DIGITAL SIGNATURE ANALYSIS OF RADAR REFLECTIONS FOR THE ASSESSMENT OF CONCRETE BRIDGE DECK DETERIORATION

by

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Abstract

Techniques for analyzing radar reflections from concrete bridge decks are developed in order to try and predict the amount of concrete deterioration in fourteen bridge decks in five New England states. Radar waves, which are transmitted from a van that an operator drives over the deck, produce reflections from material interfaces. The reflections are recorded and digitized for the computer-based analysis. Models from previous studies are used as a basis for waveform peak detection algorithms, and additional algorithms are presented to link physical properties of asphalt and concrete to features of the radar reflections. The radar analysis techniques are shown to be effective for the identification of concrete flaking, but not for locating concrete delaminations. Therefore, it is proposed that radar inspection results be combined with results of other complementary inspection technologies, such as infrared surveys and underside inspections, to obtain predictions of concrete delamination. Recommendations for additional waveform analyses and technical suggestions are presented.

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List of Variables

α	Attenuation factor for rebar reflection algorithm.
A_{PLATE}	Magnitude of the incident wave on the deck surface.
A	Reflection from air/asphalt interface.
B	Waveform trough between Peaks A and C.
C	Reflection from asphalt/concrete interface.
D	Reflection from concrete/rebar interface.
c	Speed of light.
d_{ASP}	Asphalt thickness.
d_{TC}	Concrete top cover thickness.
ε	Dielectric permittivity of a material (dielectric constant).
ε_1	Dielectric constant of material 1.
ε_2	Dielectric constant of material 2.
ε_0	Dielectric constant of a vacuum.
ε_R	Relative dielectric constant of a material.
ε_{ASP}	Relative dielectric constant of asphalt (typical value = 5).
ε_C	Relative dielectric constant of concrete (typical value = 9).
R1	Waveform trough B divided by reflection from air/asphalt interface.
R2	Reflection from asphalt/concrete interface divided by reflection from air/asphalt interface.
R3	Reflection from concrete/rebar interface divided by reflection from air/asphalt interface.
R4	Reflection from concrete/rebar interface divided by reflection from asphalt/concrete interface.
r_{12}	Reflection coefficient from air/asphalt interface.
r_{23}	Reflection coefficient from asphalt/concrete interface.
r_C	Reflection coefficient from cylindical rebar.
T	Time difference (ns) between waveform peaks.
$\tan\delta$	Loss tangent.
t_{12}	Transmission coefficient from air/asphalt interface.
t_{23}	Transmission coefficient from asphalt/concrete interface.
μ_0	Magnetic permeability of a vacuum.
w_B	A reference waveform (used to compute area coefficient).
w_I	Any waveform along a deck.
Z	Wave impedance of an electromagnetic wave in a nonconducting medium.
Z_1	Wave impedance in medium 1.
Z_2	Wave impedance in medium 2.
Z_0	Wave impedance of air.

Chapter 1

Introduction

1.1 The Need for Improved Bridge Inspection Techniques

In a February 1988 report to the President and Congress, the National Council on Public Works Improvement concluded that a more "intense national focus on public works technology" is needed to address the complex infrastructure problems in the United States. This report, Fragile Foundations: A Report on America's Public Works, suggests that innovations in public works would be accelerated by the establishment of regional research and development centers, that, in conjunction with universities, could respond to the unique requirements of each area. The Council reports that the tasks of maintenance and rehabilitation demand complex technical and professional competencies. Specialists from various fields are needed to bring new perspectives and skills to public works.[1] Of the more than 500,000 bridges in the U.S., forty percent are classified as deficient by the National Bridge Inventory, and therefore eligible for replacement or rehabilitation. In an effort to address the problems of rehabilitation and maintenance of the highway system, Maine, Massachusetts, New Hampshire, Rhode Island and Vermont have formed and committed resources to the New

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[1]National Council on Public Works Improvement, Fragile Foundations: A Report on America's Public Works (Final report to Congress, February, 1988), pp. 25-27.

England Surface Transportation Infrastructure Consortium. One goal of this group is to find a reliable means of assessing concrete bridge deck deterioration. The research described in this thesis was sponsored by the Consortium and has been led by Dr. Kenneth Maser of the Massachusetts Institute of Technology.

1.2 Condition Assessment Methods

Several technologies are available for identifying concrete deterioration. The first stage of M.I.T.'s work was to identify the technologies for the assessment of deck condition. Standard bridge inspection techniques, such as visual inspection, core drilling and examination, chloride content measurements, corrosion potential measurements and hammer and chain sounding techniques, while commonly used nationwide, are labor intensive, and the interpretations of results are highly subjective. These standard tests require highly trained and experienced inspectors and also require closing of traffic lanes.

Other techniques have the potential to assess deck condition more efficiently. These include ultrasonics, acoustic emissions, magnetics, infrared thermography and ground penetrating radar. M.I.T. has decided to explore the use of ground penetrating radar and infrared thermography in a bridge inspection program. According to this method, radar is transmitted into a medium, and the reflection from the surface of the medium provides an indication of its material properties. Enhancing the analysis, infrared thermography measures surface radiance and produces a thermal image of the surface being examined. Since concrete deterioration can affect the rate of heat transfer in the concrete, surface temperature differences may indicate the presence of deteriorated concrete.[2]

1.3 Previous Research and New Questions

Several researchers have studied the application of radar for the rapid inspection of concrete bridge decks. Published reports in the U.S. and Canada report a wide range of test success rates and use different analysis techniques. In addition, in many cases, inspection techniques have not been tested for a large number of decks. As Chapter 4 indicates, researchers' radar models of concrete delaminations differ greatly, and analysis techniques range from the visual observation of every recorded waveform, to visual analysis of clusters of waveforms, to computerized peak detection routines.

This thesis will address several questions that are raised as a result of previous research. These include:

- What is the correct model that describes radar reflections from bridge decks?
- What is the effect of delaminations on the radar

[2] W.M. Kim Roddis, "Concrete Bridge Deck Assessment Using Thermography and Radar" (Unpublished M.S. thesis, Department of Civil Engineering, Massachusetts Institute of Technology, 1987), pp. 70-76.

signal?

- Can results be reproduced for many decks?

- Can algorithms be developed that require little subjective input or analysis?

To answer these questions, this thesis models the behavior of the radar signal in the bridge deck according to the physical conditions of the deck and electromagnetic theory. Since many of the radar models proposed by researchers deal with delamination effects differently, this thesis explores the effect delaminations have on the radar signal. All analysis algorithms must be derived from the appropriate radar model and this thesis will improve upon previous techniques by incorporating changes in the dielectric properties of asphalt into the algorithms. In addition, the algorithms have been tested on thirteen decks in New England that are scheduled for repair, and one new deck. Previous studies have often presented results for only one deck. In order for radar to be successfully applied to solve the bridge deck inspection problem, analysis techniques should be fast and objective. Digital signal processing algorithms written in the ASYST programming language are used to analyze the data and produce results, and recommendations are made for future improvements that will limit the need for subjective input for the analysis or special expert advice.

1.4 Content of this Thesis

This thesis describes the theory and analysis of radar reflections recorded by M.I.T.'s van-based radar system. The system, manufactured by Syntek Corporation, transmits radar through bridge decks and records the reflections from the material interfaces in the decks. This system allows for the rapid recording of radar data without lane closures. An infrared thermography system, manufactured by Inframetrics Corporation is also mounted on the van.

Chapter 2 presents basic radar concepts that are used in the analysis and Chapter 3 describes concrete bridge deck construction. Chapter 4 reviews other researchers' techniques for radar analysis and highlights the studies that serve as a basis for the M.I.T. work. Chapter 5 details the acquisition, processing and storage of field data from radar equipment.

Chapter 6 contains the radar model that is a basis for the analyses presented in this thesis. This model expresses the magnitudes of waveform peaks recorded by the radar system in terms of electromagnetic reflection and transmission coefficients from the material interfaces in the deck.

Chapters 7 and 8 describe the original computer algorithms used to analyze the field data. Using these programs and other field data, the radar waveforms are analyzed in order to predict areas of concrete deterioration, overall percentage of deck deterioration, as well as the effects of other physical conditions. Algorithms are developed to predict locations of deterioration caused by freeze-thaw cycles and rebar corrosion. Factors such as moisture content and chloride content of concrete, and their effects on the radar signal are also discussed. The preliminary studies of Chapter 7 show that delaminations are difficult to identify with radar, however radar can be used to locate moisture saturated "punky" concrete and measure asphalt and concrete thicknesses. A final analysis program in Chapter 8 provides a method for locating "punky" concrete by incorporating asphalt dielectric constant changes into waveform peak analysis routines to determine the dielectric constant of concrete. The dielectric constant of concrete is shown to be an effective method of identifying moisture saturation that produces concrete flaking and deterioration. A program to identify delaminations by measuring the reflection from the rebar in the deck is presented in Chapter 8, but the program did not produce meaningful results for a limited data set. This program uses the rebar reflection to identify areas of high chloride content and rebar corrosion - factors that help produce delaminations. All radar analysis programs are listed in the Appendix.

Results and conclusions are presented in Chapter 9 and recommendations are in Chapter 10. This thesis concludes that by using radar to determine "punky" concrete areas and infrared thermography to locate delaminations, the total percentage of deteriorated deck area can be estimated to within five percent. This is a substantial improvement over other work that relied only on radar to locate deterioration. However, Chapter 10 recommends further software development, technical improvements to radar equipment, more tests and experimental studies to further test the computer algorithms for "punky" concrete detection and delamination detection.

Chapter 2

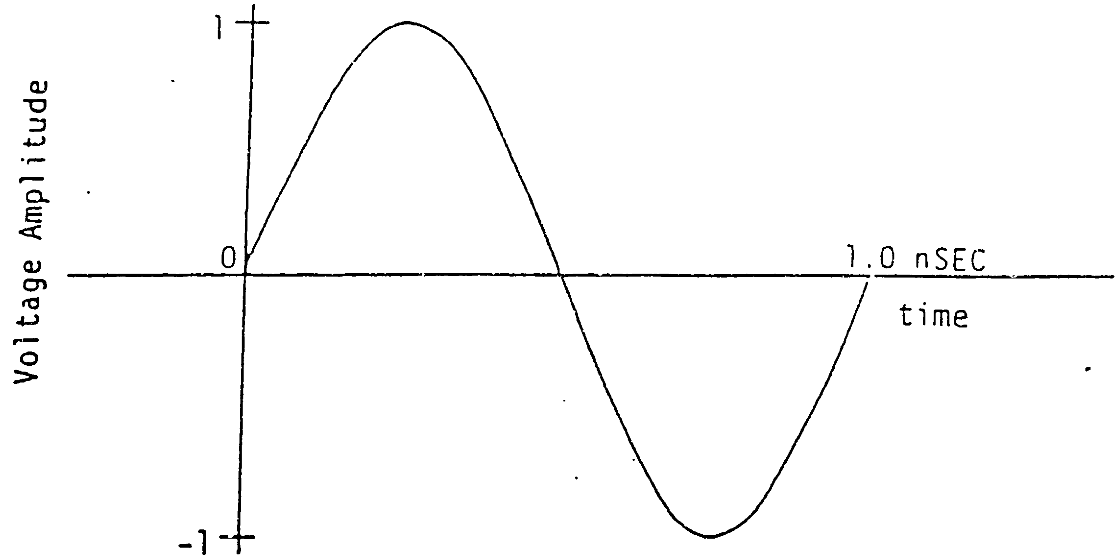
Radar Concepts

In order to understand the algorithms presented in this thesis, one must understand the basic physical principles that describe the behavior of radar waveforms at the boundaries of dielectric materials and as waves travel through dielectric materials. The most important concepts are the dielectric properties of permittivity, wave impedance and loss tangent which are used to derive expressions for radar velocity, reflection and transmission coefficients and attenuation. These expressions are the basis for radar analysis.

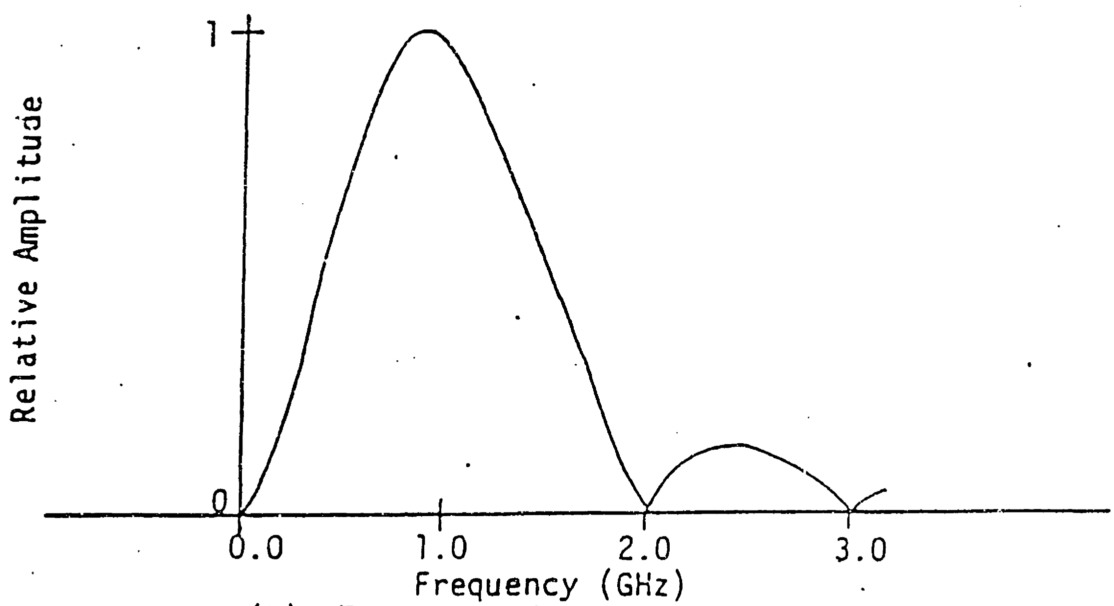
2.1 The Transmitted Radar Wave

From an antenna one foot above the pavement, the radar system transmits a one nanosecond duration sinusoidal radar pulse through the air to the deck. The pulse repetition frequency is five megahertz. Figure 2-1 describes the radar signal. This short pulse signal allows high frequency, short wavelength radar to be directed into the deck and be reflected at the boundaries of different materials. The transmitted radar wave travels through the air at the velocity of light, 11.82 inches per nanosecond, to the bridge deck. The antenna then receives fractions of the radar wave that have travelled through the bridge deck and have been reflected from the deck boundaries.

Figure 2-1: The Transmitted Radar Wave



(a) Transmitted Temporal Waveform



(b) Transmitted Waveform Voltage Spectrum

2.2 Radar Velocity Through Air and Other Media

Dielectric properties of a material affect the velocity of a transmitted radar wave. The correct velocity of radar must be obtained to compute total distance that a wave travels in a specified time period. To predict the thickness of a material layer of a bridge deck, the velocity of radar in the material can be derived from the dielectric permittivity.

2.2.1 Dielectric Permittivity

The speed of radar through a nonconductor is affected by the dielectric permittivity of the nonconductor. The dielectric permittivity of a material represents the amount of electrostatic energy stored per unit volume for a unit potential gradient. Since the dielectric permittivity (dielectric constant) of a nonconductor is always greater than the permittivity of a vacuum, a convenient expression is the relative dielectric constant, ε_R,

where,

$$\varepsilon_R = \frac{\varepsilon}{\varepsilon_o} \qquad (2\text{-}1)$$

and,

ε = dielectric constant of material, Farad/meter
ε_o = dielectric constant of a vacuum, 8.85 pF/m

2.2.2 Radar Velocity Through Dielectric Media

The velocity of radar through a medium is equal to the propagation velocity of the wave through free space (the speed of light) divided by the square root of the relative dielectric constant of the medium. This can be expressed as,

$$\text{velocity} = \frac{11.82}{\sqrt{\varepsilon_R}} \quad \text{in/ns} \qquad (2\text{-}2)$$

Since each material in a bridge deck has a different dielectric constant, the velocity of the radar wave changes as it passes through the asphalt and concrete layers of a bridge deck. This is one of the most important factors that affects the analysis of radar waveforms.

2.3 Reflection and Transmission of Waves

The dielectric properties of a material can be derived from the magnitudes of reflections and transmissions of radar waves from material interfaces. These expressions are derived from the wave impedances of materials.

