to arbitrarily select data corresponding to any areas of interest. Our radar data is stored in TDMS format, which consists of three parts:

- **Lead In**: It contains basic information about the file (e.g., a tag that identifies the file as TDMS, a version number, and the overall length of the segment);
- **Meta Data**: It contains the names and properties of all objects in this segment, such as index information used to identify the location of raw data segment; and
- **Raw Data**: Scanning data collected before data processing.

To display the collected GPR data, a computer program has been developed to read the “Lead in” and “Meta Data” portions of TDMS files and to store them in computer memory. From these two portions, the computer program identifies the GPR raw data length and the beginning address of the GPR data. A pointer is then used to localize the beginning of GPR data. One can arbitrarily select the segment of GPR data to be processed, and tag the beginning and the end of that data segment as “StartPoint” and “StopPoint”, respectively. The selected data segment can be post-processed to obtain B-Scan image. Figure 32 shows one example where a small data segment can be selected from a large data set. For the quad-core computer used in this study, up to 900 data segments (or B-scan images) can be opened simultaneously. Using the
“Previous” or “Next” buttons of the developed GUI, we were able to easily switch among B-scan images. For processing large data sets, the following steps should be followed:

- Open and read the TDMS file block by block. At each time, only one block of data is stored in computer memory;
- The smallest unit in one block is 1 segment (333 data traces). The maximum number of segments that can be displayed in one block is 900 due to the memory size limitation of the quad-core computer used in this study;
- Choose the number of segments to be displayed in one block (e.g., \( n \) segments). Each time, \( n \) segments of data will be displayed in a B-scan image; and
- Use the “Next” and “Previous” buttons (see Figure 35) to display the next and previous \( n \) segments of data, respectively.

For demonstration purpose, a 1.125 GB data set was processed. We were unable to open such a large data set using normal data processing methods. Using the above data processing tool, we were able to open the data set and read data block by block. The lead in information of this GPR (.tdms) file is shown in Figure 33.

![Figure 33 Demonstration - data file information.](image)

This data set has 5,408 segments which are saved in TDMS file format. As shown in Figure 33, the program is configured to open 500 segments in each block, which results in 11 blocks. Figure 34 through Figure 36 show some demonstration screenshots for this data set.

![Figure 34 Demonstration - data information.](image)
3.2.3. Dual Channel Control Configuration

The developed software system has two parallel scan channels that operate in “ping-pong” mode. Since both channels share the same data acquisition unit, the high speed ADC has to collect data from the two channels alternatively. A challenging issue here is when the collected data is continuously streamed into the ADC and stored in hard disk, how to identify the
source channel of each data segment precisely? To solve this problem, the frame synchronization approach used in communication systems is adopted. The proposed approach adds a synchronization head to the data to distinguish the two channels. At the beginning of each scan, one channel is set to have oscillating signal while the other is kept silent for certain clock cycles. During radar scan process, such a synchronization operation is performed periodically (e.g., once every 10 minutes) to prevent radar from losing synchronization due to system metastability or other interference effects. Figure 37 shows an example of separating radar data from different channels under time trigger mode. Figure 38 shows an example of separating radar data from dual channels under wheel encoder trigger mode.

The whole GPR data containing Channel 1 and Channel 2:

Channel 1 data:

Channel 2 data with self-check blank data:

Figure 37 Dual channels radar data under time trigger mode.
3.3. Signal Processing Algorithms

3.3.1. Railroad GPR B-Scan Image Enhancement

In addition to the user interface and the control program, a five-step signal processing approach has been developed to improve the B-scan image quality. The flowchart of this signal processing approach is shown in Figure 39. The first step is to remove random noise by performing averaging operation; the second step is image resolution improvement. In B-scan images, most object features have small dimensions and may be fuzzy to be recognized. To resolve this issue, a Bicubic interpolation algorithm is developed to leverage data resolution so as to improve image quality. The Bicubic interpolation considers not only the pixel value of the interpolation point but also the derivatives of 16 pixels (4 × 4) surrounding it. Compared to other interpolation algorithms such as bilinear and nearest neighbor, the Bicubic interpolation can generate much smoother results; the third signal processing step is the adaptive gain enhancement. Due to the signal attenuation during transmission, the reflection signals from deep layers are often blurred by the strong reflections from shallow layers. In this study, an adaptive signal gain manipulation method is applied to compensate deep layer reflection signal attenuation; Hilbert Transform is often used in communication demodulation, which can...
effectively extract the modulated baseband signal from the modulation. In our GPR image processing, Hilbert Transform is implemented to extract the pulse signal envelope based on the signal power characteristics; the fifth step is background removal. In B-scan images, the strong air-ground surface reflection and other clutters can blur subsurface object signals. The background removal step is to extract subsurface object signals from the background images. For ballast contamination assessment, an analytic method using Hilbert Transform is also applied to extract reflection signal power information.

