**Thickness Prediction Improvement using CC9 GPR Data**

CC9 baseline Ground Penetrating Radar (GPR) survey data showed 900 MHz ground-coupled antenna had a thickness difference than 0.5-inch between the mean predicted and as-built thickness for asphalt layer (P-401MR) on several test items, while the thickness difference from 2 GHz air-coupled antenna was relatively low, i.e., 0.1 – 0.6-inch. This discrepancy was possibly due to less accuracy in signal velocity (or, dielectric constant) in P-401MR, which was determined from the ‘Ground-Truth’ information for ground-coupled antenna and metal-plate calibration for air-coupled antenna. To improve the thickness prediction, following analysis procedure were taken:

1. Re-visited the ground-truth information to determine the ‘Ground-Truth Elevation’
2. Conducted the ‘Metal Plate Calibration’ test using 2 GHz air-coupled antenna at higher sampling rate
3. Performed advanced analysis on GPR data obtained from survey using 900 MHz ground-coupled antenna on the ground-truth location
4. Determined signal velocity and predicted asphalt layer thickness (i.e., P-401MR + P-403MR for LFS-1 through LFC-2 and P-401MR for LFC-3 through LFC-5)
5. Assessed improvement of thickness prediction for both ground-coupled and air-coupled antenna

***Cart-Mounted System (900 MHz Ground-Coupled Antenna)***

1. Re-visit of Ground-Truth Elevation

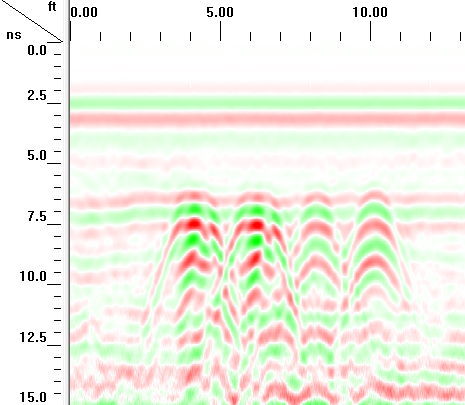
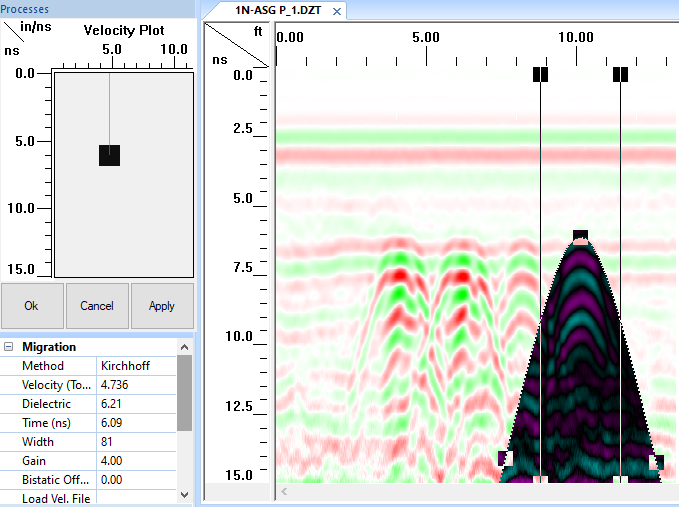
* On CC9 as-built, the depth of instrumentation (e.g., PC) was taken from the pavement surface to the middle of the sensor.
* The thickness of sensor was measured at 1-inch for PC and 0.1875~0.3125 inch for LSG/TSG (i.e., sensor and anchor respectively).
* Exact depth of PC (*h*) = as-built Z – 0.5\*PC thickness, and the depth of LSG/TSG reported on as-built was correct (information summarized in Table 1).