2.3.1 Wave Impedance

Wave impedance is a ratio of the electric field component to the magnetic field component at the same point in time and space of the same wave. The wave impedance of a medium is used to derive expressions that describe the behavior of radar in that medium. The wave impedance, Z, of an electromagnetic wave in a nonconducting medium is

$$Z = \sqrt{\frac{\mu_o}{\varepsilon}} \quad \text{Ohms} \tag{2-3}$$

where,

μ_o = magnetic permeability of air ($4\pi \times 10^{-7}$ Henries/m)
ε = dielectric constant of material

The wave impedance for air is

$$Z_o = \sqrt{\frac{\mu_o}{\varepsilon_o}} \quad \text{Ohms,} \tag{2-4}$$

therefore, Z can be written as,

$$Z = \frac{Z_o}{\sqrt{\varepsilon_R}} \quad \text{Ohms} \tag{2-5}$$

where,

ε_R = relative dielectric constant of a material

2.3.2 Reflection and Transmission Coefficients

At the boundary of two media, a fraction of the incident electromagnetic wave is reflected away from the boundary and a fraction is transmitted through the boundary. The amount of electromagnetic energy that is reflected away from the boundary is represented by the reflection coefficient, r_{12}, and the amount of energy that is transmitted through the boundary is represented by the transmission coefficient, t_{12}. The wave impedances of the media are used to define r_{12} and t_{12}:

$$r_{12} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad (2\text{-}6)$$

$$t_{12} = \frac{2(Z_2)}{Z_2 + Z_1}$$

where,

Z_1 = wave impedance of medium 1
Z_2 = wave impedance of medium 2

These coefficients can be expressed in terms of relative dielectric constants. Using Equations (2-5),

$$r_{12} = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \qquad (2\text{-}7)$$

$$t_{12} = \frac{2(\sqrt{\varepsilon_1})}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}$$

where,

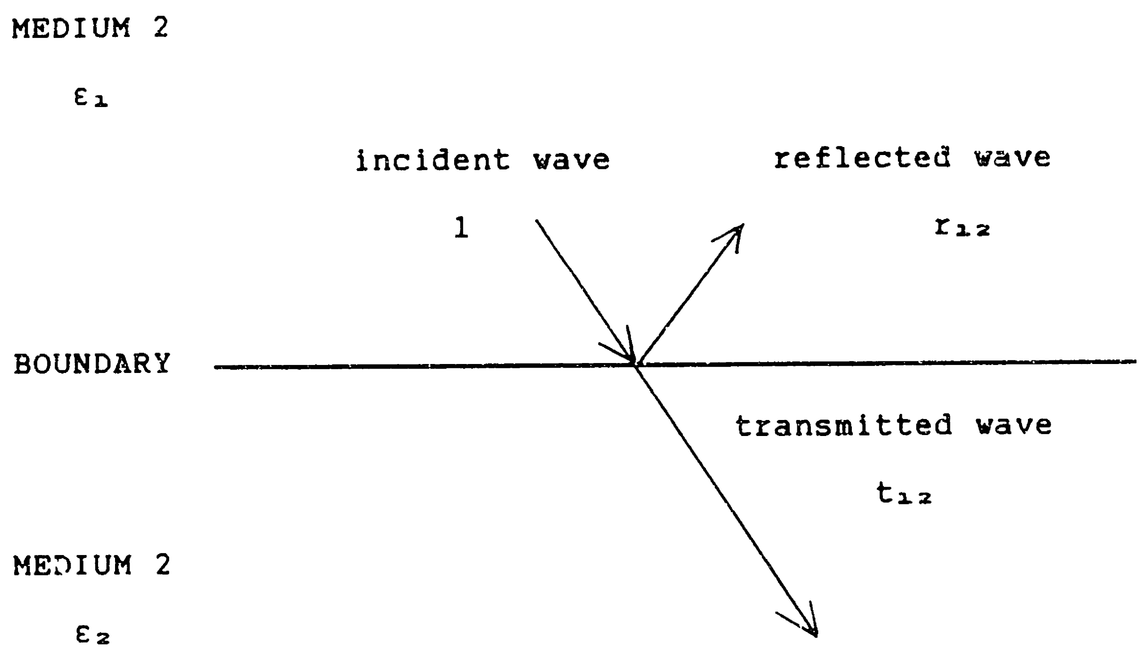
ε_1 = relative dielectric constant of medium 1
ε_2 = relative dielectric constant of medium 2

NOTE: Unless otherwise indicated, all future references to dielectric constants pertain to relative dielectric values.

2.3.3 A General Model of Reflections and Transmissions

Figure 2-2 identifies radar reflections produced at the boundary of two media. Radar equipment records the electromagnetic energy that is reflected from each interface. Accordingly, the radar receiver detects waves reflected by the boundaries between the air, asphalt, concrete and rebar.

Figure 2-2: The General Reflection and Transmission Model



When $\varepsilon_1 > \varepsilon_2$, the reflected wave is 180° out of phase with the incident wave and the value of r_{12} is negative.

2.4 Attenuation

The reflection and transmission models that are described in this thesis do not address the effects of attenuation on the radar signal. These models have been simplified in order to reduce the complexity of mathematical derivations that describe the electromagnetic energy reflected from the interfaces. However, it is necessary to describe the causes of attenuation and the effects of attenuation on the radar reflections in order to have a more complete understanding of electromagnetic wave propagation.

The attenuation of electromagnetic waves in a dielectric medium is given by

$$\text{Attenuation} = e^{-\alpha x} \qquad (2\text{-}8)$$

where,

$\alpha = (2\pi f/c)\sqrt{\varepsilon_R}\tan\delta$
f = frequency
ε_R = relative dielectric constant
$\tan\delta$ = loss tangent
c = velocity of light
x = distance the wave travels through the dielectric medium

Therefore, there are two dielectric properties that contribute to a material's attenuation characteristics: the relative dielectric constant and the loss tangent. The loss tangent, which is the ratio of the magnitude of the conduction current density to the magnitude of the displacement current density, is proportional to the conductivity of a material and inversely proportional to frequency and permittivity.

Since permittivity and conductivity are proportional to moisture content, attenuation of the radar signal is significant when the bridge deck surface is wet or when the moisture content of concrete is high. Since conductivity is also proportional to chloride content, signal attenuation increases as the chloride content of concrete increases. As the radar signal travels through the bridge deck, we expect that the signal amplitude would be attenuated significantly in areas of high moisture or chloride. Although values for permittivity and loss tangent have not been determined for concrete over a wide frequency range, researchers have estimated that the attenuation of a 1GHz wave in concrete with a ten percent moisture content at 75°F is less than one decibel per inch. If the moisture content or temperature is reduced, this loss decreases dramatically.[3]

2.5 Summary of Important Dielectric Properties

All the radar analyses presented in this thesis are based on the important dielectric properties that have been described. The dielectric permittivity is used to derive the velocity of radar in a material and since the radar receiver detects the arrival times of radar reflections from the interfaces in bridge decks, the thicknesses of the asphalt and concrete layers of the deck can be computed. Reflection

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[3]W.J. Steinway, "Locating Voids Beneath Pavement Using Pulsed Electromagnetic Waves" (Washington, D.C.: National Cooperative Highway Research Program, Report 237, November, 1981), p. 18.

and transmission coefficients at material boundaries are also expressed as functions of dielectric permittivities. The magnitudes of radar reflections that are received by the antenna are used in the algorithms that compute the dielectric permittivity of concrete. As has been indicated, attenuation effects have been left out of many models, and the attempt to measure attenuation presented in this paper was unsuccessful. The large variation of construction materials in bridge decks makes an estimate of the loss tangent of concrete difficult, especially at high frequency ranges. With more experimental studies of high frequency wave attenuation in concrete, the radar models may be modified to include attenuation factors that would more completely describe radar propagation in bridge decks.

Chapter 3

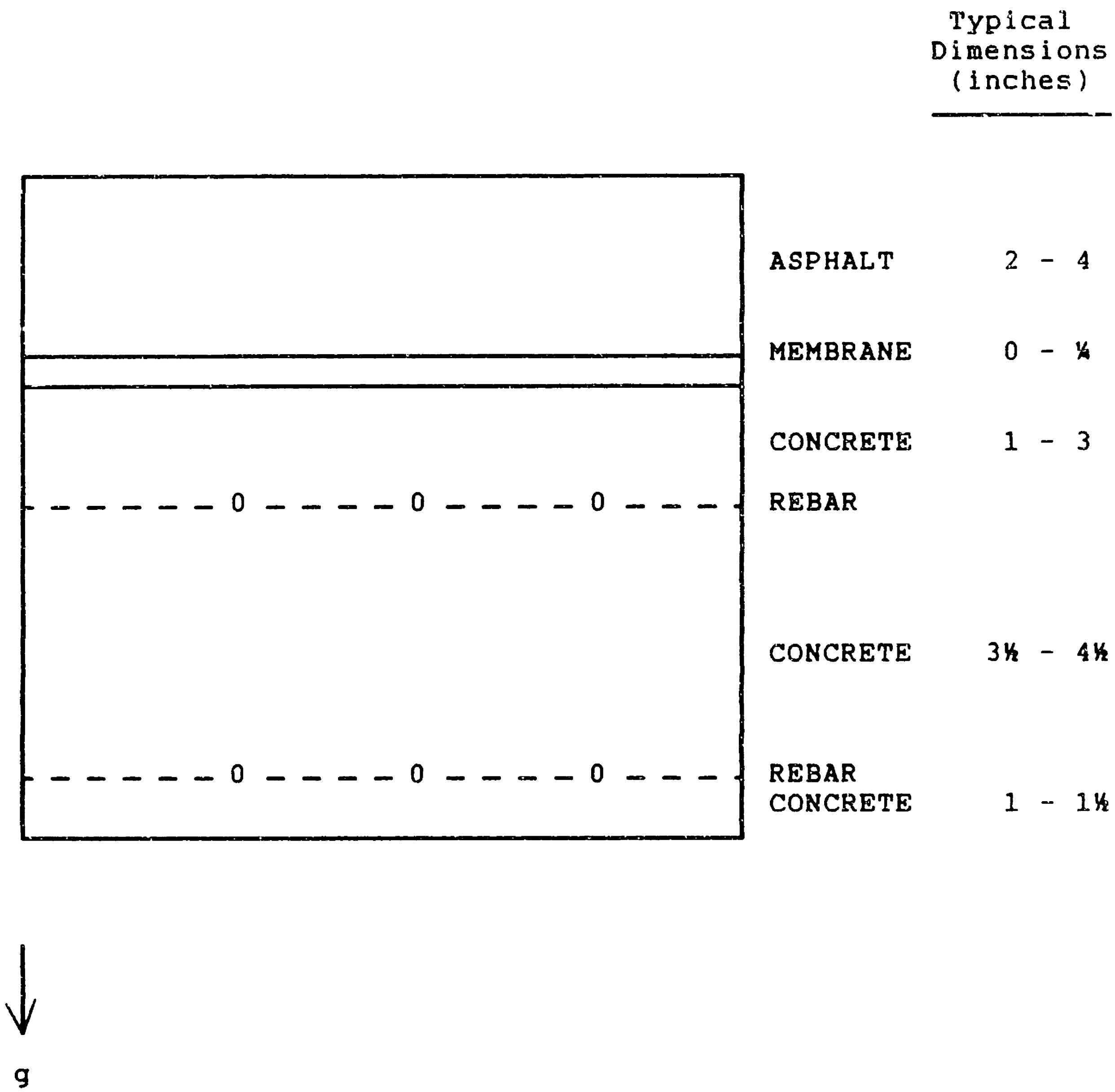
Deck Construction and Deterioration

The radar models that will be described in the following chapters use the basic concepts of electromagnetic wave velocity and reflection and transmission coefficients to identify and describe the material layers of a bridge deck. A review of bridge deck construction practices and materials helps to explain performance characteristics of decks in adverse weather and adverse loading conditions. Moisture and air contents of concrete affect the amount of concrete flaking that results from freeze-thaw cycles, and structural characteristics of decks produce various forms of cracking. These effects lead to two major forms of deterioration - "punky" concrete and delaminations. The goal of radar analysis is to identify these forms of deterioration.

3.1 Bridge Deck Construction

A typical concrete bridge deck is composed of an eight inch thick, steel reinforced concrete slab, with a two inch thick asphalt overlay. Figure 3-1 shows that the thicknesses of the layers of a deck, especially asphalt, may vary greatly. The addition of new asphalt layers to aging decks makes concrete deterioration harder to detect by standard visual inspection since a deck that appears to be sound may, in fact, have deteriorating concrete and structural defects hidden by the asphalt overlay. Many decks have a waterproof

Figure 3-1: Deck Cross Section



NOTE: For transverse rebar #6, diameter = 0.75 in. and rebar spacing is typically 8 in.

membrane that is placed between the concrete and asphalt during construction. This membrane, which is made of coal tar emulsions and fiberglass, can be applied with liquid materials or preformed sheets. Since the dielectric constant of the membrane is nearly the same as that of asphalt, a distinct dielectric boundary is not present at the asphalt-membrane interface, and strong radar returns would not be expected from the membrane.[4] Therefore, the radar reflection models do not include the membrane.

3.2 Construction Techniques that Affect Deterioration

A deck's ability to withstand forces of deterioration is closely related to fabrication processes that alter concrete strength and dielectric permittivity. Several factors cause concrete to flake and crack more easily and allow greater amounts of water and chlorides to penetrate the layers of a deck.

The porosity of concrete can affect a deck's ability to withstand frost damage. Moisture that resides in capillary voids and gel pores of the cement paste and in aggregates can freeze and produce hydraulic pressures that cause concrete flaking. Decks that are constructed with lower water/cement ratios have lower amounts of freezable water that can increase the deck's susceptibility to the damaging effects of freeze-thaw cycles. Also, the dielectric

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[4]Roddis, p. 132.

permittivity of low moisture content concrete is lower than the dielectric permittivity of high moisture content concrete.

Air content of concrete also affects the freeze-thaw durability of bridge decks. The air entrainment process, which introduces air voids in the cement paste, reduces pressures produced from freezing water. Decks with higher concrete air contents usually have lower levels of concrete flaking and have lower dielectric permittivities.

The most serious forms of cracking result from structural inadequacies that produce fracture planes and paths for moisture and chlorides. The most common type of cracking encountered on concrete bridge decks is transverse cracking. These cracks are straight and perpendicular to the centerline of the roadway, and often result from shrinkage during curing and thermal growth changes. However, other structural factors, such as span length, have been observed to influence the rate at which concrete cracks. A deck's susceptibility to transverse cracking has been shown to increase with span length since the effects of live loads, impact and longitudinal flexibility increase with increasing span length.[5]

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[5]Guy D. Busa, Jr., et al., "Modelling Bridge Deck Deterioration" (Unpublished report for the U.S. Department of Transportation, Department of Civil Engineering, Massachusetts Institute of Technology, September, 1985), pp. 31-53.

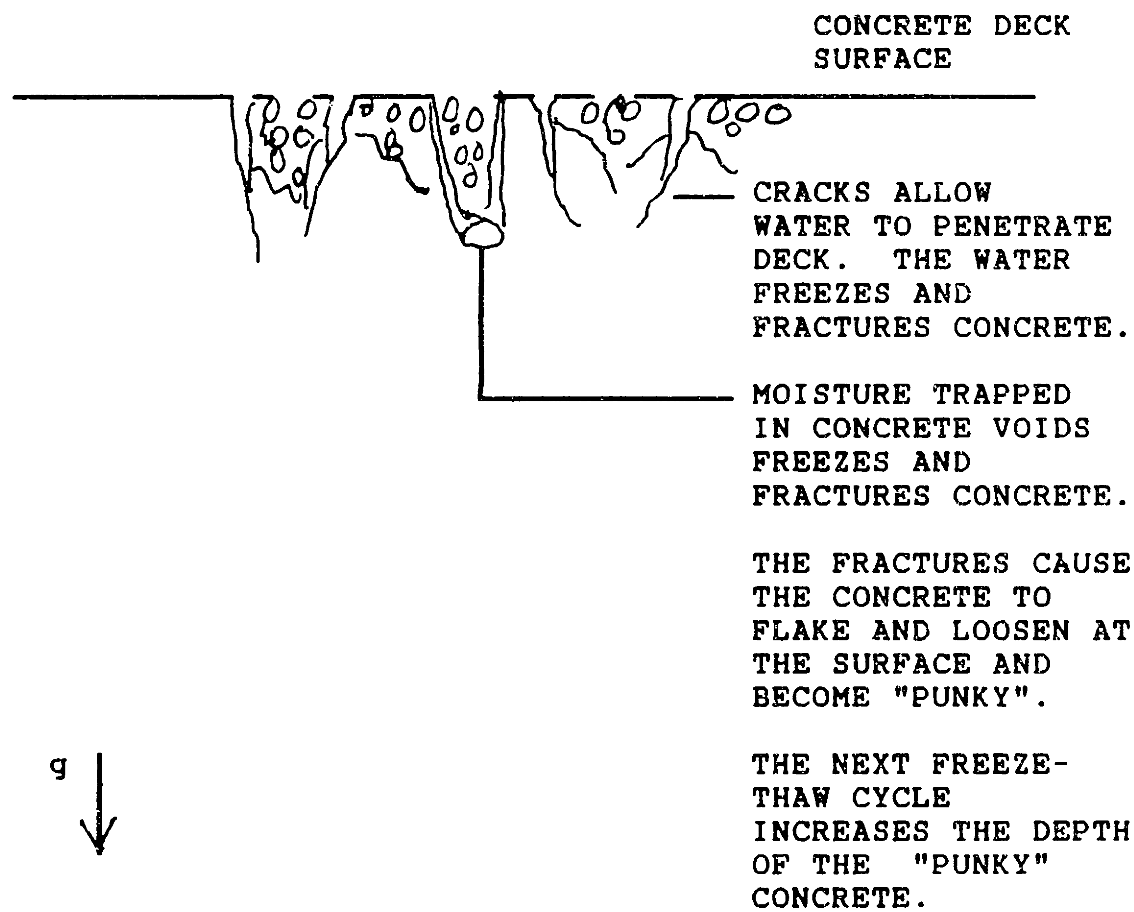
3.3 "Punky" and Delaminated Concrete

Cracking of the asphalt surface and failure of the waterproof membrane produces debonding of the membrane from the asphalt and concrete which allows a void above the concrete to remain saturated with moisture. The soaked top cover concrete endures multiple freeze-thaw cycles and begins to break down, flake and loosen. Concrete that has deteriorated in this way is referred to as "punky" (Figure 3-2).

Radar is an ideal tool for locating "punky" concrete since the moisture laden "punky" concrete has a higher dielectric constant than normal concrete. The algorithm in Chapter 8 that computes values for the dielectric constant of the concrete suggests that overall amounts of high moisture content concrete can be predicted for a deck. These areas of high dielectric constants may directly predict "punky" areas or predict locations of high moisture content concrete that are susceptible to freeze-thaw flaking, and eventually more serious deterioration.

