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Research, Development and Technology Division

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Final Report

High Accuracy Pavement Thickness Measurement Using Ground Penetrating Radar

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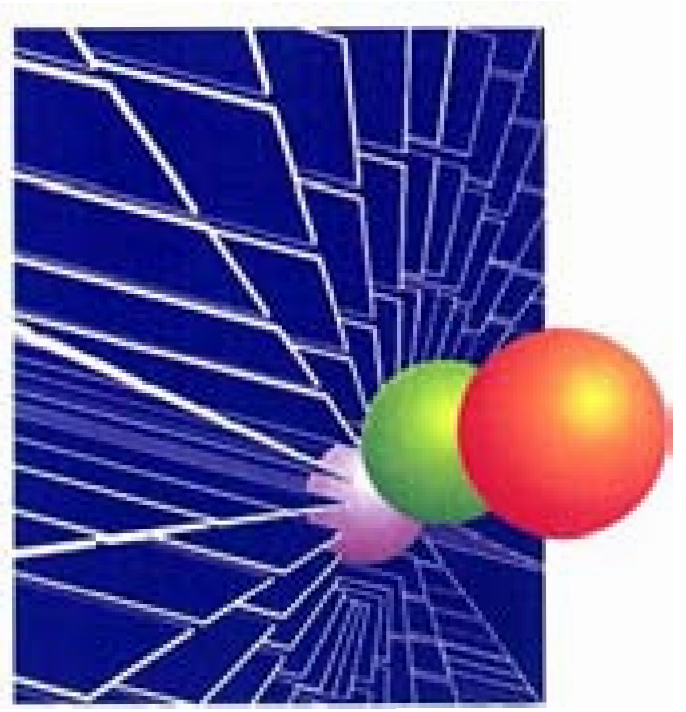

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16. Abstract

Ground Penetrating Radar (GPR) interpretation technology developed through the Strategic Highway Research Program (SHRP) was used to non-destructively determine pavement thickness on new pavements. The new pavements were bid per square yard (SY) of pavement surface area as either portland cement concrete pavement (PCCP) or full depth asphaltic concrete (AC). Since bid per SY the pavements must meet Missouri specifications requiring the pavement to be no more than 0.2 inches thin of the plan depth. MoDOT contracted with Pavement Systems Engineering and INFRASENSE Inc. to obtain and compare GPR data on the pavement thickness with the cores commonly taken for quality control and assurance by MoDOT. It was believed that GPR with good interpretation software and employing some special techniques could be capable of measuring to the 2/10 inch tolerance needed and in the future replace current coring practices (destructive testing) with GPR testing (non-destructive).

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High Accuracy Pavement Thickness Measurement Using Ground Penetrating Radar

FINAL REPORT

RDT 99-003
Research Investigation 96-011

PREPARED BY

MISSOURI DEPARTMENT OF TRANSPORTATION

RESEARCH, DEVELOPMENT AND TECHNOLOGY DIVISION

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The opinions, findings, and conclusions in this publication are those of the Missouri Department of Transportation

They are not necessarily those of the Department of Transportation, Federal Highway Administration. This report does not constitute a standard, specification or regulation.

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James Cape & Sons Co., Rt. 71, Newton County project

EXECUTIVE SUMMARY

Ground Penetrating Radar (GPR) interpretation technology developed through the Strategic Highway Research Program (SHRP) was used to non-destructively determine pavement thickness on new pavements. The new pavements were bid per square yard (SY) of pavement surface area as either portland cement concrete pavement (PCCP) or full depth asphaltic concrete (AC). Since bid per SY the pavements must meet Missouri specifications requiring the pavement to be no more than 0.2 inches thin of the plan depth. MoDOT contracted with Pavement Systems Engineering and INFRASENSE, Inc. to obtain and compare GPR data on the pavement thickness with the cores commonly taken for quality control and assurance by MoDOT. It was believed that GPR with good interpretation software and employing some special techniques could be capable of measuring to the 2/10 inch tolerance needed and in the future replace current coring practices (destructive testing) with GPR testing (non-destructive).

On the two (2) Asphaltic Concrete pavements the GPR data when calibrated with two core measurements had an accuracy of 0.17 inches or 1.4% compared to 30 cores on a 12" AC pavement and 0.2 inches or 1.1% compared to 49 cores on a 17" AC pavement. On the 14" concrete pavement GPR had an accuracy of 0.39" or 2.8% compared to 70 cores. For the AC thickness this was close to the 0.2" (accuracy figured on AC was not the absolute mean) but MoDOT may never let another AC pavement paid by the square yard. For the concrete this was at least twice the 0.2 " in the specifications. A new technique of placing a reflective target (3'x3' aluminum foil) under the pavement to increase accuracy seemed to help on the AC jobs but the aluminum reacted with cement in the PCCP and the targets couldn't be found by the GPR, using a piece of steel pipe as suggested by INFRASENSE, Inc. may increase the accuracy in the future.

Even on the PCCP results were promising enough that it is proposed that GPR should be considered as a replacement for present "destructive" coring practices. It was proposed by one of the GPR contractors that "Smart Coring" be done. GPR would be run to find the suspected thin areas of pavement and coring only done in these areas. GPR has the additional advantage that it gives a continuous reading of the thickness (every 1' or less) compared to a core every 1000 ft. It can also find anomalies which could be defects in the new pavement which couldn't be found by coring. It is proposed that more study should be made in the areas of using GPR to find defects such as stripping and segregation in new AC pavement and a study using new techniques to try and reduce the error on measuring thickness in new PCCP so that "nondestructive" GPR testing can eliminate "destructive" coring of the new pavement or to implement "Smart Coring" in place of present specifications.

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by Tom Scullion, Pavement Systems Engineering, College Station, Texas

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by Tom Scullion, Pavement Systems Engineering, College Station, Texas

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by Dr. Kenneth R. Maser, INFRASENSE Inc., Arlington, Massachusetts

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PRIORITY TECHNOLOGIES PROGRAM
REGION 7, FHWA

Ground Penetrating Radar (GPR) for Pavement Thickness - Final Report

Project Description:

Ground Penetrating Radar (GPR) interpretation technology developed through the Strategic Highway Research Program (SHRP) was used to non-destructively determine pavement thickness. Missouri Department of Transportation (MoDOT) has contracted several "Experimental Projects With Alternate Bids On Pavement Type". The new pavement was to be bid per square yard (SY) of pavement surface area as either portland cement concrete pavement (PCCP) or full depth asphaltic concrete (AC). Since let per SY the AC pavement must meet the same thickness deficiency specifications as PCCP. Missouri specifications currently require the pavement to be no more than 0.2 inches thin of the plan depth or deductions in contract price are made. It was believed that GPR with good interpretation software and employing some special techniques is capable of measuring to the 2/10 inch tolerance in the 12" to 17" pavement thickness range of these projects.

Advantages:

GPR thickness measurement is much faster than conventional coring, the GPR van can move at 15 mph or more. GPR also provides a continuous scan of the pavement thickness throughout every foot of the length of the project compared to a core taken every 1,000 feet. GPR is also non-destructive so full depth coring in the brand new pavement can be almost eliminated.

Procedure:

Ground Penetrating Radar (GPR) surveys were conducted for the Missouri Department of Transportation by Pavement Systems Engineering (PSE) and INFRASENSE Inc. to compare its accuracy to coring for quality control measurement of the thickness of three new pavements. Projects using both full depth asphaltic concrete (AC) and portland cement concrete pavement (PCCP) were measured. The projects and costs were:

			Thickness		Pavement	GPR Costs(1 pass/12' lane)	
Job No.	Route	County	PCCP	AC	Description	$/Mile	$/Square Yard
J4U0829C	10	Ray	---	12"	3.345mi. - 24'w.	$ 1188	$ 0.17
J9P0292	63	Howell	---	17"	5.261mi. - 24' w.	$ 1188	$ 0.17
J7P0490	71	Newton	14"	---	3.016mi. - 2-24'w.	$ 332	$ 0.05

A van equipped with a 1.0 GHz air launched Pulse Radar antenna and processing equipment was used to run ground penetrating radar profiles down the center of the pavement trying to measure pavement thickness. The same brand of equipment was used on all three projects.

1. First, the aluminum foil was placed on the compacted base material before the AC paving began. In the same manner the aluminum foil was also placed on top of the cement treated permeable base before the PCCP was placed. The aluminum foil test areas were staked so their exact location could be re-established.
2. After all lifts of the asphaltic concrete pavement had been placed the GPR tested the entire length of the project including taking extra tests directly over the aluminum foil test sites. Before the GPR tests were run, a core was provided for calibration of the GPR to determine a dielectric constant for the AC mix thereby providing more accurate depth measurements.
3 Cores were taken at the test sites and lengths recorded for later correlation with GPR data. The raw data was compared to some of the cores immediately for preliminary correlation. Data from both AC test sites were correlated with core data after the software program from TTI (Texas Transportation Institute) had first been used to interpret the raw data. Pavement Systems Engineering's Tom Scullion, who helped develop the software at TTI for SHRP, did the interpretation. Data from the PCCP project was interpreted and correlated to core data by INFRASENSE Inc.'s Ken Maser who also worked in developing software that came out of the SHRP program.
4. A statistical comparison was made of the thicknesses calculated from the raw GPR data, the software interpretation and the actual cores.

Again we were shooting for an accuracy of 0.2 inch to match Missouri's specification allowing no more than 0.2 inch thin of the plan depth.

Results:

The GPR data collected on the two AC projects was judged to be of good quality. The interface between the AC and the Granular Base was clear. The aluminum foil targets worked well in pinpointing the interface and in providing better accuracy for correlation to calibration cores.

I. Route 10, Ray County, 12" thick full depth Asphaltic Concrete (AC)

1. On the 12" AC the average error between the 30 measured core thicknesses and those computed blind, not correlated to cores, with GPR was 0.46 inches or 3.5%. The operator picks a standard dielectric constant such as $\varepsilon = 6$ for asphalt or calculates one from a typical trace of the AC, as was done on this job, to get a first estimate of the thickness. Before data is collected a static calibration of the system is done. The amplitude of the reflection from a metal plate on top of the pavement, A_M, (100% reflection of the signal)

and the amplitude from the top of the AC pavement, A_1, is used in the following equation to calculate the dielectric constant of the asphalt.

$$\epsilon_a = \left[\frac{1+A_1/A_m}{1-A_1/A_m}\right]^2$$

For the AC on Rt. 10, Ray County the dielectric constant was first figured to be $\epsilon_a = 6.54$

2. When two core lengths were plugged in for the two locations given and the software re-figured the ϵ_a, accuracy improved to 0.17 inches or 1.4%.

Figure 11 taken from Pavement Systems Engineering's project report shows a comparison of cores versus GPR calculated thickness for six (6) locations; blind (before correlation with cores) and after correlation with two (2) of the cores.

	Thicknesses (ins)		
Station	**Blind**	**Calibrated**	**Measured**
890 EB	12.3	12.0	12.0
910 EB	13.2	12.9	12.6
930 EB	13.8	*	13.4
935 WB	14.1	*	13.8
905 WB	13.3	13.0	12.8
815 WB	13.9	13.5	13.3
n	6	4	
Mean Error (ins)	0.46	0.17	
Mean Error (%)	3.5	1.4	

Figure 11. Slow Roll Over Test Results, Comparing Calculated and Measured Thicknesses. * Given Core Thickness.

[An additional test was conducted at Station 895WB. At the location the measured and computed (blind) thicknesses were 12.2 and 13.3 inches, respectively. However, upon review there was some uncertainty about whether the GPR data was collected at the correct station. This result was subsequently dropped from the analysis.]

II. US Route 63, Howell County, 17" thick AC

On the 17" AC the average error between the 49 measured core thicknesses and those computed with GPR was 0.2 inches or 1.1%.

The average AC thickness in both lanes was greater than 17.5 inches. Less than 1% of the total project was computed to be less than 16.4 inches thick (the point of 100% deduction in pay or removal by the contractor), these being highly localized short problem areas. In its report, Pavement Systems Engineering stated that GPR may never totally replace coring, but it has the potential of identifying where cores should be taken and to radically reduce the number of cores required on any project. GPR has one more potential benefit, it can be used to check for other defects such as poorly compacted lower layers and for the presence of anomalies within the AC pavement such as stripping or segregation in the mix.

III. US Route 71, Newton County, 14" Portland Cement Concrete Pavement (PCCP)

Several difficulties arose when trying to measure the 14" PCCP.

1. Because the dielectric properties of concrete change as the concrete cures, the pavement could not be surveyed until it was 30 days old.
2. The objective of the aluminum foil sheets placed on top of the base was to provide a reflective target to enhance the detection of the bottom of the concrete using GPR. Coring later showed no signs of the foil, suggesting that the foil had disintegrated through reaction between aluminum and concrete.
3. It has been shown in previous studies that the interface between concrete pavement and crushed limestone base is hard for GPR to distinguish because the dielectric properties of the two are so similar. This has been found a problem more often in old pavement structures. We, however, were interested in seeing the effects over two different types of bases on new construction.
   This project had a cement stabilized permeable base which had a very open void structure. Some limited testing was done on an adjoining job with a Type 5 Aggregate Base which was a much denser graded, compacted, crushed limestone. There was no trouble picking out the interface between the concrete and either the cement treated permeable base or the concrete and the Type 5 base. The thickness data looked good on both projects, however, we had very limited data and no cores to compare thickness calculations against on the Type 5 base project.

Even with the above limitations the average error between the 70 measured core thicknesses on the PCCP and those computed by GPR was 0.39 inches or 2.8%.

In their report, INFRASENSE proposed a way to get better accuracy by picking out the interface between the PCCP and base rock, "An alternative to the aluminum foil ..., would be sections of steel pipe: about 1.5 inches in diameter and 3 feet long, laid flush with the top of the base and transverse to the pavement." (see Figure 11 in the attached INFRASENSE report) "These pipes

would present an even more prominent target than the dowels because of their orientation, and would clearly distinguish the bottom of the concrete from other events in the data."

The table below shows a comparison of the accuracy from each project. A head to head comparison of thicknesses at each of the cores is available in the attached reports from Pavement Systems Engineering (PSE) and INFRASENSE Inc.

Accuracy of GPR calculated thickness versus Core measurements

Route	County	Pavement	No. Cores Compared To	Accuracy (Inches)	Accuracy (%)
10	Ray	12" AC (blind)	30	0.46"	3.5%
10	Ray	12" AC (calibrated)	30	0.17"	1.4%
63	Howell	17" AC (calibrated)	49	0.2"	1.1%
71	Newton	14" PCCP (calibrated	70	0.39"	2.8%

Conclusions and Recommendations:

It was proven that GPR can measure the thickness of AC pavement up to 17" with an accuracy of 0.2 inches. MoDOT at this time, however, is not letting any more pavements for alternate AC/PCCP bids. Additionally a continuous read out of thicknesses will give a more accurate record of the pavement thickness of the project than conventional coring would.

1. If in the future another alternate bid pavement is let and awarded with AC paid by the square yard GPR should be used to measure the pavement thickness and make coring decisions using the GPR data.

2. Of more benefit than thickness measuring, however, would be the use of GPR to look for defects in the new pavement. A study trying to identify AC mixture segregation behind the paver on a new full depth AC pavement or an AC overlay project next construction season should be seriously considered. Texas DOT has several studies going on looking at the use of GPR for quality control of asphalt pavements.

GPR has proven promising enough to consider using it on another new PCCP project as soon as possible. In this study GPR measured to within 0.39 inches on a 14" thick PCCP. With more experience the accuracy can get closer to the 0.2 inches desired. New techniques, such as the target proposed by INFRASENSE, should make thickness measurement accurate enough to cut down or even eliminate the need for coring. Two studies should be considered for use of GPR on PCCP.

1. On an upcoming PCCP job, a special provision could be written calling for cores to be cut only to calibrate the GPR and then coring only to verify areas the collected data shows have deficient pavement thickness or show anomalies which may be due to inferior quality concrete. Advantages over coring would be a continuous record of the whole length of the pavement. Additionally anomalies would be pinpointed so, if desired, coring and repairs of these areas, if warranted, could be made before opening the road to traffic.
2. The effect of different types of base rock being used by MoDOT and GPR's ability to distinguish a clear interface between the PCCP and the top of the base rocks should be studied. This could be incorporated into the same paving project with the GPR thickness of PCCP mentioned above, or incorporated into a later project, or split up between several projects designed using different base rocks or the dielectric constants of different bases could be determined in the laboratory.

Study 2 above needs to be done, however, if ground penetrating radar is going to be used in the future by MoDOT. It is necessary to know the characteristics of the base rock to interpret data from both new or old pavements. The completion of the two studies above would verify that GPR measurement of thickness could be substituted for present coring procedures for all future PCCP projects.

Appendix A

LAYER THICKNESS MEASUREMENTS WITH GROUND PENETRATING RADAR ON SH 10 NEAR RICHMOND, MISSOURI

by

Tom Scullion
Pavement Systems Engineering
College Station, Texas

LAYER THICKNESS MEASUREMENTS WITH GROUND PENETRATING RADAR ON SH 10 NEAR RICHMOND, MISSOURI

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This project was funded by the Missouri Department of Transportation (MoDOT). Mr. John Wenzlick of the Missouri DOT is acknowledged for proposing and sponsoring the study. The support of Mr. Steve Saxton of the FHWA is greatly appreciated. Mr. Dave Turner of Pulse Radar Inc., Houston collected the GPR data and performed the required calibration tests.

DISCLAIMER

Mr. Tom Scullion P.E. of Pavement Systems Engineering processed the GPR data and wrote this report. The conclusions drawn are his and do not necessarily represent the views of the Missouri Department of Transportation.

SECTION 1. SUMMARY OF RESULTS

1.1) Purpose of Study

This study was conducted by Pavement Systems Engineering (PSE) of College Station Texas in cooperation with Pulse Radar Inc. of Houston Texas to demonstrate the capabilities of Ground Penetrating Radar (GPR) and automated signal processing techniques to the Missouri Department of Transportation (MoDOT). The application involved measuring the thickness of the Hot Mix Asphalt (HMA) of a recently completed section of SH 10 near Richmond, in Ray County, Missouri. The plan thicknesses called for 1.75 inches of Type C Asphaltic Concrete, 10.25 inches of Plant Mix Bituminous Base and 4 inches of Type 5 Aggregate base. The paving of SH10 was let as an Experimental Project for Alternate Bids on Pavement Type, with either alternate concrete or asphalt pavement. As is common practice for concrete pavement the contractor will receive a penalty if the total layer thickness is greater than 0.2 inches less than the design thickness of 12 inches. A "no-pay" or "dig out and replace" situation occurs in sections where the total thickness is greater than 0.6 inches less than the design thickness. To validate the in place thicknesses MoDOT takes cores from the pavement at regular intervals along the completed project. If deficient sections are detected the coring interval is reduced to define the extent of the problem. In the "no-pay" situation a core may be taken as frequently as every 20 foot in all lanes.

There are several problems with the current thickness verification procedure. Firstly, there is no guarantee that the coring operation will locate any problem areas, it is essentially a hit and miss operation. Secondly, when the "no-pay" situation is found numerous cores are taken from the new pavement, which at the very least is difficult to explain to the traveling public and at the worst the coring may reduce the strength of the remaining pavement. For these reasons the MoDOT is evaluating if Ground Penetrating Radar can assist in this task. GPR may never totally replace coring but it has the potential of identifying where cores should be taken and to radically reduce the number of cores required on any project. GPR has one more potential benefit, it can be used to check for other defects such as poorly compacted lower layers and for the presence of anomalies within the HMA.

To evaluate the potential of GPR the Missouri DOT contracted with PSE of College Station, Texas to evaluate two new thick HMA projects in Missouri. This report presents the

results from the first of these projects a 3.345 mile section of SH 10 near Richmond, Missouri. In the following sections of this report the basics of GPR will be presented as well as detailed listings of the computed thicknesses. In the remainder of this section a summary of the results obtained will be presented.

1.2) Thickness Results

A summary of the deficient sections found on SH10 are tabulated below;

"No-Pay" locations detected by GPR (Thickness less than 11.4 ins)

Lane	Station From	To	Distance Feet
EB	838+59	839+33	74

Deficient Sections less than 11.8 inches thick

Lane	Station From	To	Distance Feet
EB	774+01	774+17	16
EB	832+69	832+83	14
EB	838+69	839+70	97 **
EB	841+98	842+22	24
EB	842+85	843+00	15
EB	843+18	843+27	9
EB	843+41	844+70	29
EB	892+75	893+72	97
WB	880+09	879+88	21
WB	771+11	771+30	19

**** includes section (74 ft) less than 11.4 inches thick.**

1.3) Location of Defects in HMA

The GPR data were also used to identify possible defects in the completed HMA layer, while no major defects were detected two areas were identified where potential problems may exist; these being,

Lane	Station		Defect
	From	To	
EB	857+05	860+55	**High reflections from lowest HMA layer 10 ins below surface, perhaps low density layer holding moisture or moisture trapped at interface between Hot Mix layers.**
EB	782+05	786+05	**Intermittent high reflections from 1.7 inches below the surface, perhaps debonding of top overlay.**

These defects were not thought to be particularly serious but it is recommended that a core be taken at the worst location according to the GPR data (between stations 857+05 and 857+75) to check the condition of the lowest layer of Hot Mix.

SECTION 2. LAYER THICKNESS CALCULATION PROCEDURE

2.1) Equipment Used

Pulse Radar Inc's Ground Penetrating Radar vehicle with their air launched horn antenna is shown in the top half of Figure 1. This antenna transmits pulses of radar energy, with a central frequency 1 GHz, into the pavement. Each radar wave is reflected at significant layer interfaces in the pavement. The reflected wave is captured by the system and displayed as a plot of return voltage versus arrival time. In a typical data collection cycle the GPR system can transmit and receive up to 50 GPR traces per second. Traveling at 30 mph this would be approximately one trace for every foot of pavement.

As shown in the bottom half of Figure 1 the largest peak is the reflection from the pavement surface, the amplitudes before the surface reflection are internally generated. The time delay between the internal "end reflection" and the surface echo is the time for the wave to travel from the tip of the antenna to the pavement surface and back. Knowing the speed of the wave in air it is therefore possible to estimate the height of the antenna above the pavement. As will be described later in this report this time interval and the computed height are used in the calculation process to account for antenna bounce as the GPR unit travels over the test pavement. However, the reflections of major significance to pavement engineers are those that occur after the surface echo. These represent reflections from significant interfaces within the pavement, and the measured layer travel time is related to the thickness of the layer. For example, the time between the surface echo A_1 and A_2 is related to the thickness of the top layer. Reflections A_2 and A_3 are from the top of the granular base material and the top of the subgrade, the time between these reflections is related to the thickness of the granular base. The amplitude of reflection from a layer is a function of the moisture content of that layers, high reflection imply high moisture contents. For example if amplitude A_2 increases for one section of pavement, then this indicates that the base moisture content has increased.

Pulse Radar Inc's 1GHz Horn Antenna

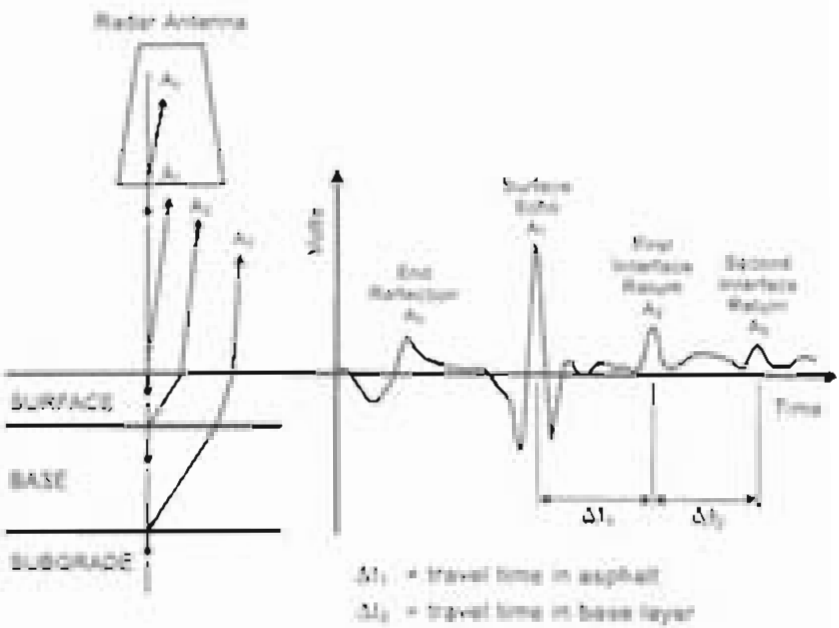

Figure 1. Principles of Ground Penetrating Radar. The Incident Wave is Reflected at Each Layer Interface and Plotted as Return Voltage Against Time of Arrival in Nanoseconds.

2.2) Typical GPR Traces

A typical GPR return waveform from SH 10 is shown in Figure 2 Peaks A_1, A_2 and A_3 are reflections from the surface, top of the granular base and subgrade, respectively. The hot mix surfacing is classified as "homogeneous and uniform" because there are no significant peaks between the surface and base reflections. If a defect were present in the HMA layer then a significant reflection would be found in between the surface and base reflections. Defects can cause both positive and negative reflections within layers. All of the reflections in Figure 2 are classified as positive reflections, that is they all have the same shape and orientation as the surface reflection. This is normal in HMA pavements where the layer moisture contents (and layer dielectrics) increase with depth. If a positive reflection were found within the HMA layer then this would most probably indicate either a layer interface problem where debonding of the layers has occurred letting moisture into the interface or the lower layer of asphalt has become saturated.

Negative reflection have their polarity reversed , these "upside down" reflections are related to the presence of low density layers within the HMA and are frequently used as indicators of stripping in older pavements. As will be described later some unexpected positive reflections were observed within the HMA at a few locations on SH 10.

A typical GPR trace collected in a location where the metal kitchen foil was placed under the HMA is shown in Figure 3. The reflection from the foil is very large, metal objects are strong reflectors of GPR energy. If the metallic object is large enough 100% of the energy hitting it will be reflected back to the antenna and none will be transmitted to the lower layers. The negative reflection observed around 14.5 ns is what is called a multiple reflection of GPR energy. Multiple reflections are caused when some of the energy returning from the first reflection from the metal foil is again reflected at the HMA/air interface, it goes back to the foil and is again reflected. Multiple reflections travel through the HMA layer two or more times.

The amplitude of reflection from any layer is a function of the contrast in dielectrics between layers. The main factor which influences the dielectric properties of pavement materials is its moisture content. As the moisture content increase the layer dielectric increase. In terms of the captured GPR wave if the base moisture increases then the amplitude of reflection from the top of the base would increase. In Figure 2 this would be observed as increase in the amplitude for peak A_2.

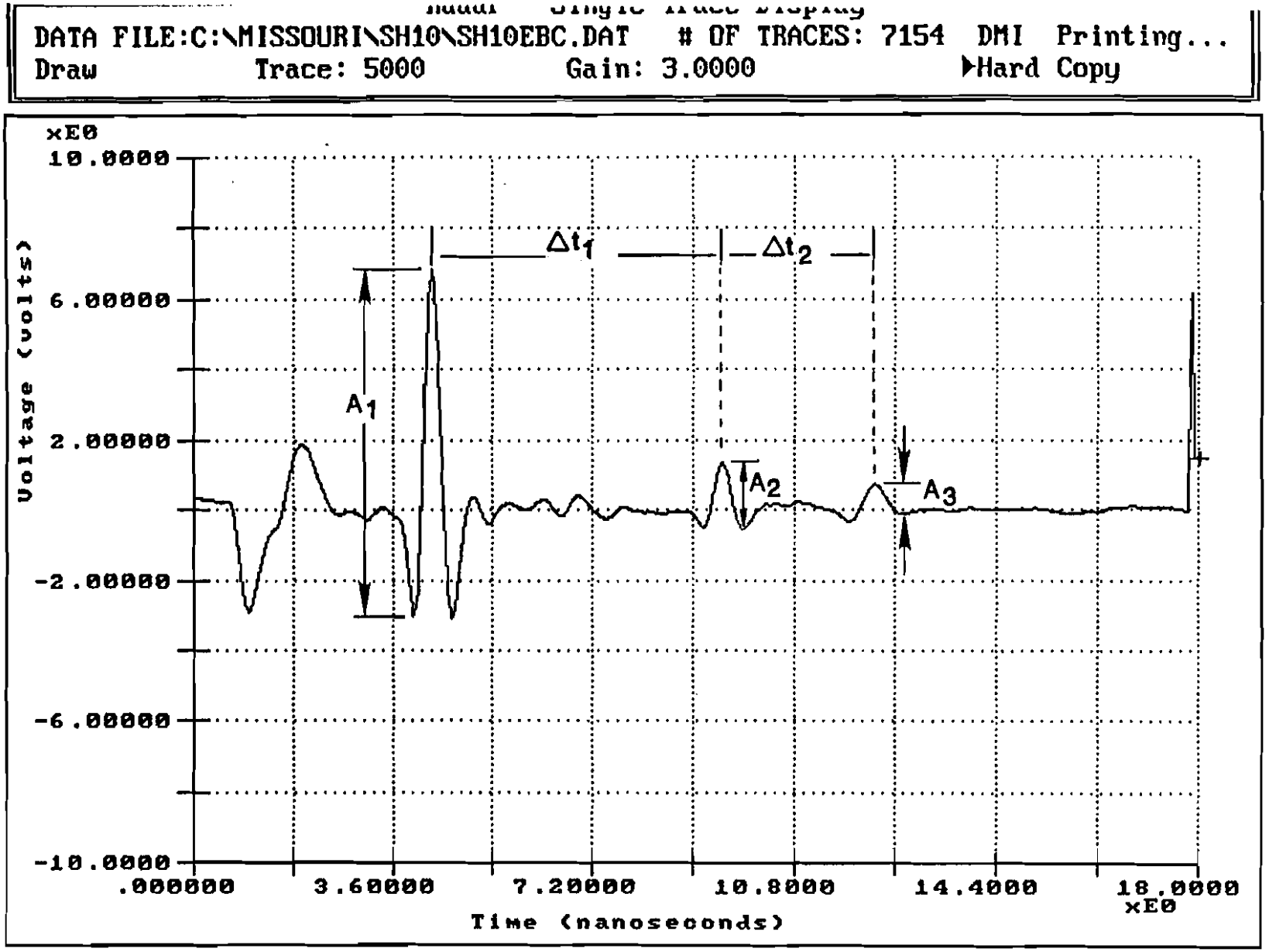

Figure 2. A Typical 1GHz GPR Trace Obtained on SH10. The Amplitudes A_1, A_2 and A_3 are the Reflections from the Surface, Top of Base and Subgrade. Δt_1 and Δt_2 are the Time of Travel in the HMA and Granular Base Layers.