Table 1. Summary of Ground-Truth Elevation

|  |  |  |  |
| --- | --- | --- | --- |
| Test Item | Gage ID | Depth of Gage (inch) | |
| As-Built | Exact |
| LFS-1N | PC-LFS1N-1 | 11.0 | 10.5 |
| LSG-LFS1N-1/2 | 11.0 | 11.0 |
| LFS-2N | PC-LFS2N-1 | 11.0 | 10.5 |
| LSG-LFS2N-1/2 | 11.0 | 11.0 |
| LFC-3N | PC-LFC3N-1 | 5.0 | 4.5 |
| LSG-LFS3N-1/2 | 5.0 | 5.0 |
| LFS-4N | LSG-LFS4N-1/2 | 5.0 | 5.0 |
| LFC-5N | PC-LFC-5N-11 | 9.0 | 8.5 |
| LSG-LFS5N-1/2 | 3.0 | 3.0 |

Note-1: PC is installed underneath P-209MR base layer

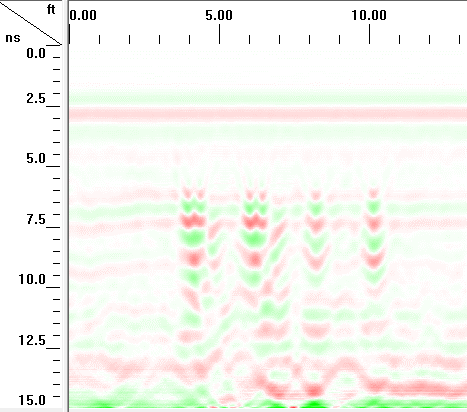
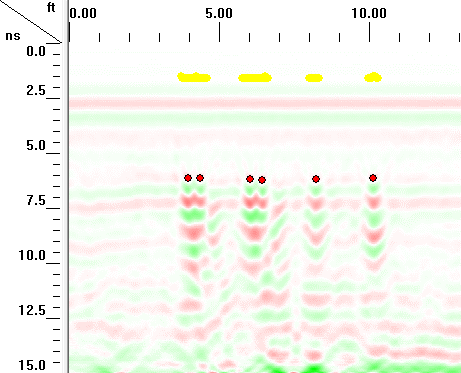
1. Advanced analysis of GPR Ground-Truth Data
2. Several options (which are embedded in RADAN 7) were explored that includes filtering, background removal, migration, and so on. ‘Infinite Impulse Response (IIR) filter’ and ‘Migration’ were selected to enhance GPR image quality and improve the accuracy of thickness prediction.
3. Multiple rounds of discussions were conducted with the experts from GSSI, including data sharing. While agreed on the proposed procedure, GSSI provided recommendations on the sequence of analysis, accurate method of performing ‘Migration’, and acceptable limits for ‘IIR filter’.
4. Analysis details included: (a) Apply ‘Migration’ technique to locate the apex of the hyperbolic reflection that corresponds to the exact location of ‘Ground-Truth’; (b) Apply filter (High Pass: 300 MHz and Low Pass: 2500 MHz) to reduce noise level; (c) Track the pavement surface and exact location of ‘Ground-Truth’ to determine the 2-way travel time (*t*) in asphalt layer, i.e., P-401MR + P-403MR for LFS-1 through LFS-2 and P-401MR for the remaining test items; and (d) Determine the signal velocity: , where depth of ‘Ground-Truth’ as obtained in Step A. Note that GSSI suggested to adjust the pole number during implementation of IIR filter, however this option is currently not available in FAA’s RADAN 7 (may need software update).
5. Examples of the image processing are shown in Figure 1 and 2 for strain gages (LSG and TSG) and pressure cell locations, respectively. The hyperbolas on Figure 1(a) and 2(a) were generated due to the multiple signal reflections from the embedded gages at varying distance during the GPR cart movement. On Figure 1(b) and 2(b), the so-called ‘Ghost Hyperbola’ was positioned on the original hyperbola, followed by adjusting the shape and width. After executing the ‘Migration’, the ‘IIR Filter’ was applied to remove the possible noise and the images are shown in Figure 1(c) and 2(c). On both images, the hyperbolas were concentrated or shifted to ‘Dot(s)’, which correspond to the exact location of the embedded gages. The ‘Total 2-way Travel Time’ of signal reflected from pavement surface and embedded gages was determined after tracking these interfaces, as shown in Figure 1(d) and 2(d).
6. 2-way travel time () between pavement surface and embedded gages was then determined from the Total 2-way Travel Time, as extracted in the previous Step 4. Signal velocity in asphalt layer was then determined using the relationship: , and averaged per test item. Distribution of the average signal velocities in asphalt layer are shown in Figure 3.