Small cracks in asphalt and concrete also provide paths for moisture and salt to reach the steel rebars and initiate their corrosion. This corrosion produces oxides and hydrated oxides of the alloying elements in the steel that occupy a greater volume than the elemental iron and alloying materials. These expanding corrosion products produce internal pressures in the concrete that eventually cause horizontal cracks parallel to the deck surface. Large cracks

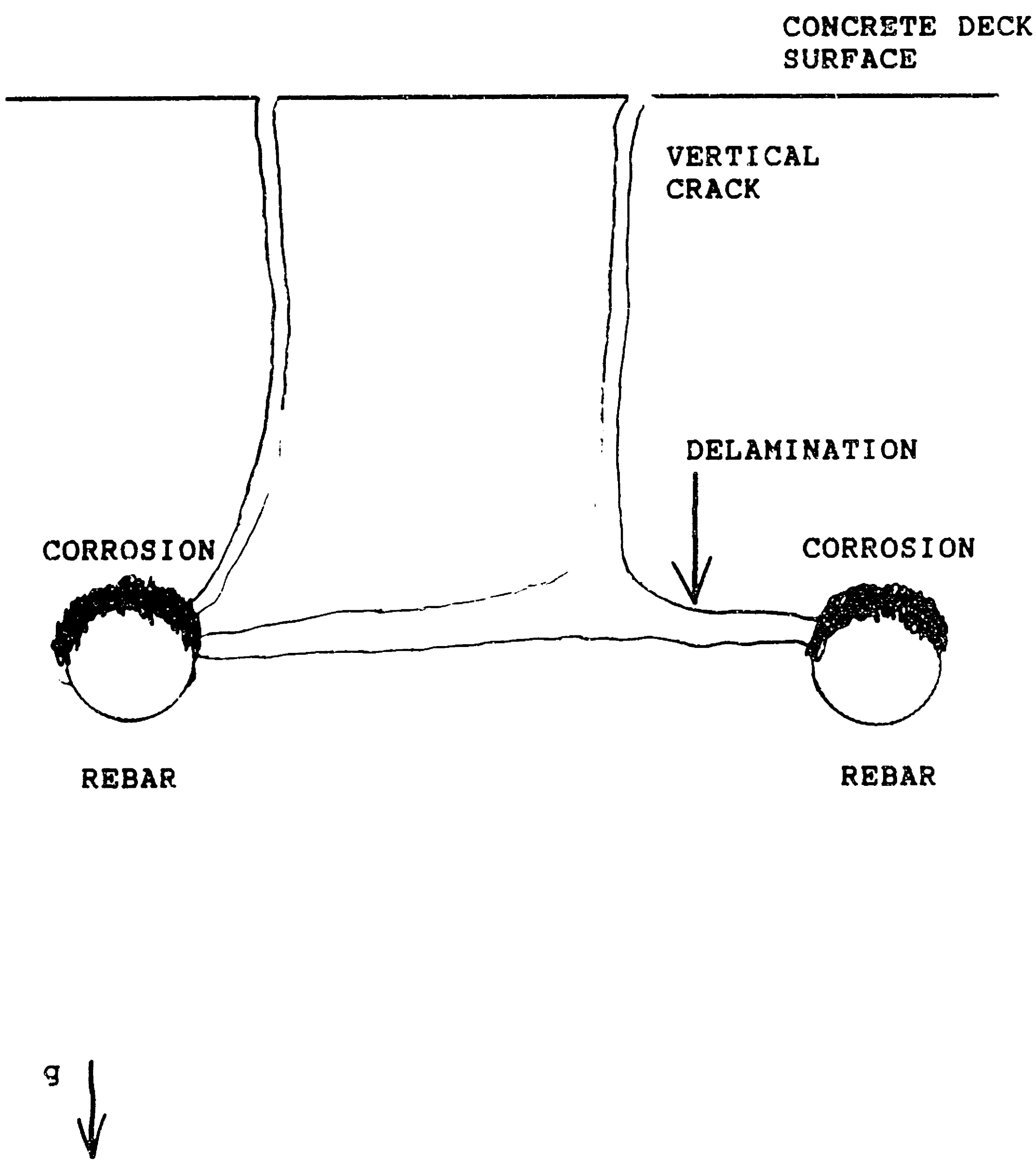
Figure 3-2: "Punky" Concrete



can be produced in this manner, and they soon form air-filled, or water-filled delaminations as shown in Figure 3-3. The separation of the layers of concrete lowers the load carrying capability of the deck and is of great concern to transportation agencies since the delaminations are difficult to detect.

When a hammer is used to strike a deck, a hollow sound is produced at delaminated areas. This manual sounding technique is often used by transportation agencies to locate delaminations, but this technique is slow and requires traffic lane closures. By identifying the reflections from the delamination cracks, radar was investigated as a means of locating these defects. Since the difference in dielectric permittivities of concrete and water is greater than the difference in dielectric permittivities of concrete and air, water-filled delaminations produce stronger radar reflections and should be more easily observed. Several researchers claim to be able to detect delaminations, but radar analysis algorithms attempted at M.I.T. and presented in Chapters 7 and 8 were unsuccessful in predicting the location of delaminations.

Figure 3-3: Delamination



Chapter 4

A Description of Previous Radar Analysis Techniques

4.1 Introduction

Several researchers have explored the use of ground penetrating radar to locate concrete deterioration in bridge decks. Clemena's study for the Virginia Highway and Transportation Research Council,[6] and Cantor and Kneeter's study[7] rely on visual observation of every recorded radar waveform to identify locations where radar reflections appear to be distorted. Their analyses are labor intensive, subjective, and do not incorporate complete models of the reflection and transmission characteristics of radar through bridge decks. Research performed for the Ontario Ministry of Transportation and Communications[8] improves upon the earlier studies by describing radar waveforms in terms of reflection and transmission coefficients at dielectric interfaces, and uses digital signal processing to speed the analysis. A commercial radar system produced by the Penetradar Corporation presents other methods for the prediction of

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[6]Gerardo G. Clemena, "Nondestructive Inspection of Overlaid Bridge Decks with Ground-Penetrating Radar," Transportation Research Record 899 (1983), p. 28.

[7]T.R. Cantor and C.P. Kneeter, "Radar as Applied to Evaluation of Bridge Decks," Transportation Research Record 853 (1982), p. 40.

[8]C.R. Carter, et al., "An Automated Signal Processing System for the Signature Analysis of Radar Waveforms from Bridge Decks," Canadian Electrical Engineering Journal, Volume 11, Number 3 (1983), pp. 128-137.

bridge deck deterioration.

This thesis uses Ontario's basic reflection and transmission coefficient model to describe radar propagation, but Chapter 7 will show that attempts to replicate the results of Ontario's analyses were unsuccessful. Therefore, the original algorithms presented in Chapter 8 extend part of the Ontario analysis to produce direct calculations of concrete dielectric constants that identify the locations of moisture filled "punky" concrete.

4.2 Literature Review

Clemena has towed a ground penetrating radar system over decks in an effort to find areas of delamination. Clemena's judgemental interpretations to locate delaminations are based on identifying deviations from waveforms produced by sound concrete and this technique did not employ any digital signal processing to speed the analysis. Large variations in the data from deck to deck and, in some cases, inconclusive data make this technique insufficient for an accurate appraisal of deck conditions. M.I.T.'s goal is to eliminate this need for a subjective evaluation of radar reflections for each deck by identifying components of the waveforms that are directly affected by the condition of the concrete.

Cantor and Kneeter use a cluster analysis to group waveforms into categories of "good," "distressed," and "intermediate." They suggest that waveforms from good concrete are "smoother" than those from deteriorated concrete and, from viewing the radar waveforms, the researchers claim 90 percent correlation between radar predictions and actual deck core samples. However, Cantor and Kneeter recommend that an automatic processing technique be employed for more efficient evaluation of the radar data.

Joyce's lab and field experiments* showed that delaminations are not easily predicted from human visual analysis of radar waveforms that are displayed on an oscilloscope and he indicated that the detection of delaminations requires advanced data processing techniques as well as analysis of the dielectric properties of the concrete.

4.3 The Ontario Ministry of Transportation and Communications - The DART Radar System

In the study sponsored by the Ontario Ministry of Transportation and Communication, Carter, Chung, Holt and Manning described the results of bridge inspection with a van equipped with a Penetradar Model PS-24 impulse radar and recording equipment. Using a computer to calculate magnitudes of waveform peaks, time differences between peaks, and to calculate other waveform properties, the group claims to be able to predict areas of deterioration and debonding. Asphalt thickness calculations are also produced. Their analysis begins with a model of radar reflections from

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*Richard P. Joyce, "Rapid Non-Destructive Delamination Testing" (Washington, D.C.: Federal Highway Administration, Report FHWA/RD-85/051, April, 1985), pp. 39-40.

an ideal structure (Figure 4-1).

According to this model, a portion of the radar reflection produced by a deck with a sound structure has a W-shape which is produced by the reflections from the asphalt/concrete interface and the rebars. The researchers claim that this characteristic W is poorly defined or absent when delaminations are present. By searching for the appearance of the characteristic W in the waveform, and its lack of appearance thereof, Ontario's signal processing algorithms attempt to predict the locations of delaminations. However, Carter, et al.[10] report that this delamination analysis failed to detect several large delaminated areas on the Papineau Creek Bridge deck. In addition, other researchers have not identified the characteristic W that the Ontario group claims to see in the radar waveform. Preliminary tests at M.I.T. indicated that the W shape rarely appears, and does not correspond to delaminated areas. As the Ontario group and this thesis concludes, further investigations into delamination prediction with radar are required.

The researchers also developed two ratios for use in their analysis. The ratio R1 is defined as the magnitude of trough B to the magnitude of peak A, and R2 is defined as the ratio of the magnitude of peak C to the magnitude of peak A. Debonding and "punky" concrete are detected by using the

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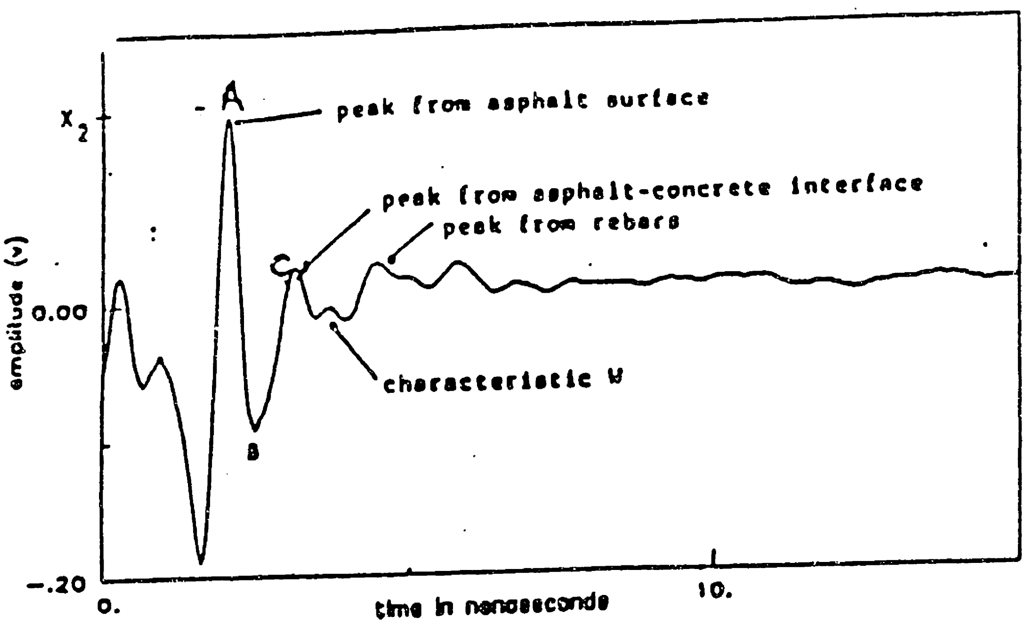
[10]C.R. Carter, et al., p. 136.

Figure 4-1: The Ontario Radar Model



ratios R1 and R2. By digitally processing reflected waves the values for the ratios are calculated over a deck and deck condition can be evaluated as good, debonded, deteriorated or indeterminate. The ranges of values used in this analysis are shown in Table 4-1.

This analysis is reportedly successful in predicting "punky" concrete, however, this thesis will show that a ratio analysis similar to the one performed by Carter, et al. does not yield meaningful results. The R1 ratio is based on trough B, which is a trailing transient of the radar pulse and does not have a physical link to Ontario's own radar reflection and transmission model, and therefore is not pursued further in this thesis. The R2 ratio, however, is determined from reflections from the material interfaces in the deck and will be used in the algorithms presented in later chapters. The Ontario ratio analysis is based on identifying areas where ratio values fall into certain general ranges that are not adjusted for changes in the condition of the asphalt. This thesis extends the use of the R2 ratio by deriving expressions that use measured R2 values as well as measured values for the dielectric constant of asphalt to calculate values for the dielectric constant of concrete. The dielectric constant of concrete provides a direct measurement of moisture content and can be used to infer the locations of deck areas that are "punky" or highly susceptible to deterioration. Thus, by taking into account the dielectric changes of asphalt, a stronger physical basis

Table 4-1: Ratio Values Used in Ontario Evaluation

CONCRETE CONDITION	R1	R2
Good	<0.85	<0.27
Debonded	<0.85	>0.27
Deteriorated	>0.85	>0.27
Indeterminate	>0.85	<0.27

for the prediction of "punky" concrete is provided.

The Ontario report does cite a physical basis for the calculation of asphalt thickness. The asphalt thickness, d_{asp}, is the product of the time delay between peaks A and C, and radar's velocity of propagation in asphalt ($c/\sqrt{\varepsilon_{asp}}$), or

$$d_{asp} = \frac{cT}{2\sqrt{\varepsilon_{asp}}} \qquad (4\text{-}1)$$

where,

T = time difference (ns) between peaks A and C
c = velocity of light
ε_{asp} = dielectric constant of asphalt

Carter, et al. conclude that asphalt thickness prediction is exact for thicknesses exceeding 50mm and this method for thickness prediction is used by M.I.T. as well.

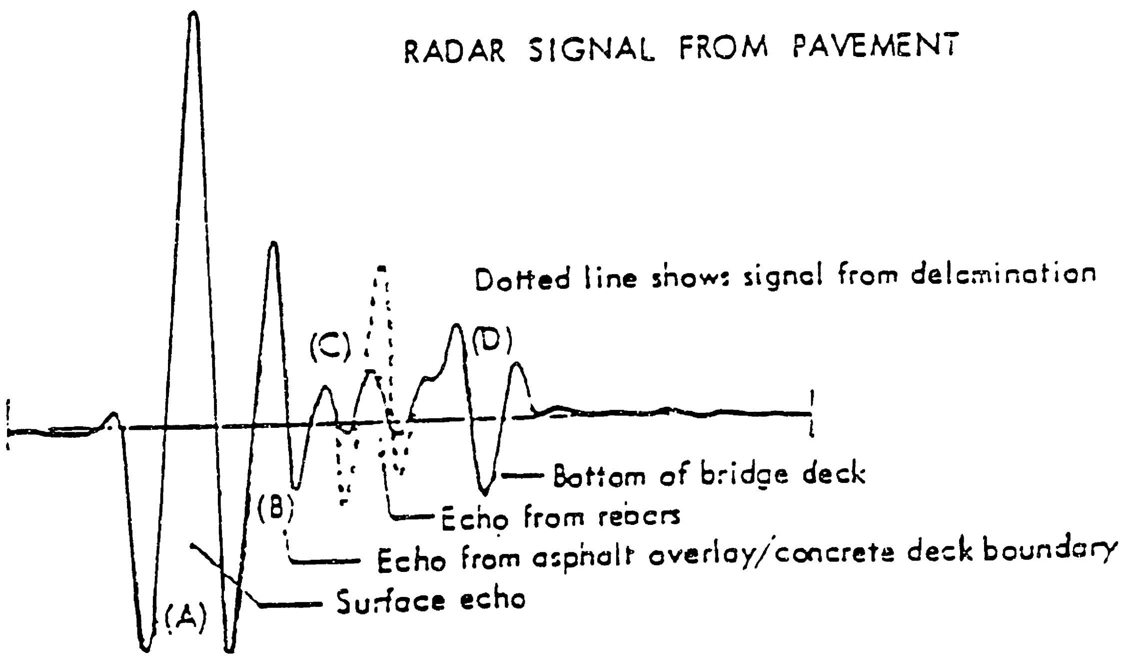
4.4 Commercial Radar Inspection

The Penetradar Corporation of Niagara Falls, New York has developed and operated an inspection system that they claim detects deterioration and delamination in pavements. Penetradar uses a van, equipped with radar units and data acquisition equipment, to record radar waveforms and signal processing equipment and a computer to produce maps of deterioration and delamination in pavements. According to Penetradar, deteriorated concrete, which allows moisture to be trapped in the concrete, results in a signal with a higher amplitude at the asphalt/concrete interface. This is similar to the Ontario group's R2 analysis. Penetradar also reports that concrete delamination produces an increase in signal amplitude at the depth where the delamination occurs. Penetradar's model of the radar signal from pavement is shown in Figure 4-2. This model does not include the characteristic W that is present in the Ontario model. This model is more similar to the waveforms that are recorded by the M.I.T. system, but preliminary tests did not identify the increased reflection near the rebar that Penetradar cites as evidence of delamination.

4.5 Conclusion

As has been described, investigators have identified different signatures to attempt to explain the effects that concrete deterioration has on radar reflections. Data interpretation has often been performed by visual observation and is subjective and in some cases lacks a strong physical basis. Relatively few bridge decks have been studied and prior knowledge of the deck deterioration process, and other deck conditions have not been considered in radar interpretation. Therefore, results have not been convincing and many techniques have not gained full acceptance. The Ontario study, which includes a complete model of reflection and transmission coefficients, and the Penetradar radar model serve as a starting point for the work described in this thesis. Dr. Kenneth Maser of M.I.T. has proposed using a basic model of radar reflection and transmission coefficients to describe the radar waveform produced from fourteen bridge decks in five New England states. Ontario's ratio analysis

Figure 4-2: Penetradar's Radar Model



will be examined and the R2 ratio will be used along with values for the dielectric constant of asphalt to derive the dielectric properties of concrete, and new techniques for delamination prediction will be explored.