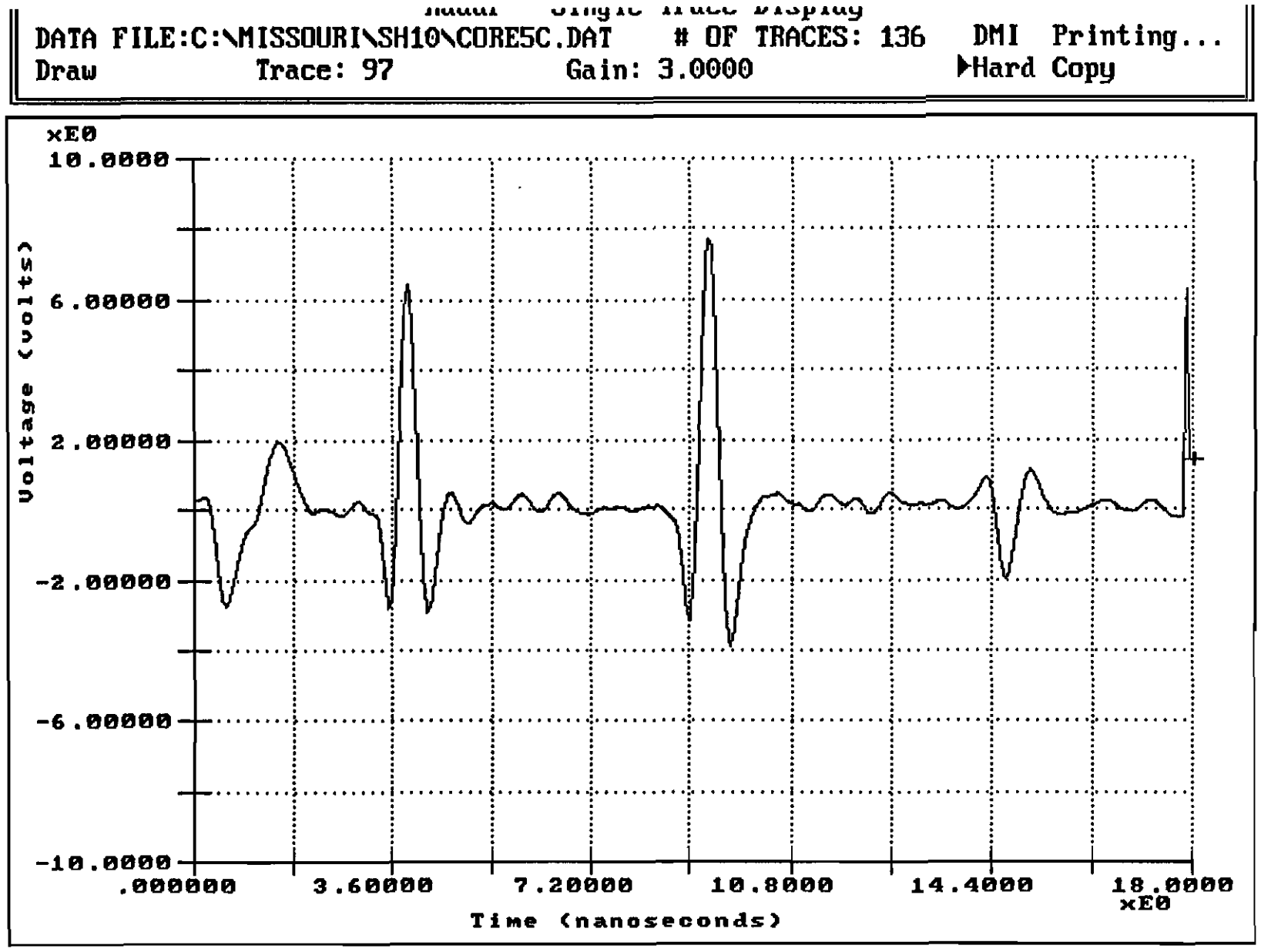

Figure 3. GPR Trace From a Location where Metal Foil was Placed Under the HMA.

The secondary factor influencing dielectrics is density. If the density of a layer increases then the dielectric for the layer will increase, and the amplitude of reflection will increase. Research efforts are underway to determine if surface reflections can be used as a measure of HMA density. This may permit GPR to be used to locate segregation in HMA materials.

Material properties can also influence the reflection from any pavement layer. The use of lightweight (less dense) aggregate in asphalt surfacings will influence the amplitude of the surface echo. Transitioning from a section of HMA made with normal aggregates to one constructed with lightweight would be observed in the GPR signal as a reduction in the amplitude of surface reflection (A_1 from Figure 2).

2.3) Automatic Signal Processing

Two GPR signal processing software packages were used to process the GPR waveforms collected on SH 10. The first package, known as DACQ, will be described in this section , the second package known as COLORMAP will be described in section 3. Both packages were developed by the Texas Transportation Institute in College Station, Texas in research projects funded by the Texas DOT. These packages are described in TTI reports 1233-1 and 1341-1 (Scullion, Chen and Lau, 1994 and 1995).

In DACQ the user specifies windows where significant reflections occur. The software automatically tracks and measures the amplitudes of reflection and time delays between peaks. Using these it possible to calculate layer dielectrics, layer thicknesses and to estimate the moisture content of granular base material. The equations used are summarized below;

$$\epsilon_a = \left[\frac{1 + A_1/A_m}{1 - A_1/A_m}\right]^2 \qquad (1)$$

where

ϵ_a = the dielectric of the asphalt layer

A_1 = the amplitude of reflection from the surface in volts (peak A_1 in Figure 2)

A_m = the amplitude of reflection from a large metal plate in volts (this represents the 100% reflection case)

$$h_1 = \frac{c \; x \; \Delta t_1}{\sqrt{\epsilon_a}} \tag{2}$$

where

h_1 = the thickness of top layer

c = a constant (speed of radar wave in air, see Section 2.4)

Δt_1 = the time delay between peaks A_1 and A_2 of Figure 2

$$\sqrt{\epsilon_b} = \sqrt{\epsilon_a} \left[\frac{1 - \left[\frac{A_1}{A_m}\right]^2 + \left[\frac{A_2}{A_m}\right]}{1 - \left[\frac{A_1}{A_m}\right]^2 - \left[\frac{A_2}{A_m}\right]} \right] \tag{3}$$

where

ϵ_b = the dielectric of base layer

A_2 = the amplitude of reflection from the top of the base layer in volts (peak A_2 in Figure 2)

$$M = \frac{\sqrt{\epsilon_b} - 1 - \gamma(\sqrt{\epsilon_s} - 1)}{\sqrt{\epsilon_b} - 1 - \gamma(\sqrt{\epsilon_s} - 22.2)} \tag{4}$$

where

M = the moisture content of base (% of total wt.)

ϵ_s = solids dielectric constant (varies from 4 to 8 depending on source material)

γ = dry density γ_d (lbs/ft ^{3}) divided by density of solids γ_s (165 lbs/ft^3)

Note equation 4 assumes that the density along a highway remains constant. This clearly is not the case and will limit the accuracy of moisture content estimation. However, the moisture content is the major factor which influences the calculated base dielectric constant ϵ_b. The relative dielectric constants of air, dry granular base and water are approximately 1, 6, and 81 respectively. High base dielectrics are almost certainly attributable to high moisture contents. The accuracy of equation 4 has yet to be determined.

The above equations serve as the basis for analysis of the data collected, as described below. They are based on the assumption that the layer materials are non-conductive and homogeneous. This assumption means that the imaginary component of the dielectric constant tends to zero; and the medium does not attenuate the radar signal. Therefore all of the energy is either reflected or transmitted and none is lost in heating free water in the layer. The assumption of a very low imaginary dielectric from laboratory tests at the Texas Transportation Institute appears to be reasonable for asphalt concrete hot mix. However, it does not seem to be the case for either concrete or wet base course material. Because of the higher attenuation, it is thought that the accuracy of layer thickness estimates for both concrete layers and wet granular base layers may be less than for hot mix layers. The layer thickness estimates for hot mix asphalts was found to be good (± 3%). The accuracy on granular base courses was reasonable, but this was also tied to the inability to physically measure the thickness of bases in older pavements given the mixing of base and subgrade materials at the interface between layers.

To demonstrate how these equations are used the HMA and granular base thicknesses will be computed for the individual GPR trace shown in Figure 2. Figure 4 is a repeat of Figure 2 showing the measured amplitudes and time delays. To clearly show the peaks an amplitude gain factor of 3 was used, the measured values for A_1 and A_2 are 3.276 and 0.635 volts respectively. The time delay between reflections Δt_1 and Δt_2 is 5.203 and 2.742 nanoseconds. The amplitude of metal plate reflection A_m is shown in Figure 5 to be 7.48 volts.

Using Equation 1 the dielectric of the HMA is calculated;

$$\epsilon_a = \left[\frac{1+0.438}{1-0.438}\right]^2 = 6.54$$

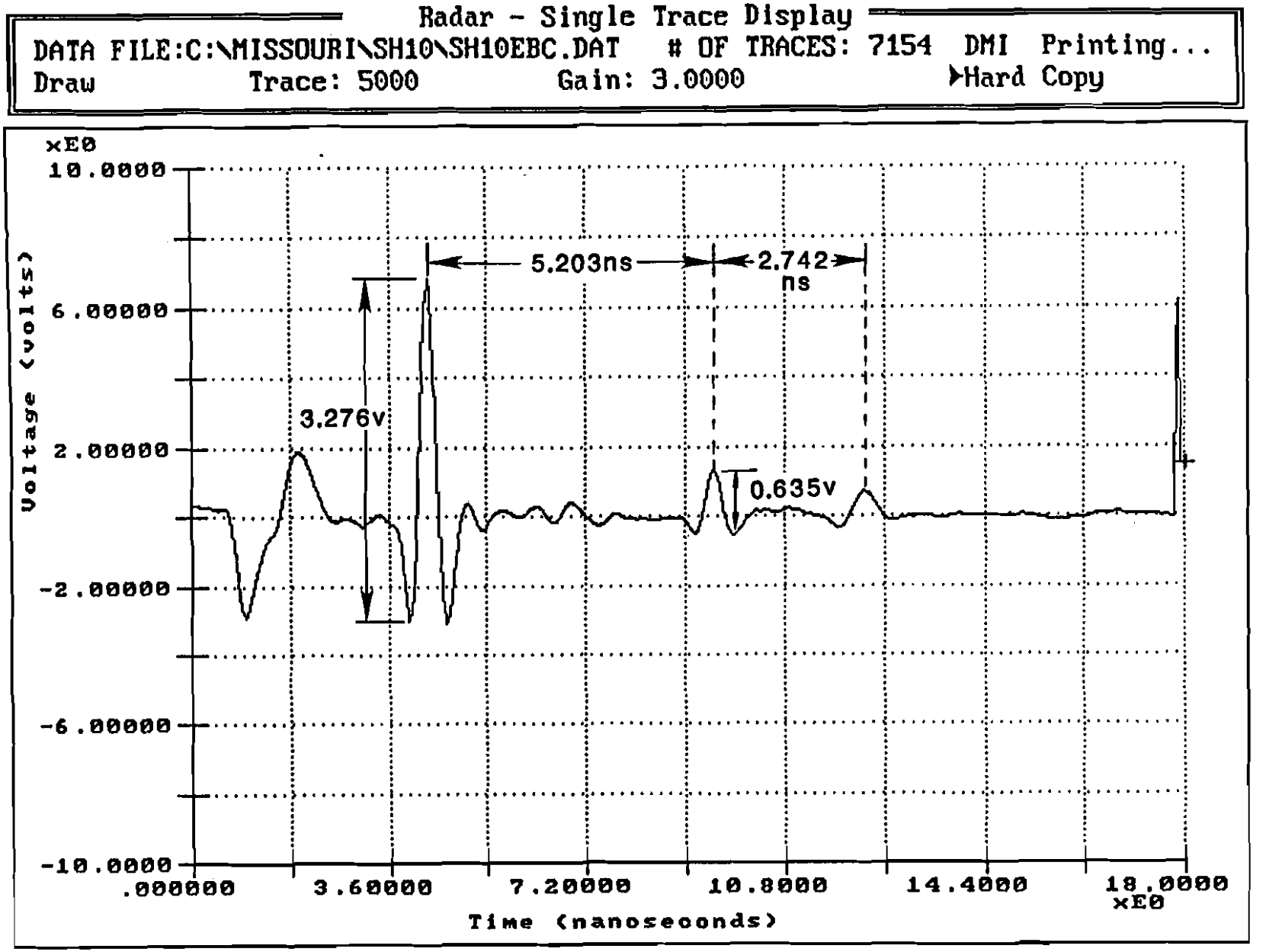

Figure 4. Measured Amplitudes and Time Delays for the GPR Shown in Figure 2 (Gain Factor = 3).

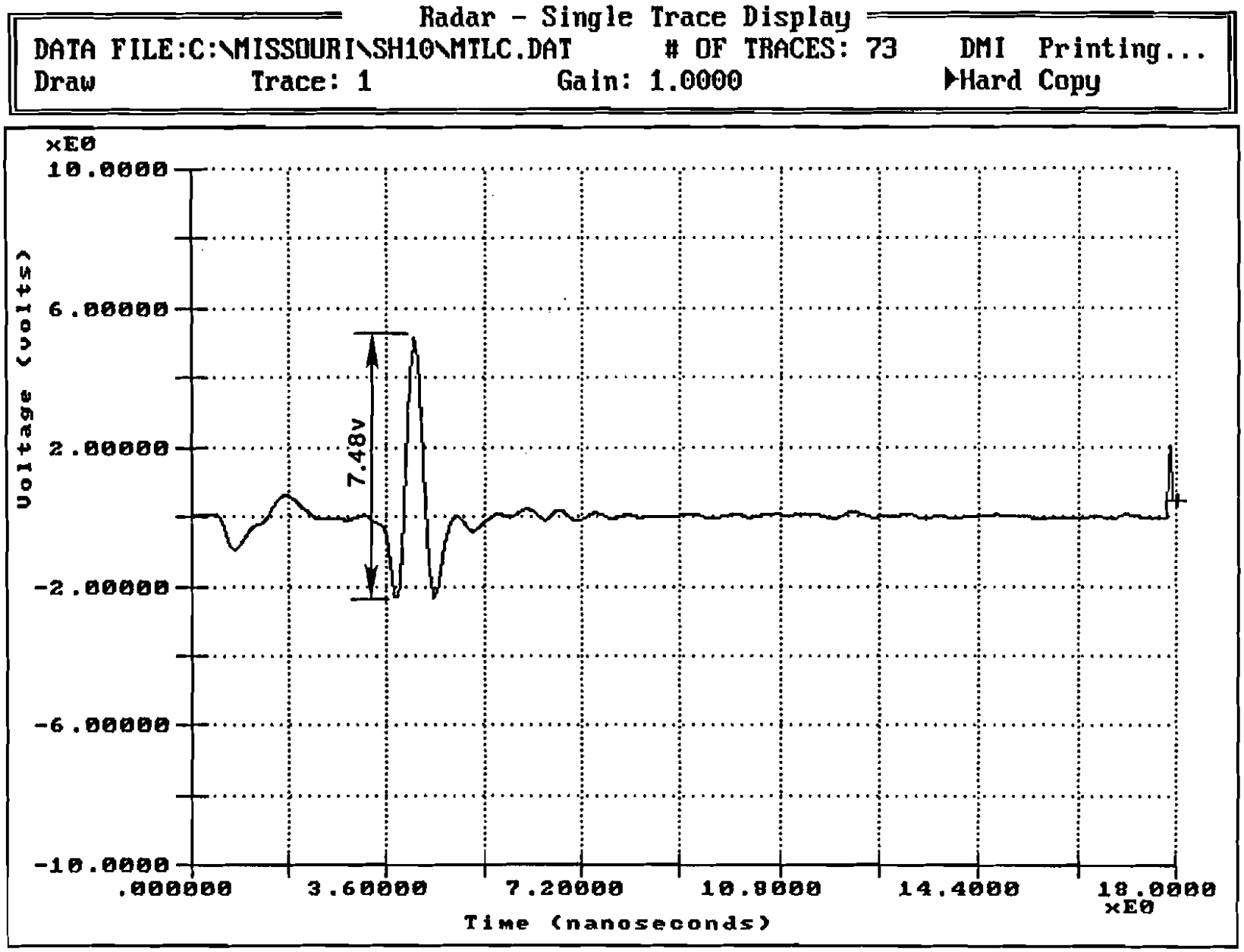

Figure 5. Metal Plate Reflection (Gain Factor = 1).

$$h_1 = \frac{5.9 \ x \ 5.203}{\sqrt{6.54}} = 12.0 \ inches$$

Using Equation 3

$$\sqrt{\epsilon_b} = \sqrt{6.54} \left[\frac{1 - 0.192 + 0.0849}{1 - 0.192 - 0.0849} \right]$$

$$\sqrt{\epsilon_b} = \sqrt{6.54} \left[\frac{0.893}{0.723} \right]$$

$$\epsilon_b = 9.98$$

Using Equation 2 for granular base thickness,

$$h_2 = \frac{5.9 \ x \ 2.742}{\sqrt{9.98}} = 5.1 \ inches$$

2.4) Height and Time Calibration Tests

The thickness calculation procedure used with in the DACQ signal processing package is essentially that demonstrated above. DACQ is an automated package which allow the user to input a height and time calibration factor to improve the accuracy of thickness estimate. These factors are described below.

The time calibration test is used to calculate the "c" factor from Equation 2, the speed of the GPR wave in air as measured by the data acquisition system. Theoretically this should be 5.9 inches per nanosecond for two way travel, this is the speed of light in air and radar waves are electromagnetic waves. This test involves capturing two metal plate reflections with the bottom of the antenna at 16 and 28 inches above the metal plate. The change in travel time between the end reflection and the surface echoes is the time to travel 12 inches in air. This test was conducted in Missouri and repeated on return to Texas, in both instances the value obtained was very close to 5.9, so this value was used in all thickness computations.

The Height calibration test is to account for changes in the height of the antenna as it surveys the pavement. It is important as in the calculation of the dielectric for any GPR trace the ratio of surface reflection to metal plate reflection is used assuming that both are collected

at the same height above the pavement. The metal plate reflection is recorded in the field with the equipment stationary above a large metal plate. However during data collection particularly at high speed there is no guarantee that the antenna will be at the same height as that used when capturing the metal plate reflection. As mentioned when discussing Figure 1 the time between the internal antenna end reflection and the surface echo is a measure of the height of the antenna above the pavement. This can be measured for the metal plate reflection and for each trace capture during the pavement test. The height calibration test involves capturing metal plate reflections throughout the possible range of working heights in one inch intervals from 13 inches to 17 inches. Then plotting the measured time interval between end reflection and metal plate reflection against the amplitude of metal plate reflection. With the antenna used in Missouri this graph was found to be best fit with a straight line of slope -1.0529 volts per nanosecond. Therefore in performing the calculation of the asphalt layers dielectric for each field trace the time between end reflection and surface reflection was calculated and compared to that found on the metal plate trace, if they are different then an adjusted amplitude of metal plate reflection was computed. Using this procedure it is possible to account for antenna "bounce" as data is collected along any highway.

2.5 Detailed Thickness Results

In testing SH 10 GPR data was collected at between 30 and 40 mph. A total of 7154 and 8463 trace were collected in East bound and West bound passes, the difference in the number of traces being related to the speed of travel and the length of lead into the test section. The total length of the test run was approximately 17400 feet as measured by the Distance Measuring Device in Pulse Radar's vehicle. This means a GPR trace was collected for approximately every 2.5 foot of travel. In order to process this large amount of data the DACQ signal processing system developed by the Texas Transportation Institute was used. This system incorporates all of the equations and calibration factors discussed above. The results of this analysis are shown in Figure 6.

Figure 6 shows the first 2.6 miles of the Eastbound lane of the project. The sketch at the top of the figure shows the stationing and major features along the highway. No major deficiencies were detected in the Westbound direction. As shown in Figure 6 the problem areas are Eastbound between Stations 838 and 845, and around Station 893.

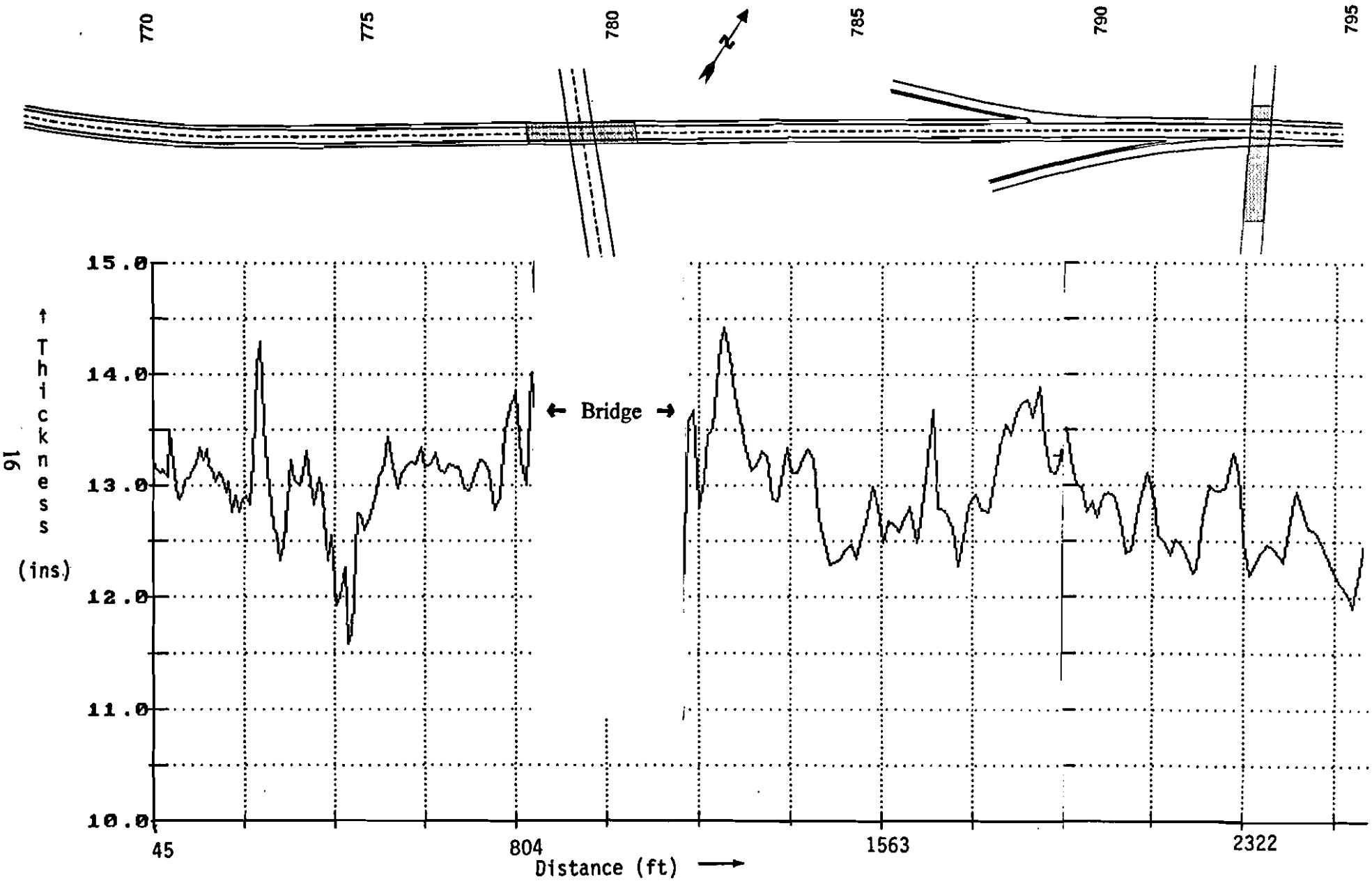

Figure 6a. Eastbound Lane HMA Thicknesses (ins) for Stations 770 to 795.

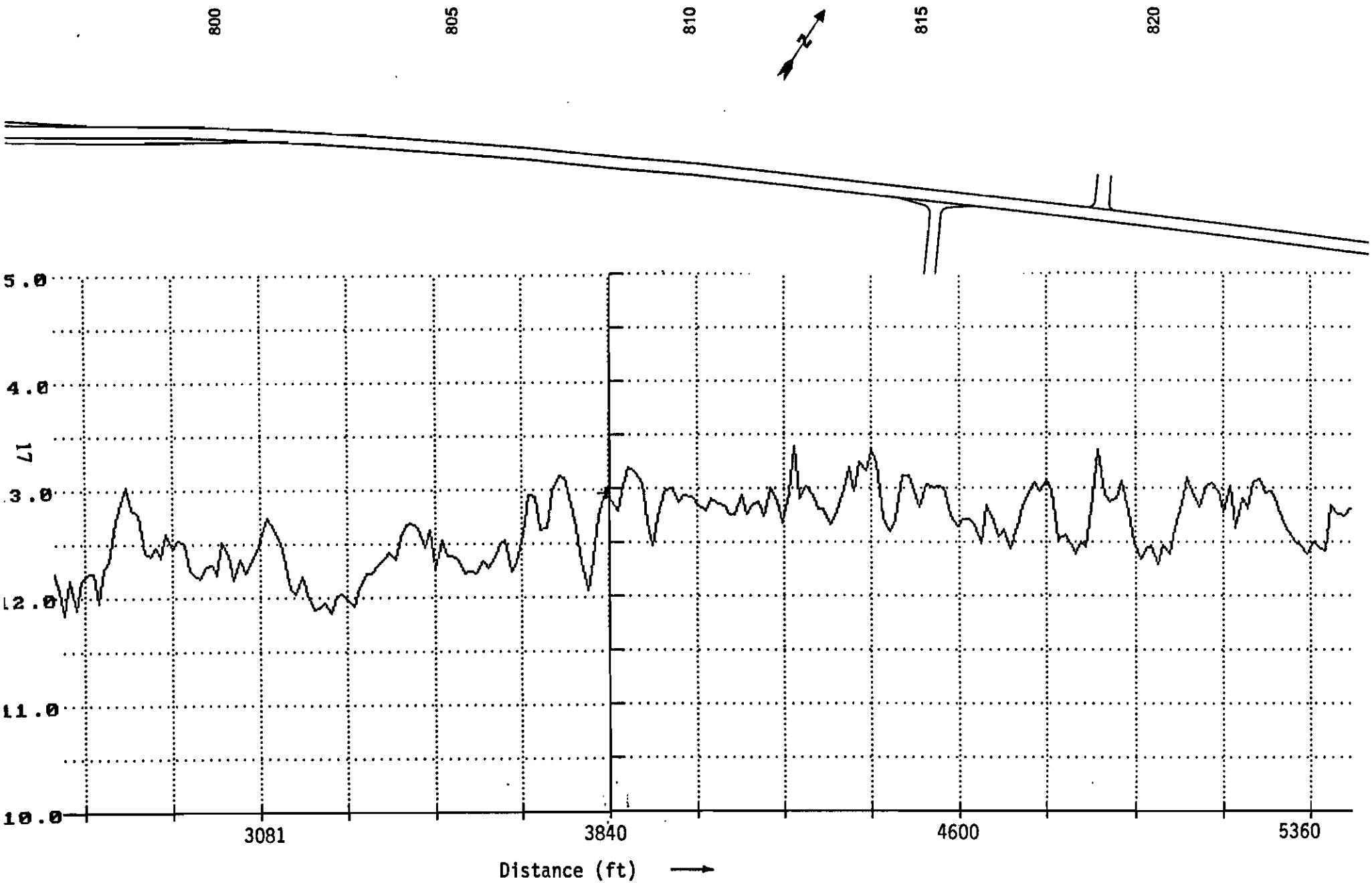

Figure 6b. Eastbound Lane HMA Thicknesses (ins) for Stations 795 to 820.