Hyperbolas at LSG & TSG locations

Ghost Hyperbola

(a) (b)

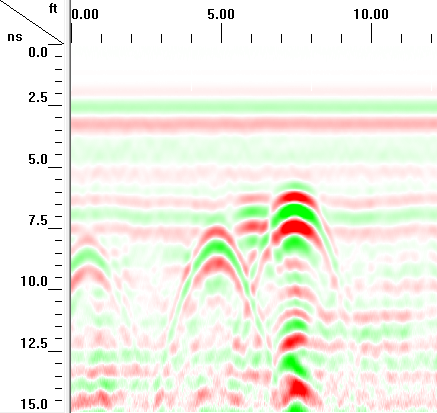
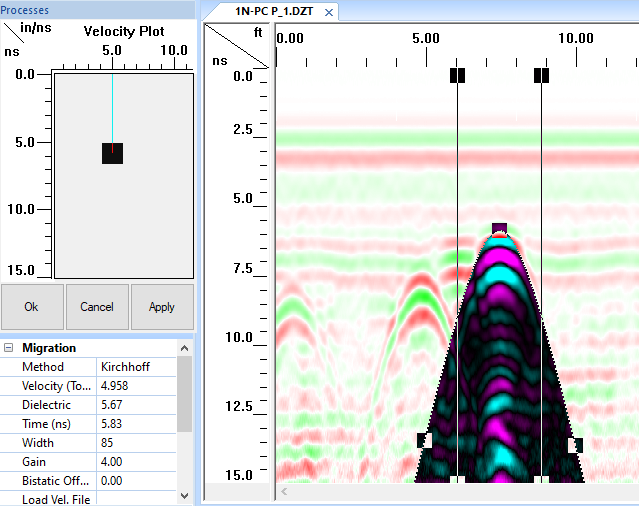
Total 2-way Trave time (LSG & TSG)

Total 2-way Trave time (Pavement Surface)

Dots at LSG & TSG locations after Migration & Filter

(c) (d)

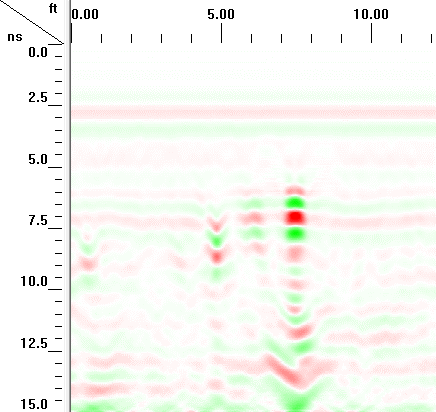
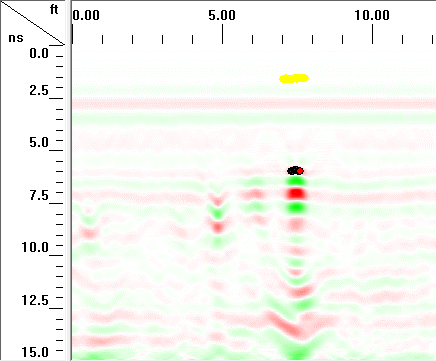
Figure 1. GPR Image Processing on LSGs and TSGs in LFS-1N: (a) Raw data; (b) Migration; (c) After Migration & Filtering; and (d) Extraction of 2-way travel time.