Chapter 5

Data Acquisition

5.1 Vehicle Hardware

The radar system that is used by Dr. Maser's bridge deck project team is designed and assembled by Syntek Corporation (formerly Gulf Applied Research) of Marietta, Georgia, and mounted in a U.S. Department of Transportation van. System components are stored in racks provided in the vehicle and external mounts on the rear of the van support the antenna and radar transducer. An optical encoder and fifth wheel are also mounted on the van's rear fender. The encoder and fifth wheel provide a data location reference that is recorded along with the radar signal on a Hewlett-Packard 3964A magnetic four-channel instrumentation recorder. Figure 5-1 is a schematic of the system.

5.2 Field Data Collection

Radar data was collected on bridges scheduled for maintenance in Maine, Massachusetts, New Hampshire, Rhode Island and Vermont. State transportation department engineers obtained core and dust samples of asphalt and concrete and provided M.I.T. with thickness, moisture content and chloride content values for each bridge deck. Data from a new bridge was also obtained so that a comparison could be made with the deteriorated bridges. Table 5-1 lists the locations of decks that were tested and the corresponding

Figure 5-1: Radar System

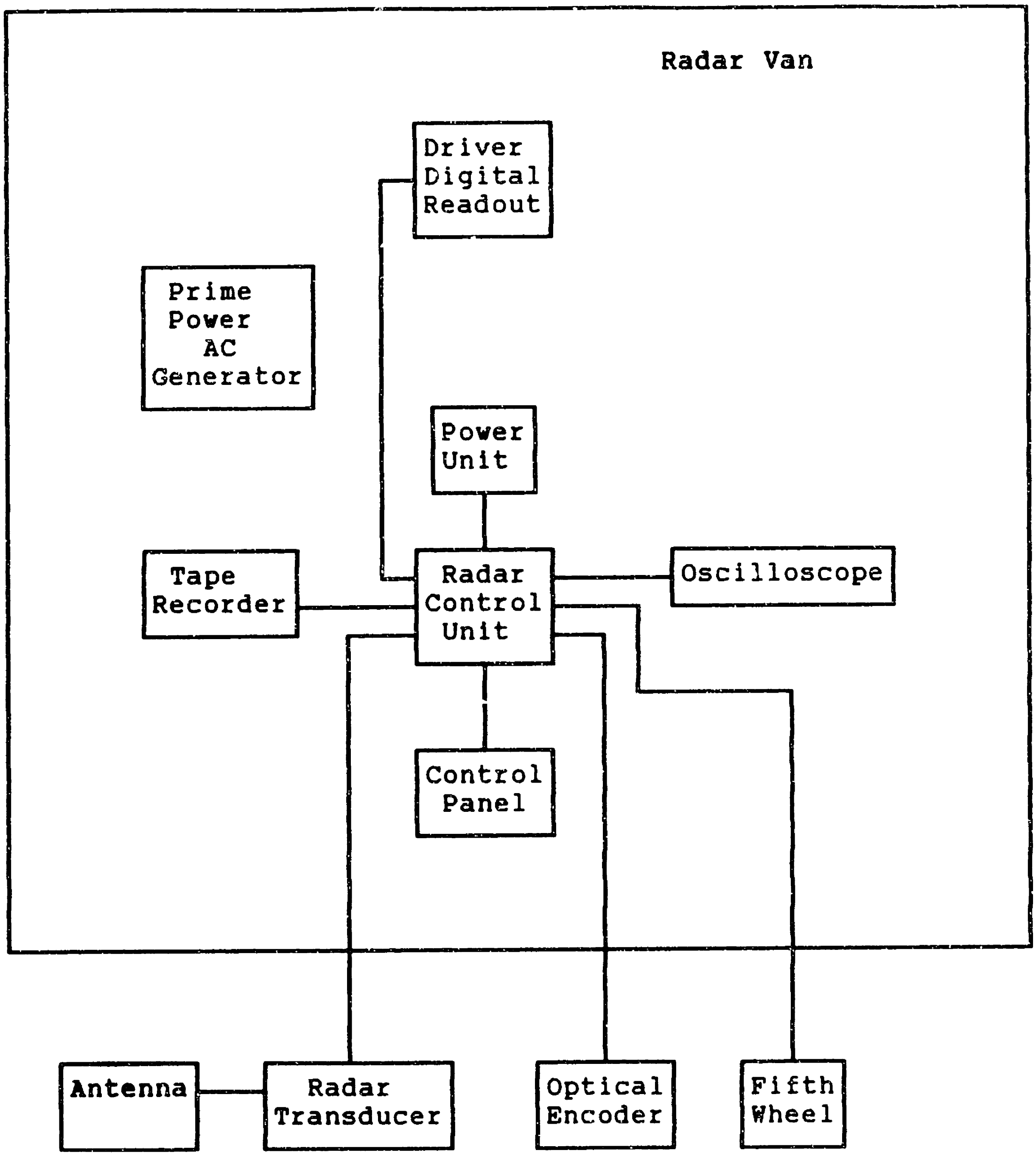


Table 5-1: Test Bridges

STATE	LOCATION	DATA FILE NAME
Maine	U.S. 202 over CNRR	mi1
Massachusetts	I 93 over Rt. 128	m1
	Rt. 44 - Middleboro	m2
	Roosevelt Circle over I 93	m3
	Washington St. over B&M RR	m4
New Hampshire	I 93 - New Hampton	n1
	I 89 - Sutton	n2
	I 95 - ME/NH bridge	n3
	U.S. 1 Bypass - ME/NH	n4
Rhode Island	Breakneck Hill	r1
	Main Road, southbound	r2.1
	Main Road, northbound	r2.2
	Sprague St.	r3
Vermont	I 89 - Montpelier	v1
	I 89 over Winooski R.	v2

data file names.

In the M.I.T. tests, a van operator drives the van along the bridge deck at under five miles per hour in passes that are one and one-half feet apart. Guidelines must be painted on the deck so that the van driver can keep the van in the appropriate radar pass lane. The radar system operator controls the radar unit and the recorder. Figure 5-2 is a side view of the van and antenna mounted in the operating position.

5.3 Recording, Digitizing and Storage of Data

The radar reflections are recorded using the equivalent time sampling method. This method is used to obtain a high bandwidth measurement of very fast, repetitive signals with a low bandwidth oscilloscope. With the equivalent time sampling method, only one sample is taken every pulse period. The sample point is delayed for each period by one predetermined small time increment relative to the previous period. Thus, the sample point will appear to slowly move along the sampled waveform with each passing period until it has covered the desired time window. Figure 5-3 is an illustration of the equivalent time sampling method.[11] As this figure shows, this procedure results in a sampled replica that is a low frequency version of the real time pulse. Following system calibration, 1 ms of equivalent

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[11]Syntek Corporation, Radar System Tutorial (Marietta, Georgia).

Figure 5-2: Side View of the Radar Van and Antenna

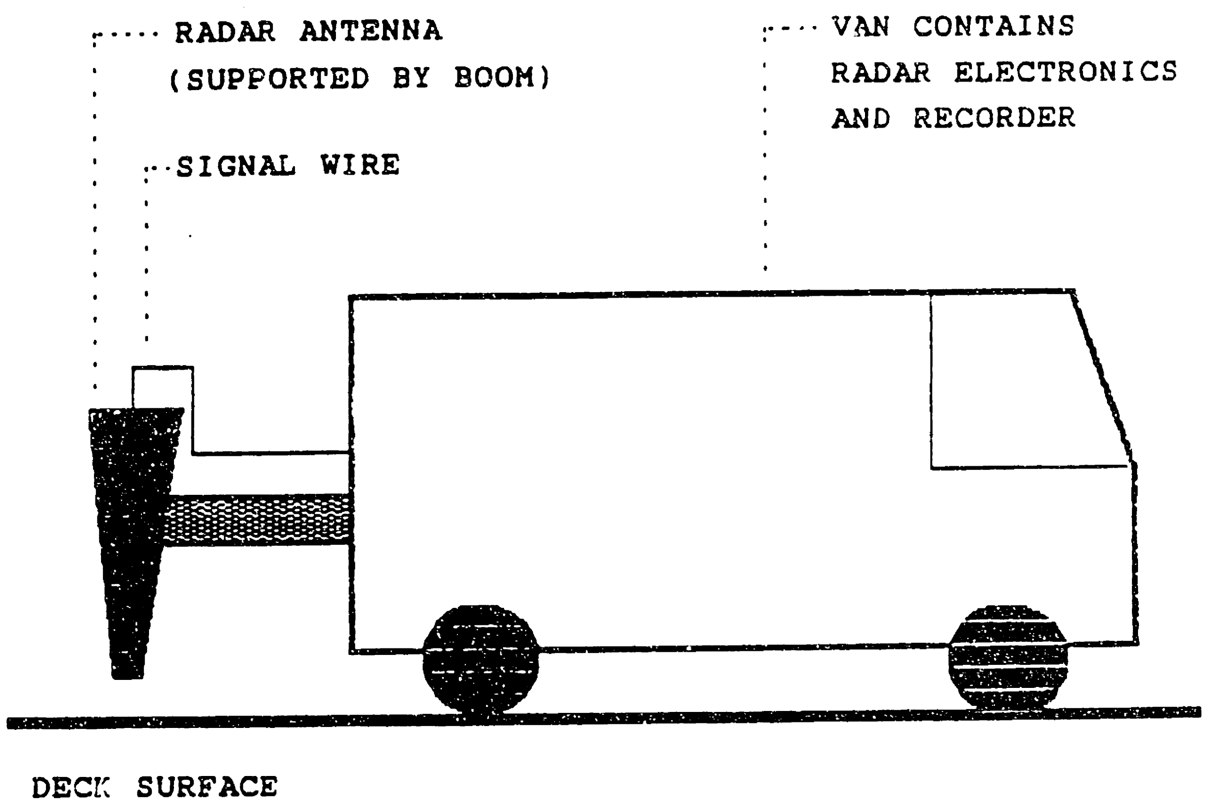
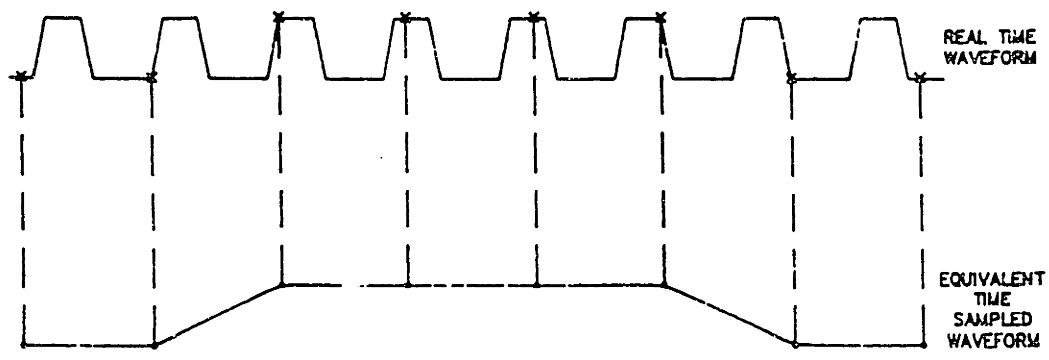


Figure 5-3: Equivalent Time Sampling Illustration



sample time equals 1 ns of real time.

The radar transmitter fires a 1 ns sinusoidal pulse at a 5 MHz rate. The returning radar signal is sampled at a 5 MHz rate and is constructed over an 18 ms scan window. Therefore, for one scan period,

$$18 \text{ ms} \times 5 \text{ MHz} = 90{,}000 \text{ pulses/scan}$$

The radar system looks at 90,000 periods of the radar wave to construct one waveform. The sample point time delay allows samples to be taken at 200 locations along a radar pulse. In real time, samples are taken every 90 picoseconds, since,

$$\frac{18 \text{ ns}}{200 \text{ points}} = 90 \text{ ps}$$

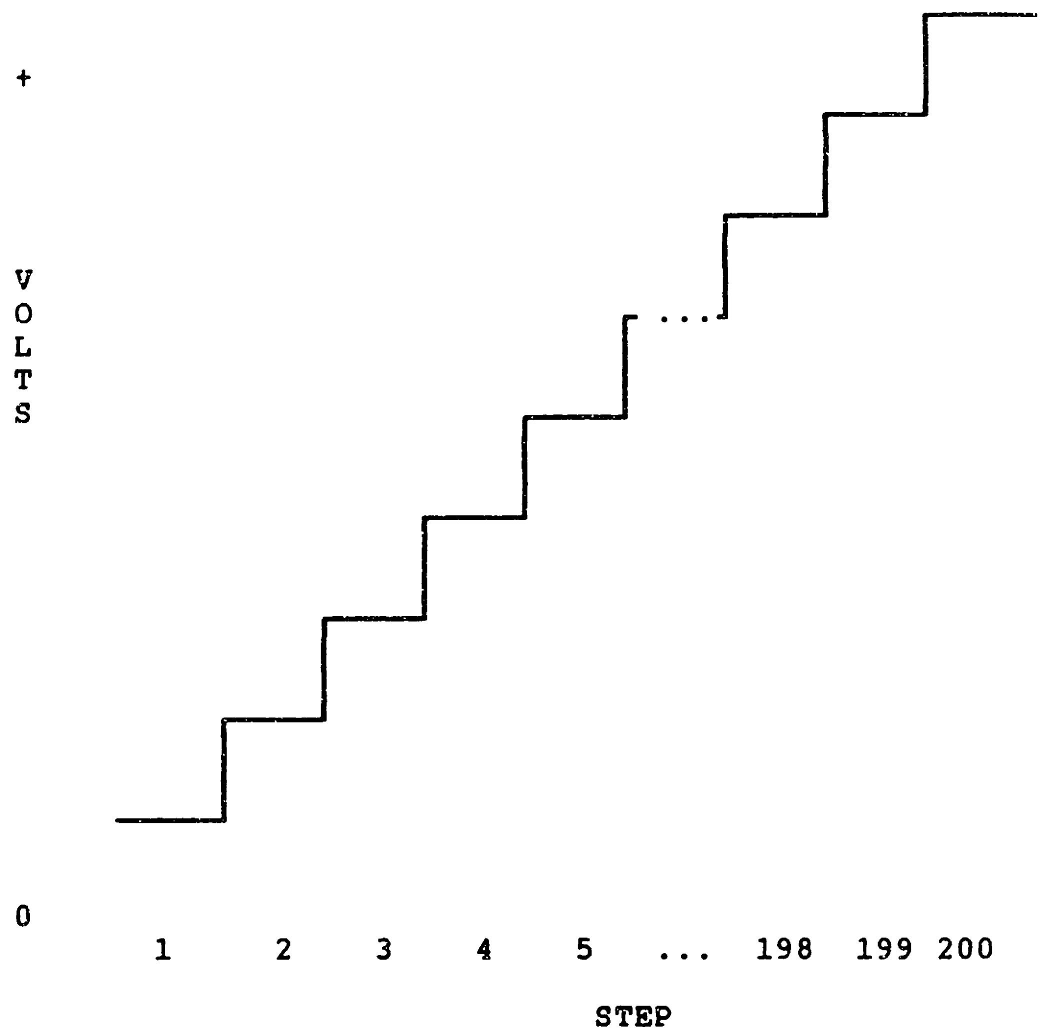
The time delay that allows for sampling to occur at 200 locations along the radar pulse is controlled by a voltage staircase ramp, shown in Figure 5-4. At each step of the ramp, the timing circuitry allows 450 samples to be taken:

$$\frac{90{,}000 \text{ pulses}}{200 \text{ steps}} = 450 \text{ pulses/step}$$

The 450 samples at each sample step are integrated to increase the signal-to-interference ratio. Thus, each of the 200 sample points which are used to construct the final radar waveform is composed of 450 samples at the same location on the radar wave.

The reconstructed radar waves and pulses that represent travel distance of the fifth wheel are recorded on audio

Figure 5-4: Staircase Ramp for Sample Point Time Delay Circuit



tape. A Keptrol counter and an RC Electronics analog-to-digital board were used to transfer the waveforms to the hard drive of a Compaq 286 Deskmate microcomputer. Waveforms were stored at one foot intervals along every pass along the deck and were placed in DOS files that are accessed by the data analysis programs. A/D samples of the waveforms were taken at 50 kHz (one sample every 0.02 ms), therefore, the real time sample period is 0.02 ns. Thus, each data point in a stored radar waveform is separated by the equivalent of 0.02 ns.

Assuming a time measurement error, Δt, of 0.02 ns, the distance the radar wave travels in this time is

$$\begin{aligned} \text{distance} &= c \times \Delta t \\ &= 6 \text{ mm, or } 0.24 \text{ in.} \end{aligned}$$

For the radar van moving at five miles per hour (87.96 in./s) and a real scan time of 18 ns, a waveform is constructed over a travel distance of

$$\begin{aligned} \text{distance} &= \text{van speed} \times \text{scan time} \\ &= 1.6 \times 10^{-6} \text{ in.} \end{aligned}$$

Since the thicknesses of the asphalt and concrete layers of the bridge decks range from one to four inches and radar waveforms are digitized at one foot intervals along the deck, the distance errors are within the required resolution.

Chapter 6

The Radar Analysis Approach

6.1 Derivation of Radar Models

6.1.1 The Radar and Deck Cross Section Model

An accurate model of relationships between physical characteristics of a bridge deck and radar reflections is necessary for the development of analysis algorithms based on electromagnetic theory. Figure 6-1 shows the basic bridge deck model that has been proposed by Maser.[12]

Peak A on the radar waveform represents the reflection from the air/asphalt interface, peak C the reflection from the asphalt/concrete interface, and peak D the reflection from the first layer of rebar. A_{PLATE} is the magnitude of the incident radar wave.