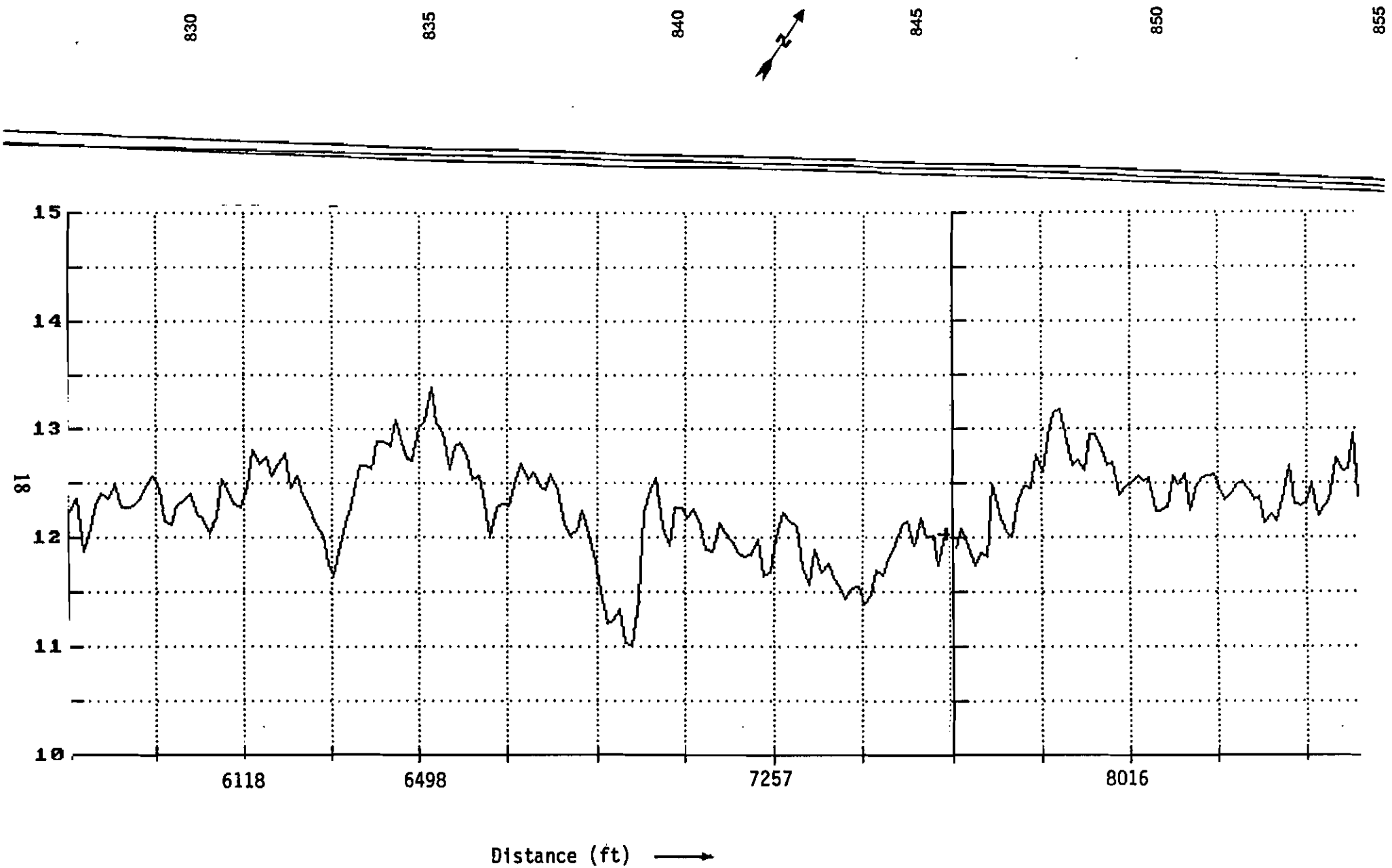

Figure 6c. Eastbound Lane HMA Thicknesses (ins) for Stations 830 to 855.

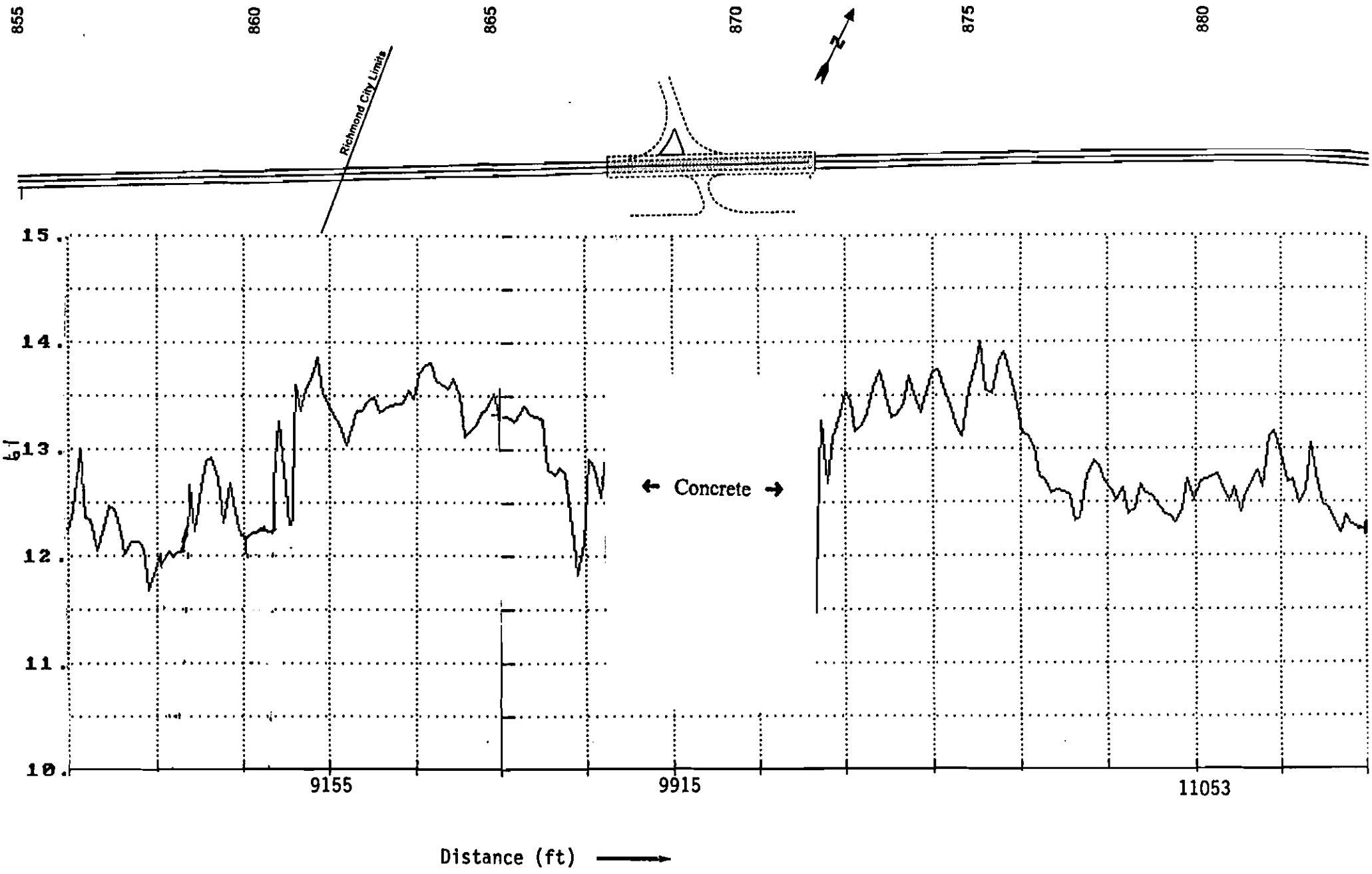

Figure 6d. Eastbound Lane HMA Thicknesses (ins) for Stations 855 to 880.

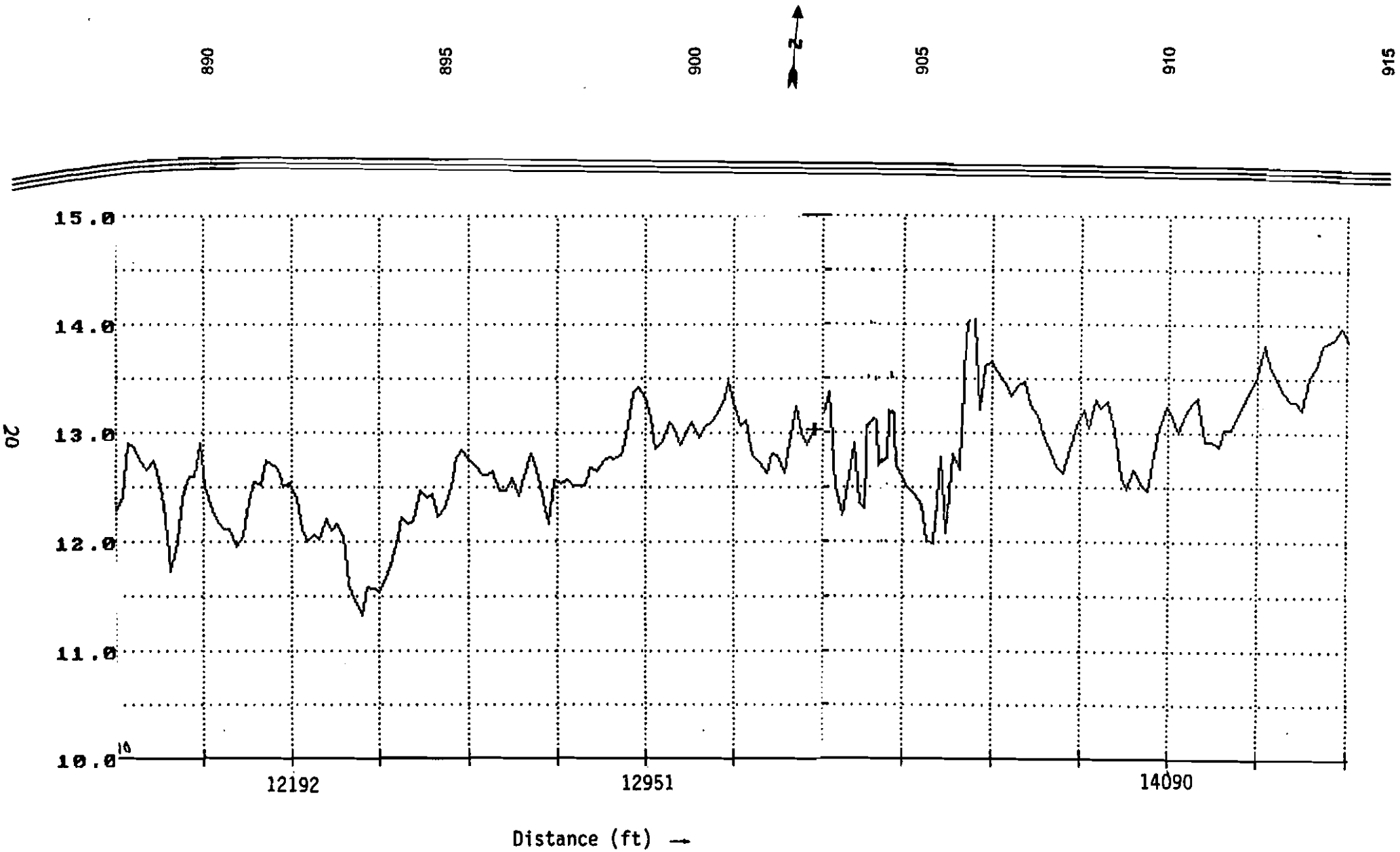

Figure 6e. Eastbound Lane HMA Thicknesses (ins) for Stations 890 to 915.

SECTION 3. COLOR DISPLAYS OF GPR DATA

3.1 Description of COLORMAP

COLORMAP is the most recent GPR processing package developed by the Texas Transportation Institute for the Texas DOT, it is described in detail in TTI Research Report 1341-1 by Scullion, Chen and Lau, 1995. This is intended to include most of the feature of the DACQ program described earlier but be easier for DOT personnel to use. The system has been implemented within the Texas DOT and several training schools have been conducted for TxDOT personnel.

COLORMAP is a windows based system in which a color coding scheme is used to transform the GPR return waves into a single line scan. The line scans are stacked side by side and a picture of the highway is produced. A typical color display for approximately 1500 feet of the Eastbound run is shown in Figures 7. This is from the problem area where the HMA layer is significantly less than 12 inches. The depth scale at the right of the figure is used for estimating the thickness of the asphalt layer. The distance scale at the bottom is in miles and feet. The surface is the solid red line at the top of the figure. In this display it is possible to see reflections from two locations where foil was placed at the top of the granular base, these being at approximately 1 mile + 750 feet and 1 mile + 1750 feet.

3.2) Locating Defects in the HMA

One of the benefits of the COLORMAP display is that it permits the user to rapidly locate areas of deficient thickness and potential defects within layers. On SH 10 very few defects were found in either direction, but two short sections were found with anomalous GPR returns. One such area is shown in Figure 8. In this case a positive peak (red line) is observed at approximately 10 inches below the surface between 1 mile + 3480 feet and 1 mile + 3830 feet (Stations 857+05 to 860+55). A single GPR reflection from this area is shown in Figure 9 this should be contrasted with the typical "homogeneous HMA" trace shown in Figure 2. The cause of the additional reflector at the 10 inch depth is not known at this point. The lower layer in the HMA has a higher dielectric in this area, this will be a moisture related problem where either moisture is found below the layers or the lowest asphalt layer is holding more moisture than the layer above it perhaps indicating a compaction problem. The severity of the problem is

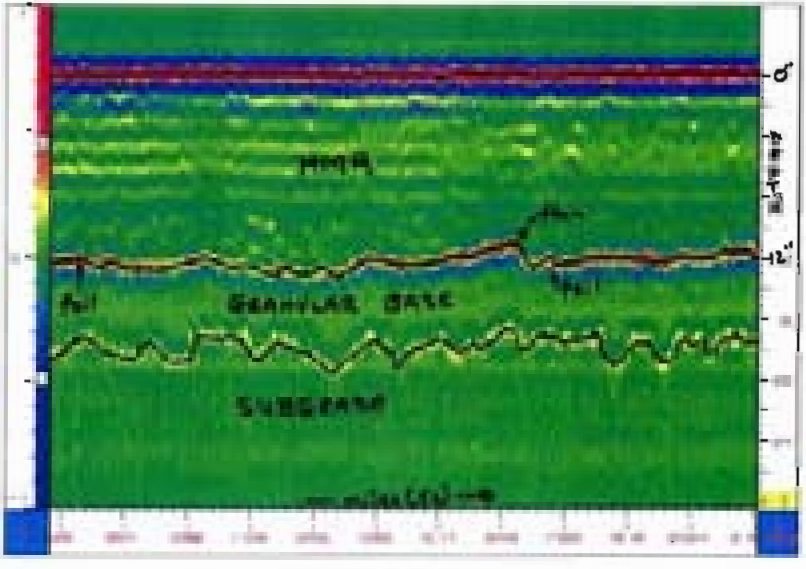

Figure 1. [illegible]

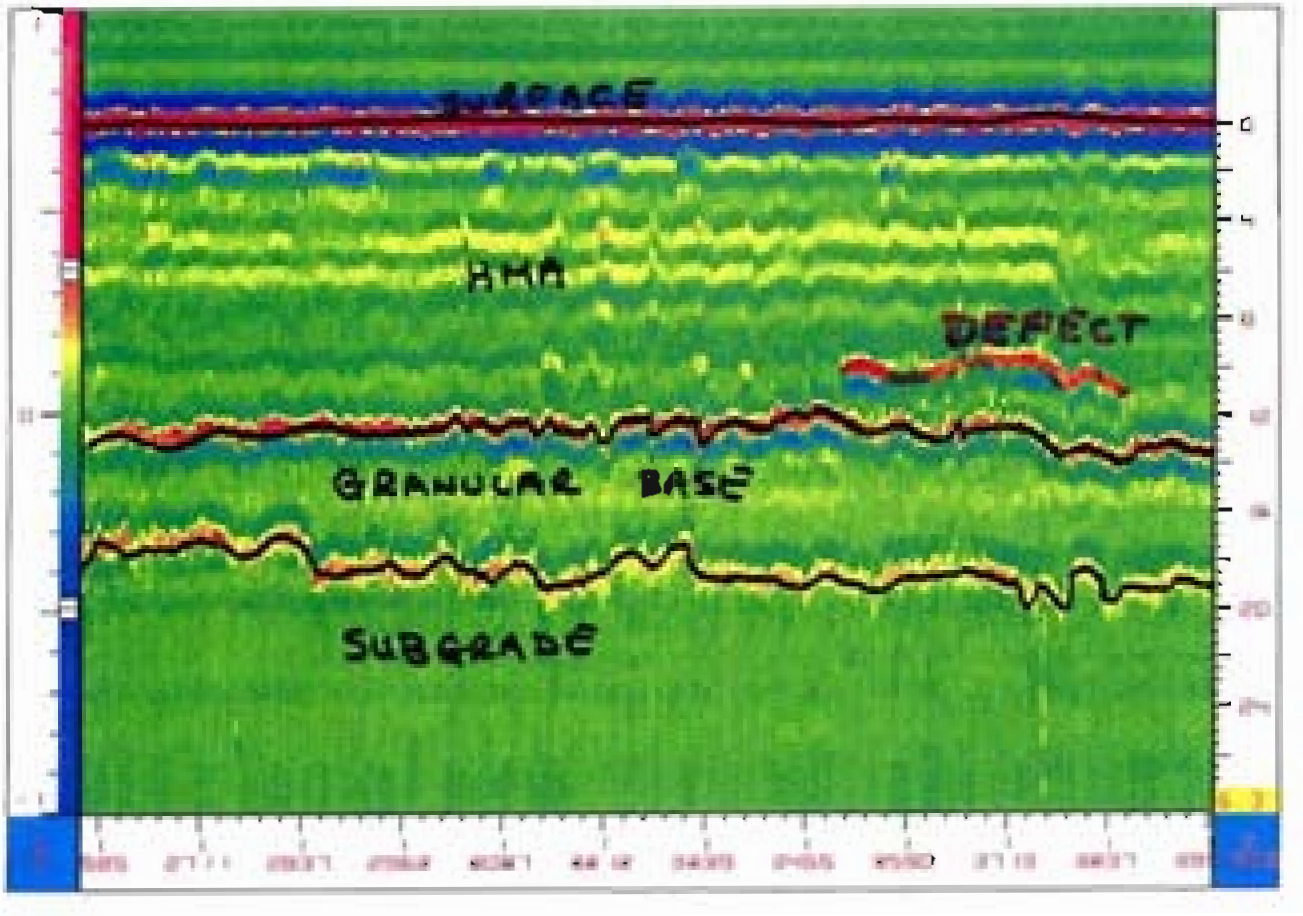

Figure 8. COLORMAP Output from a Section of SH10 Eastbound with Defects Near the Bottom of the HMA

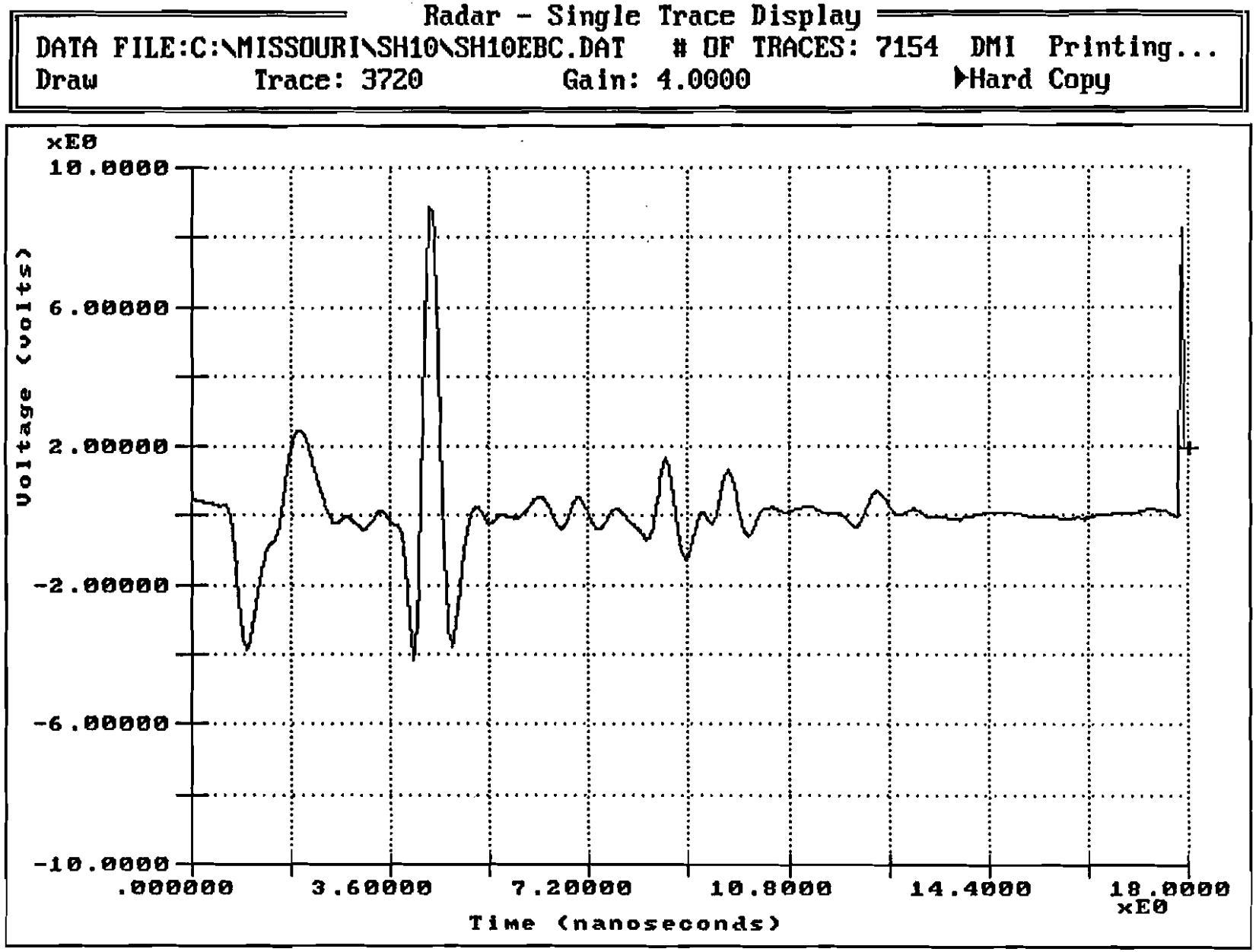

Figure 9. Single GPR Trace from a Problem Area in the EB Lane of SH10. The Additional Reflection at Approximately 8.5 ns Indicates a Potential Problem.

difficult to determine but it is recommended that a single core be taken in the outer wheel path of the EB lane at station 857+75 to assess this concern.

A second small defect was found earlier in the section and is shown in Figure 10. This time the defect is located 1.7 inches beneath the surface at the bottom of the final HMA layer. These are assumed to be minor intermittent problems occurring at the interface between layers.

3.3) Comparing Estimated and Measured Thicknesses

To evaluate the accuracy of GPR, thickness estimates were made at several locations where cores had already been taken. As discussed below GPR data from two different runs was processed to make this comparison,

a) Results From Slow Roll Over Tests After completing the high speed data collection a series of slow roll tests were conducted at six core locations selected by MoDOT. The thickness calculations were made "blind", using the DACQ software described in section 2 of this report, without knowing any of the core thicknesses. MoDOT then supplied the actual core thicknesses for two locations (stations 930EB and 935WB). In both instances the measured thicknesses were less than the computed thicknesses by 0.4 and 0.3 inches. An average calibration factor of 0.975 was established between measured and computed thicknesses . The "blind" thicknesses at the remaining 4 locations were then multiplied by this calibration factor to compute the calibrated thickness. MoDOT then supplied the measured thicknesses for these four locations. The results from this analysis are shown in Figure 11.

The purpose of this analysis was to estimate the accuracy of the "blind" thickness estimates and to evaluate the improvement that was found if one or more calibration cores were used to adjust the calculated thicknesses. As shown in Figure 11 the average error in the "blind" thickness estimates was 3.5%, with the use of the calibration cores the average error reduced to 1.4% or 0.17 inches.

b) Results from High Speed Tests MoDOT took cores at many more locations than the six tested in the low speed tests. The original intention was to take a core at every location where the metal foil was placed. As shown earlier in Figure 7 using COLORMAP it is possible to locate each of these foil locations. Furthermore, within COLORMAP it is possible to calculate the HMA thickness at each of these locations using the equations

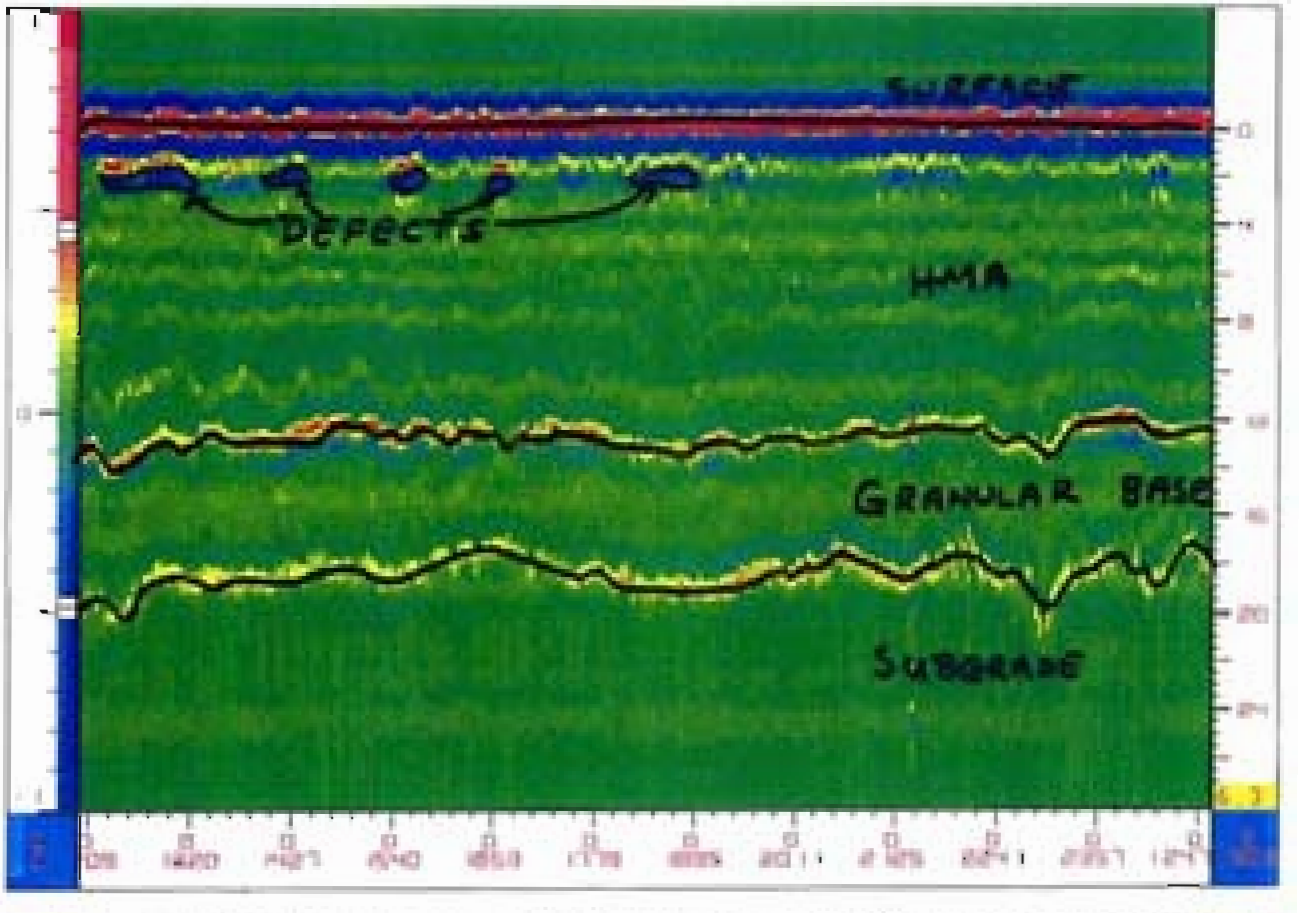

Figure 10. COLORMAP Output from a Section of SH10 Eastbound with Defects Near the Surface. The Potential Defects are the Intermittent Blue Areas Just Beneath the Solid Red Line which is the Surface Reflection.