- **System and Environmental Noise Removal**
  - Ensemble Averaging
- **Image Resolution Improvement**
  - Bicubic Interpolation Algorithm
- **Signal Attenuation Compensation**
  - Adaptive Gain Adjustment
- **Signal Envelope Extracting**
  - Hilbert Transform
- **Background Removal**
  - Average Subtracting Filter

Figure 39 B-scan image enhancement flowchart.

To evaluate the performance of the five-step signal processing approach, experiments were conducted with two different setups. The first setup was designed for mimicking a railroad segment with wood ties and subsurface pipelines. The second setup was for inspecting railroad segments containing fouled ballast.

![Figure 40 Setup with wood ties and underground pipelines: (a) lab setup, and (b) subsurface features.](image)

Figure 40(a) shows the test platform used to emulate a segment of railroad. The wood ties (lumbers) are spaced 1 foot apart. Figure 40(b) illustrates how the subsurface structures are designed: (1) The ballast layer right above the soil is 8 inches thick; (2) One rebar is buried at the ballast-soil interface. The rebar diameter is 2 inches; and (3) Two metal pipes (diameter = 2 inches) and one PVC pipe (diameter = 4 inches) are buried inside the soil layer. Their burying depths are 18 inches, 24 inches, and 26 inches from the surface of the ballast layer, respectively.
Figure 41 B-scan results for wood ties and pipelines: (a) raw B-scan, (b) interpolation + adaptive gain enhancement, and (c) background removal.

Figure 41(a) is the raw B-scan image after noise removal. Figure 41(b) is the image after interpolation and adaptive gain adjustment. Figure 41(c) is the image obtained from Figure 41(b) after background removal. It can be seen that after removing background clutters, the features for surface and subsurface objects become much more pronounced. As shown in Figure 41(c), these features include four hyperbola curves for the wood ties, one hyperbola for the rebar, two hyperbolas for the metal pipes, and one hyperbola for the PVC pipe.

Figure 42 Ballast condition assessment test configuration: (a) dry and clean ballast, (b) dry and fouled ballast, (c) wet and fouled ballast, (d) ballast buried in ground, and (e) GPR system.

To further test the GPR system and the five-step signal processing approach, the developed GPR system was used for assessing ballast conditions. As shown in Figure 42, three different test scenarios were considered, including dry and clean ballast, dry and fouled ballast, and wet and fouled ballast. For the dry and clean ballast scenario, a 2 feet long, 1 foot wide, and 3 inches deep hole was filled up with dry and clean ballast. For the dry and fouled ballast scenario, soil and sand was mixed with the clean ballast. For the wet and fouled ballast scenario, approximately one gallon of water was evenly spread over the fouled ballast surface.
For the dry and clean ballast scenario, large air voids exist in the ballast, causing strong signal scattering effect. For the dry and fouled ballast scenario, since the air voids are filled by a mixture of soil and sand, the scattering effect is relatively low. While for the wet and fouled ballast scenario, the moisture content further reduces the strength of the reflected radar signal, which results in the weakest scattering effect and the lowest reflection signal amplitude.

![Figure 43 B-scan images for dry and clean ballast: (a) raw B-scan, (b) processed B-scan, and (c) normalized energy map.](image)

![Figure 44 B-scan images for dry and fouled ballast: (a) raw B-scan, (b) processed B-scan, and (c) normalized energy map.](image)
Figure 45 B-scan images for wet and fouled ballast: (a) raw B-scan, (b) processed B-scan, and (c) normalized energy map.

Figure 43(a), Figure 44(a), and Figure 45(a) show the de-noised (i.e., the first step in Figure 39) B-scan images for dry and clean ballast, dry and fouled ballast, and wet and fouled ballast, respectively. In these images, the direct coupling signal between the transmitter and the receiver antennas locates between 1 ns and 4 ns. For the ballast, its top surface’s reflection signal locates at 5 ns; the reflection signal of ballast locates between 6 ns and 8 ns; and its bottom surface’s reflection is at 8 ns. A comparison of the three images does show some differences. However, they are insignificant and can be easily overlooked. Therefore, the remaining four steps of the five-step signal processing method were applied to these images.

After applying the remaining four steps, the power distribution features of reflection signals are extracted and plotted in Figure 43(b), Figure 44(b), and Figure 45(b) for the three scenarios. Their normalized power maps are shown in Figure 43(c), Figure 44(c), and Figure 45(c), respectively. For the dry and clean ballast, its normalized energy is close to 1, while the corresponding value is 0.9 for the dry and fouled ballast and 0.5 for the wet and fouled ballast. As the above analysis suggests, these quantitative power parameters can effectively characterize ballast conditions.