While some researchers attempted to model reflections from delaminations above the first layer of rebar, others reported that small air-filled delaminations do not produce extraordinary reflections that can be detected with standard radar equipment. Polarity changes of radar reflections from the top and bottom of air-filled cracks, small differences in the arrival times of reflections from the top and bottom of delaminations, and the cancelling of internal reflections within these cracks make direct delamination identification

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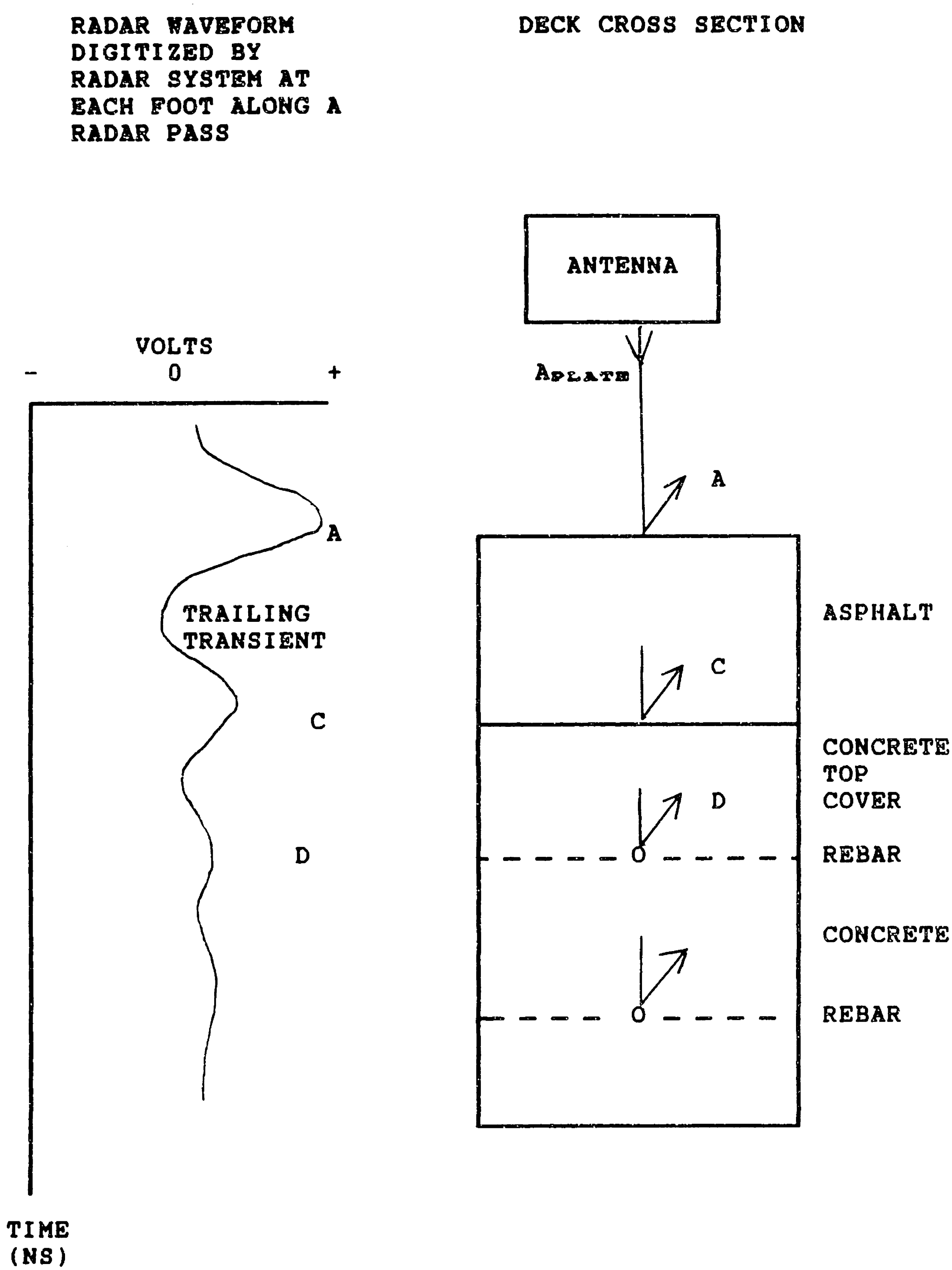
[12]Kenneth Maser, ed., "New England Transportation Consortium Bridge Deck Project Technical Committee Meeting" (Proceedings of a meeting held at the Massachusetts Institute of Technology, March 14, 1988), p. 5.

Figure 6-1: Radar Reflections and the Bridge Deck Model



virtually impossible.[13] Chapter 8 presents a new method of locating delaminations which uses rebar reflections to predict rebar corrosion and delamination. Radar attenuation is affected by the amount of corrosion on the rebars and since the expanding products of rebar corrosion cause delaminations, a prediction of delaminations may be obtained from an analysis of radar attenuation from rebars.

6.1.2 The Reflection and Transmission Coefficient Model

Using the laws of reflection and transmission, the behavior of a radar wave as it penetrates a bridge deck can be modeled as in Figure 6-2.[14] This model is based on the model described by the Ontario group, but does not specifically account for reflections from a delamination.

This model can be used to derive expressions for the dielectric constants of the different layers of the deck. For example, since the reflection coefficient of the air/asphalt interface, r_{12}, is defined as

$$r_{12} = A/A_{PLATE} = \frac{1-\sqrt{\varepsilon_{ASP}}}{1+\sqrt{\varepsilon_{ASP}}} \qquad (6\text{-}1)$$

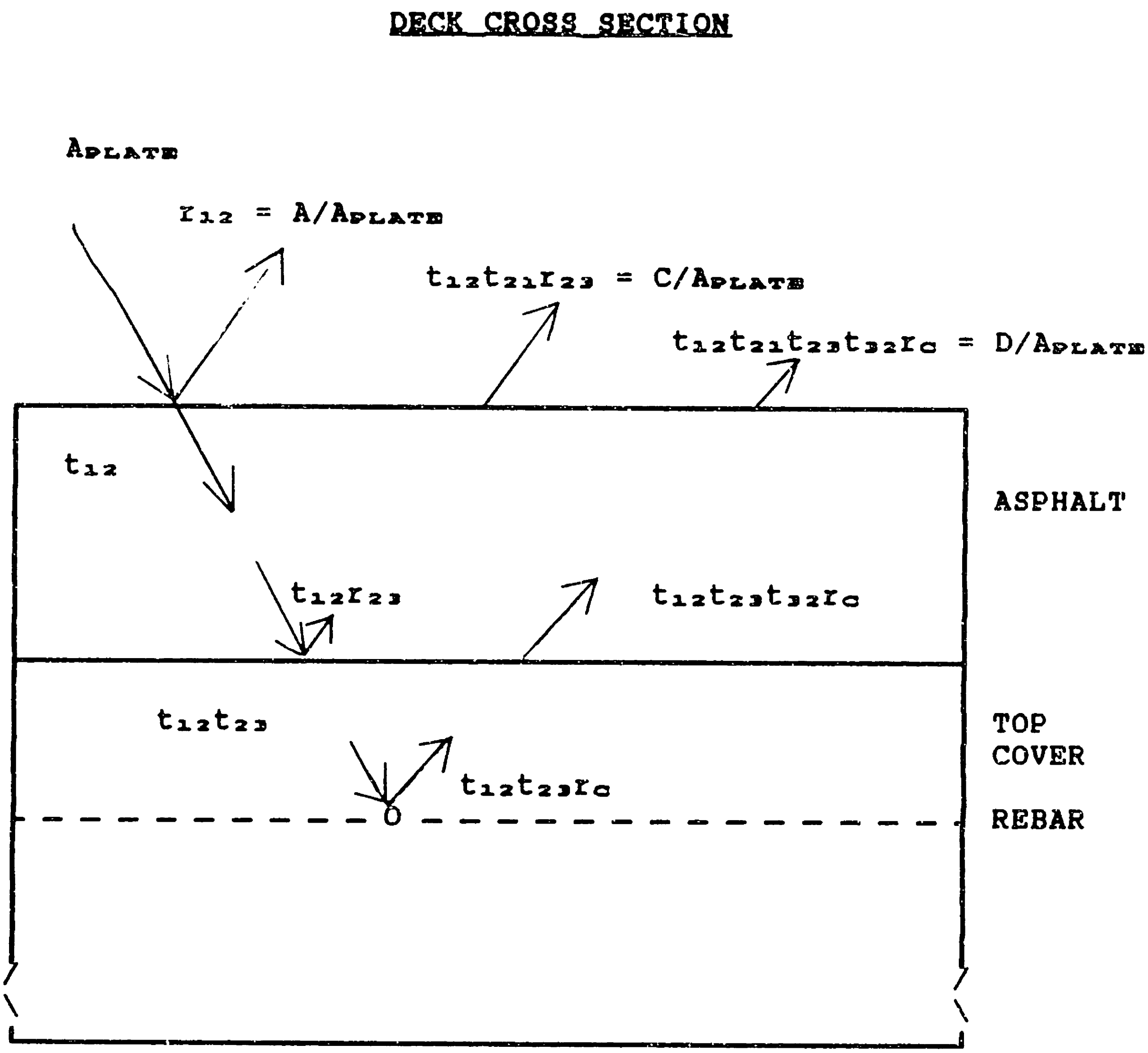
solving for the dielectric constant ε_{ASP},

$$\sqrt{\varepsilon_{ASP}} = \frac{1-r_{12}}{1+r_{12}},$$

[13]Roddis, p. 129.

[14]Maser, "New England Transportation...," p. 6.

Figure 6-2: Reflection and Transmission Coefficient Model



A_{PLATE} = magnitude of incident radar wave
r_{12} = reflection coefficient from air/asphalt interface
t_{12} = transmission coefficient from air/asphalt interface
r_{23} = reflection coefficient from asphalt/concrete interface
t_{23} = transmission coefficient from asphalt/concrete interface
r_c = reflection coefficient from cylindrical rebar

and

$$\sqrt{\varepsilon_{ASP}} = \frac{1-A/A_{PLATE}}{1+A/A_{PLATE}} \qquad (6-2)$$

where,

A = reflection from air/asphalt interface
A_{PLATE} = incident radar wave magnitude
ε_{ASP} = dielectric constant of asphalt

6.1.3 Thickness Expressions

Dielectric constant values are used to calculate asphalt and top cover thicknesses. Since the velocity of light in a vacuum, c, is 11.82 in/ns, and depth represents half the total distance travelled by the radar signal, asphalt thickness, d_{ASP}, can be represented as

$$d_{ASP} = \frac{cT}{2\sqrt{\varepsilon_{ASP}}} \qquad (6-3)$$

where,

T = time difference (ns) between peaks A and C,

and top cover thickness, d_{TC}, can be written as

$$d_{TC} = \frac{cT}{2\sqrt{\varepsilon_{C}}} \qquad (6-4)$$

where,

T = time difference (ns) between peaks C and D
ε_C = dielectric constant of top cover of concrete

6.1.4 Effect of Moisture Content

The effect of moisture content on radar signals will also be investigated. The R2 ratio, the magnitude of peak C divided by the magnitude of peak A, can be expressed using the reflection and transmission coefficients model. This model is used to derive an expression for R2 in terms of asphalt and concrete dielectric constants. Accordingly, R2 can be written as

$$R2 = C/A_{PLATE} \times A_{PLATE}/A =$$

$$\frac{t_{12}t_{21}r_{23}}{r_{12}} = \frac{4\sqrt{\varepsilon_{ASP}}\ (\sqrt{\varepsilon_{ASP}} - \sqrt{\varepsilon_C})}{(1 - \sqrt{\varepsilon_{ASP}})\ (\sqrt{\varepsilon_{ASP}} + \sqrt{\varepsilon_C})} \qquad (6\text{-}5)$$

Since ε_C can be expressed as

$$\varepsilon_C = \sum_I \phi_I \sqrt{\varepsilon_I} \qquad (6\text{-}6)$$

where,

I = air, water, or solid
ϕ = volume fraction of constituent I
ε_I = dielectric constant of constituent I,

theoretical variations of ε_C and R2 with moisture can be determined by varying the volume fraction of water in the concrete. Theoretical ε_C values are plotted versus moisture content in Figure 6-3. Theoretical R2 values are plotted against moisture content in Figure 6-4. Sample calculations of the data points in Figures 6-3 and 6-4 are located in Appendix A. Moisture content data from core samples of actual decks will be used to experimentally verify the theoretical effect of moisture on ε_C and R2 values.

Figure 6-3: ε_c Versus Moisture Content (Theoretical)

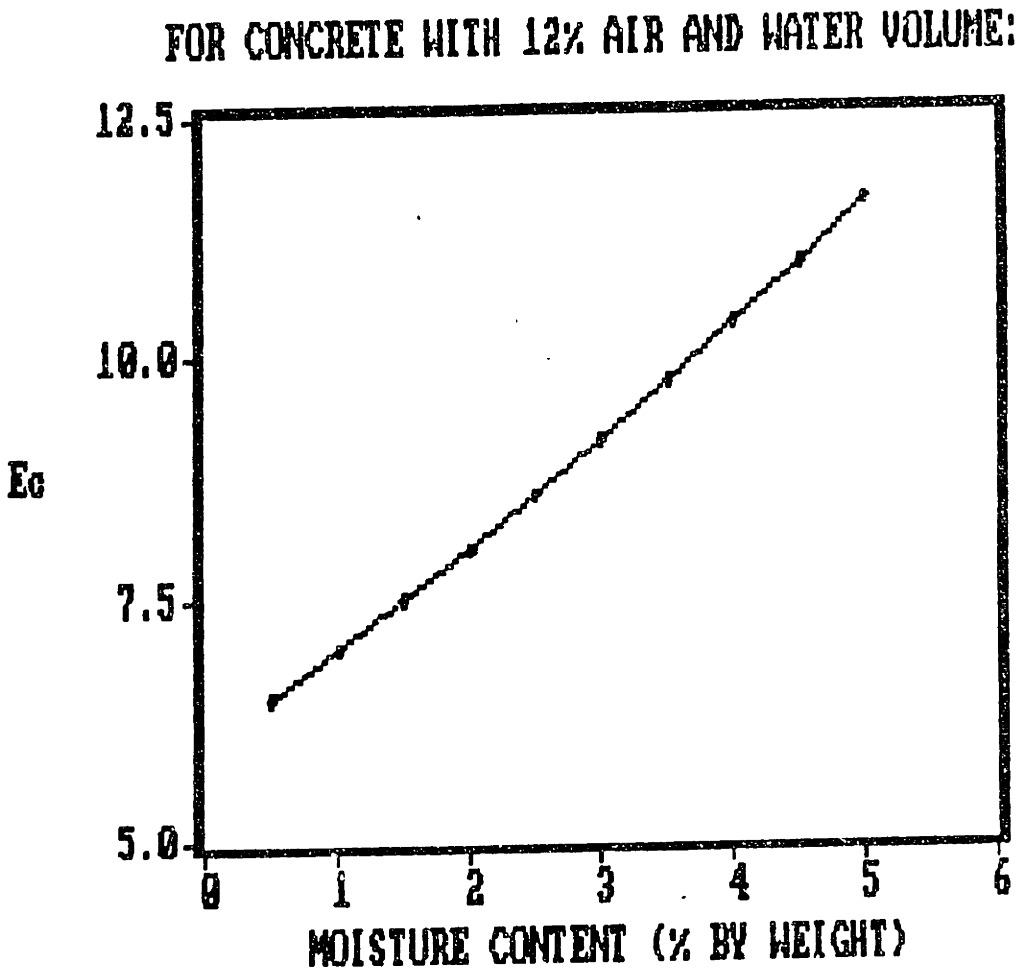
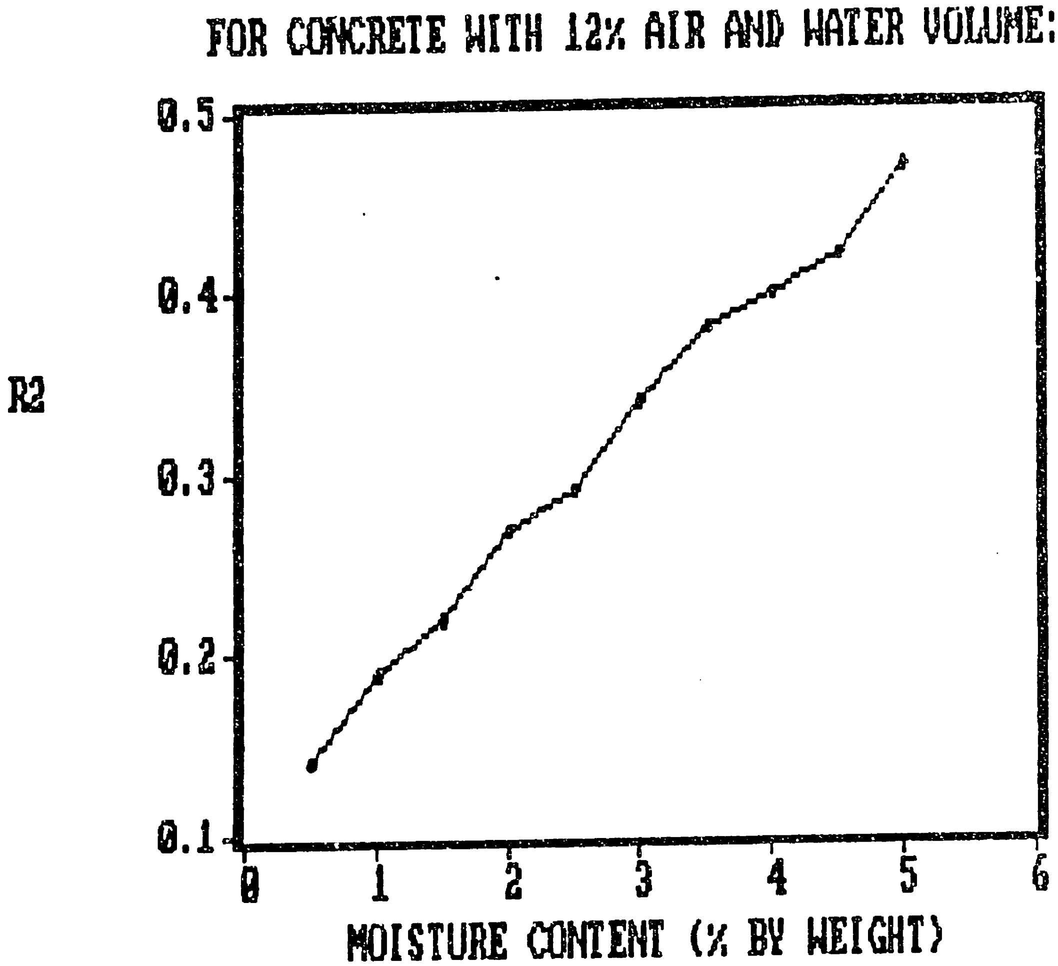


Figure 6-4: R2 Versus Moisture Content (Theoretical)



6.2 Software Tools

In order to analyze radar waveforms that have been recorded and stored in microcomputer memory, a mathematical software package must be used. The ASYST programming language, which allows the entry of simple commands or complex mathematical operations, has been used to calculate waveform characteristics needed to determine R2 ratios, thicknesses, dielectric constants, and perform all the computer analyses described in this thesis.