	Thicknesses (ins)		
Station	**Blind**	**Calibrated**	**Measured**
890 EB	12.3	12.0	12.0
910 EB	13.2	12.9	12.6
930 EB	13.8	*	13.4
935 WB	14.1	*	13.8
905 WB	13.3	13.0	12.8
815 WB	13.9	13.5	13.3
n	6	4	
Mean Error (ins)	0.46	0.17	
Mean Error (%)	3.5	1.4	

Figure 11. Slow Roll Over Test Results, Comparing Calculated and Measured Thicknesses. * Given Core Thickness.

[An additional test was conducted at Station 895WB. At the location the measured and computed (blind) thicknesses were 12.2 and 13.3 inches, respectively. However, upon review there was some uncertainty about whether the GPR data was collected at the correct station. This result was subsequently dropped from the analysis.]

described in Section 2.3. Figure 12 is a list of the thicknesses calculated from the high speed GPR data collection run at each of the observed foil locations. The computed thicknesses estimates were not adjusted for the two known thicknesses (930EB and 935WB). The measured thickness column was supplied by MoDOT.

As shown in Figure 12, MoDOT supplied actual core thicknesses at 17 locations. From processing this high speed GPR data through the automated COLORMAP signal processing system the average error of estimate was found to 0.21 inches or 1.7%.

Eastbound Thicknesses (ins)			Westbound Thicknesses (ins)		
Station	Computed	Measured	Station	Computed	Measured
791	12.5	12.4	935	14.1	13.8
800	12.3	N.A.	925	14.3	14.4
810	12.8	12.8	915	13.8	13.7
820	12.6	N.A	905	13.2	12.8
830	11.8	N.A.	895	12.4	12.2
840	12.3	N.A.	885	13.3	13.1
850	12.8	N.A.	875	13.6	13.2
860	13.1	N.A.	865	14.3	N.A.
880	12.4	12.6	855	12.8	N.A.
890	12.2	12.0	845	12.6	N.A.
900	13.1	12.8	835	13.7	N.A.
910	12.6	12.6	825	12.7	N.A.
920	13.7	13.9	815	13.5	13.3
930	13.2	13.4	805	13.5	12.9
			795	12.9	N.A.
			785	12.6	N.A.

Figure 12. Comparing Measured Core Thicknesses with Those Computed with COLORMAP.

- N.A. - No core Available
- Average Error Estimate 0.21 ins (1.7%)

SECTION 4. CONCLUSION AND RECOMMENDATIONS

1) The GPR data collected on this project was judged to be of high quality. The interfaces between the HMA/Granular Base and Granular Base/Subgrade were clear.

2) Signal Processing determined that there were few defects in the WB direction. The problems were largely found in the EB data. One substantial section of thickness less than 11.4 inches was detected and several other locations where the thickness was less than 11.8 inches were found.

3) In terms of defects no major problems were found. Minor problems were noted in two locations. In the most significant, unusual GPR reflections were observed from the lowest HMA layer, 10 inches below the surface. Coring at this location is recommended.

4) The accuracy of GPR thickness estimates was found to be reasonable. Using COLORMAP the average error between measured and calculated thicknesses was 0.21 inches or 1.75%.

5) As stated earlier it is believed that GPR will not replace coring but permit DOT's to core "smarter", and hopefully avoid taking multiple cores in deficient areas. Figure 13 shows the pavement after coring the thin section found on SH10.

6) For the second GPR test, scheduled for the summer of 1997 on Route 63 in Howell County, it is proposed that the GPR test be performed prior to conducting the field coring. The coring pattern to be used on the project is predefined, however by collecting and processing the GPR data prior to coring it should be possible to;

   a) accurately define the location of the buried foil, this was a problem on SH 10.

   b) suggest locations where thin sections are thought to occur which would be missed in the normal coring process.

   c) provide a good case study to demonstrate how GPR can be incorporated into MoDOT's thickness validation process.

Figure 13. SH10 After Coring of Thin Section.

Appendix B

LAYER THICKNESS MEASUREMENTS WITH GROUND PENETRATING RADAR ON US 63, HOWELL COUNTY , MISSOURI

by

Tom Scullion
Pavement Systems Engineering
College Station, Texas

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DISCLAIMER

Mr. Tom Scullion P.E. of Pavement Systems Engineering processed the GPR data and wrote this report. The conclusions drawn are his and do not necessarily represent the views of the Missouri Department of Transportation.

SECTION 1. SUMMARY OF RESULTS

1.1) Purpose of Study

This study was conducted by Pavement Systems Engineering (PSE) of College Station, Texas to demonstrate the capabilities of Ground Penetrating Radar (GPR) and automated signal processing techniques to the Missouri Department of Transportation (MoDOT). The application involved measuring the thickness of the Hot Mix Asphalt (HMA) on two recently completed highways in Missouri. This is the second and final report of this study, a Phase 1 report describing the findings of the GPR survey on SH 10 near Richmond has been forwarded to MoDOT. This report describes the findings on the second project on a recently completed section of US Route 63 in Howell County.

On US Route 63 the plan thicknesses called for 1.75 inches of Type C Asphaltic Concrete, 15.25 inches of Plant Mix Bituminous Base and 4 inches of Type 5 Aggregate base. The paving of US 63 was let as an Experimental Project for Alternate Bids on Pavement Type, with either alternate concrete or asphalt pavement. As is common practice for concrete pavements the contractor was to receive a penalty if the total layer thickness is greater than 0.2 inches less than the design thickness of 17 inches. A "no-pay" or "dig out and replace" situation occurs in sections where the total thickness is greater than 0.6 inches less than the design thickness. To validate the in place thicknesses MoDOT takes cores from the pavement at regular intervals along the completed project. If deficient sections are detected the coring interval is reduced to define the extent of the problem. In the "no-pay" situation a core may be taken as frequently as every 20 foot in all lanes.

There are several problems with the current thickness verification procedure. Firstly, there is no guarantee that the coring operation will locate any problem areas, it is essentially a hit and miss operation. Secondly, when the "no-pay" situation is found numerous cores are taken from the new pavement, which at the very least is difficult to explain to the traveling public and at the worst the coring may reduce the strength of the remaining pavement. For these reasons the MoDOT is evaluating if Ground Penetrating Radar can assist in this task. GPR may never totally replace coring but it has the potential of identifying where cores should be taken and to radically reduce the number of cores required on any project. GPR has one more potential benefit, it can be used to check for other defects such as poorly compacted lower layers and for the presence of anomalies within the HMA.

In this study the GPR data was collected by Terracon Consultants Inc. of Lenexa, Kansas using a 1 GHz air launched horn antenna manufactured by Pulse Radar Inc., of Houston, Texas. In Section 2 of this report the basics of using GPR for layer thickness calculation will be presented together with a graphical display of the computed thicknesses for US 63 as well as correlations with the ground truth core data. In the remainder of this section a summary of the results obtained will be presented.

1.2) Thickness Results

GPR data was collected in both the newly constructed Right (slow) and Left (fast) travel lanes, a summary of the deficient sections found in each lane are tabulated below;

"No-Pay" locations detected by GPR (Thickness less than 16.4 ins)

Lane	Station		Distance
	From	To	Feet
Slow	835+10	835+46	36
Slow	837+96	838+39	43
Slow	920+22	920+27	5
Slow	935+50	935+71	21
Slow	954+35	954+59	14
Slow	1026+90	1027+39	49
Slow	1059+05	1059+55	50
Slow	1059+72	1060+23	51
Slow	1064+69	1064+75	6
Slow	1076+27	1076+64	37
Fast	837+41	837+50	11
Fast	837+78	837+34	56
Fast	880+39	880+60	21
Fast	881+79	882+01	22

Lane	Station		Distance
	From	To	Feet
Fast	919+89	920+20	31
Fast	964+50	965+31	81
Fast	981+08	981+21	13
Fast	994+30	994+41	11
Fast	1023+62	1023+68	6

In summary, it was predicted that both lanes had a total of 550 feet of pavement below the "no-pay" thickness of 16.4 inches. This represents approximately 1.0% of the total section length which is considered to be very low, indicating that the contractor maintained good quality control on this project. The average thicknesses in both lanes was above 17.5 inches.

As will be described in Appendix C of this report Ground Penetrating Radar has the capability of locating defects within any HMA layer. On US 63 no significant defects (low density layers or moisture damage layers) were detected. It is concluded that the HMA on US 63 is well compacted, homogeneous and of adequate thickness.

SECTION 2. LAYER THICKNESS CALCULATION PROCEDURE

2.1) Equipment Used

Terracon's Ground Penetrating Radar vehicle with their air launched horn antenna is shown in the top half of Figure 1. The GPR system was manufactured by Pulse Radar Inc. of Houston, Texas. This antenna transmits pulses of radar energy, with a central frequency 1 GHz, into the pavement. Each radar wave is reflected at significant layer interfaces in the pavement. The reflected wave is captured by the system and displayed as a plot of return voltage versus arrival time. In a typical data collection cycle the GPR can transmit and receive up to 50 GPR traces per second. Traveling at 30 mph this would be approximately one trace for every foot of pavement.

As shown in the bottom half of Figure 1 the largest peak is the reflection from the pavement surface. The positive peak before the surface reflection is known as the "end reflection", this is internally generated. The time delay between the end reflection and the surface echo is the time for the wave to travel from the tip of the antenna to the pavement surface and back. As the radar wave travels at the speed of light it is therefore possible to estimate the height of the antenna above the ground. This time delay and the computed height are used in the layer thickness calculation process to account for antenna bounce as the GPR unit travels over the pavement.

The reflections of major significance to pavement engineers are those that occur after the surface echo. These represent reflections from significant interfaces within the pavement structure, and the measured layer travel time is related to the thickness of these layer. For example, the time between the surface echo A_1 and A_2 is related to the thickness of the top layer. Reflections A_2 and A_3 are from the top of the granular base material and the top of the subgrade, the time between these reflections is related to the thickness of the granular base. The amplitude of these reflections is a function of the moisture content of the layers, the higher the reflection the more moisture in the layer. For example if the amplitude A_2 increases in one section of the pavement, then this indicates that the base moisture content has increased at this location.

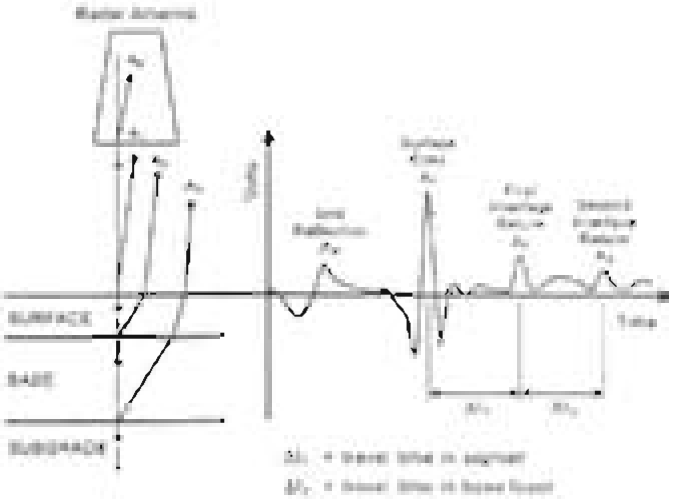


Figure 1. Principle of Ground Penetrating Radar. The Incident Wave is Reflected at Soil Layer Interface and Plotted as Return Voltage Against Time of Arrival in Nanoseconds.

2.2) Layer Thickness Calculation

A typical GPR return waveform from Missouri is shown in Figure 2 where Peaks A_1, A_2 and A_3 are reflections from the surface, top of the granular base and subgrade, respectively. The hot mix surfacing is classified as "homogeneous and uniform" because there are no significant peaks between the surface and base reflections.

The amplitude of reflection from any layer is a function of the contrast in dielectrics between layers. The main factor which influences the dielectric properties of pavement materials is the moisture content of the material. As moisture content increases then the layer dielectric will increase. In terms of the captured return GPR wave if the base moisture increases then the amplitude of reflection from the top of the base would increase. In Figure 2 this would be observed as increase in the amplitude for peak A_2.

Using these amplitudes and time delays it's possible to calculate layer dielectrics, layer thicknesses and to estimate the moisture content of granular base material. The equations used are summarized below;

$$\epsilon_a = \left[\frac{1 + A_1/A_m}{1 - A_1/A_m}\right]^2 \tag{1}$$

where

ϵ_a = the dielectric of the asphalt or concrete surfacing layer

A_1 = the amplitude of reflection from the surface in volts (A_1=3.276v in Figure 2)

A_m = the amplitude of reflection from a large metal plate in volts (this represents the 100% reflection case)

$$h_1 = \frac{c \; x \; \Delta t_1}{\sqrt{\epsilon_a}} \tag{2}$$

where

h_1 = the thickness of top layer

c = a constant (5.9 ins/ns two way travel)

Δt_1 = the time delay between peaks A_1 and A_2 of Figure 2

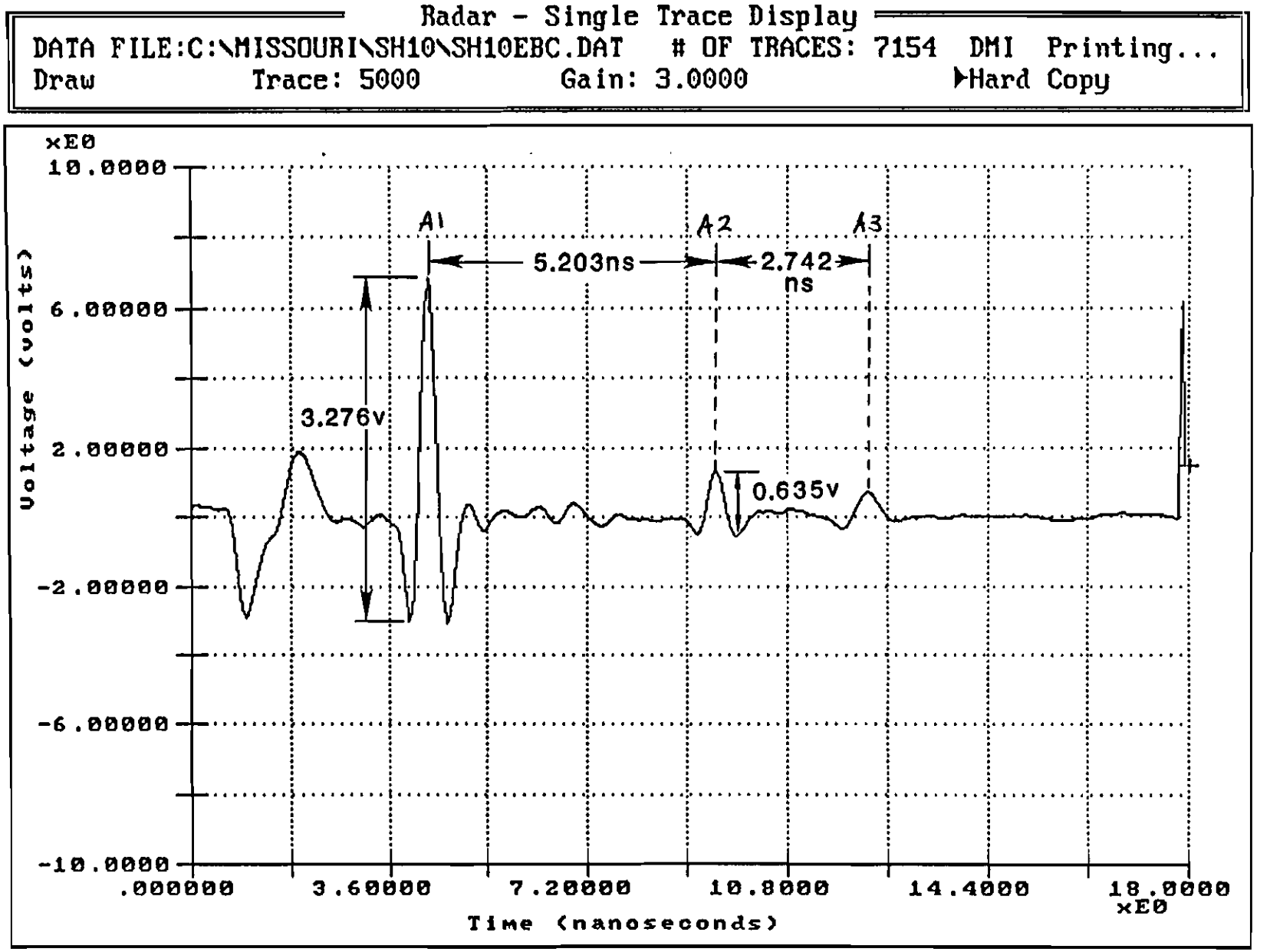


Figure 2. Measured Amplitudes and Time Delays for the GPR Shown in Figure 2 (Gain Factor = 3).

$$\sqrt{\epsilon_b} = \sqrt{\epsilon_a}\left[\frac{1 - \left[\frac{A_1}{A_m}\right]^2 + \left[\frac{A_2}{A_m}\right]}{1 - \left[\frac{A_1}{A_m}\right]^2 - \left[\frac{A_2}{A_m}\right]}\right] \tag{3}$$

where

ϵ_b = the dielectric of base layer

A_2 = the amplitude of reflection from the top of the base layer in volts (peak A_2 in Figure 2)

$$h_{base} = \frac{c\Delta t_2}{\sqrt{\epsilon_b}} \tag{4}$$

To demonstrate how these equations are used to calculate thicknesses the HMA and granular base thicknesses will be computed for the individual GPR trace shown in Figure 2. To clearly show the peaks in Figure 2 a voltage amplification factor of 3 was used, the measured values for A_1 and A_2 are 3.276 and 0.635 volts respectively. The time delay between reflections Δt_1 and Δt_2 is 5.203 and 2.742 nanoseconds. The amplitude of metal plate reflection A_m was 7.48 volts.

Using Equation 1

$$\epsilon_a = \left|\frac{1+0.438}{1-0.438}\right|^2 = 6.54$$

Using Equation 2 for HMA thickness h_1,

$$h_1 = \frac{5.9 \ x \ 5.203}{\sqrt{6.54}} = 12.0 \ inches$$

Using Equation 3

$$\sqrt{\epsilon_b} = \sqrt{6.54}\left[\frac{1 - 0.192 + 0.0853}{1 - 0.192 - 0.0853}\right]$$

$$\sqrt{\epsilon_b} = \sqrt{6.54}\left[\frac{0.893}{0.723}\right]$$

$$\epsilon_b = 9.98$$

Using Equation 2 for granular base thickness

$$h_2 = \frac{5.9 \ x \ 2.742}{\sqrt{9.98}} = 5.1 \ inches$$

Using these equations it is therefore possible to compute the layer thicknesses and dielectrics for any location in the section under test. The use of the thickness information is obvious to DOT personnel in quality control of new pavements and in evaluating existing pavements. For example layer thickness information is critical in the interpretation of Falling Weight Deflectometer data. What is not understood and is the subject of continuing research is the significance of the calculated dielectric values. The dielectric value for any layer is a composite of the individual components dielectrics and their volumetric ratios. The dielectric for a granular base is related to the dielectrics and volumetric ratios of the components (aggregate, air and water). Work at the Texas Transportation Institute has found that granular materials at or below their optimum moisture contents have dielectric values of less than 12.0. The ability of any base to attract and hold moisture is largely a function of the fine fraction of the aggregate, particularly the minus 200 fraction. It is proposed that aggregate bases with high dielectric values (> 16) will be saturated and prone to freeze thaw damage. A laboratory tube suction test to measure the moisture affinity of any base has been developed and it is currently the subject of continuing field and laboratory research studies in Texas, Finland and Minnesota.

The significance of the dielectric value for the asphalt layer is less well understood. The main components of the HMA layer are asphalt cement, aggregate and air. Of interest to all DOT's is the density of the HMA layer and detection on possible segregation. In both of the cases the air content of the HMA layer would increase and the composite dielectric would decrease. In theory GPR has the potential to be used for real time density control of newly constructed HMA layers. The is being currently investigated in Finland where GPR antennas are being attached to the finishing rollers.

2.3) Detailed Thickness Results

In testing US 63 two passes were made in each lane. The first pass was made at a constant speed of 40 mph. A second pass was made to identify the core locations. MoDOT had taken the thickness verification cores a week prior to the GPR testing and the core locations were clearly visible on the pavement surface. In this second pass, at each core location, the speed was

reduced to a crawl and the driver indicated when the antenna passed over the core hole. At each core location a mark was placed in the GPR data file. Upon reviewing the data from each of these runs it was decided that the calculated layer thicknesses were very similar. It was therefore concluded to perform the thickness estimates on the pass 2 file which contained the marked core locations. In this section of the report a graphical representation will be made of the layer thicknesses calculated for each lane. In section 2.4 the correlation between measured and computed thicknesses will be given.

In the second passes over the section a total of 23662 and 25068 traces were collected in the slow (right) and fast (left) travel lanes, the difference in the number of traces being related to the speed of travel and the length of lead into the new section. This means a GPR trace was collected for approximately every 1.0 foot of pavement. In order to process this large amount of data the DACQ signal processing system developed by the Texas Transportation Institute was used. This system incorporates all of the equations and calibration factors discussed above. The results of this analysis are shown graphically in Figure 3.

2.4) Comparing Estimated and Measured Thicknesses

In the Phase 1 report on SH 10 it was concluded that in the high speed GPR analysis when comparing the thicknesses computed from GPR data with those obtained from actual core measurements the average error of estimate was found to be 0.21 inches or 1.7%. This being the average value for 17 core locations. A similar exercise was conducted with the layer thickness predictions from US 63. The results are shown in Table 1. The GPR thickness estimates were made by Pavement Systems Engineering and the results forwarded to MoDOT who supplied the actual field core thicknesses. The results are encouraging in that the average error was 0.2 inches or 1.1% for US 63. As can be seen in Table 1 most of the error occurred towards the end of the section at stations greater than 1050. The cause of these localized errors is unknown.

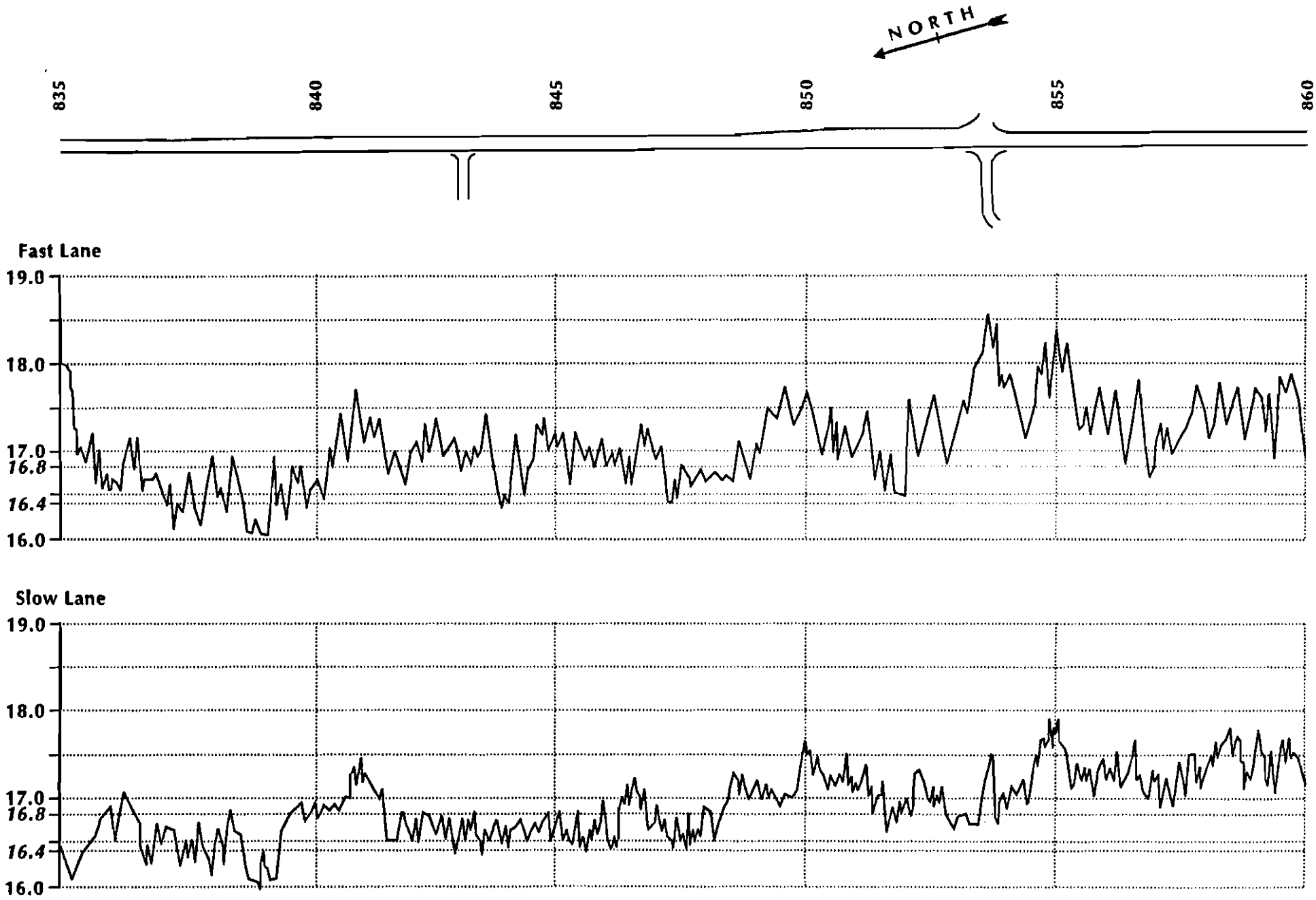


Figure 3. HMA Thickness Estimates for US63. Stations 835-860

(Page 1 of 10)

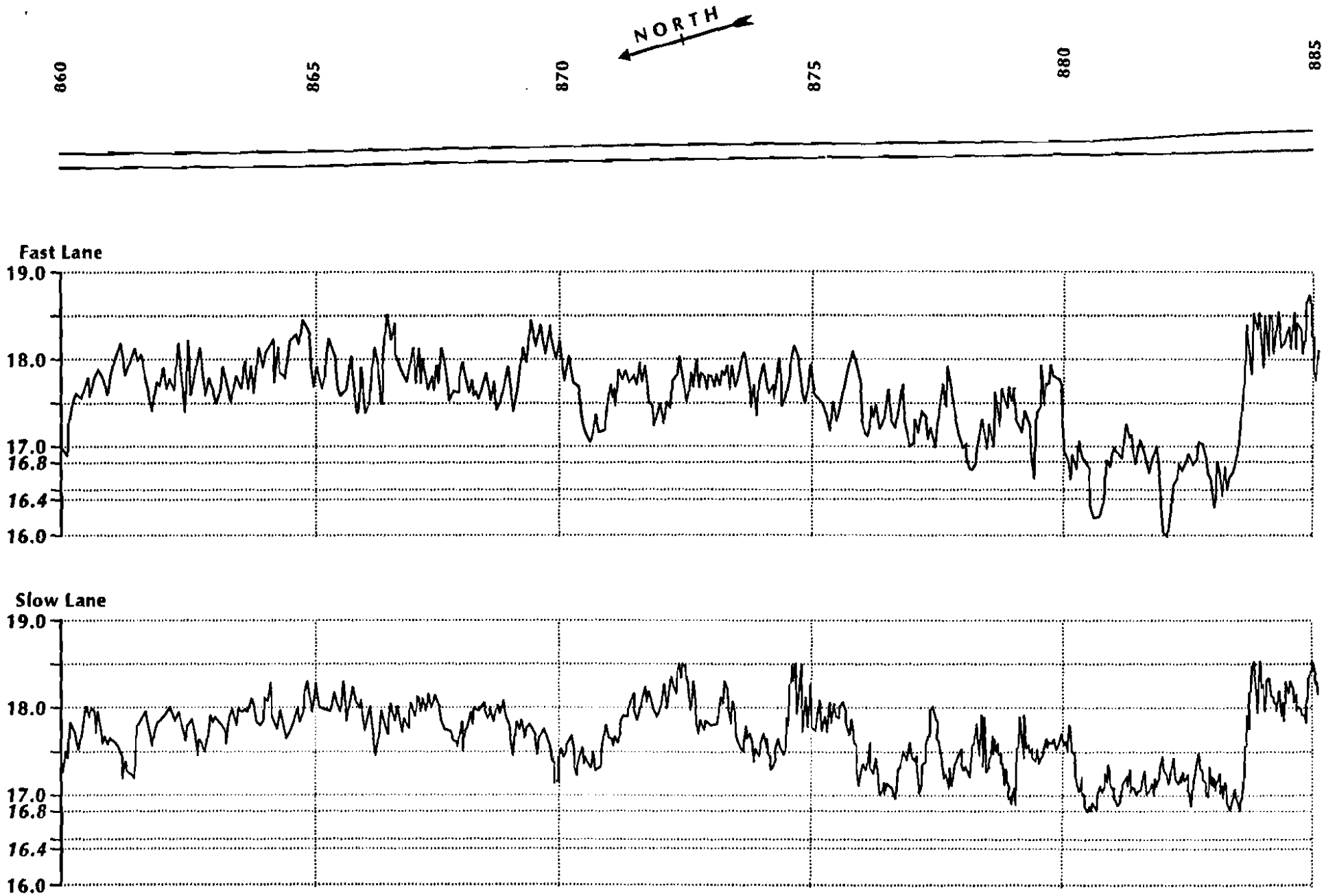


Figure 3. HMA Thickness Estimates for US63. Stations 860 - 885

(Page 2 of 10)