Hyperbola at PC location

Ghost Hyperbola

(a) (b)

Total 2-way Trave time (PC)

Total 2-way Trave time (Pavement Surface)

Dot at PC location after Migration & Filter

(c) (d)

Figure 2. GPR Image Processing on PC in LFS-1N: (a) Raw data; (b) Migration; (c) After Migration & Filtering; and (d) Extraction of 2-way travel time.



Figure 3. Distribution of Signal Velocity in Asphalt Layer.

1. Prediction of Layer Thickness
2. CC9 baseline GPR data analysis showed a close match between as-built and predicted asphalt thickness, i.e., P-401MR + P-403MR, for test items LFS-1N and -2N, whereas the remaining test items showed asphalt thickness difference at varying degree. Therefore, GPR data from LFS-1N and -2N were excluded from this advanced data analysis.
3. GPR data files considered in the analysis: (a) Sta: 0+15 and 0+30 (LFS-1S); (b) Sta: 0+75 and 0+90 (LFS-2S); (c) Sta: 1+35 and 1+50 (LFC-3N and -3S); (d) Sta: 1+95 and 2+10 (LFC-4N and -4S); and (e) Sta: 2+55 and 2+70 (LFC-5N and -5S). Note that no GPR data (image) re-processing was needed and the 2-way travel time in asphalt layer was obtained from the baseline data processing.
4. Predicted asphalt layer thickness incorporating the revised signal velocities are summarized in Table 1. Overall, an improvement in thickness prediction was evident (i.e., thickness difference < 10%). It should be pointed out that in case of LFC-5N and -5S the change in asphalt layer thickness during traffic test may not be captured by 900 MHz ground-coupled antenna. A higher frequency antenna is recommended to address the resolution limitation at lower signal frequency.

Table 1. Summary of Layer Thickness (900 MHz Ground-Coupled Antenna)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Test item | Station | Layer | Signal Velocity, in/ns | As-built Thickness, inch | Predicted Thickness, inch | | (%) Difference in Thickness | |
| Advanced Analysis | Baseline | Advanced Analysis | Baseline |
| LFS-1S | 0+15 | P-401MR+P403MR | 4.80 | 8.9 | 8.9 | 9.1 | 0.0 | 2.2 |
| 0+30 | 9.1 | 9.3 | 2.2 | 4.5 |
| LFS-2S | 0+76 | P-401MR+P403MR | 5.63 | 8.7 | 8.4 | 9.0 | 3.4 | 3.4 |
| 0+90 | 8.7 | 9.2 | 0.0 | 5.7 |
| LFC-3N | 1+35 | P-401MR | 4.77 | 5.1 | 4.9 | 6.4 | 3.9 | 25.5 |
| 1+50 | 5.1 | 6.6 | 0.0 | 29.4 |
| LFC-3S | 1+35 | P-401MR | 4.77 | 5.2 | 5.0 | 6.5 | 3.8 | 25.0 |
| 1+50 | 5.2 | 6.8 | 0.0 | 30.8 |
| LFS-4N | 1+95 | P-401MR | 4.45 | 5.1 | 4.6 | 6.4 | 9.8 | 25.5 |
| 2+10 | 4.7 | 6.4 | 7.8 | 25.5 |
| LFC-4S | 1+95 | P-401MR | 4.45 | 5.2 | 5.1 | 6.9 | 1.9 | 32.7 |
| 2+10 | 5.2 | 7.0 | 0.0 | 34.6 |
| LFC-5N | 2+55 | P-401MR | 4.39 | 3.3 | 3.6 | 5.1 | 9.1 | 54.5 |
| 2+70 | 3.5 | 5.0 | 6.1 | 51.5 |
| LFC-5S | 2+55 | P-401MR | 4.39 | 3.3 | 3.6 | 5.1 | 9.1 | 54.5 |
| 2+70 | 3.5 | 5.0 | 6.1 | 51.5 |