ASYST requires the following hardware:

- IBM PC/XT/AT or compatible
- Minimum 512K of RAM (640K recommended)
- 2 floppy disk drives, or 1 floppy and a hard disk
- IBM Color Graphics Adaptor, IBM EGA, etc.
- Intel 8087 or 80287 mathematics coprocessor

ASYST consists of 6 diskettes which are loaded onto a hard drive. Programs written in ASYST and presented in the following chapters access radar waveforms stored on the hard drive of a microcomputer or on a diskette, calculate values used in waveform analysis, and plot results according to the language's graphics commands.

6.3 The Development of Analysis Algorithms

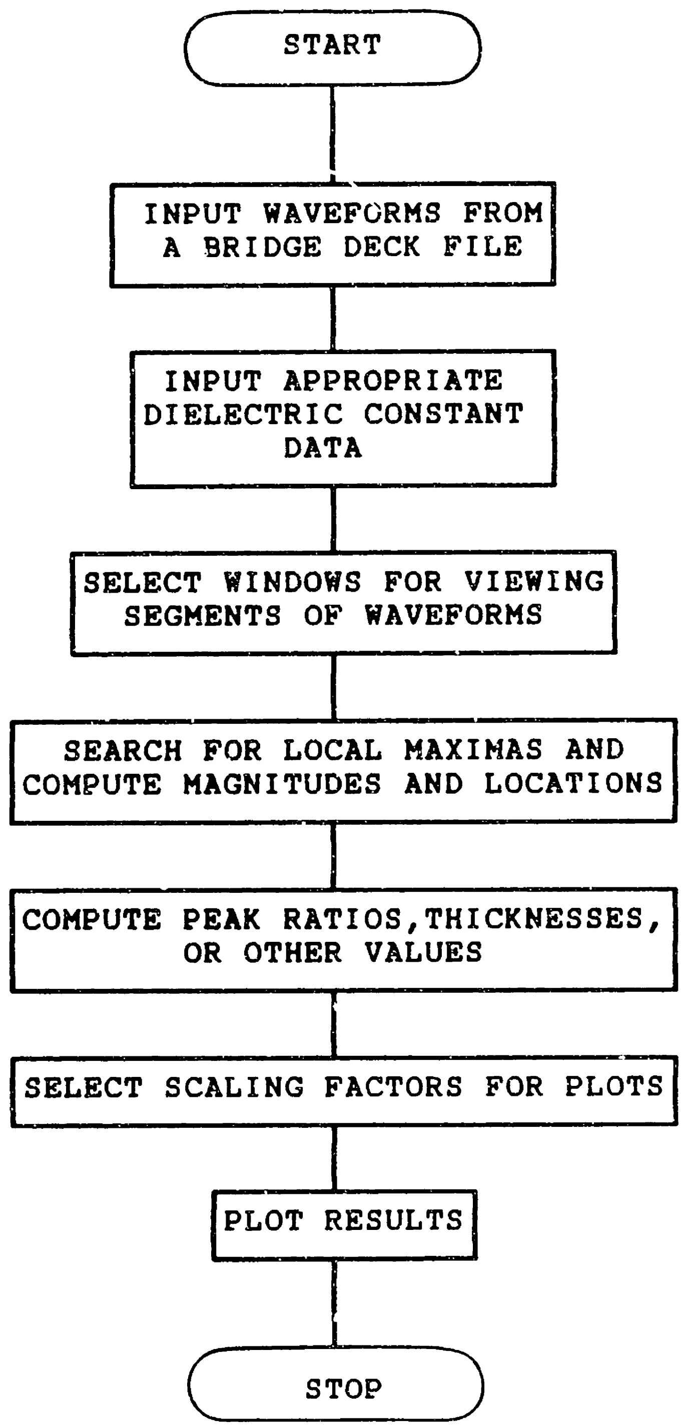
ASYST's pre-defined routines perform peak detection, waveform integration, filtering, frequency analysis, statistics, and graphics. The radar reflections recorded and digitized at each foot along a radar pass are the inputs to the programs that perform waveform analysis. ASYST enables the user to compute magnitudes of reflections from various interfaces in bridge decks, time differences between peaks, integrals of waveforms, and other characteristics. Calculations performed in ASYST, along with other data, can be compared to theoretical results based on the radar model. For example, the variation of the R2 ratio with moisture content can be verified with R2 calculations performed in the ASYST language and data from core sample tests. A flowchart of a typical program written in ASYST is shown in Figure 6-5.

ASYST's statistical routines are also used to provide estimates of a deck's condition by computing variations of selected factors, such as the dielectric constant of concrete.

6.4 Mapping of Predicted and Actual Deteriorations

ASYST's graphics algorithms are employed to produce maps of predicted deterioration that can be compared to actual deterioration maps. Maps that combine the predicted results of radar and infrared thermography inspections, as well as the results of underside deck surveys are simple and easy to read. In this way, the ability of radar and other technologies to predict areas of concrete deterioration can be accessed.

Figure 6-5: Flowchart of a Typical ASYST Program



Chapter 7

Preliminary Studies

7.1 Possibilities for Computer Analysis

With the tools provided by the ASYST programming language, the study of the effects of physical conditions on several waveform characteristics can be pursued expediently. By calculating locations and magnitudes of waveform peaks, ratios such as R2 and thickness measurements can be obtained. Comparisons can then be made to actual moisture constant levels and actual areas of deterioration. While the peak ratio analysis performed by the Ontario Ministry of Transport appears interesting, and serves as a basis for the M.I.T. work, another technique for deterioration and delamination prediction is explored. This technique uses ASYST's integration routines to compute the total area under waveforms in an attempt to detect overall attenuation of the radar signal as it passes through delaminated areas.

7.2 Early Results

Preliminary results of several tests proved that delaminations are difficult to detect with radar. Maser used laboratory models of narrow air-filled and rust-filled gaps between concrete blocks to prove that unless delaminations are moisture filled, or unless the physical properties of the concrete above and below the crack differ significantly, the delaminations do not produce their own reflections and have no easily observable effects on the other reflections.

Since delaminations may attenuate the transmitted radar signal and lower the magnitude of the reflections from the rebar, the area under the radar waveform for a one nanosecond interval around the rebar reflection was examined. A waveform from a non-delaminated area of the deck was selected as a reference waveform, w_m, and an area coefficient, which measures changes in a segment of the area under every other digitized waveform, was computed at each foot along a radar pass. The area coefficient is defined below in Equation (7-1).

$$\text{area coefficient} = \frac{\int_a^b w_I \times w_m \, dt}{\int_a^b w_m \times w_m \, dt} \qquad (7\text{-}1)$$

where,

w_I = any waveform along a deck
w_m = a reference waveform

and the integration limits are,

a = 0.4 ns after Peak C (asphalt/concrete interface)
b = 1.4 ns after Peak C
dt = change in time (ns)

A decrease in the area coefficient may indicate signal attenuation as radar passes through delaminations. However, the behavior of the coefficient appears to be highly erratic, and no relationship between the coefficient and actual delaminations was found. An example of the calculations for pass b along a bridge deck Vermont 1 are shown in Figure 7-1. This figure also shows the locations of actual delaminations that were detected when the deck was opened for repair.

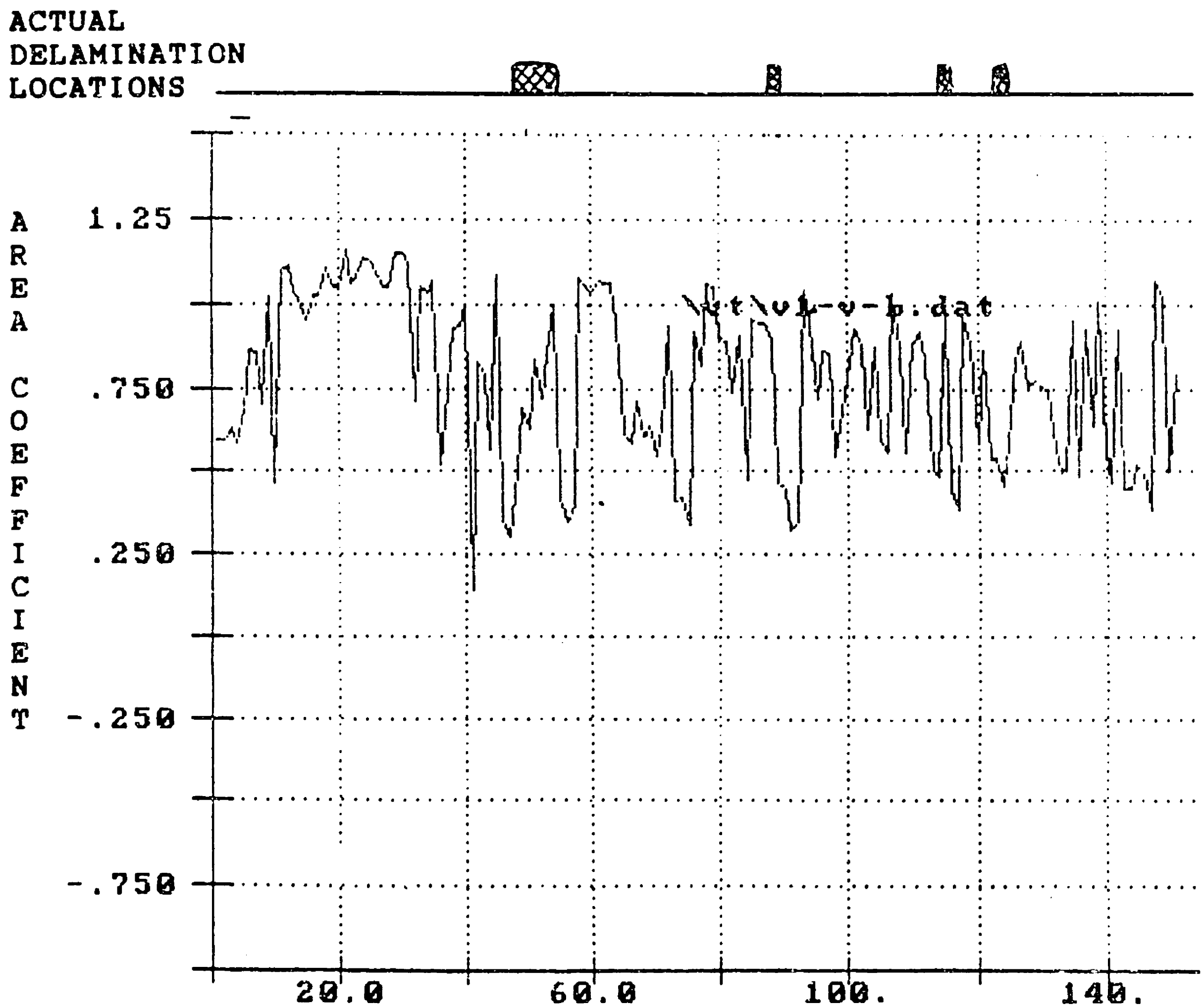
Since it appears that delaminations cannot be directly observed from distinct peaks or area changes of the radar waveform, future algorithms to predict delaminated locations of bridge decks will use rebar reflections to give an estimate of the amount of delamination-producing rebar corrosion. The following chapter presents a new algorithm to measure the rebar reflection, but tests on limited data sets will show that the program is also unsuccessful in identifying delaminations. However, since the ASYST software can effectively locate waveform peaks, an analysis based on peak detection will be attempted to locate the other major form of deterioration - "punky" concrete.

7.3 Results for Further Consideration

7.3.1 Windows and Peak Detection

With proper identification of waveform peaks, the routines to determine peak magnitudes, peak ratios, thicknesses and dielectric constants produce meaningful results. Figure 7-2 and Figure 7-3 show the reflections from two decks with different asphalt thicknesses. In Figure 7-3, the small peak between A and C represents not an interface in the deck, but a portion of the radar's transmit pulse visible only when the asphalt is thick. Therefore, any algorithm to

FIGURE 7-1: Area Coefficient Values



POSITION ALONG DECK (FEET)

Figure 7-2: Radar Waveforms

(Waveforms digitized at one foot intervals along a pass are plotted successively, one over another.)

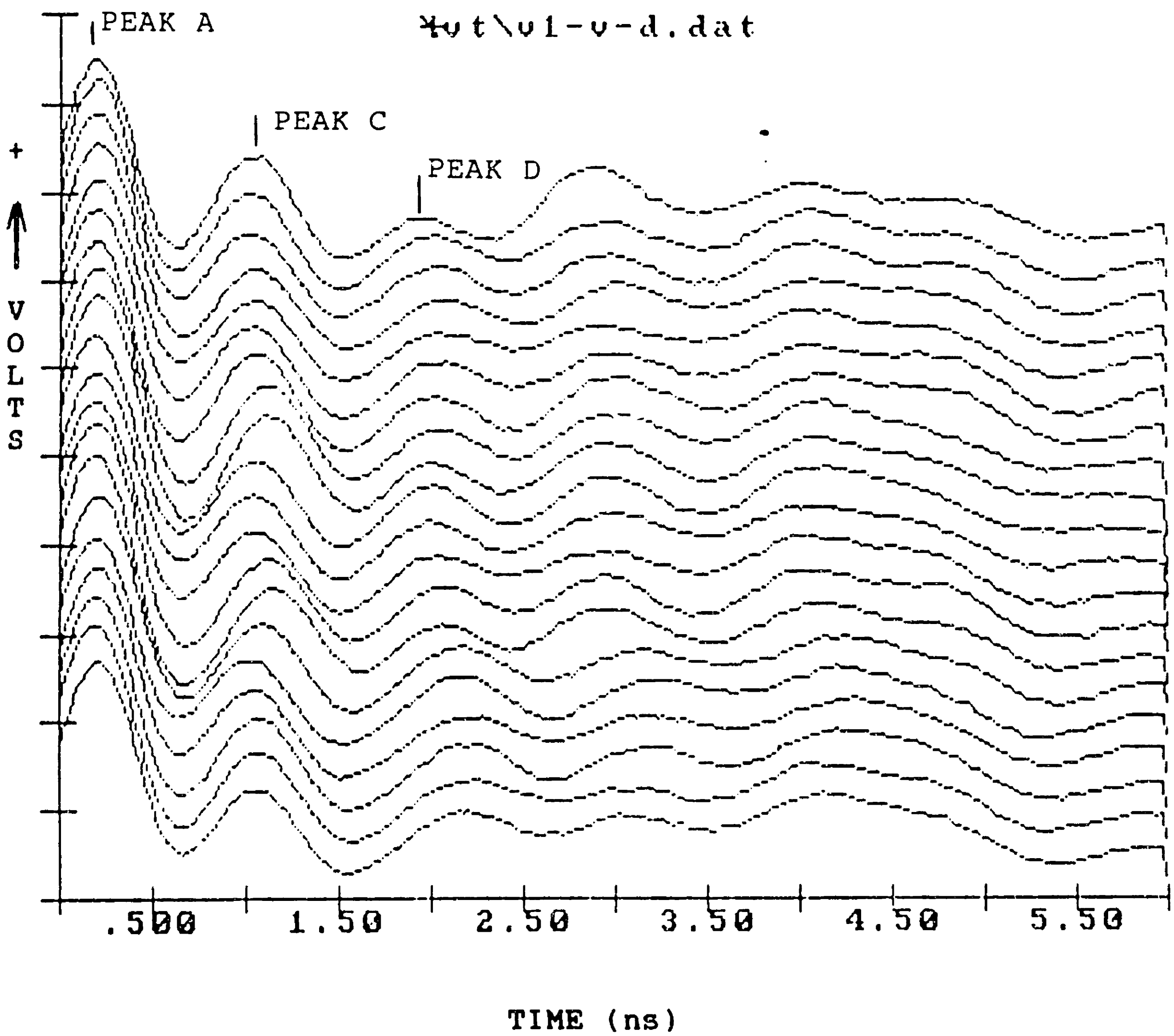
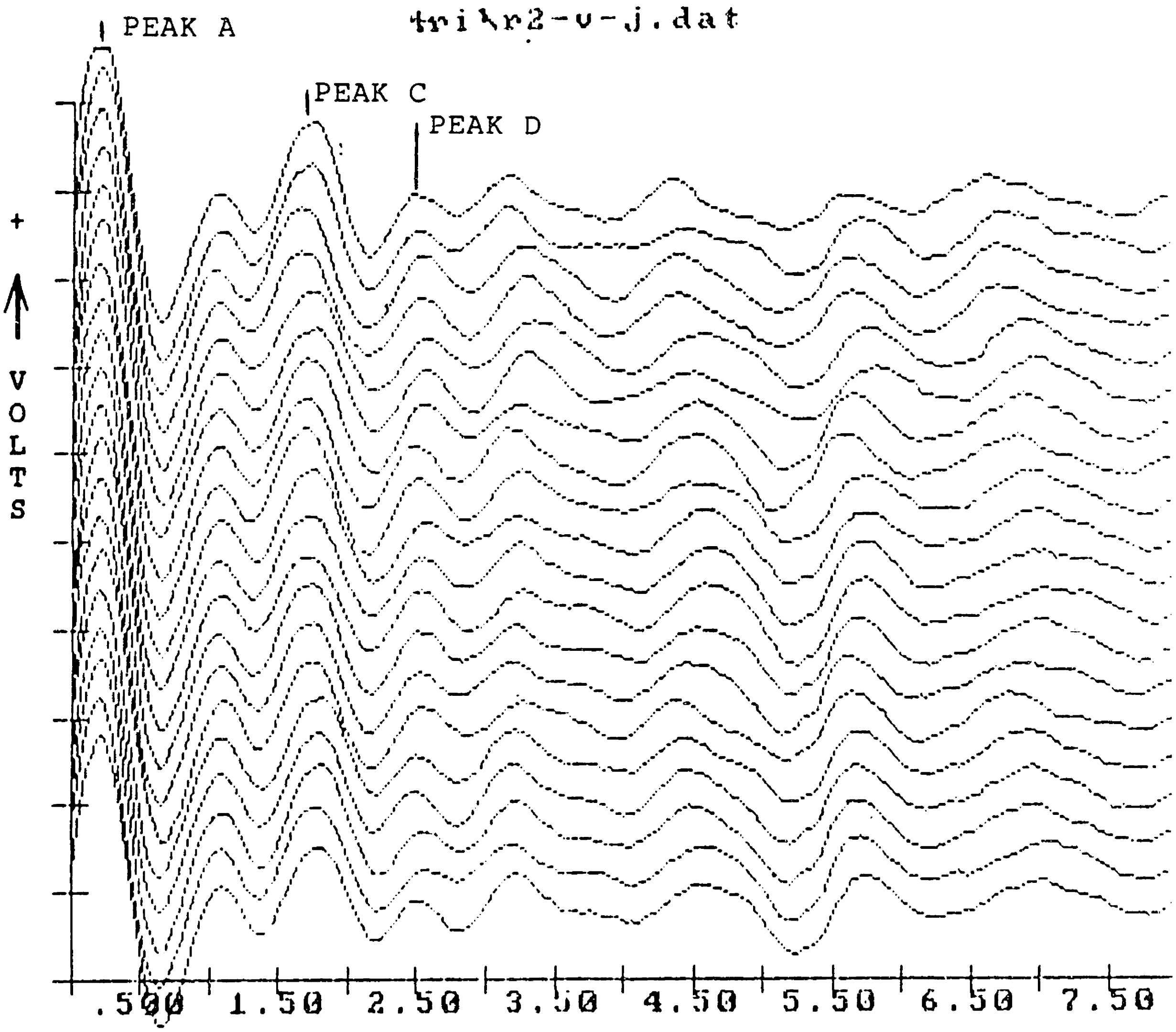


Figure 7-3: Radar Waveforms



select waveform peaks must be adjusted for large asphalt thickness values to insure that interfaces in decks are correctly identified.