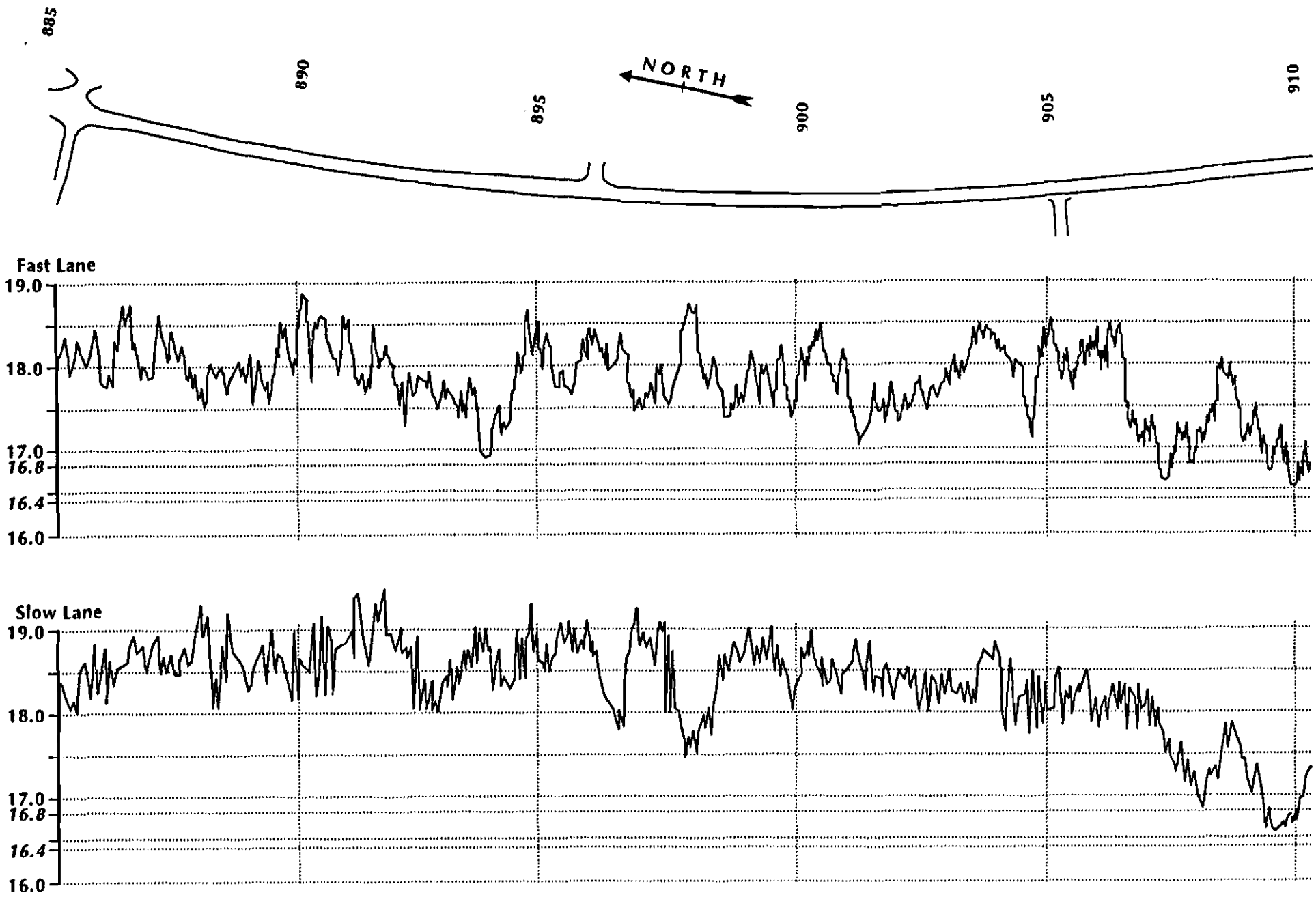


Figure 3. HMA Thickness Estimates for US63. Stations 885 - 910

(Page 3 of 10)

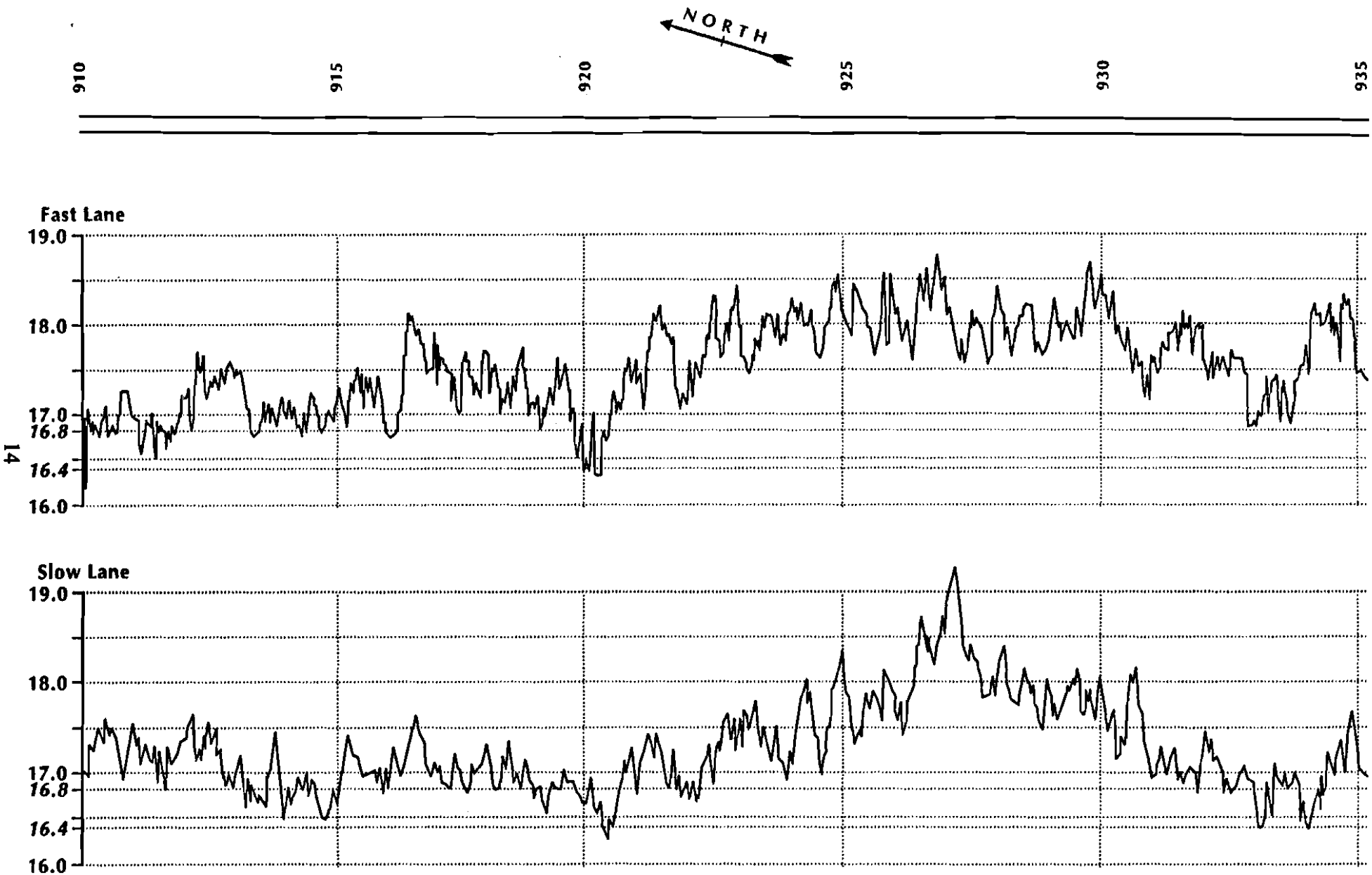


Figure 3. HMA Thickness Estimates for US63. Stations 910 - 935

(Page 4 of 10)

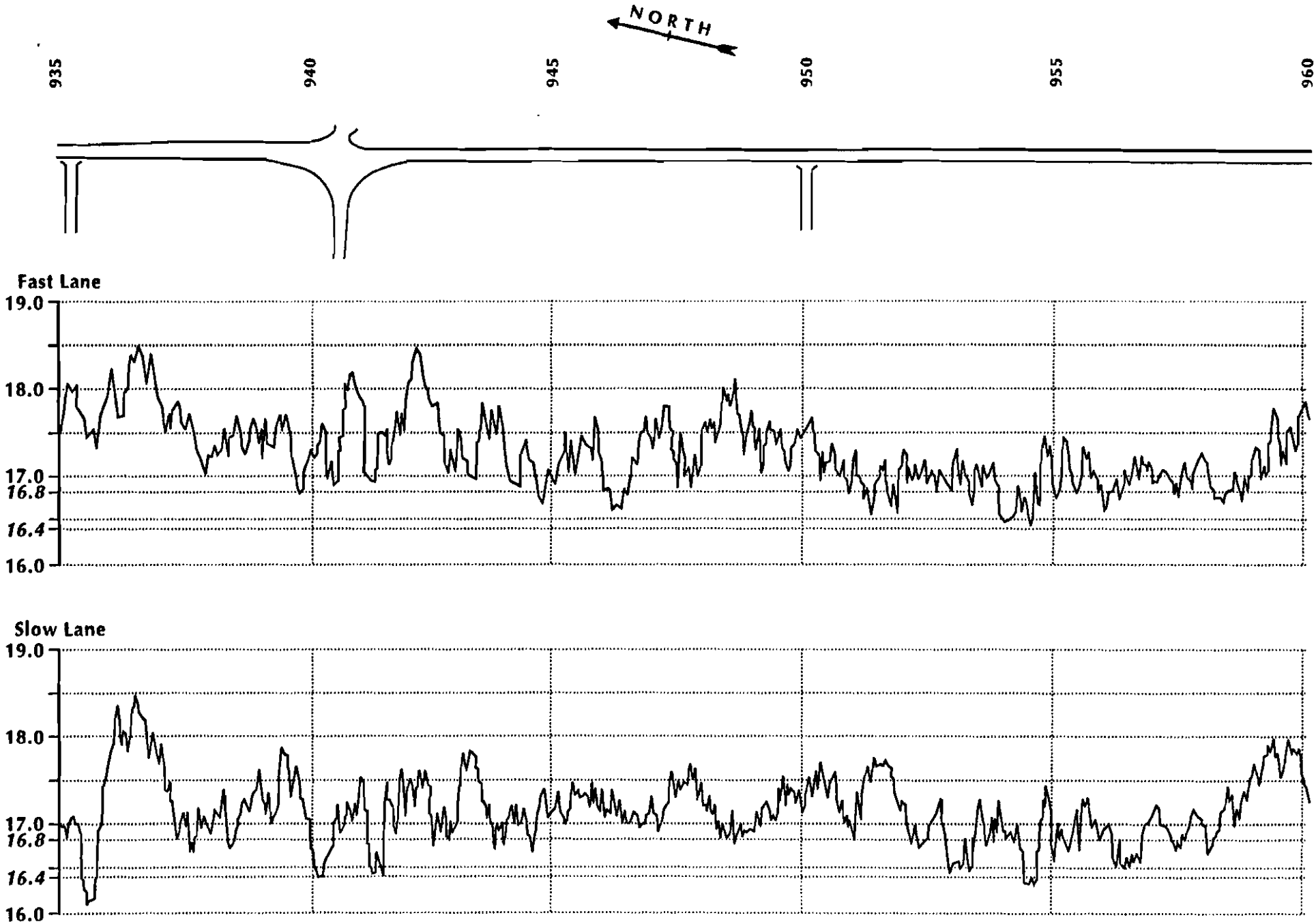


Figure 3. HMA Thickness Estimates for US63. Stations 935 - 960

(Page 5 of 10)

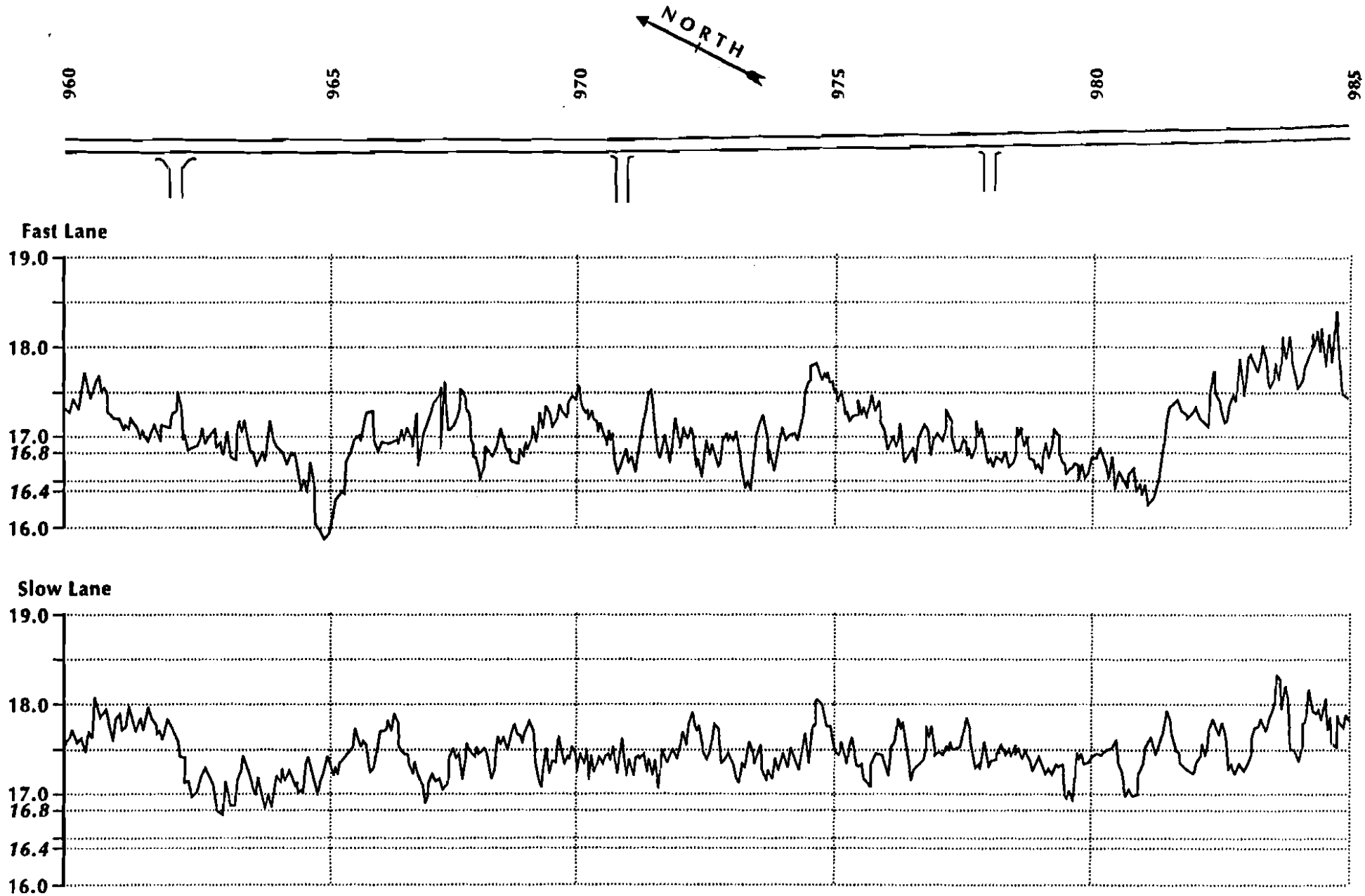


Figure 3. HMA Thickness Estimates for US63. Stations 960 - 985

(Page 6 of 10)

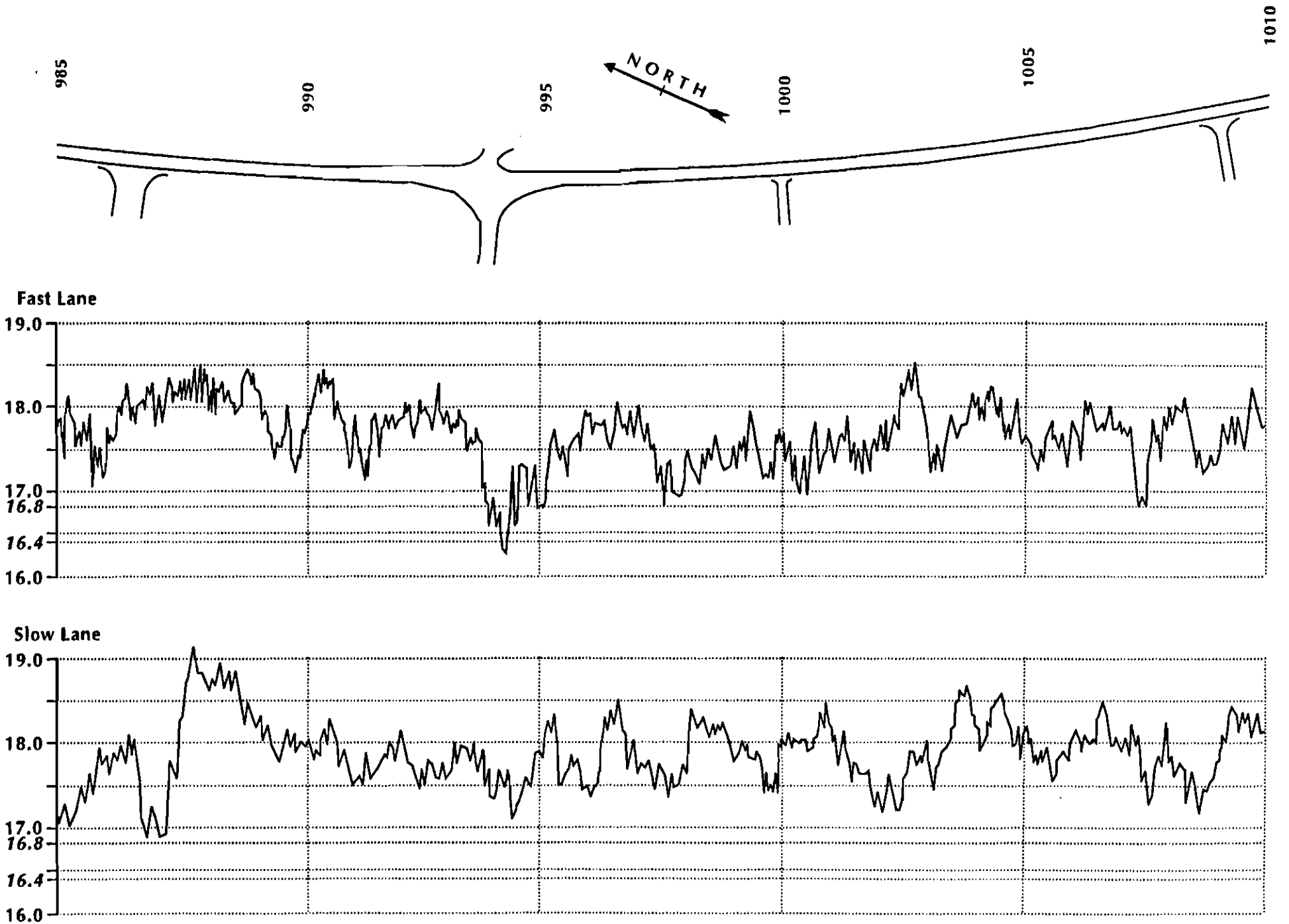


Figure 3. HMA Thickness Estimates for US63. Stations 985- 1010

(Page 7 of 10)

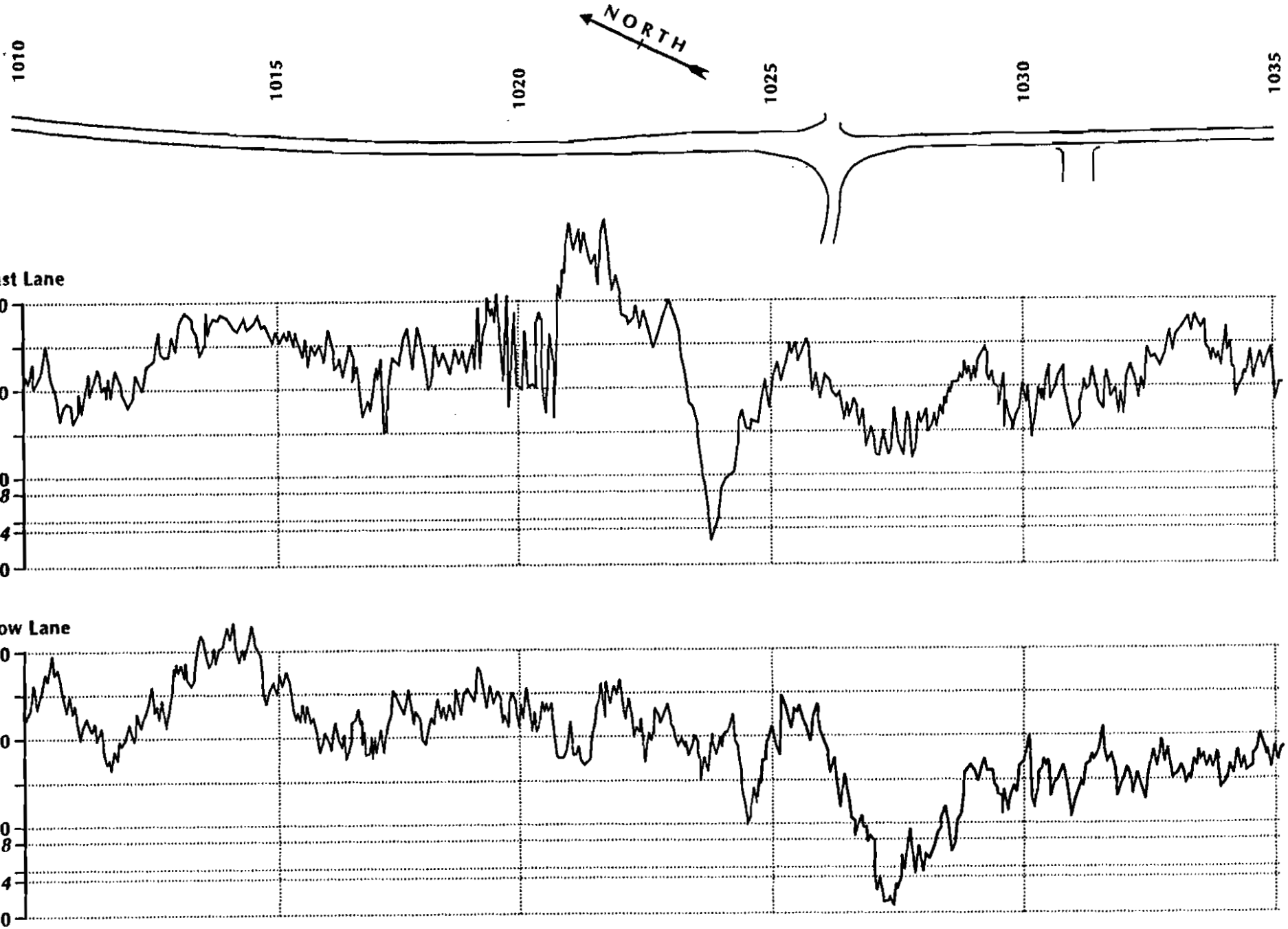


Figure 3. HMA Thickness Estimates for US63. Stations 1010 - 1035

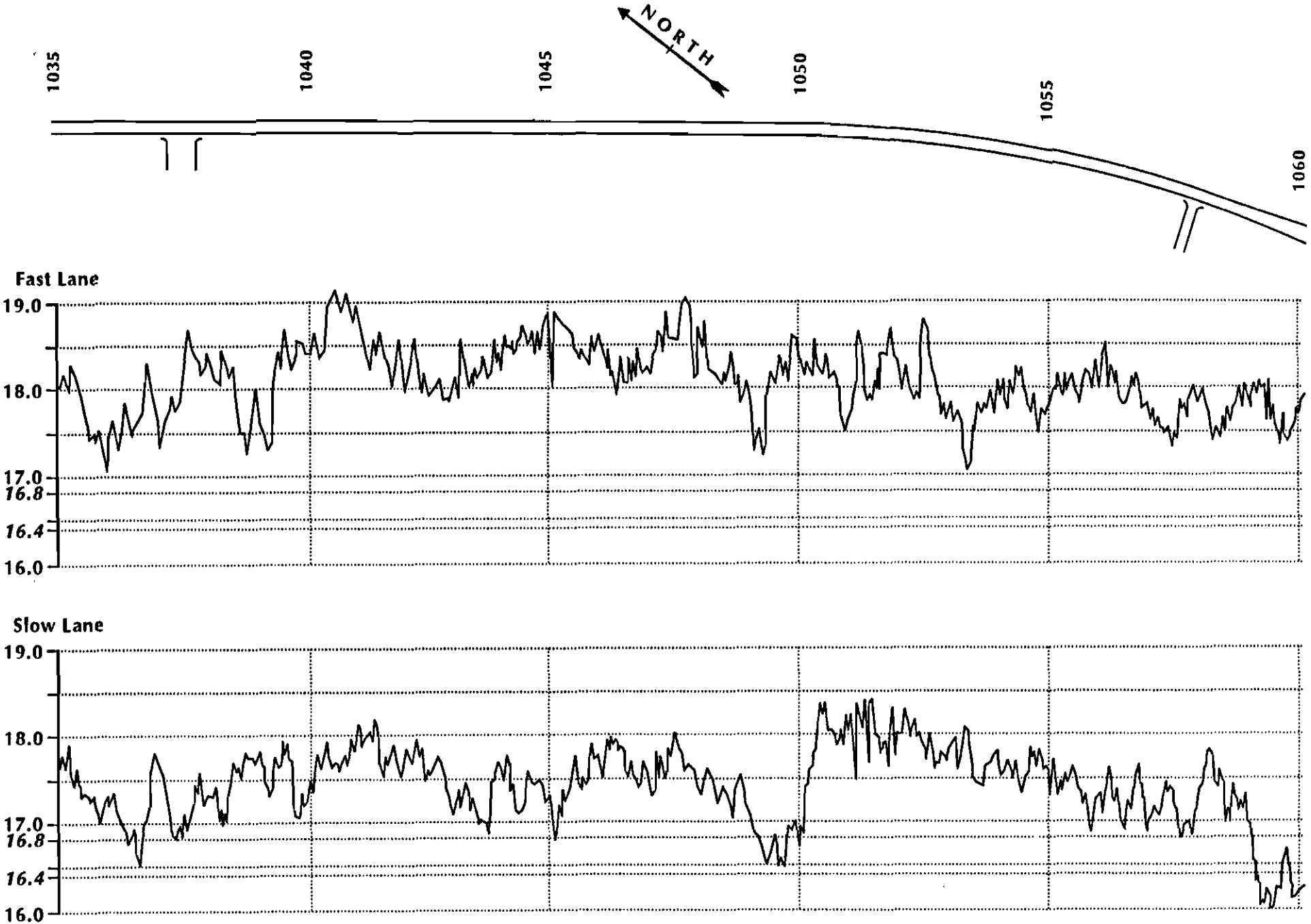


Figure 3. HMA Thickness Estimates for US63. Stations 1035 - 1060

(Page 9 of 10)

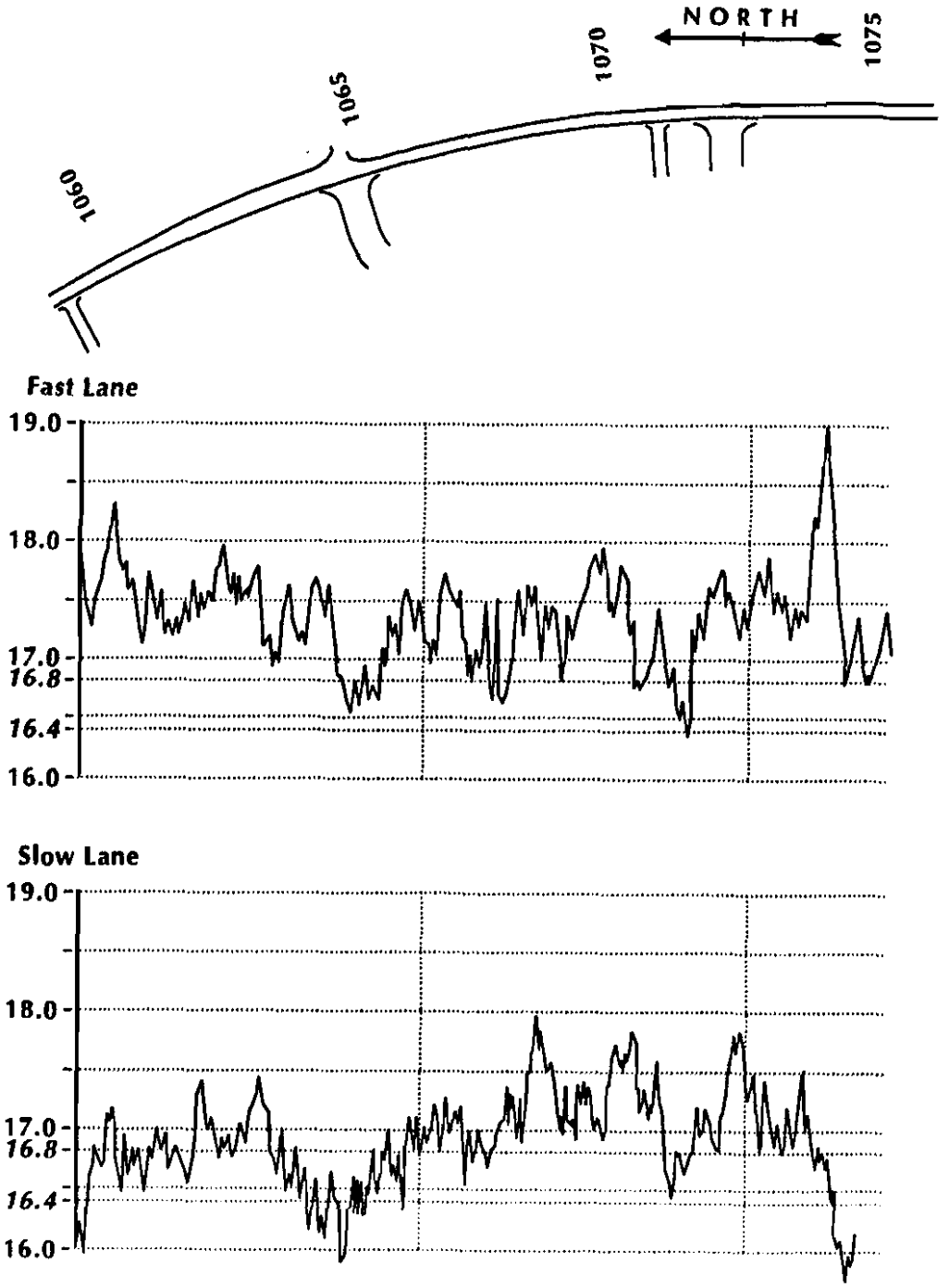


Figure 3. HMA Thickness Estimates for US63. Stations 1060 - 1075 (Page 10 of 10)

Table 1. Measured (Core) versus Computed (GPR) Core Thicknesses, Average Error 0.2 ins (1.1%).