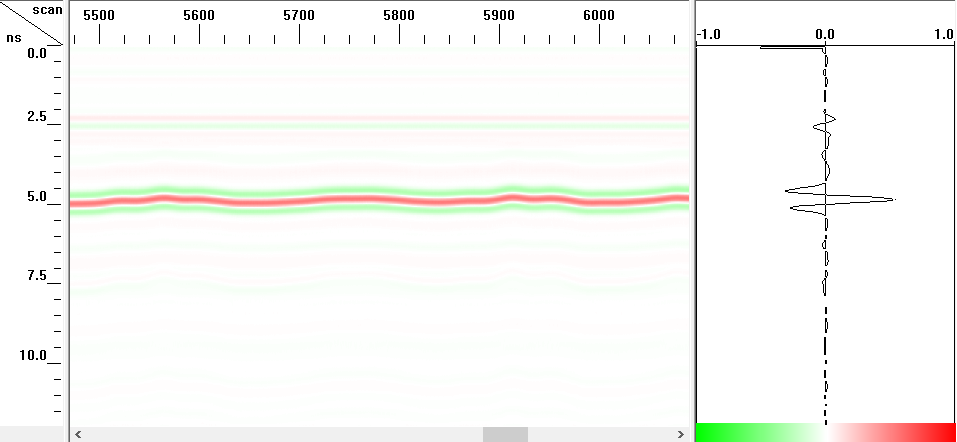
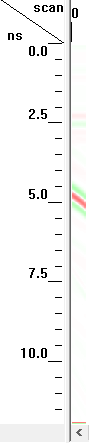
***Van-Mounted System (2 GHz Air-Coupled Antenna)***

CC9 baseline analysis on GPR data from 2 GHz air-coupled antenna showed much less thickness difference between the predicted and as-built thickness, which was performed in the following sequence:

* 1. Performed ‘Metal Plate Calibration’ test at a sampling rate of 256 samples/scan
  2. Conducted one full-length survey on north side of CC9 test pavement at the same sampling rate
  3. Determined signal velocity in asphalt layer from the two files as obtained from Step 1 and 2 using the so-called ‘Surface Reflection’ method
  4. Extracted 2-way travel time in asphalt layer from the GPR survey data from the raw image (data)
  5. Predicted asphalt thickness from the signal velocity and 2-way travel time.

Above data processing and analysis were time-consuming, therefore the automated method embedded in RADAN 7 was evaluated to facilitate the entire process:

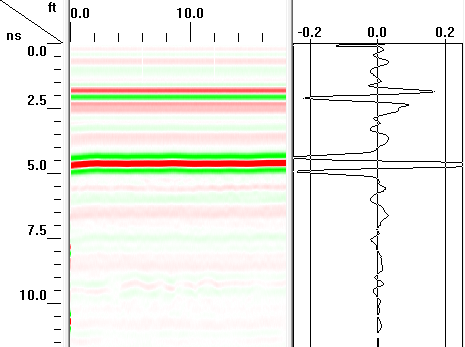
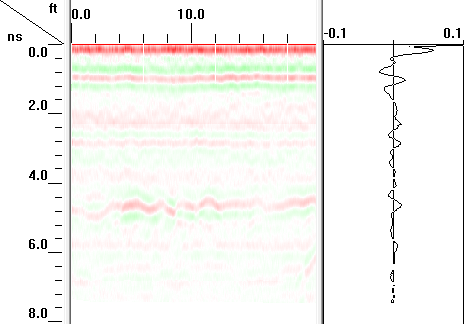
1. A metal plate calibration test was conducted at higher sampling rate such as 512 samples/scan, while another set of data at lower sampling rate, such as 256 samples/scan, was available from the baseline survey. During the test, the 2 GHz antenna was placed above a metal plate with cleaned dry surface, and the data was collected in ‘Time Scan’ mode (an illustration was included in the baseline report).
2. These data files (at 256 and 512 samples/scan) were then converted to the calibration file (.czt) in RADAN 7 (using the ‘Horn Calibration’ option), as shown in Figure 4.
3. Converted calibration files were then integrated to the baseline GPR survey data files obtained at -17.25 and +17.25 feet offset (north and south side respectively) to: (a) eliminate the direct-coupling and re-position the pavement surface on the GPR image (see Figure 5); and (b) determine the signal velocity in asphalt layer (the correlation was included in the baseline report).
4. Layer interface (i.e., bottom of asphalt layer) was tracked and 2-way travel time in asphalt layer was determined. Asphalt layer thickness was then determined from the 2-way travel time and signal velocity (the correlation was included in the baseline report).
5. Predicted asphalt thickness distribution over the test items is summarized in Table 2. Overall, noticeable improvement was not observed in thickness prediction. However, thickness difference was less than 10% on most of the test items, which agreed with the opinion from GPR experts. Between sampling rate, (%) thickness difference was relatively low for sampling rate of 256 samples/scan.
6. On LFC-5S, thickness difference was more than 10%. Field cores are needed to further improve thickness prediction.