3.3.2. Interest Region Detection Using 2D Entropy

About 300 GB GPR data was collected during the field tests. Given such a large data set, it would be difficult and time-consuming to review the B-scan images manually. Automating the data analysis becomes both important and necessary. Since the developed GPR system is mainly for subsurface defect inspection, an A-scan decomposition method was first utilized to automatically separate cross-ties from ballast layer before any further data analyses. After these two layers are separated, different algorithms can be developed to analyze them separately rather than applying the same algorithm to both of them. For the subsurface layers, a 2D entropy method was developed to automatically identify problematic or suspicious features for further analysis. Before the 2D entropy analysis, four pre-processing steps are applied:

- Step 1: Stacking every 100 traces waveforms;
- Step 2: Background removal using subtracting average;
- Step 3: Low pass filter with 2 GHz cutoff frequency to remove high frequency noise; and
- Step 4: Stacking every 10 traces waveforms.

After the pre-processing steps, signal decomposition based on cross correlation was applied to mark the cross-ties. Using the direct coupling pulse as the reference signal, an A-scan waveform can be decomposed into combinations of this reference signal with varying amplitudes and time delays. The decomposed signal patterns represent the reflection signals from scatters (e.g., underground objects and layer interfaces). In our B-scan images, the first echo was the antenna direct coupling signal, and the second echo was the reflection signal from cross-ties. Based on the signal decomposition result, the cross-ties were marked out and separated from the ballast and soil layers underneath it.

Following the signal decomposition, the 2D entropy method was utilized to characterize the singularity and similarity of subsurface structures. High entropy values indicate high similarity, while low entropy values mean high singularity. Based on this principle and the entropy analysis results, heterogeneous regions in B-scan images were marked out automatically. This 2D entropy method has been applied to the data collected both in the UMass Lowell radar lab and from Metro St. Louis.

![Figure 46 Test configuration in UMass Lowell radar lab.](image)

Figure 46 shows the test platform containing both dry and wet ballast in the UMass Lowell radar lab. The region inside the red circle contains wet ballast while the remaining region contains dry ballast.
Figure 47 shows the pre-processed B-scan image for the lab test configuration shown in Figure 46. Based on the A-scan decomposition result, the subsurface layers are located and shown in Figure 48.

Figure 47 Pre-processed B-scan image based on UMass Lowell lab data.

Figure 48 Subsurface layers.
The 2D entropy was calculated for the subsurface layers and the result is shown in Figure 49. The left figure shows the entropy values in the horizontal direction while the right one shows the entropy values in vertical direction. The two dashed lines in Figure 49 illustrates the thresholds. The thresholds were determined by the OTSU method. The regions below the threshold lines are considered singular.

Figure 50 shows the 2D entropy analysis result for the UMass Lowell radar lab data, which is for wet and fouled ballast. The red horizontal line is the ballast-soil interface. The region below this line is for soil. The focus in this experiment is the ballast layer so the singular region in the soil layer is not considered. As Figure 50 suggests, the 2D entropy method was able to successfully identify the wet ballast region and automatically mark it by a red rectangle. The location of the red rectangle matches the actual wet ballast region in the lab setup.
Figure 51 Field tests.

Figure 51 shows the GPR field test in St. Louis. An approximately 8-meter section from the St. Louis MetroLink’s Cross County line was selected to demonstrate the developed GPR system and the signal processing algorithms. This 8-meter section consists of 300 segments and each segment consists of 333 data traces.

Figure 52 Processed B-scan image.
The pre-processed B-scan image for this 8-meter section is shown in Figure 52. After applying the signal decomposition method, the cross-ties were singled out and the result is shown in Figure 53. The red line is the marker for antenna direct coupling signal. The light blue curves are the markers for cross-tie reflection signals.

Figure 54 Localized subsurface layer.
Based on the marked cross-ties, the subsurface ballast layer was localized to be from 13 ns to 24 ns as shown in Figure 54. The 2D entropy was calculated for the ballast layer as shown in Figure 55. Based on the 2D entropy result and the threshold values determined by the OTSU method, three suspicious subsurface ballast regions were marked by red rectangles in Figure 56. These three regions in this section may contain abnormal features (e.g., pipelines or fouled ballast) that deserve further investigation.

As shown in Figure 56, the developed signal processing algorithms were able to
automatically identify abnormal regions from the field data. Unfortunately, the research team was not allowed to dig in the field (This was why a wooden box was constructed in the UMass Lowell radar laboratory) due to safety reasons. Otherwise, it would be very interesting to find out what was there in the field and use it to validate the developed signal processing algorithms.

3.3.3. Batch Processing

A Matlab code frame has been implemented to run the abovementioned algorithms. This code frame has been applied to process the collected radar .tdms data files. Each rail transit line was divided into 10-meter blocks and a JPEG file was generated for each block. A flow chart describing the Matlab code frame is shown in Figure 57.

![Figure 57 Flow chart showing the Matlab code frame.](image)

During batch processing the GPR data, the Matlab program went through data blocks one by one using an address pointer as the indicator. For each data block, the GPR data was processed by the above enhanced 2D entropy algorithm. The processed result was then saved as a JPEG image.