7.3.2 Peak Ratios and Thicknesses

After the correct selection of waveform peaks, several waveform peak ratios can be calculated, as in the Ontario analysis. These ratios are summarized in Table 7-1. Assuming constant dielectric permittivity values for asphalt and concrete, thickness values can also be obtained using Equations (6-3) and (6-4). The outputs of programs to accomplish these tasks are shown in Figures 7-4 and 7-5. Core sample data obtained by the University of New Hampshire verifies that these algorithms are capable of predicting asphalt thicknesses to within 0.75 inches. Also, it appears that areas of deteriorated and moisture-filled concrete may correspond to high R2 values. However, the algorithms do not address changes in dielectric constants.

7.3.3 Dielectric Constant Calculations

The flat plate reflection tests performed on bridge decks can be used to calculate the dielectric constant of asphalt. The incident radar wave, which can be measured from the reflection from a metal plate, divided by the reflection from the air/asphalt interface is equal to the reflection coefficient r_{12} in the model described in Figure 6-2. Accordingly, the dielectric constant of asphalt can be

Table 7-1: Waveform Peak Ratios

RATIO	PEAKS	DEFINITION
R2	C/A	Reflection from the asphalt/ concrete interface divided by the reflection from the air/ asphalt interface.
R3	D/A	Reflection from the concrete/ rebar interface divided by the reflection from the air/asphalt interface.
R4	D/C	Reflection from the concrete/ rebar interface divided by the reflection from the asphalt/ concrete interface.

Figure 7-4: R2 Ratios and Asphalt Thicknesses

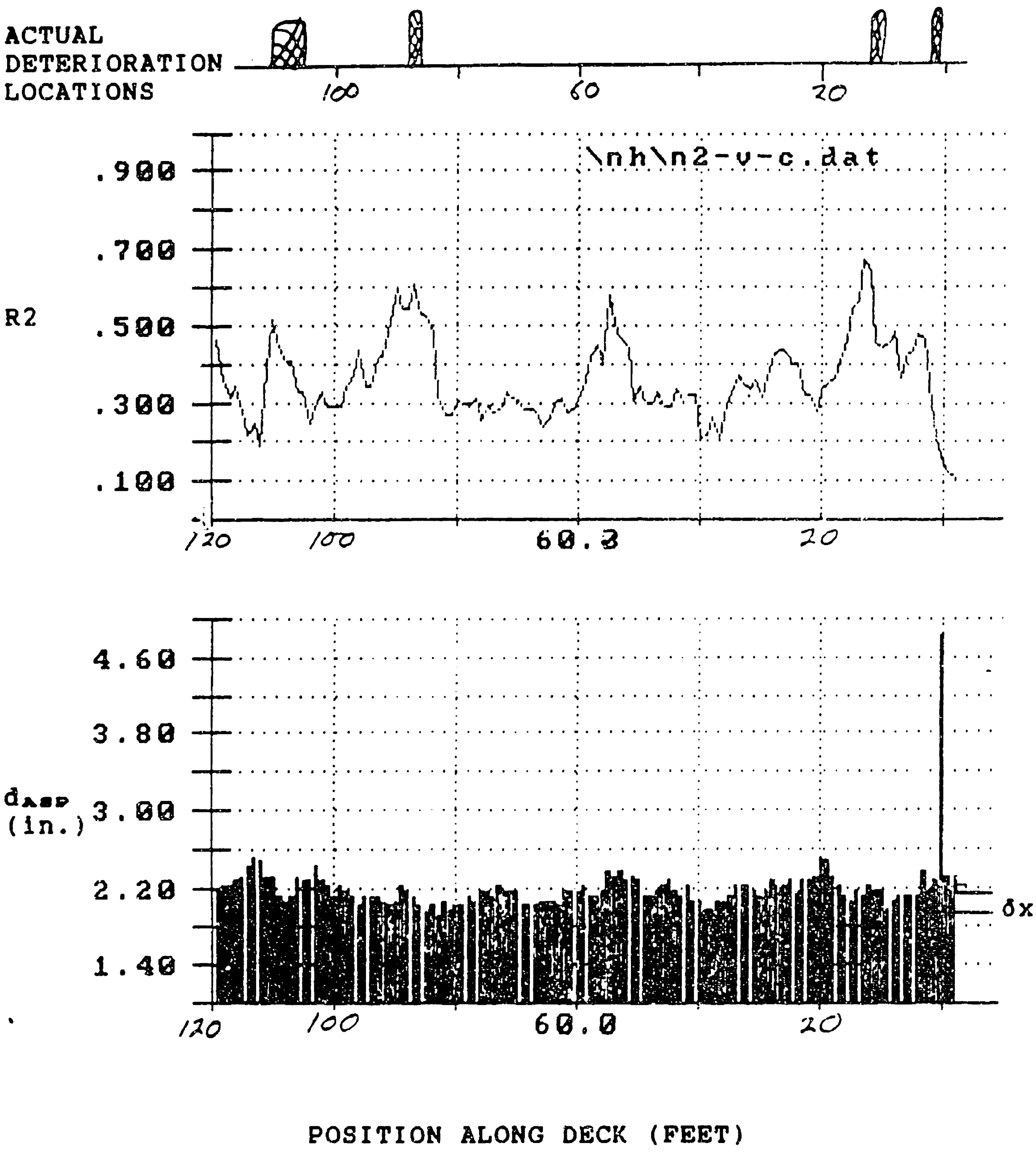
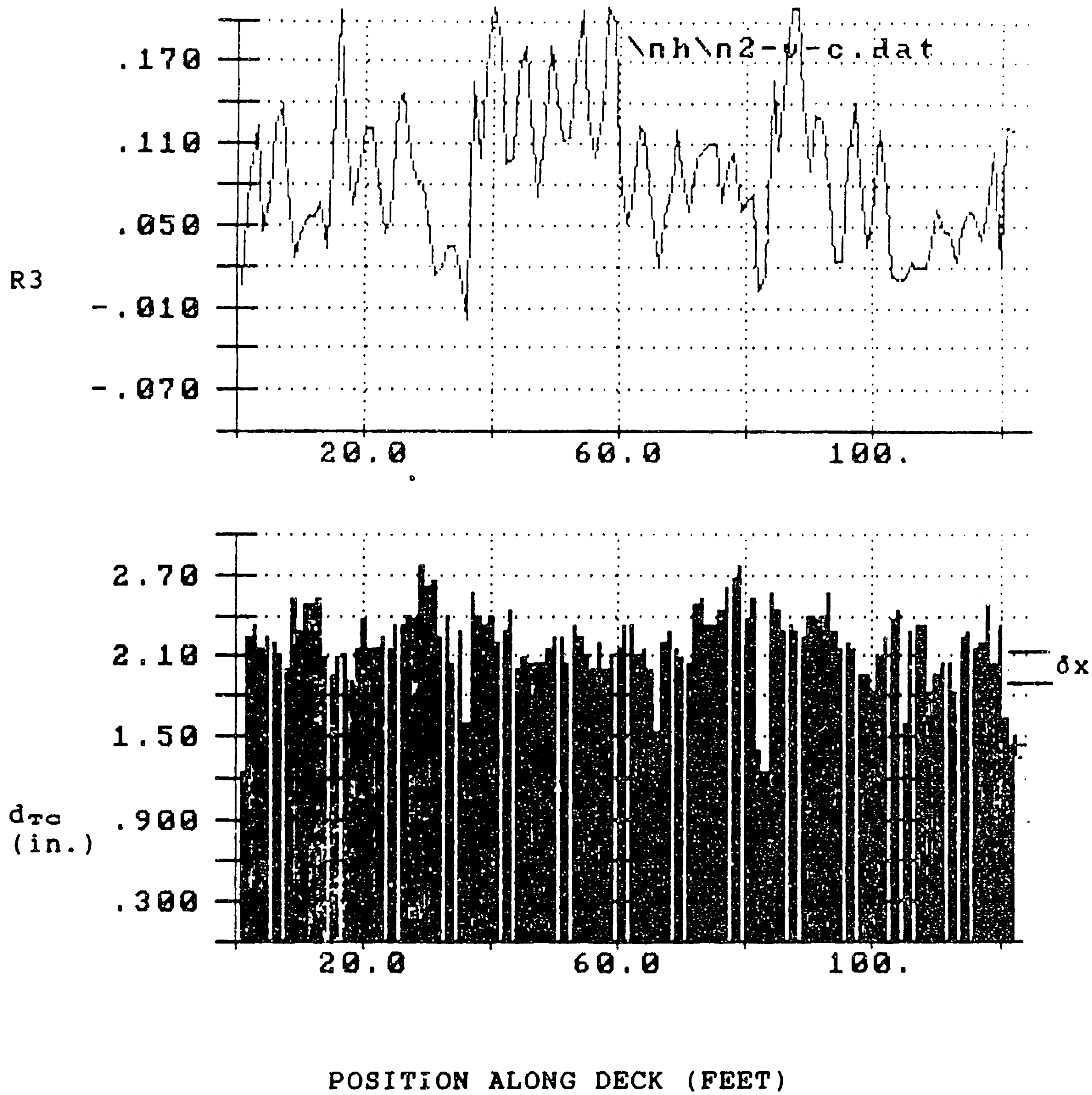


Figure 7-5: R3 Ratios and Top Cover Thicknesses



computed from Equation (6-2):

$$\sqrt{\varepsilon_{ASP}} = \frac{1-A/A_{PLATE}}{1+A/A_{PLATE}}$$

From Figure 6-2,

$$C/A_{PLATE} = t_{12}t_{21}r_{23} = \frac{4\sqrt{\varepsilon_{ASP}}\,(\sqrt{\varepsilon_{ASP}} - \sqrt{\varepsilon_{C}})}{(1 + \sqrt{\varepsilon_{ASP}})\,(\sqrt{\varepsilon_{ASP}} + \sqrt{\varepsilon_{C}})} \qquad (7\text{-}2)$$

This equation can be solved for the dielectric constant of the top cover of concrete,

$$\sqrt{\varepsilon_{C}} = \sqrt{\varepsilon_{ASP}} \left[\frac{1 - \dfrac{C\,(1 + \sqrt{\varepsilon_{ASP}})^2}{A_{PLATE}\,(4\sqrt{\varepsilon_{ASP}})}}{1 + \dfrac{C\,(1 + \sqrt{\varepsilon_{ASP}})^2}{A_{PLATE}\,(4\sqrt{\varepsilon_{ASP}})}} \right] \qquad (7\text{-}3)$$

An attempt to compute more accurate values for asphalt and concrete thicknesses is made by calculating dielectric constants at each location along a deck and using these values in Equations (6-3) and (6-4). A flowchart to describe this algorithm is presented in Figure 7-6. A sample of the output is provided in Figure 7-7. Although this algorithm extends the Ontario analysis by computing asphalt and concrete dielectric constants at each location of the deck, the results do not show strong correlations to actual deck conditions.

Gain adjustment problems with the radar force the final "punky" concrete analysis program of Chapter 8 to be

Figure 7-6: Flowchart of Ratio and Thickness Algorithm Based on "Floating" Dielectric Constants

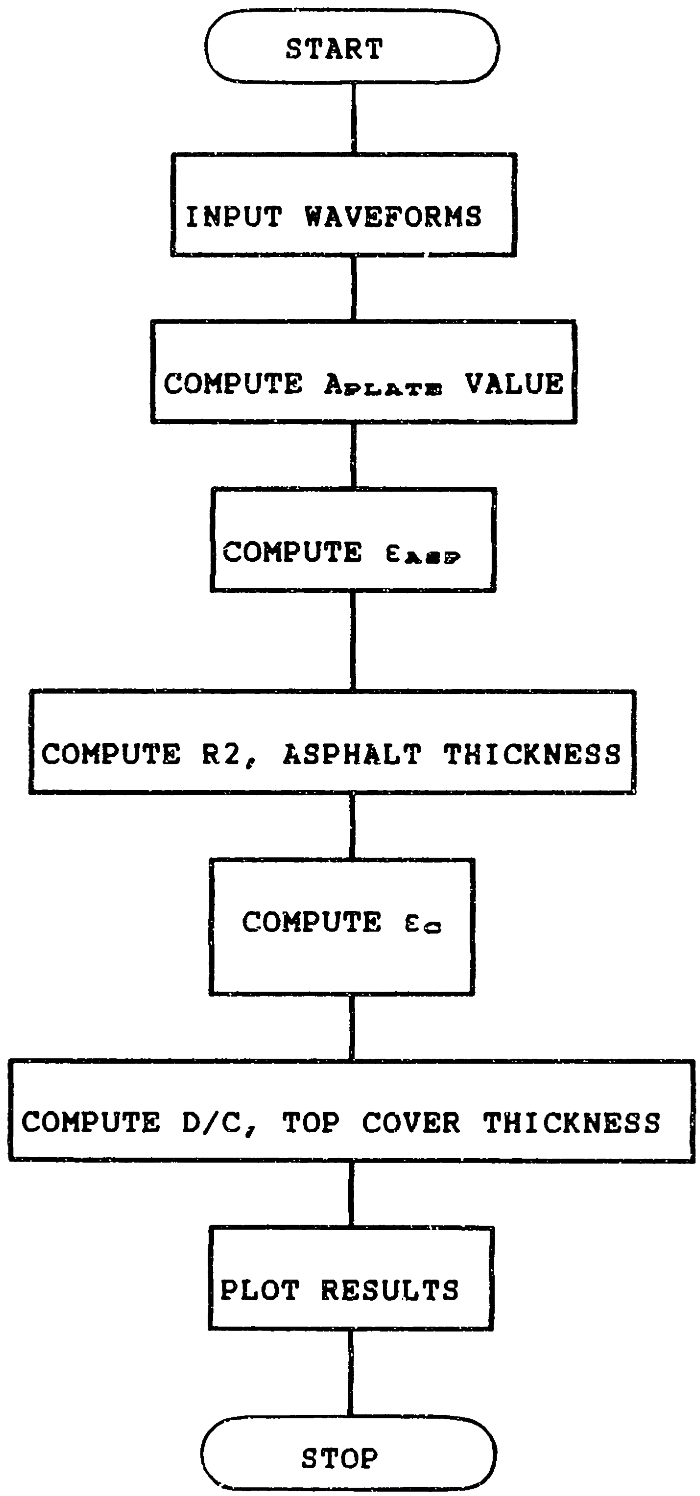
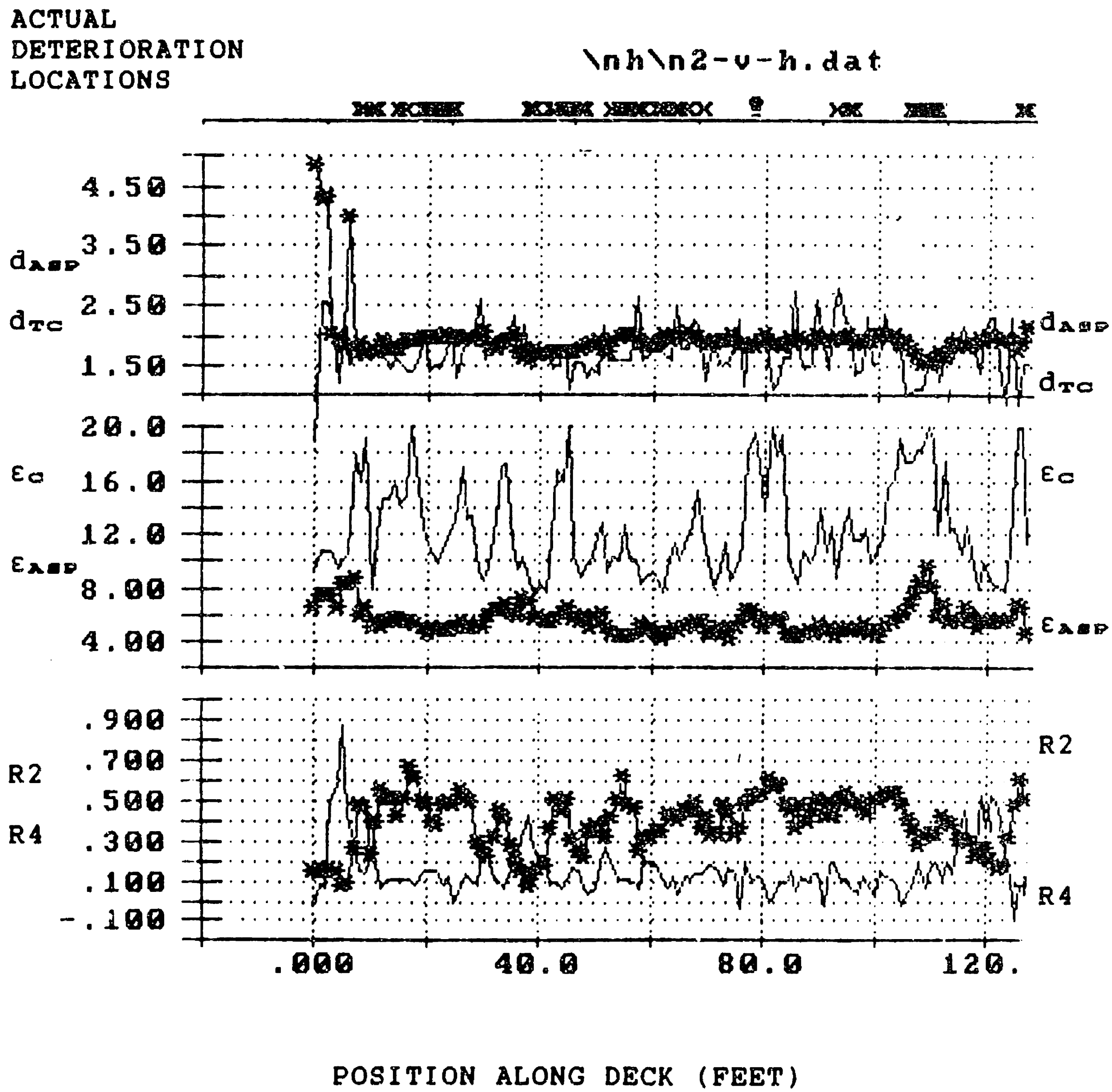