Direct Coupling

Undulation in Metal Plate Reflection during Bumper Jump

Figure 4. Generation of Calibration File (in RADAN 7).

Bottom of P-403MR

Pavement Surface

Bottom of P-403MR

Pavement Surface

(a) (b)

Figure 5. Processing of 2 GHz Air-Coupled Antenna Data: (a) Raw data; and (b) After integrating calibration file.

Table 2. Summary of Layer Thickness (2 GHz Air-Coupled Antenna)

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Test Item | Station | | As-built Thickness, inch | Sampling Rate: 256 samples/scan | | Sampling Rate: 512 samples/scan | | Baseline Analysis | |
| Predicted Thickness, inch | (%) Difference in Thickness | Predicted Thickness, inch | (%) Difference in Thickness | Predicted Thickness, inch | (%) Difference in Thickness |
| Start | End |
| LFS-1N | 0+00 | 0+45 | 10.8 | 11.3 | 4.6 | 11.4 | 5.6 | 10.7 | 0.9 |
| LFS-1S | 0+00 | 0+45 | 8.9 | 9.4 | 5.6 | 9.4 | 5.6 | 8.7 | 2.2 |
| LFS-2N | 0+60 | 1+05 | 10.8 | 11.4 | 5.6 | 11.7 | 8.3 | 10.7 | 0.9 |
| LFS-2S | 0+60 | 1+05 | 8.7 | 9.1 | 4.6 | 9.2 | 5.7 | 8.5 | 2.3 |
| LFC-3N | 1+20 | 1+65 | 5.1 | 5.5 | 7.8 | 5.6 | 9.8 | 5.3 | 3.9 |
| LFC-3S | 1+20 | 1+65 | 5.2 | 5.5 | 5.8 | 5.6 | 7.7 | 5.1 | 1.9 |
| LFS-4N | 1+80 | 2+25 | 5.1 | 5.1 | 0.0 | 5.2 | 2.0 | 5.0 | 2.0 |
| LFC-4S | 1+80 | 2+25 | 5.2 | 5.5 | 5.8 | 5.6 | 7.7 | 5.2 | 0.0 |
| LFC-5N | 2+40 | 2+85 | 3.3 | 3.5 | 6.1 | 3.6 | 9.1 | 3.4 | 3.0 |
| LFC-5S | 2+40 | 2+85 | 3.3 | 3.8 | 15.2 | 3.9 | 18.2 | 4.0 | 21.2 |

***Recommendations***

* Full-width 900 MHz ground-coupled antenna survey is recommended to continue for the monitoring of possible layer thickness change during traffic test, because significant improvement in thickness prediction was achieved.
* GPR survey using 2 GHz air-coupled antenna shall be performed at sampling rate of 256 samples/scan due to the level of accuracy. In addition, data size will be smaller, which may save memory storage and reduce processing time.
* Field cores are needed to enhance thickness prediction by the air-coupled antenna, especially LFC-5S.
* RADAN 7 needs software upgrade to obtain additional features that may be required in advanced data analysis.