Indent No.	Lane	Station (Plan)	Actual Core Location	Thicknesses (ins)		
				GPR	Core	Diff
3	LT SBL	842+00	842+03	16.9	16.8	0.1
4	RT SBL	846+00	845+78	16.5	16.9	-0.4
5	LT SBL	850+00	850+08	17.7	17.4	0.3
6	RT SBL	855+00	855+07	17.8	17.8	0.0
7	RT SBL	862+00	862+12	18.0	18.1	0.1
8	LT SBL	870+00	870+18	17.8	17.6	0.2
9	LT SBL	877+00	877+18	17.0	17.1	0.1
10	RT SBL	882+00	882+15	17.1	17.2	0.1
11	LT SBL	887+00	887+13	18.2	18.5	0.3
12	RT SBL	895+00	895+34	18.9	18.6	0.3
13	LT SBL	900+00	900+22	18.4	18.4	0.0
14	RT SBL	905+00	905+44	18.3	18.4	0.1
15	LT SBL	908+00	908+25	17.7	17.9	0.2
17	LT SBL	919+00	920+48	17.2	17.5	0.3
18	RT SBL	923+00	923+45	17.2	17.4	0.2
19	LT SBL	928+00	929+60	18.3	18.3	0.0
20	RT SBL	930+00	930+37	17.4	17.4	0.0
21	LT SBL	935+00	936+52	18.0	17.8	0.2
22	RT SBL	944+00	944+65	17.1	17.2	-0.1
23	LT SBL	950+00	951+60	17.0	17.3	-0.3
24	RT SBL	955+00	955+42	17.1	16.9	0.2
25	LT SBL	960+00	960+60	18.0	18.0	0.0
26	RT SBL	969+00	969+73	16.9	16.9	0.0
27	LT SBL	974+00	974+60	18.3	17.6	0.7

Indent No.	Lane	Station (Plan)	Actual Core Location	Thicknesses (ins)		
				GPR	Core	Diff
28	RT SBL	978+00	978+77	17.1	17.1	0.0
29	LT SBL	983+00	983+60	18.0	18.0	0.0
30	RT SBL	988+00	988+71	18.7	18.7	0.0
31	LT SBL	990+00	990+38	18.1	17.7	0.4
32	RT SBL	995+00	995+24	18.0	18.1	-0.1
33	LT SBL	1000+00	1000+75	17.6	17.5	0.1
34	RT SBL	1005+00	1005+60	17.9	17.6	0.3
35	LT SBL	1010+00	1010+35	18.1	18.3	-0.2
37	LT SBL	1020+00	1020+92	19.7	19.4	0.3
38	RT SBL	1025+00	1026+02	17.6	17.8	-0.2
39	LT SBL	1030+00	1030+92	17.5	18.0	-0.5
40	RT SBL	1035+00	1036+09	17.3	17.2	0.1
41	LT SBL	1040+00	1040+95	18.7	18.8	-0.1
42	RT SBL	1045+00	1046+13	17.8	17.8	0.0
43	LT SBL	1050+00	1051+20	18.6	17.9	0.7
44	RT SBL	1055+00	1056+18	17.5	17.4	0.1
45	LT SBL	1060+00	1061+15	17.5	17.8	-0.3
46	RT SBL	1065+00	1066+19	16.7	16.9	-0.2
47	LT SBL	1070+00	1071+15	17.3	~~17.2~~ 17.7	~~-0.1~~ -0.4
48	RT SBL	1075+00	1076+22	16.2	16.8	-0.6
49	LT SBL	1080+00	1080+85	16.3	17.0	-0.7
			Sum (45 cores)		796	9.2
			Average (ins)		17.7	0.2
			Average % Error			1.1%

SECTION 3. COLOR DISPLAYS OF GPR DATA

3.1) Description of COLORMAP

The COLORMAP system was developed by the Texas Transportation Institute for the Texas Department of Transportation. The intent was to provide DOT Engineers with a simple software package for interpreting GPR data in order for them to rapidly gain the subsurface layer information needed to make their engineering decisions. TxDOT engineers are trained how to use this system in a 2 day training school, the system has been implemented within TxDOT. In this section of the report several color displays of data from US 63 will be presented together with the appropriate interpretation.

COLORMAP is a windows based system in which a color coding scheme is used to transform the GPR return waves into a single line scan. This transformation is shown in Figure 4. The line scans are stacked side by side and a subsurface picture of the highway is produced. A typical color display for approximately 7 stations (station 1082 to 1089) of the slow lane of US 63 is shown in Figure 5. This is from near the south end of the project. The reflections from the surface (a) and top of base (b) are displayed as horizontal red lines. The reflection from the base/subgrade interface (c) is faint, but could be amplified with additional signal processing. The scale on the right hand side (e) is an approximate depth scale. From Figure 5 it is apparent that the total asphalt layer becomes thinner towards the right of this figure it is apparent that from Stations 1087 + 50 to 1088 + 00 the pavement appears to be less than the required 17 inches.

3.2) Calculating HMA Thicknesses COLORMAP

Figure 6 provides an example of how layer thicknesses are calculated within COLORMAP. The two vertical lines on the color display denote the limits of the user defined section. Within this section the lines drawn over the reflections from the bottom of the HMA and granular base layers were automatically generated by the system. COLORMAP then calculates and graphs each layer thickness for the section as shown in the lower graph on Figure 6. It is interesting to note the thickness of the granular base layer around station 883 + 50, it is substantially thinner than designed.

Principles of Ground Penetrating Radar

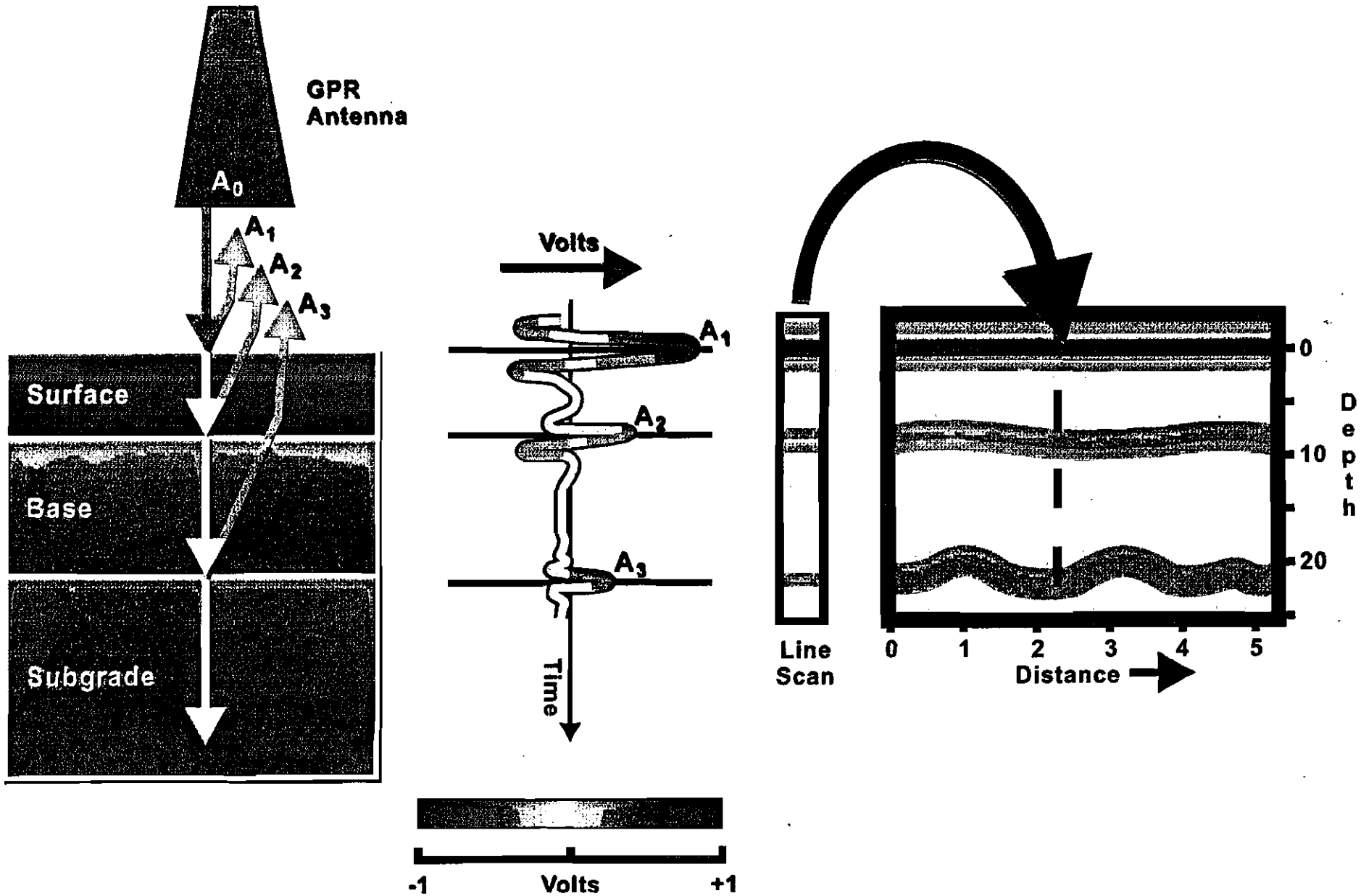


Figure 4. Converting the GPR Traces into COLORMAP Displays.

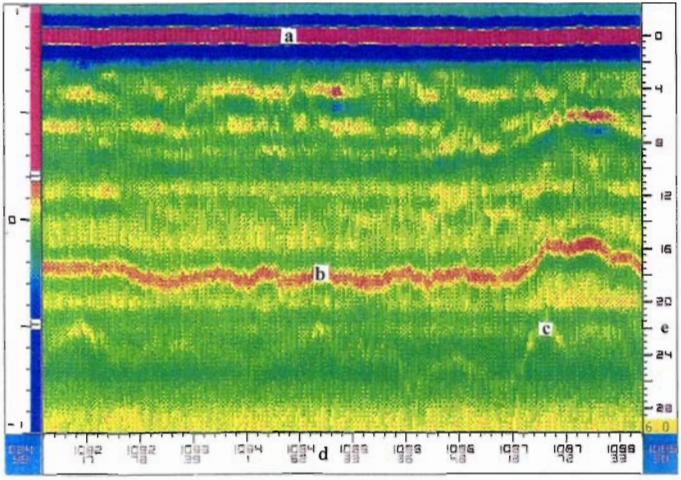


Figure 5 COLORMAP Display of GPR Data from the Slow (Right) Lane of US 63.

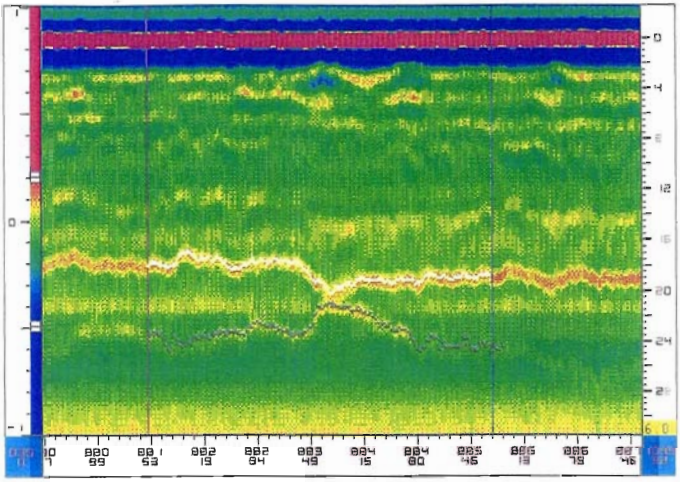
Key: a Surface

b Bottom of HMA Layer

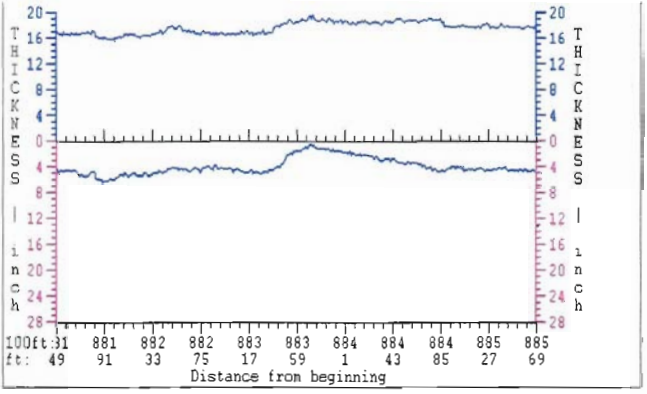
c Bottom of Granular Base

d Distance Scale Stations/Offset

e. Depth Scale in Inches



a. COLORMAP Display Defining Section and Layer Interfaces.



b. Computer Layer Thicknesses for Section.

Figure 6. Automated Layer Thickness Computation Using COLORMAP.

3.3) Locating Defects in the HMA

One of the benefits of the COLORMAP display is that it permits the user to rapidly locate areas of deficient thickness and potential defects within layers. On US 63 very few defects were found in either lane, this was confirmed by the coring where all of the cores obtained were homogeneous with no apparent defects. The focus of this study is to evaluate the use of GPR as a thickness measuring tool for quality control purposes. However in recent years it has become apparent that the detection of construction defects is an important additional benefit of GPR testing. These defects in HMA layers often are areas of low density material or areas where moisture damage such as stripping has occurred. An example of using GPR to detect construction defects in HMA pavements is given in Appendix C.

On US 63 a few short sections were found with anomalous GPR returns. One such area is shown in Figure 7. In this case a negative peak (blue line) is observed at approximately 10 inches below the surface between Stations 984 + 40 to 984+70. A single GPR reflection from this area is shown in the lower part of Figure 8, this should be contrasted with the typical "homogeneous HMA" trace shown in the upper part of this figure. The cause of the additional negative reflector at the 10 inch depth is not known at this point. This type of reflector is often caused by the presence of a thin poorly compacted layer. The severity of the problem is difficult to determine directly from GPR. This can best be done by coring the suspected areas. The benefit of GPR for quality control purposes is not that it eliminates coring, but that it tells you where to core.

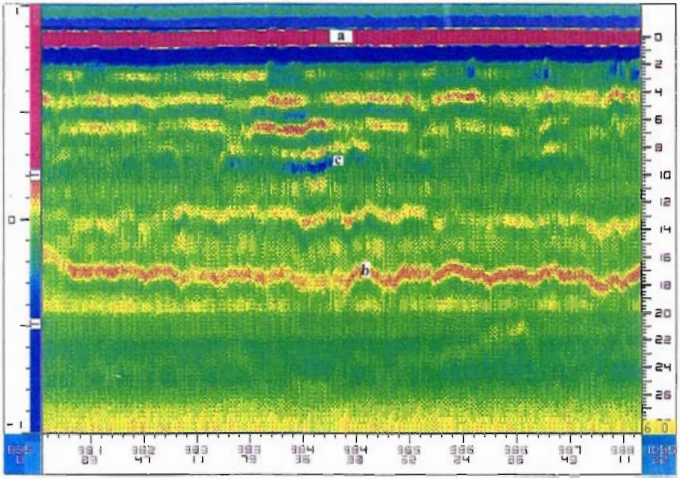
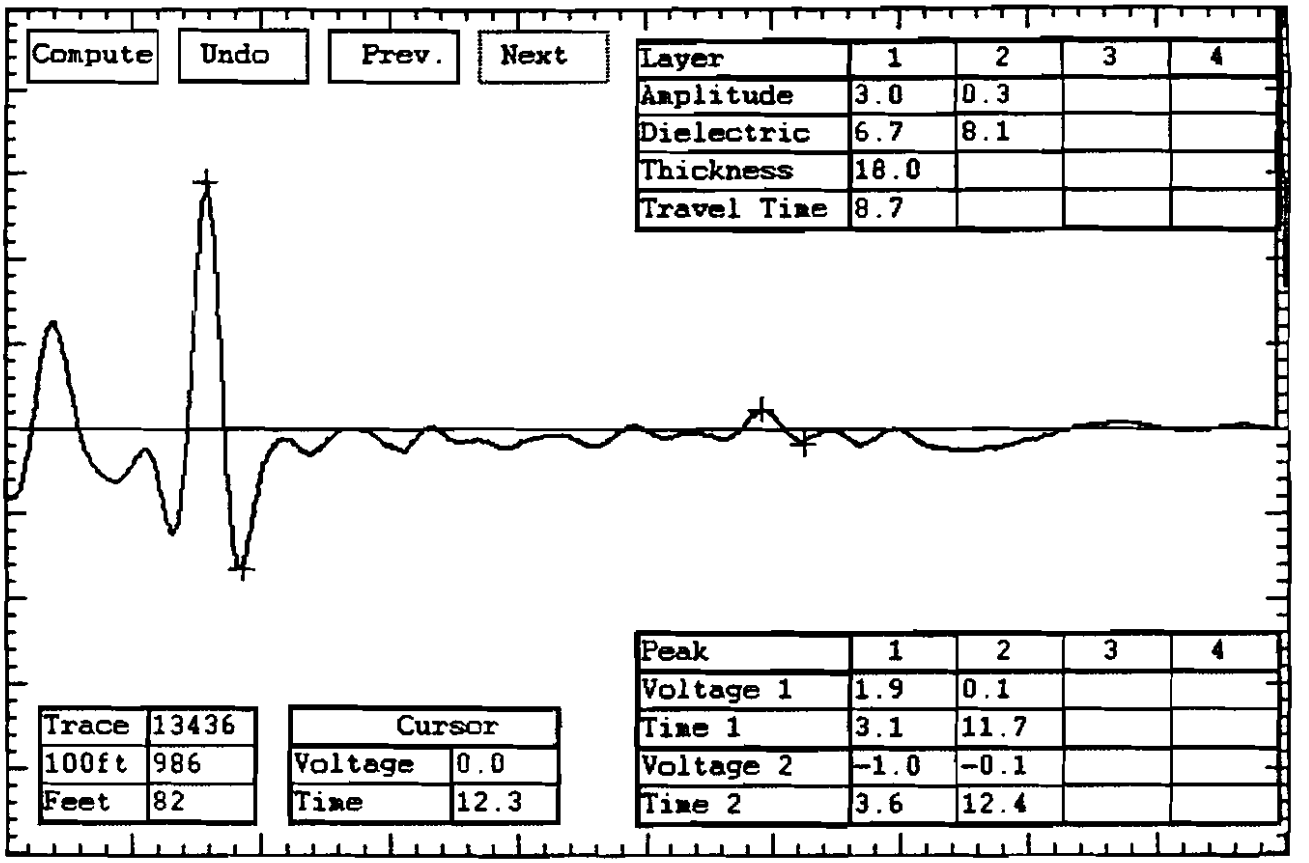


Figure 7. COLORMAP Display of GPR Data Showing Possible Defect.

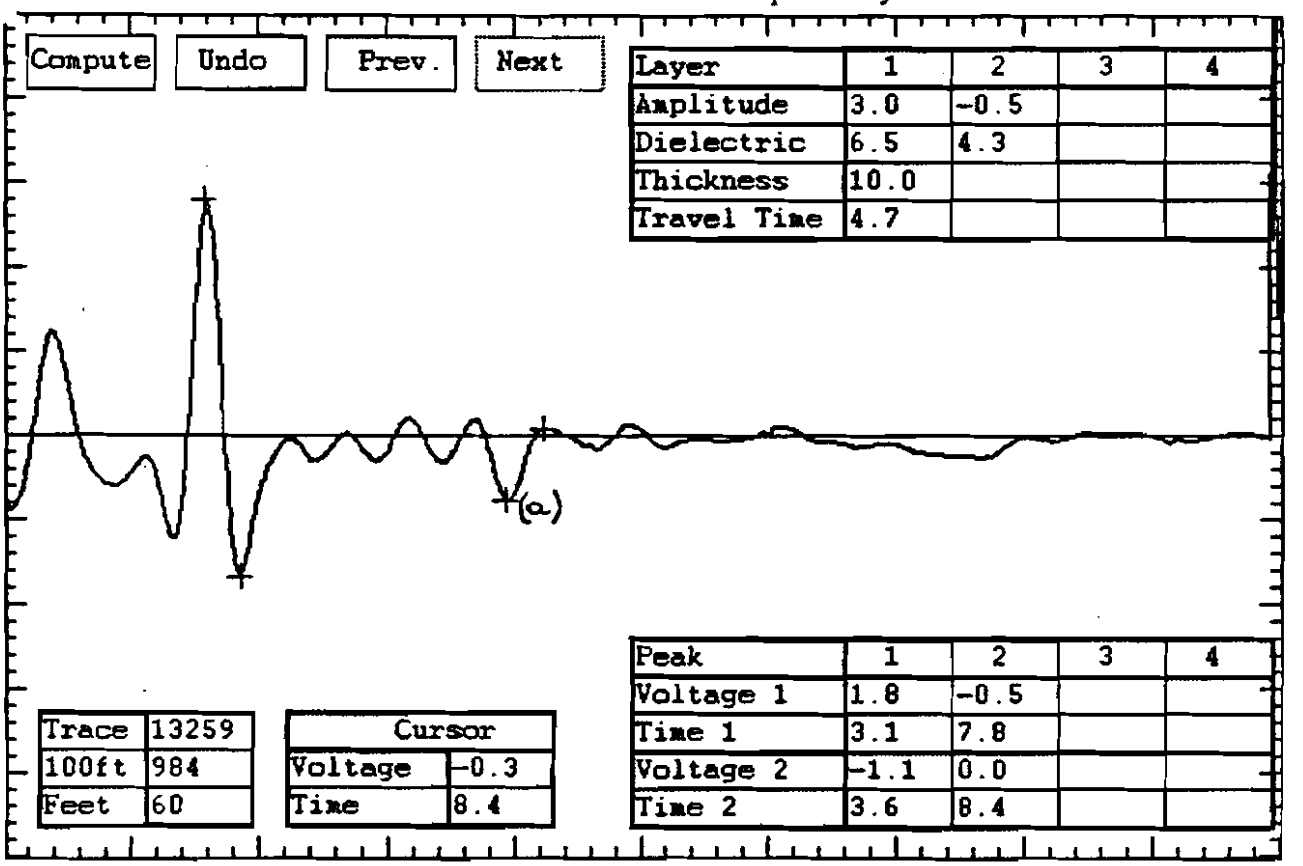
Key: a. Surface

b. Bottom of HMA Layer

c. Possible Defect



a. GPR Trace from a "Good Asphalt Layer".



b. GPR Trace from a Suspected Defect (a) = Defect.

Figure 8. Individual GPR Traces from Good and "Bad" Areas (Figure 7)of US 63 (Fast Lane)

SECTION 4. CONCLUSION AND RECOMMENDATIONS

CONCLUSIONS

1) The GPR data collected on this project was judged to be of good quality. The interface between the HMA and the Granular Base was clear and between the Granular Base and Subgrade was faint but still identifiable.
2) Signal Processing determined that there were no major defects in the HMA layer in either lane.
3) The average HMA thickness in both lanes was greater than 17.5 inches. Less than 1% of the total project was computed to be less than 16.4 inches thick, these being highly localized short problem areas.
4) The accuracy of GPR thickness estimates was thought to be reasonable, normally within 3% of the measured core thickness. As stated earlier it is believed that GPR will not replace coring but permit DOT's to core "smarter", and hopefully avoid taking multiple cores in deficient areas.
5) In conclusion the US 63 project had good thickness control and the HMA layer appears to be defect free. The Contractor and DOT inspectors did a good job.

RECOMMENDATIONS

The studies completed on SH 10 and US 63 have demonstrated to MoDOT one possible use of Ground Penetrating Radar technology in pavement evaluation. It must be emphasized that using GPR for thickness determination is a very limited use of this technology. GPR is the only technology available to the highway community with the ability to monitor subsurface conditions at close to highway speed. Many other applications of GPR exist, for example;

a) as a pavement evaluation tool when planning rehabilitation projects. A GPR run would provide a subsurface map of the project including surfacing thickness, section breaks, the location of subsurface defects and areas of wet base. The GPR would dictate where the Falling Weight Deflectometer tests should be conducted and where cores are required. The thickness information is also critical in the interpretation of FWD data,

b) in Pavement Management Systems as one of the tools required to either establish or verify a pavement layer data base,

c) in evaluating the condition of asphalt covered bridge decks, and

d) in forensic engineering to investigate the cause of unexplained rapid pavement deterioration. Most pavement failures are associated with moisture and this is readily identified with GPR.

Should MoDOT wish to proceed with further evaluation and/or implementation of GPR technology the following should be considered;

1) In January, 1998 the TRB will hold a one day workshop on GPR technology on the Sunday before the annual Transportation Research Board Meeting. Numerous speakers from around the world and from three DOT's will be making presentations on their GPR implementation efforts. Someone from MoDOT should attend this workshop.

2) The Texas DOT sponsors a two day training school on GPR technology with practical training on how to process GPR signals with COLORMAP. Someone from MoDOT should attend one of these schools. Even if MoDOT's intention is to hire a consultant to perform the required GPR work it will be essential to have someone in-house familiar with the Do's and Don'ts of this technology.

3) Should MoDOT wish to purchase a 1 GHz air launched GPR system the specifications supplied in Appendix B should be used. If a system passes these tests it will provide signals of sufficient quality for automated signal processing.

4) An implementation plan is critical. GPR can only be successfully implemented with a) good hardware (Appendix B), b) good software (similar capabilities to COLORMAP) and c) an established data base of experience with local surfacing and base materials. The variety of materials used in pavements is tremendous and how each responds to GPR signals under varying environmental conditions is not fully understood. In the early days of GPR implementation substantial coring is required to verify GPR interpretation.

5) The most cost-effective use of GPR is in the area of flexible pavement rehabilitation, particularly on pavement that are severely deteriorated or which have deteriorated rapidly. GPR can assist in identifying the cause of the problem and identifying the optimal rehabilitation strategy. This current GPR evaluation has focussed on thickness measurements on new pavements, MoDOT should consider conducting a similar evaluation on pavements scheduled for major rehabilitation in the near future.

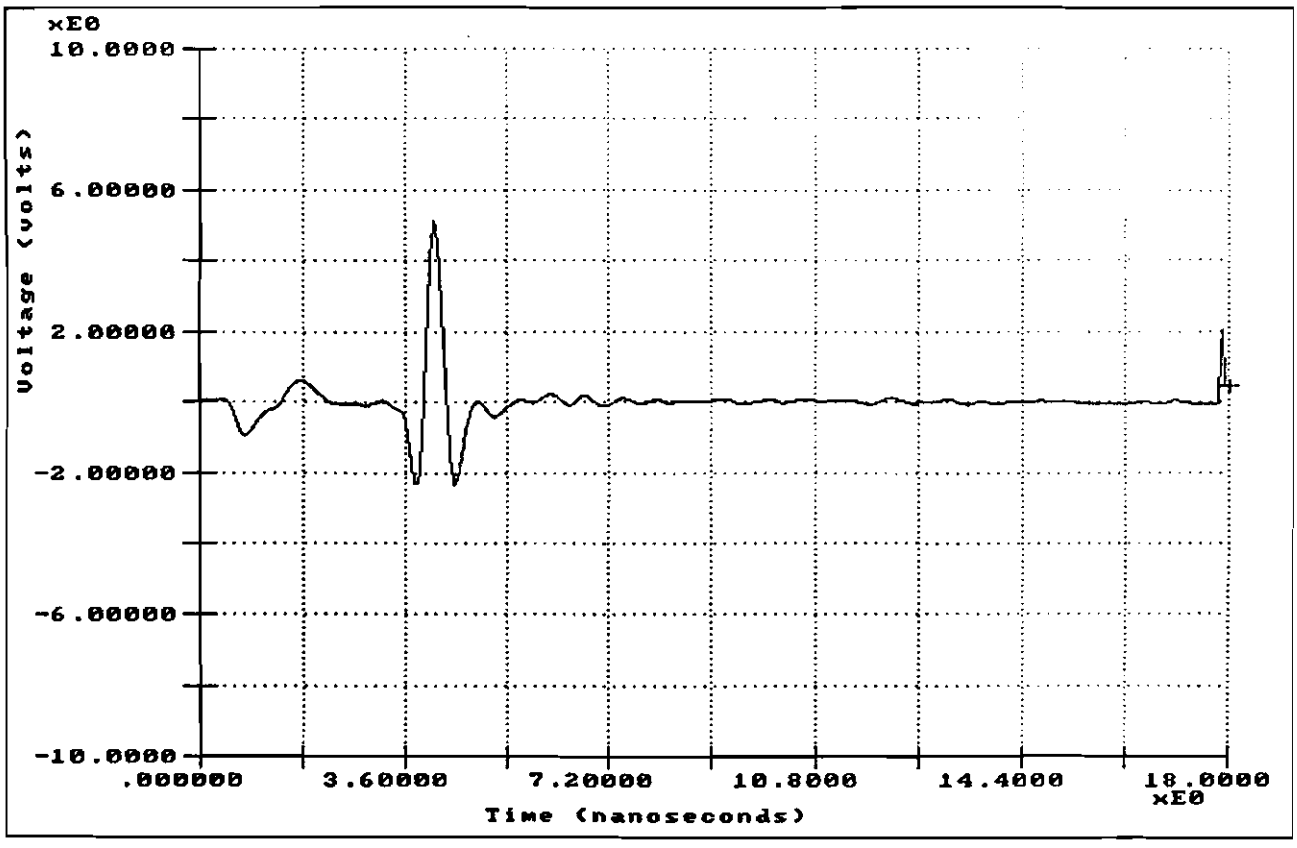
APPENDIX A - COMPARING PHASE I AND II ANTENNAS

Two different Pulse Radar antennas were used on the two HMA projects in Missouri. On the SH 10 job the GPR system was owned by Pulse Radar Inc. of Houston, Texas. On the US 63 job the GPR system was owned by Terracon Inc. of Kansas. Figures A1 and A2 present typical metal plate and pavement reflections from the two supposedly identical GPR systems. However as the discussion below will describe the antenna used on the SH 10 was judged to generate better quality signals than the US 63 system. This section was added to the report to demonstrate that GPR system manufacture is still in some ways an "art" where the system designer has several options on how to tune the antenna.

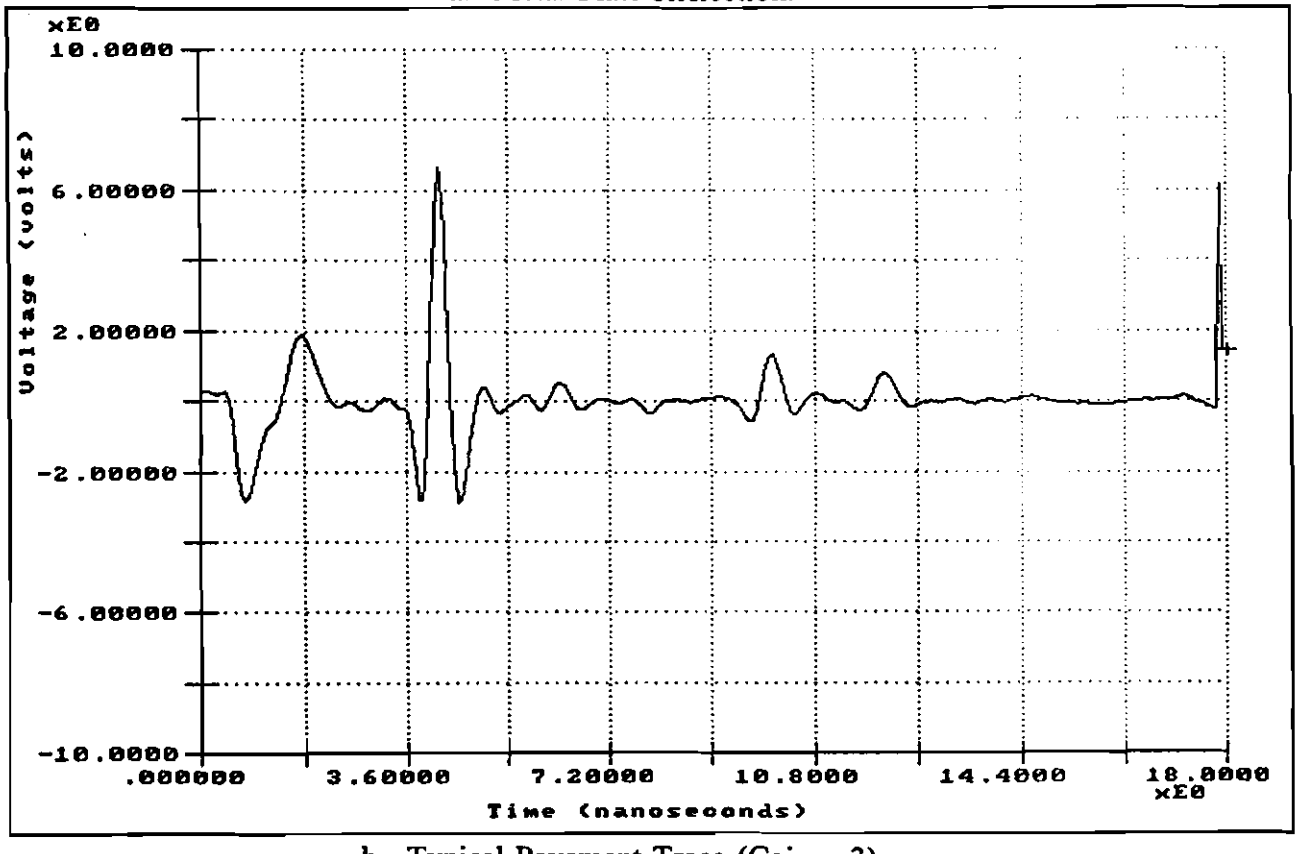
Figure A1 shows a typical metal plate reflection and pavement reflection from SH 10. Figure A2 shows similar traces from US 63. The SH 10 system is viewed as better for the following reasons,

1) The metal plate reflection is more symmetrical, with equal length legs,
2) The trailing leg of the surface reflection returns to the zero line faster, this is important when testing pavements with thin surfacings, and
3) The end reflection (peak before surface reflection) is smaller and does not overlap with the surface reflection. This overlap means that additional signal clean up may be required to process the data from the US 63 system.

In processing the GPR data it was easier to process the SH 10 data. This leads to the conclusion that in order to purchase a GPR system of sufficient quality to permit automated signal processing of pavement data detailed performance specifications need to be developed. These specifications are to be used when purchasing systems or possibly when contracting services. The most recent performance specification that were used by the Texas DOT in their recent bid request for pavement GPR systems are shown in Appendix B. These specifications were recently updated based on the findings of this study. The GPR system used on SH 10 passes these specifications the unit used on US 63 does not pass.

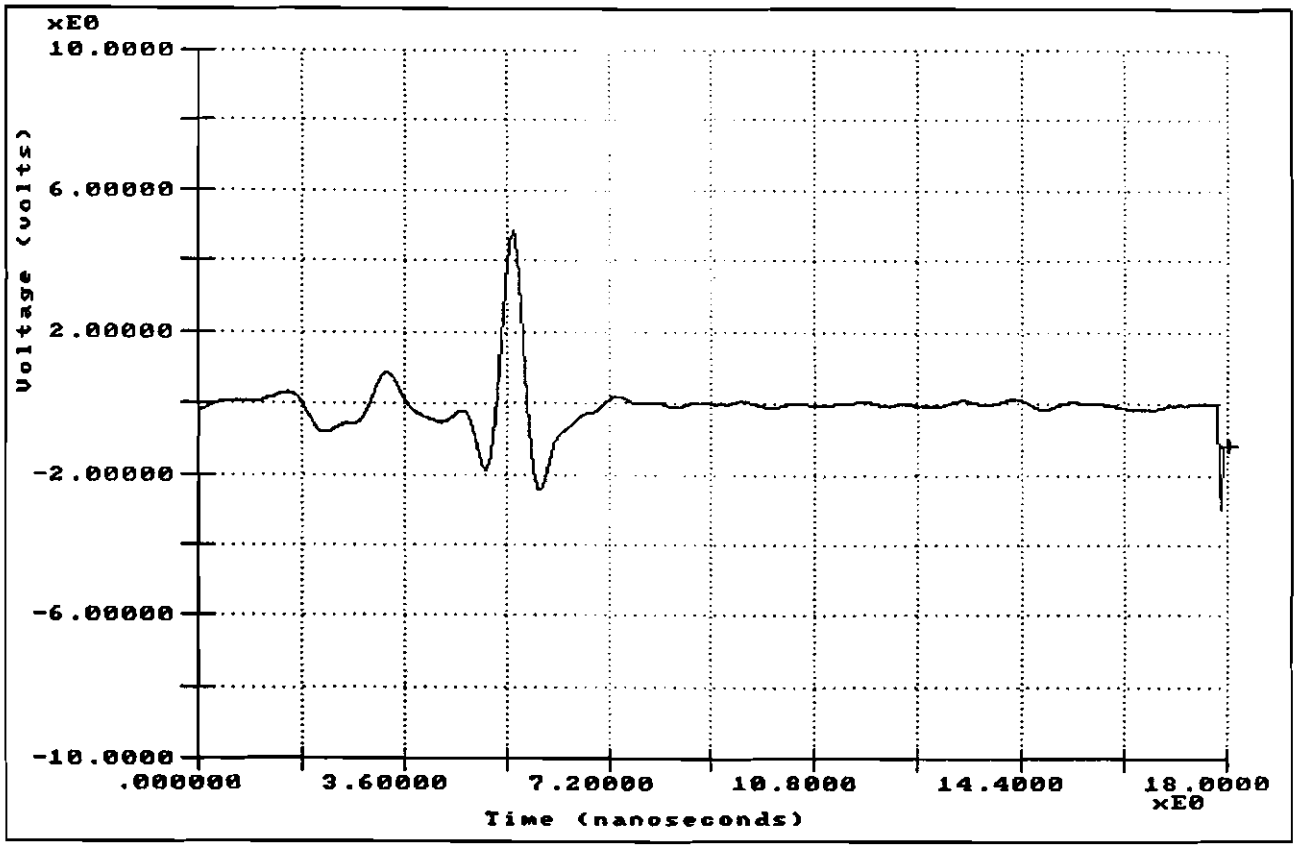


a. Metal Plate Reflection.

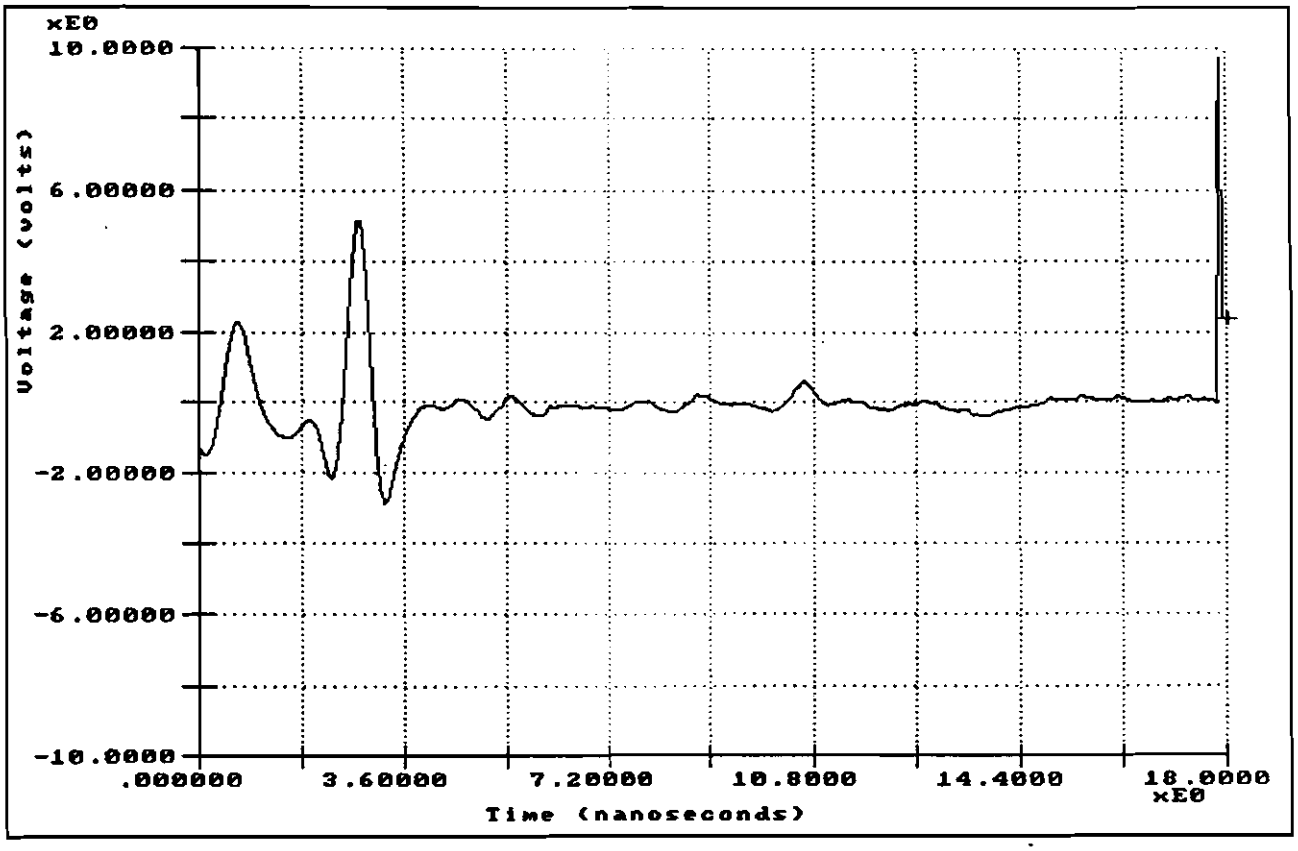


b. Typical Pavement Trace (Gain = 3).

Figure A1. Pulse Radar Antenna Used on SH 10.



a. Metal Plate Reflection.



b. Typical Pavement Trace (Gain = 3)

Figure A2. Typical Traces from Second Pulse Radar Antenna Used on US 63.

APPENDIX B - TxDOT SPECIFICATIONS FOR ANTENNA PURCHASE

The following specifications were used by the Texas DOT in their recent bid request (Oct 97). The specification were sent to the three US based GPR manufacturer's, namely Pulse Radar, Houston, Texas, Penetradar, Buffalo, New York and GSSI, North Salam, New Hampshire.

Proposed Radar Specifications for 1 GHz Air-Coupled Transceiver Units

Performance Specifications:

1. Noise to Signal Ratio Test: The antenna will be positioned at its recommended operating height above a minimum sixteen square foot (4' x 4') metal plate. The radar unit shall be turned on and allowed to operate for a fifteen (15) minute warm up period. After warm up, the unit shall be operated at maximum pulse rate and a single radar waveform pulse shall be recorded. The recorded waveform shall then be evaluated for noise to signal ratio. No averaging or signal clean up such as sky wave removal (and reflection subtraction) shall be allowed. The noise to signal ratio is described by the following equation:

$$\frac{Noise\ Level\ (A_n)}{Signal\ Level\ (A_{mp})} \leq 0.05\ (5\%)$$

Noise Voltage (A_n) is defined as the maximum absolute signal level amplitude occurring between 2 and 10 ns after the surface echo. Signal Voltage A_{mp} is defined as the metal plate return amplitude measured from the peak to the preceding minimum. The noise to signal Ratio Test results for the GPR unit shall be less than or equal to 5%.

2. Signal Stability Test: The same test configuration shall be used as described in the Noise to Signal Ratio test. Fifty (50) traces shall be recorded at the minimum data rate of 25 traces/second. The signal stability shall be evaluated using the following equation:

$$\frac{A_{max} - A_{min}}{A_{AVG}} \leq 0.01(1\%)$$

A_{max} is defined as the maximum amplitude for all 50 traces.

A_{min} is defined as the minimum amplitude for all 50 traces.

A_{AVG} is defined as the average trace amplitude of all 50 traces.

The signal stability test results for the GPR shall be less than or equal to 1%.

3. Long Term Signal Stability: The same test configuration as used in the Signal to Noise ratio test shall be used. The Radar shall be switched on and allowed to operate for 2 hour continuously. As a minimum, a single waveform shall be captured every 2 minute, 60 in total. The amplitude of reflection shall be calculated and plotted against time. For the system to be performing adequately the amplitude should remain constant after a short warm up period. The stability criteria is as follows:

$$\frac{A_{max} - A_{20}}{A_{20}} \leq 0.03 \ (3\%)$$

where:

A_{20} is the amplitude measured after 20 minutes.

A_{max} is the largest amplitude measured after 20 minutes.

4. Variations in Time Calibration Factor: The same test configuration as used in the Signal to Noise ratio test shall be used. A single waveform is collected and the height of the antenna is measured. The test is repeated at two other heights. Typically heights of approximately 10", 16" and 22 inches are used. The time delay from the end reflection at the tip of the antenna to the metal plate reflection is measured for each trace as time t_i (where t_1 represents height position 1). The difference between t_2 and t_1 represents the time to travel a fixed distance in air. For bistatic antennas the travel distance must be calculated based on the system geometry. The factor C_1 is calculated by dividing the distance by the time difference (inches per nanosecond). The factor C_2 represents the speed between heights 2 and 3. The variation in time calibration factor is as shown below:

$$\frac{C_1 - C_2}{\text{Mean of } C_1 \text{ and } C_2} \leq 0.02 (2\%)$$

The variation in time calibration factor shall be less than 2% .

5. <u>End Reflection Test</u>: The same test configuration as used in the Signal to Noise ratio test shall be used. The amplitude of the end reflection directly preceding the metal plate reflection shall be measured. The size of the end reflection shall be;

$$\frac{A_E}{A_{mp}} < 0.10 \ (10\%)$$

where:

A_E is the amplitude of end reflection in the 4 nanosecond window preceding the surface echo.

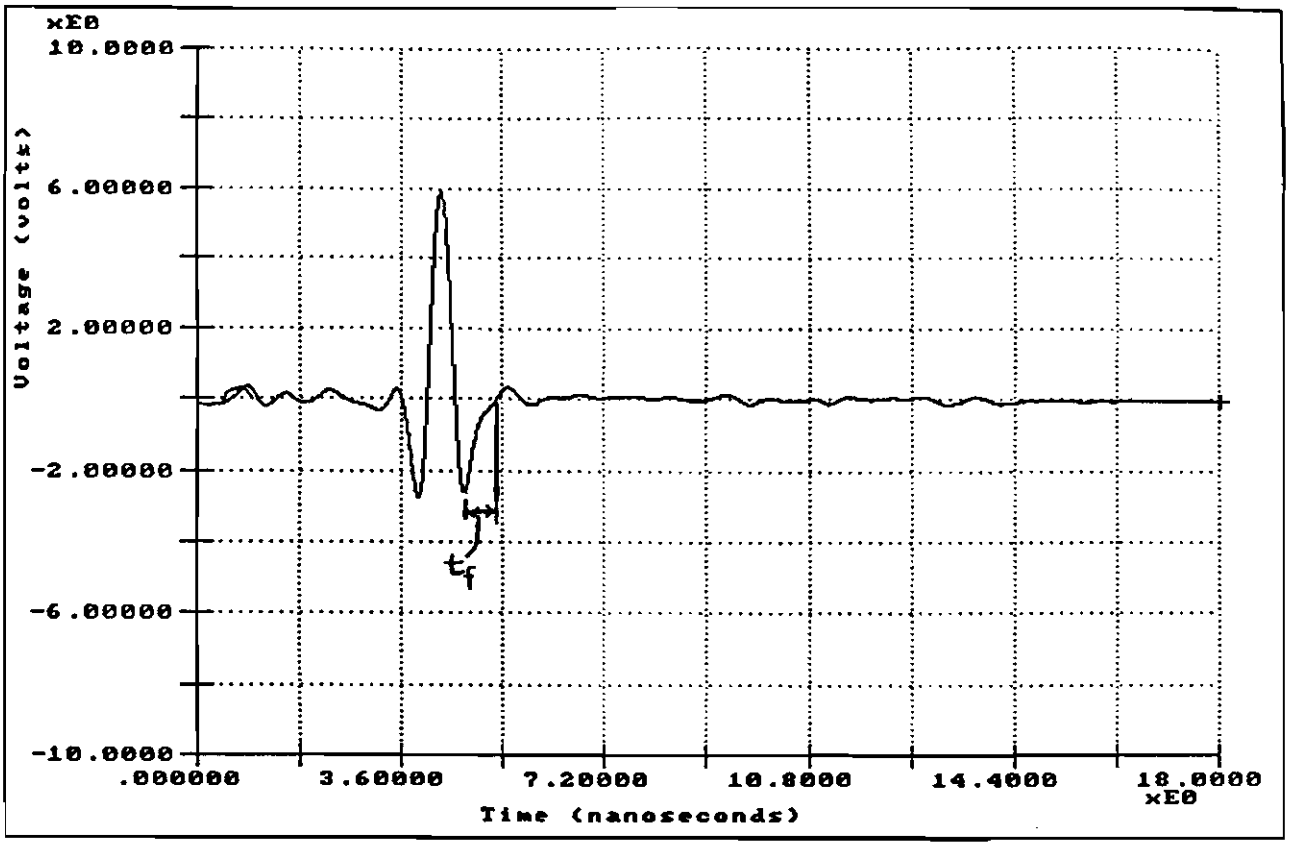
A_{mp} is the amplitude of reflection from the metal plate.

The end reflection in the metal plate test shall be less than 10% the amplitude of metal plate reflection.

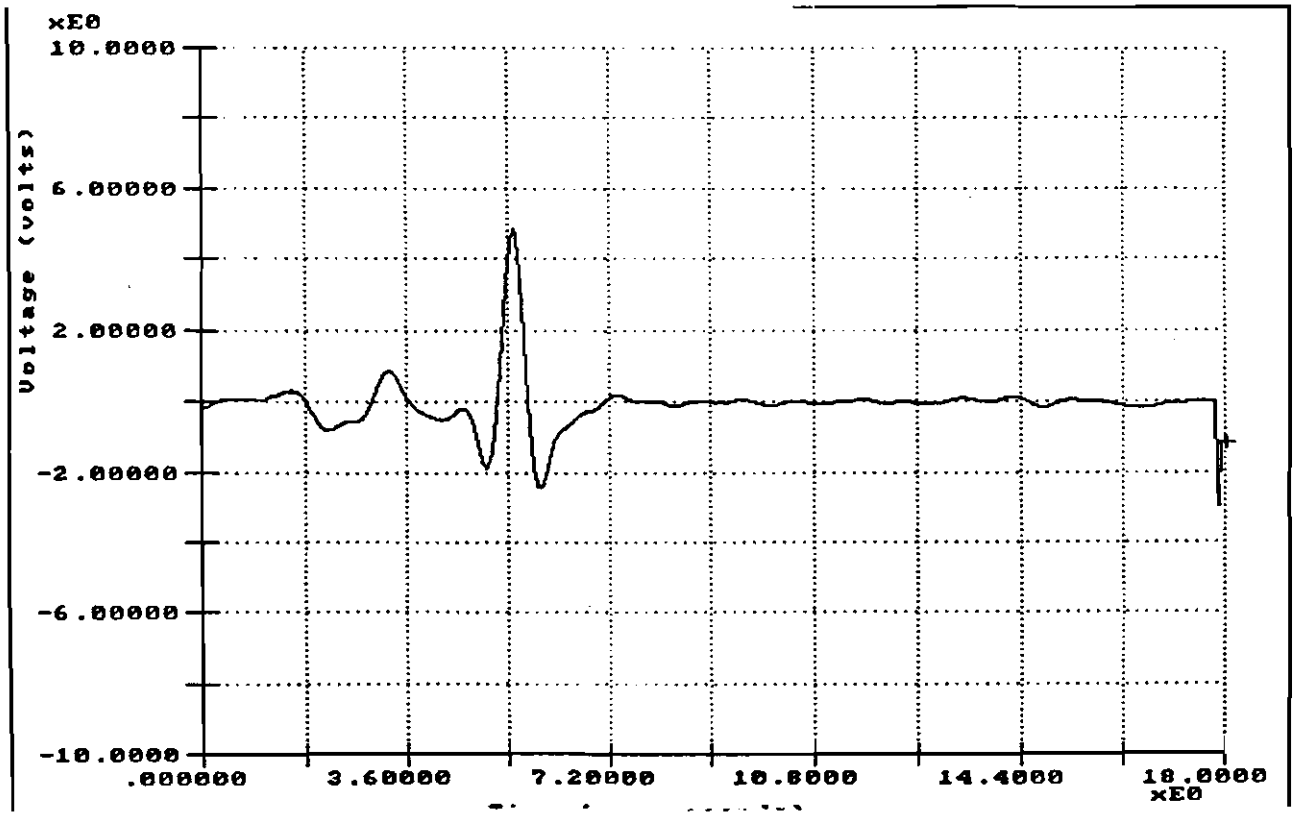
6. <u>Symmetry of Metal Plate Reflection</u>. The same test configuration as used in the Signal to Noise ratio test shall be used. The time from the maximum negative peak following the surface reflection to the zero crossing point shall be measured. This time (t_f) is shown in Figure B1. The required specification is:

$$t_f \leq 0.75 \text{ ns}$$

An example of metal plate reflections which pass and fail this specification are shown in Figure B1.



Acceptable Metal Plate Reflection



Unacceptable Metal Plate Reflection Fails Specification Tests 5 and 6.

Figure B1. Examples of Acceptable/Unacceptable Metal Plate Reflections.

7. Concrete Penetration Test: The antenna shall be placed at its recommended operating height above a six inch (6") thick concrete block. The concrete block shall be non-reinforced, minimum age of 28 days, and a minimum 3000 psi compressive strength. The block shall be 3 foot (36") x 3 foot (36") or greater to ensure that all the GPR energy enters the concrete. The concrete block shall be placed on top of a metal plate. The reflection amplitude from the top and bottom of the concrete block shall be measured. The concrete Penetration test is defined by the following equation:

$$\frac{A_{bottom}}{A_{top}} \geq 0.25 \ (25\%)$$

A_{top} is defined as the measured return amplitude from the top of the concrete slab.
A_{bottom} is defined as the measured return amplitude from the metal plate.

The concrete penetration test results for the GPR shall be greater than or equal to 25%.

APPENDIX C - USING GPR TO FIND DEFECTS IN NEW PAVEMENTS

The focus of the studies on SH 10 and US 63 has been to evaluate the use of GPR as a HMA thickness measuring tool to replace or minimize field coring. With new thick asphalt pavements GPR can also be use to detect any construction defects in the completed pavement. Figures C1, C2 and C3 show results from SH 10, this is from a homogeneous well compacted thick HMA layer. Figure C1 is the COLORMAP display which shows strong reflections from the surface and subsurface interfaces with no strong reflections between these layers. In COLORMAP strong reflections would be characterized by red or blue lines. An individual GPR return trace from SH 10 is shown in Figure C2 and the typical core that was removed from the pavement is shown in Figure C3.

The results from SH 10 should be compared with the GPR results from another recently constructed HMA section, shown in Figures C4, C5 and C6. This section was not in Missouri. In Figure C4 it is observed that major reflectors are present within the HMA layer. Bright red reflectors indicate areas of trapped moisture and localized blue areas indicate areas of low density, potentially stripping. An individual GPR trace is shown in C5 and this traces shows a major negative reflection in the HMA layer. The resulting core is shown in Figure C6. This GPR testing and coring was completed before the highway was opened to traffic. The cause of these problems is currently under investigation.

This example was included to demonstrate how GPR could be potentially used for more than thickness control. The technology can also be used to identify construction defects which are usually related to either materials problems, density control or moisture damage.

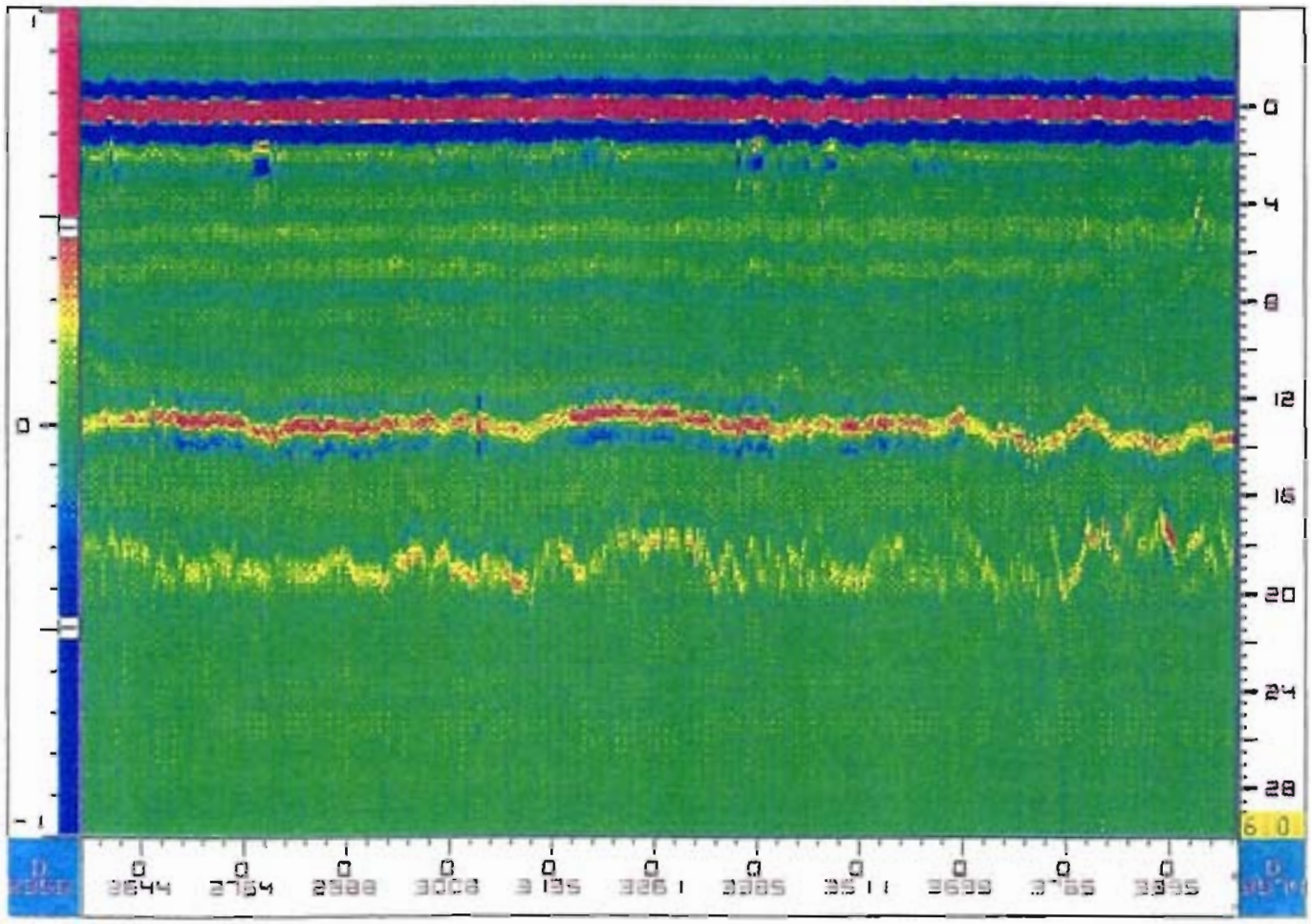


Figure C1. COLORMAP Output From SH 10. Thick Plant Mix Bituminous Base - Good Condition No Defects.

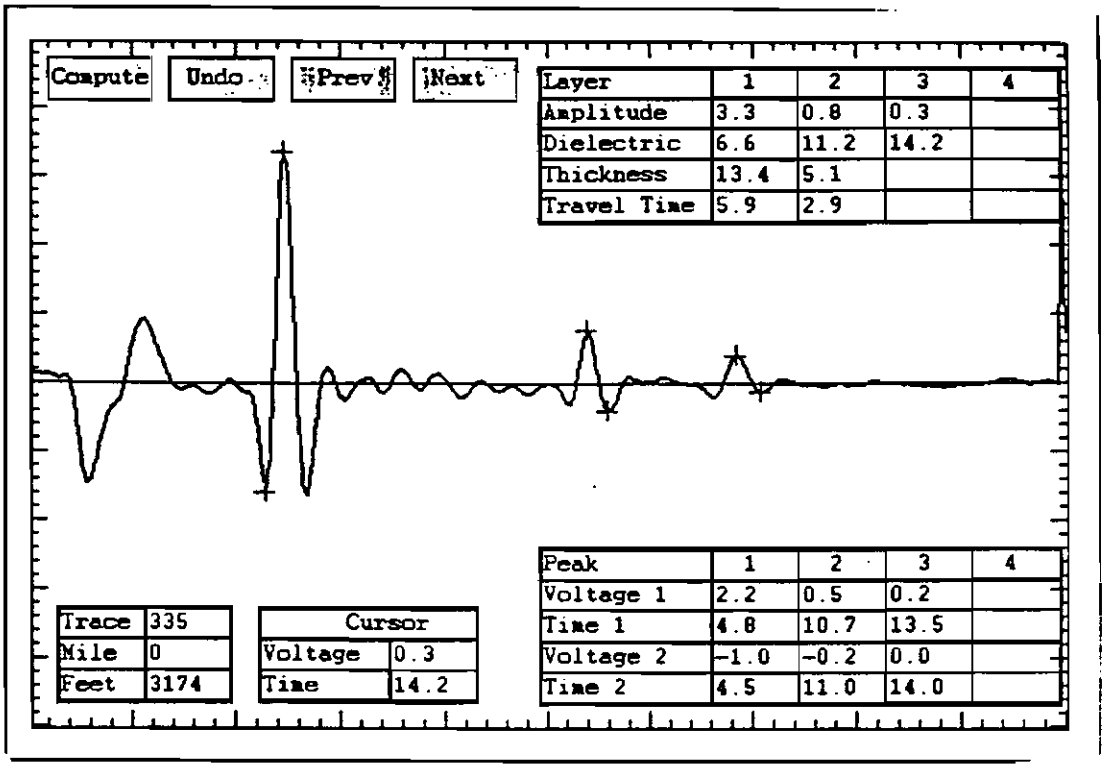


Figure C2. Typical GPR Trace From SH 10. Clearly Defined Positive Peaks Indicating Homogeneous Layer.

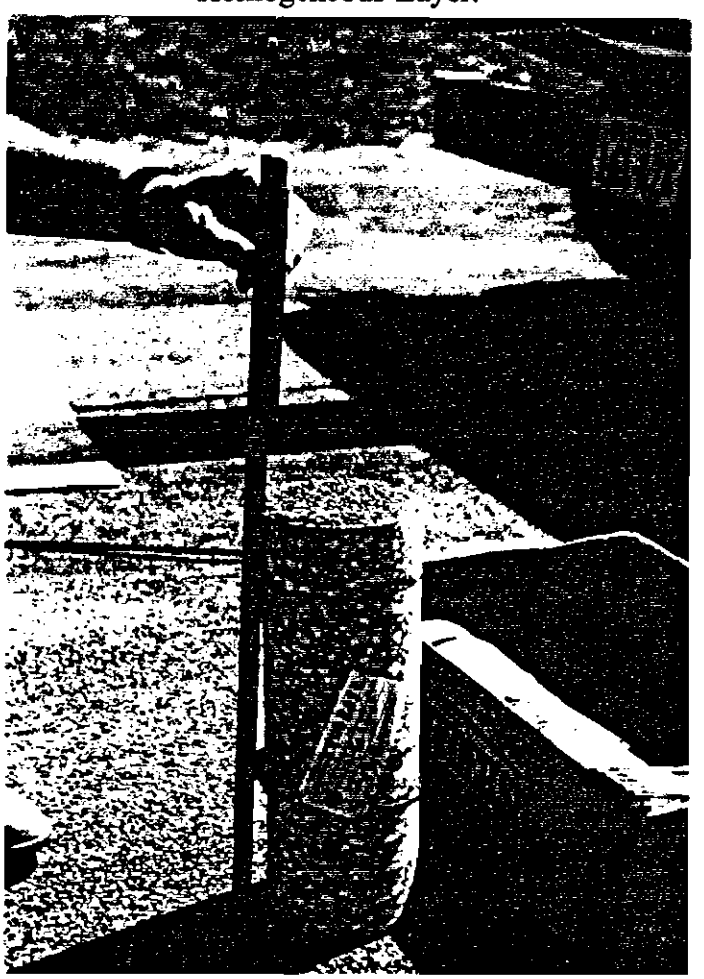


Figure C3. Result Core From This Location.

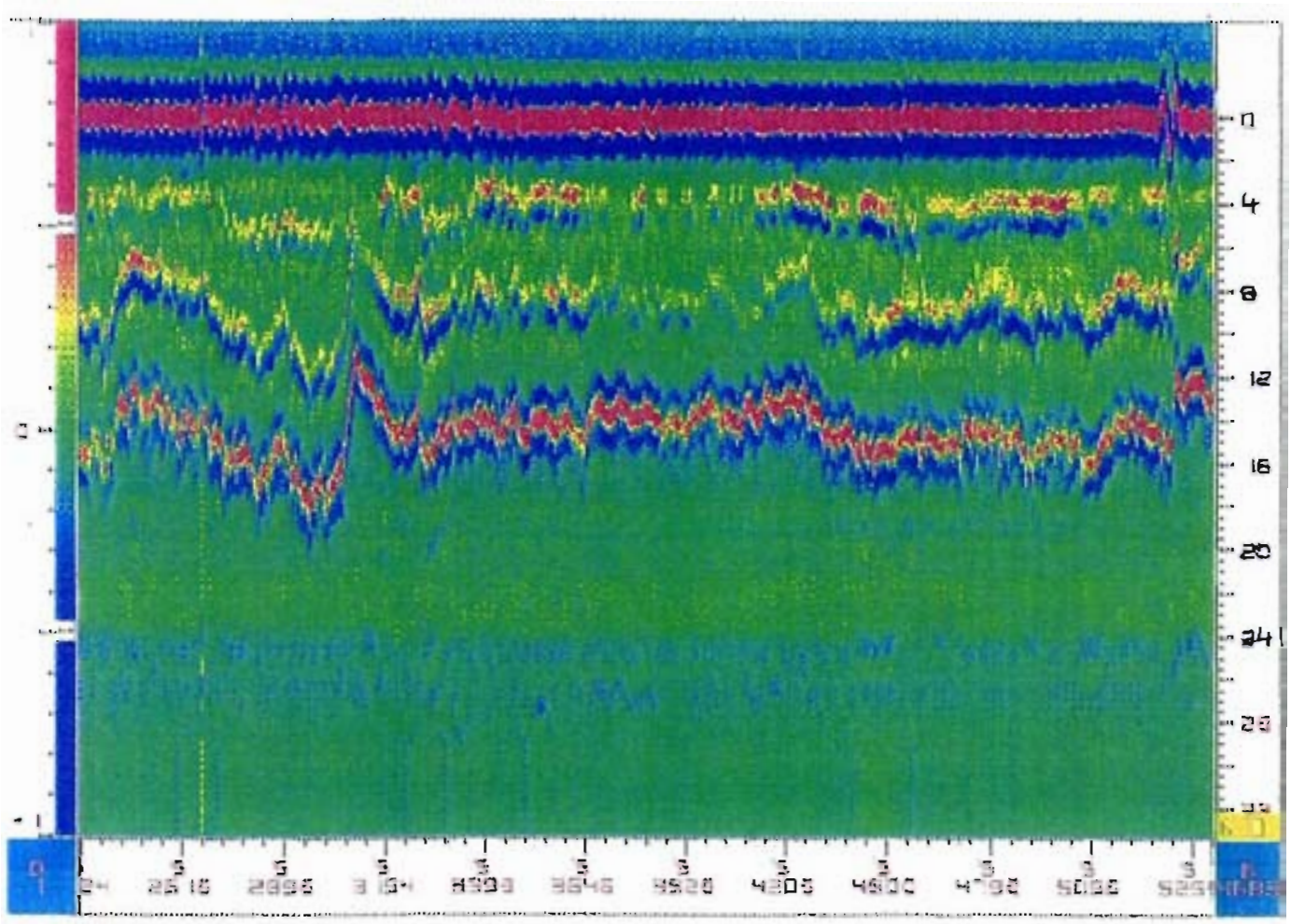


Figure C4. COLORMAP Trace From a Thick Plant Mix Bituminous Base Pavement with Substantial Subsurface Defects. Solid Blue Lines at Approximately 8" Below Surface is "Stripped" Layer.

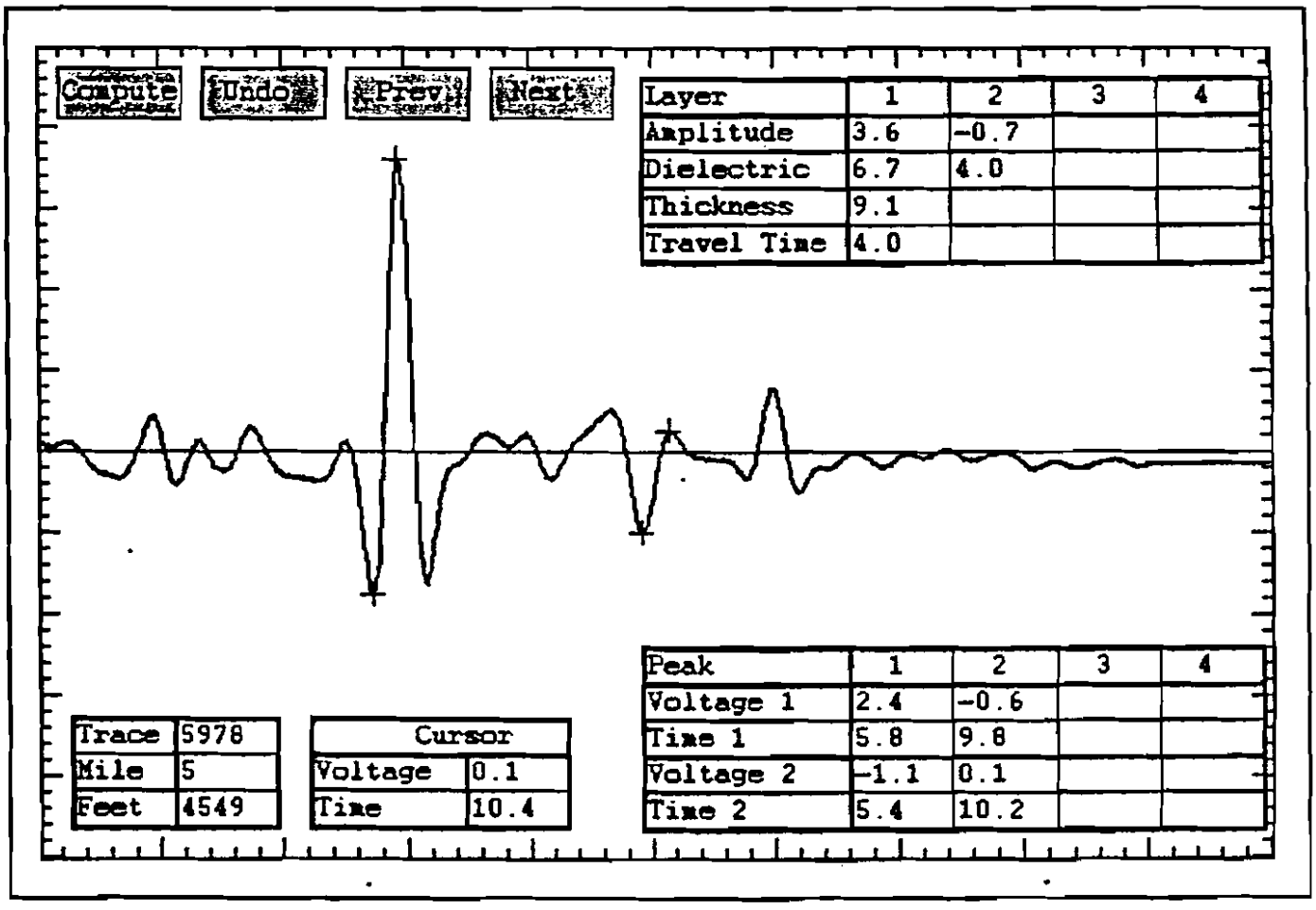


Figure C5. Individual Trace From Location With Major Subsurface Defect (Negative Reflection).

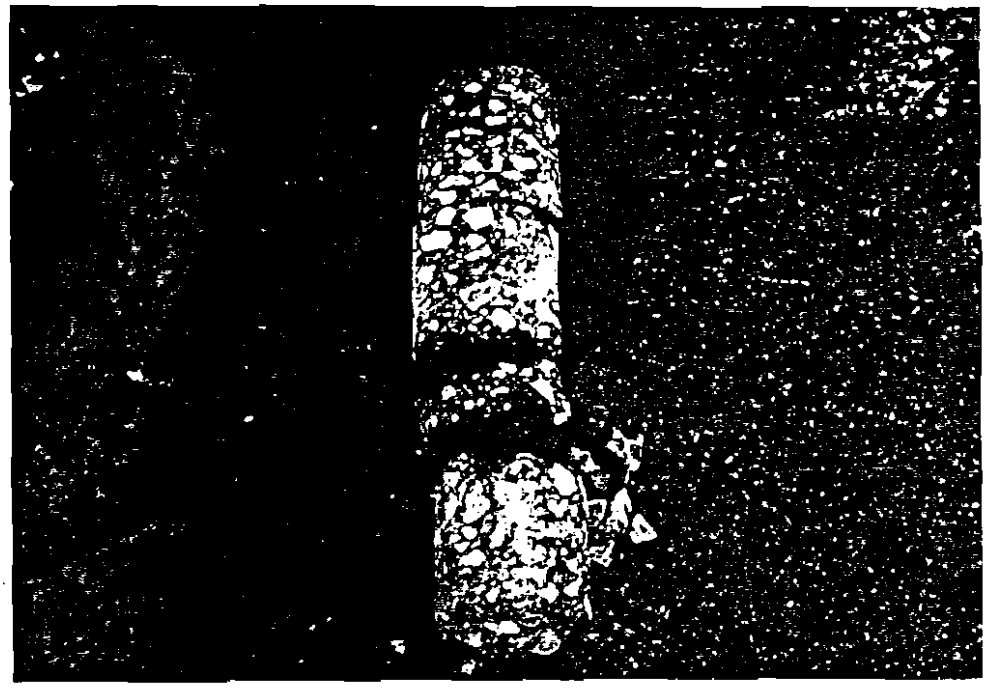


Figure C6. Core Extracted at Defect Location.

Appendix C

GPR Evaluation for Concrete Thickness Quality Control Project Route 71, Newton County 3 Mile Dual Lane 14" Non-Reinforced Concrete Pavement

by

Dr. Kenneth R. Maser
INFRASENSE Inc.
Arlington, Massachusetts

GPR Evaluation for Concrete Thickness Quality Control Project Route 71, Newton County
3 Mile Dual Lane 14" Non-Reinforced Concrete Pavement

Data for the subject project was collected on October 22, 1997, approximately 50 days after the concrete was placed. Four lines were surveyed, representing the inside and outside lanes of the northbound and southbound directions, from station 632+00 to 788+00. The inside lane was surveyed 7 feet to the left of the centerline, and the outside lane was surveyed 7 ft. to the right of the centerline. The data was collected at approximately 5 mph.

Aluminum foil sheets were placed on top of the base by MoDOT, at future core locations prior to the placement of concrete. The objective of the foil sheets was to provide a reflective target to enhance the detection of the bottom of the concrete using GPR. Subsequent coring at these locations showed no signs of the foil, suggesting that the foil had disintegrated through the reaction between aluminum and concrete. The GPR data did not show any evidence of the presence of the foil.

Markers were placed in the GPR data when the GPR antenna crossed the location of each core. The GPR data was subsequently analyzed at these marker locations to produce a thickness calculation for comparison with the cores. Table 1 on page 3, shows the comparison between the thickness data calculated with GPR compared to that obtained from the cores for 70 cores. The shaded core values were made available for calibration of the GPR analysis prior to the comparison with the remaining cores. The following statistics summarize the deviation between the GPR and core results in Table 1:

Deviation Between GPR and Core Results (70 Cores)

Statistic	Value (inches)	Percent
Mean Absolute Deviation	0.39	2.8%
Standard Deviation	0.51	4.0%
Maximum Deviation	1.64	11.6%

Figure 1 on the following page, shows a sample of the raw GPR data, with very high amplification. The data shows evidence of dowels at the pavement joints. The bottom of the concrete appears prominent, but appears to occur at lesser depth below the dowels than would be expected. Also, the concrete dielectric constant computed using the calibrating cores is much lower than one would normally expect for concrete; raising the possibility that the interface shown in Figure 1 may not actually be the bottom of the concrete.

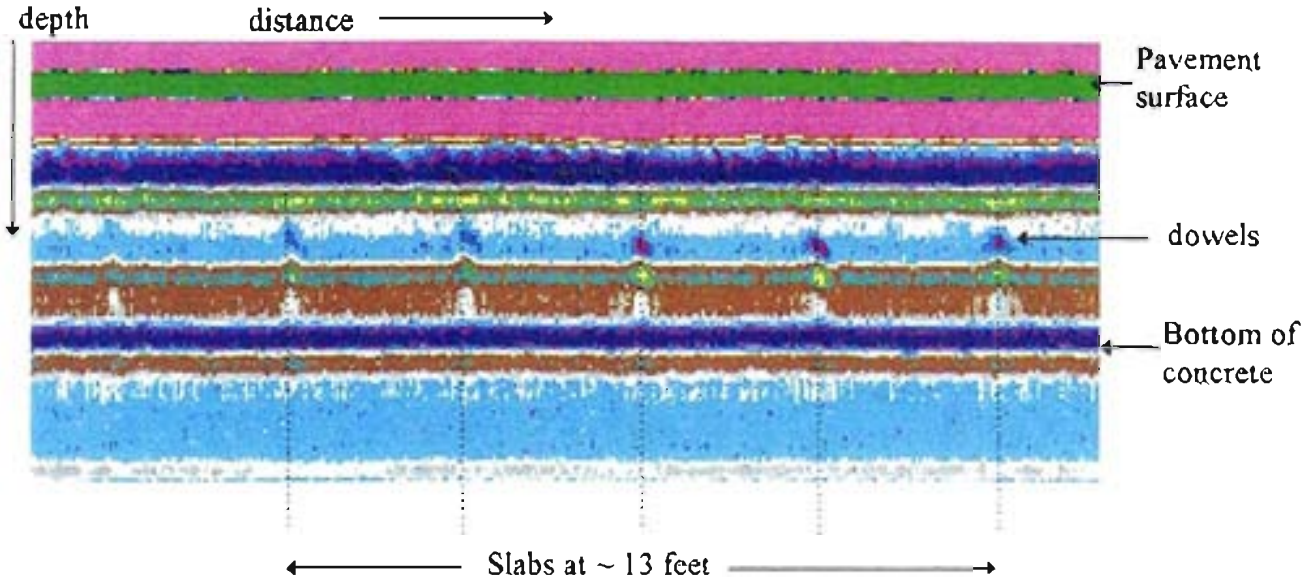


Figure 1 -- Sample of GPR Data

The results of Table 1, and the associated statistics show a reasonable level of accuracy. However, the procedure would benefit if well-defined targets could be placed on top of the base before paving. An alternative to the aluminum foil, which did not work here, would be sections of steel pipe; about 1.5 inches in diameter and 3 feet long, laid flush with the top of the base and transverse to the pavement (see Figure below). These pipes would present an even more prominent target than the dowels because of their orientation, and would clearly distinguish the bottom of the concrete from other events in the data.

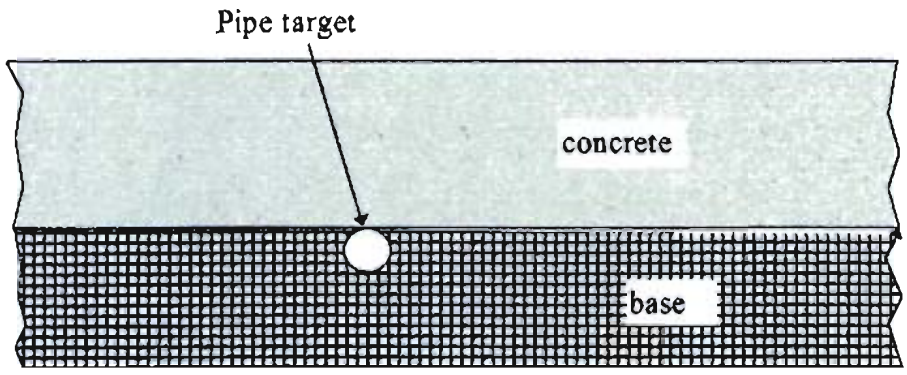


Figure 2 -- Recommendation Target Configuration for Future GPR Concrete Surveys

Table 1

Route 71, Neosho, MO – GPR Concrete Pavement Thickness Evaluation

Summary of Results

Survey Line	Core #	Thickness (in.) GPR	Thickness (in.) Core
Southbound, Outside Lane			
	1	15.09	14.7
	3	14.80	14.8
	8	14.74	15.2
	11	14.43	14.2
	14	14.39	15.0
	16	14.40	15.2
	17?	14.28	15.2
	18	14.44	14.9
	19	14.24	13.8
	24	14.19	14.2
	26	14.28	14.2
	28	14.36	14.0
	30	14.36	14.4
	31	14.24	14.2
	33	13.94	14.7
	35	14.27	14.4
southbound, inside lane			
	2	14.70	14.7
	4	14.34	15.6
	6	14.25	14.6
	7	14.45	14.2
	9	14.36	15.2
	10	14.19	14.5
	12	14.38	13.7
	13	14.47	14.2
	20	14.06	14.2
	22	14.10	14.6
	23	14.04	14.2
	25	14.00	13.2
	27	13.83	14.5
	29	14.12	14.3
	32	13.99	14.1
	34	13.77	14.6

Survey Line	Core #	Thickness (in.) GPR	Thickness (in.) Core
Northbound, Outside Lane			
	70	14.37	14.5
	68	14.53	14.4
	67	14.46	14.1
	66	14.51	14.2
	63	14.56	14.5
	61	14.55	14.0
	59	14.61	14.0
	56	14.70	14.7
	53	14.53	13.9
	48	14.62	14.0
	47	14.66	14.2
	46	14.75	14.6
	45	14.56	13.5
	42	15.74	14.1
	40	15.67	14.5
northbound, inside lane			
	72	13.90	13.8
	71	13.99	14.2
	69	14.33	14.2
	65	13.89	14.5
	64	13.93	14.4
	62	14.06	14.1
	60	14.11	14.0
	58	14.11	13.9
	57	14.00	14.3
	55	13.89	14.3
	54	13.85	14.2
	52	14.11	14.3
	51	14.20	13.9
	50	13.92	14.1
	49	13.99	14.4
	44	13.93	14.1
	43	13.93	14.5
	41	14.01	14.2
	39	13.96	14.4
	38	14.01	14.4
	37	14.03	14.4

Appendix D

PHOTOGRAPHS

Above: Coring 12" AC on MO Rt. 10, Ray County

Above: Coring 17" AC on new northbound lanes of US RT. 63, Howell County

Left: GPR testing 14" PCCP on southbound lane of new dual lane US Rt. 71, Newton County

1 GHz Horn antenna set up for metal plate calibration

PC station, for input of site information, processing data

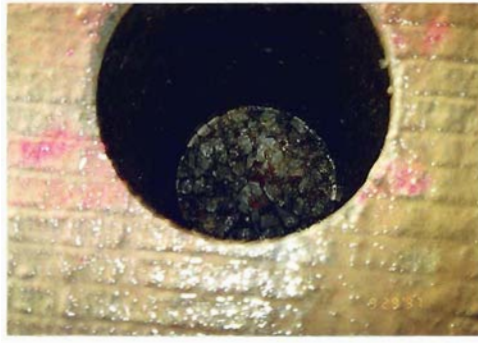
Signal processing

Top of Horn antenna with transmitter and receiver boxes

Well consolidated 12" AC core from MO Rt. 10

Above: PCCP core from US Rt. 71, had to knock off stuck base aggregate before measuring

Above: PCCP core came out smooth on bottom where foil was set on top of cement treated base rock



Left: Bottom of core hole, could find no aluminum foil, it had reacted with cement in base and PCCP