Figure 7-7: Output of Ratio and Thickness Algorithm Based on "Floating" Dielectric Constants



simplified. A problem arose because in order to record the strong metal plate reflections and the weaker reflections from the deck layers, the radar gain must be varied. These gain changes may make radar measurements inaccurate since field tests showed that gain settings on the equipment were occasionally unstable during even constant gain operation. Instead of computing asphalt dielectric constants at each location, core sample data obtained by the University of New Hampshire will be used to estimate a single asphalt dielectric constant for each deck.

Chapter 10 describes a calibration test that may be used to compute the magnitude of the incident radar wave at each data point along a radar pass. Therefore, any gain changes of the radar equipment will be embodied in each measurement of the incident radar wave amplitude and more accurate ε_{ASP} values may be obtained.

7.4 Summary

Area measurements, R3 and R4 ratios do not predict delaminated areas, and, although high R2 values do seem to correlate roughly to areas of "punky" concrete, instrumentation problems make the algorithm presented in the previous section insufficient for a final analysis. Gain changes of the radar may prevent accurate calculation of the metal plate reflection. Thus, asphalt dielectric constants may be inaccurate and ε_{C} calculations, which depend on ε_{ASP}, may also be incorrect. Therefore, the algorithm, while an interesting approach, is insufficient with present radar equipment. The final analysis programs presented in the next chapter will use the radar models of Chapter 6 to derive expressions for the dielectric constant of concrete and radar attenuation from rebar that are not subject to the gain variations that made the algorithm of Section 7.3.3 unsuccessful. Asphalt thickness data from core samples must be incorporated into the algorithms and moisture and chloride content values may be useful in future analyses.

Chapter 8

Selection and Testing of Final Analyses

The information gained from previous studies helped to focus the final analysis toward techniques that could provide meaningful results based on the radar models. The identification of waveform peaks and the accurate measurements of the magnitudes of these peaks are necessary for the development of more advanced analyses. This chapter presents new algorithms developed from previous ratio and thickness analyses in order to further link the behavior of the radar signal to actual deck conditions.

8.1 Time Scale Calibration

The algorithms to detect the time differences between peaks determine the number of radar samples between peaks. Multiplying the number of samples by the time scale factor expresses time differences in nanoseconds. The time difference, T, is used in Equations (6-3) or (6-4) to compute asphalt or top cover thicknesses. Early programs assumed that radar samples are digitized at effective intervals of 0.02 nanoseconds. However, calibration tests performed in the field indicate that the radar equipment may have timing errors as large as ±10%.

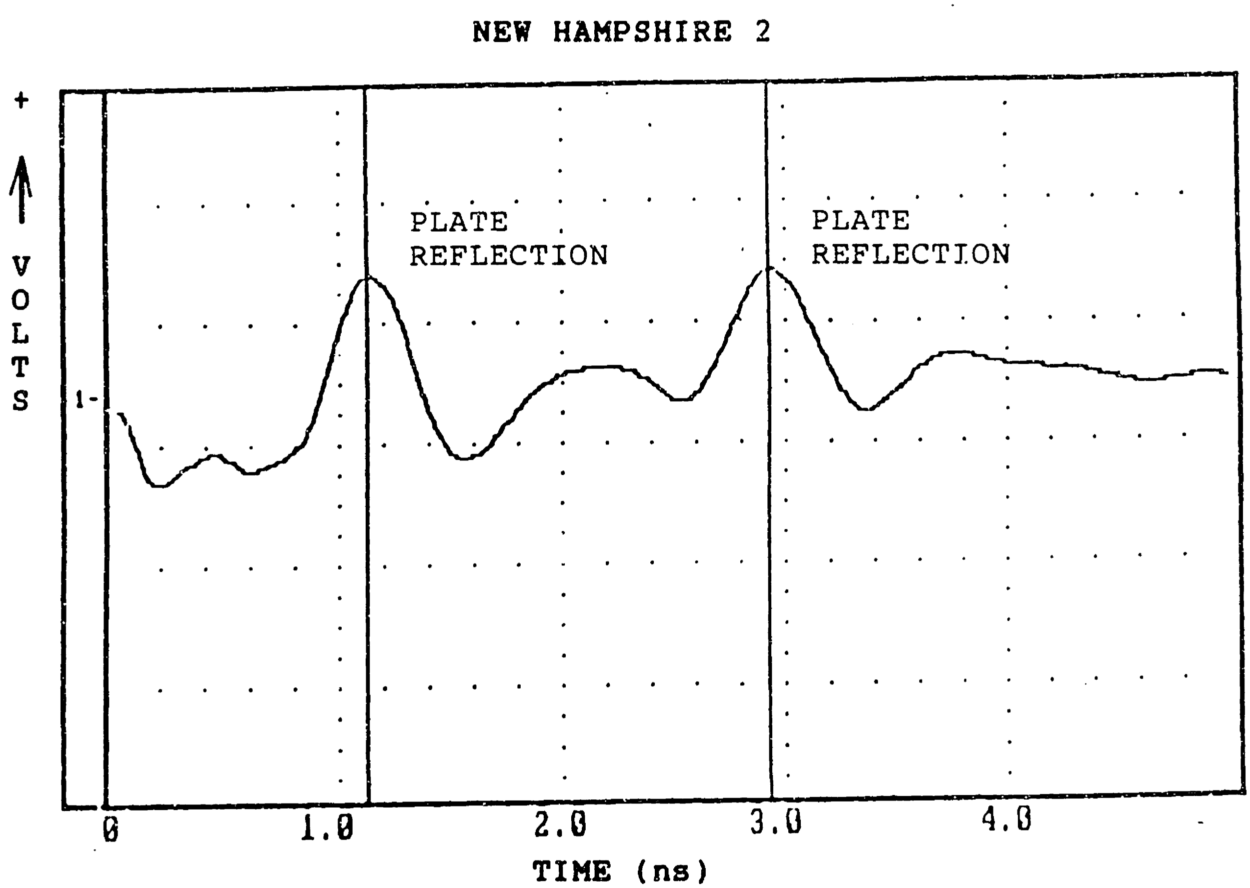
A calibration test that records the radar waveform produced by placing two aluminum plates exactly twelve inches apart was used to determine the appropriate time scale factors. The radar waveform produced in this calibration test is shown in Figure 8-1. The two peaks in this waveform are reflections from the metal plates. Knowledge of the speed of light in air, 11.82 in/ns, and the time difference between the two peaks, measured on a digital oscilloscope, allow for accurate calibration of the time scale factor. With this modification of time scale factors, more accurate asphalt and concrete thicknesses are obtained.

The radar gain calibration test that will be presented in Chapter 10 may also be used to provide time scale factors for each data point along the deck. Thus, with gain and timing factors for each data point along a deck, the accuracy of the algorithms may be further improved.

8.2 Determination of Asphalt Dielectric Constants

Other methods to determine the dielectric constant of asphalt have a theoretical basis, but, as described in Section 7.3.3, these "floating" dielectric values are not reliable due mainly to the gain instability of the radar equipment. However, the bridge deck core and dust samples conducted by the University of New Hampshire provide asphalt thickness measurements that can be used in conjunction with radar waveforms to predict average and estimated ε_{ASP} values. U.N.H.'s tests provide actual asphalt thicknesses and the radar waveforms provide the time differences between peaks A and C that are used to solve Equation (6-3) for the dielectric constant of asphalt.

Figure 8-1: Calibration Test



For each core and dust sample on nine decks the dielectric constant of asphalt was computed using Equation (6-3). Average dielectric values were then calculated and estimates of a single dielectric constant of asphalt for each deck were made. Since ε_{ASP} is typically between 5.0 and 5.5, the estimates are biased toward these values. The core and dust sample data and results of ε_{ASP} calculations are shown in Table 8-1.

8.3 Dielectric Constant of the Top Cover of Concrete

A method of predicting locations of "punky" concrete based on an analysis of changes in the dielectric constant of the concrete can now be attempted using the new estimated ε_{ASP} values from Table 8-1. The physical model of the reflections in a bridge deck serves as a basis for the development of an expression describing the behavior of ε_{C}. Rewriting Equation (6-5),

$$\sqrt{\varepsilon_{C}} = \sqrt{\varepsilon_{ASP}} \left[\frac{\dfrac{4\sqrt{\varepsilon_{ASP}}}{1-\varepsilon_{ASP}} - R2}{\dfrac{4\sqrt{\varepsilon_{ASP}}}{1-\varepsilon_{ASP}} + R2} \right] \tag{8-1}$$

the dielectric constant of the top cover of concrete can be computed from the asphalt dielectric constant and the R2 ratio. Since the dielectric constant of concrete increases as the moisture content increases (Equation 6-6), high ε_{C}

Table 8-1: Calculation of ε_{ASP} Values

DECK	LOC	ASPH (d)(in)	CALIB (ns/pt.)	Δt (pts)	Δt (ns)	$v=2d/\Delta t$ (in/ns)	$\varepsilon_{ASP}=(c/v)^2$	Av ε_{ASP}	Est ε_{ASP}
V1	D-69	2	.018	45	.81	4.94	5.9	6.6	6.0
	D-70	2.25		46	.828	5.43	4.9		
	D-71	2		48	.864	4.63	6.7		
	F-89	2		55	.99	4.04	8.8		
N2	**A-54**	2	.022	43	.946	4.23	8.1	7.6	5.5
	B-54	2		40	.88	4.55	7.0		
M3	C-41	3	.021	46	.966	6.21	3.7	4.0	5.0
	C-49	3		52	1.092	5.49	4.8		
	C-50	3		52	1.092	5.49	4.8		
	C-51	3		51	1.071	5.60	4.6		
	C-99	4		49	1.029	7.77	2.4		
	C-101	3		50	1.05	5.71	4.4		
	C-103	3		51	1.071	5.60	4.6		
	C-105	3.5		48	1.008	6.94	3.0		
	C-107	3.25		47	.987	6.59	3.3		
	C-129	3.5		48	1.008	6.94	3.0		
	C-131	3		49	1.029	5.83	4.2		
	C-132	3		49	1.029	5.83	4.2		
	C-133	3		50	1.05	5.71	4.4		
	I-105	3.25		50	1.05	6.19	3.8		
	I-111	3		55	1.155	5.19	5.3		
R1	**B-22**	2.25	.02	43	.86	5.23	5.3	6.6	6.4
	B-60	2.5		53	1.06	4.72	6.5		
	D-5	2.5		47	.94	5.32	5.1		
	D-8	2		52	1.04	3.85	9.7		
	D-12	3		59	1.18	5.08	5.6		
	D-63	2.25		49	.98	4.59	7.5		
M1	H-92	3	.019	63	1.197	5.01	5.7	5.7	5.5
M11	**E-16**	3.5	.021	73	1.533	4.56	6.9	7.1	6.0
	E-26	3.5		72	1.512	4.63	6.7		
	F-16	3.5		77	1.617	4.33	7.7		
NH1	**G-63**	3.75	.022	72	1.584	4.73	6.4	6.4	6.4
R2	**F-45**	3.5	.021	71	1.491	4.69	6.5	5.4	5.5
	H-3	4		66	1.386	5.77	4.3		
R3	**B-82**	5	.02	75	1.5	6.67	3.2	3.8	5.0
	B-126	4		70	1.4	5.71	4.4		

BOLD = asphalt thickness values obtained from core samples

N3	calib=.021	A/Apl=.33	ε_{ASP}=3.9	Est.ε_{ASP}=5.0
V2	calib=.022	A/Apl=.4	ε_{ASP}=5.4	Est.ε_{ASP}=5.4
M4	calib=.02	A/Apl=.4	ε_{ASP}=5.4	Est.ε_{ASP}=5.4

values may indicate the presence of moisture-laden "punky" concrete. Figure 8-2 is a flowchart of the algorithm that computes ε_a from Equation 8-1. Samples of the output and plots of actual "punky" areas of decks Maine 1 and New Hampshire 2 are displayed in Figures 8-3, 8-4, 8-5 and 8-6. An observation of these plots suggests a correlation between areas of high ε_a values and actual "punky" areas, particularly on Maine 1 passes b through g at the ninety foot marker and at many locations along passes f, g and h. The plots for New Hampshire 2 suggest a correlation around the 10, 50 and 90 foot markers on passes c through i. Chapter 9 presents the results of a computerized search for locations of high ε_a values that is used to provide estimates of the total percentage of the deck area that can be classified as "punky".

8.4 Calculation of Top Cover Thickness

With the new algorithm for determining the dielectric constant of concrete and more accurate time scale factors, the concrete top cover thickness can also be recalculated. Top cover thicknesses provide important information to bridge inspectors, since low top cover values are often indicators of potential concrete deterioration. The top cover measurements can also be used to estimate the quantity and cost of concrete removal. Figure 8-7 shows a flowchart of the program to compute top cover thickness and Figure 8-8 displays a sample of the output. No studies were performed

Figure 8-2: Flowchart of the ε_c Algorithm

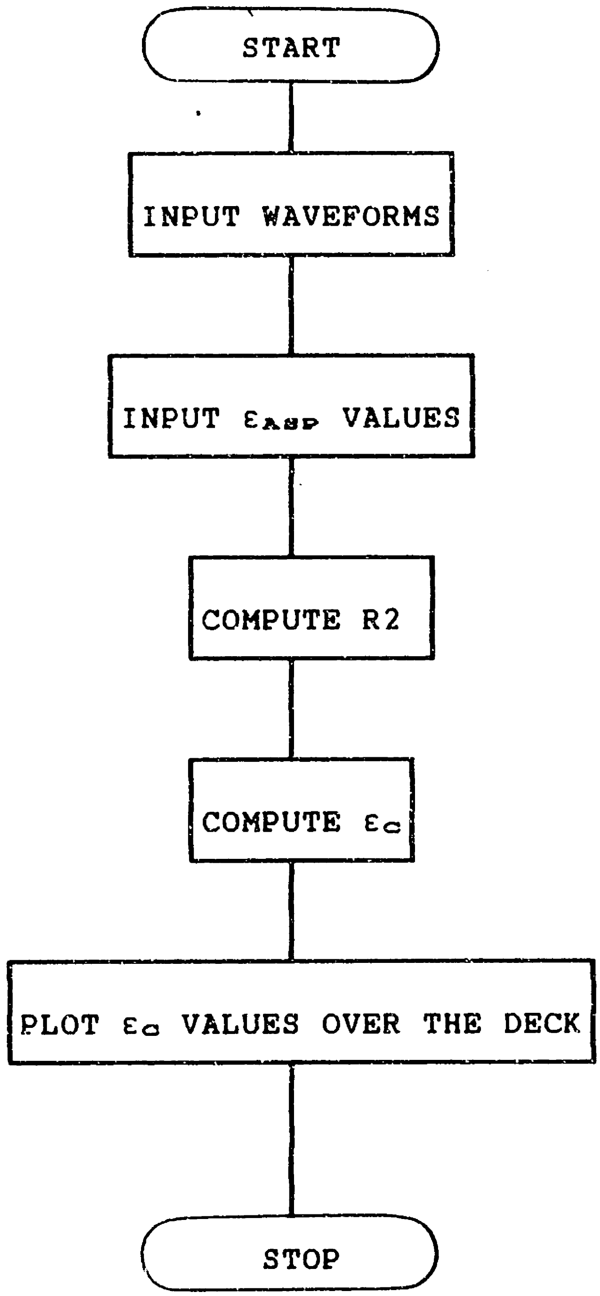
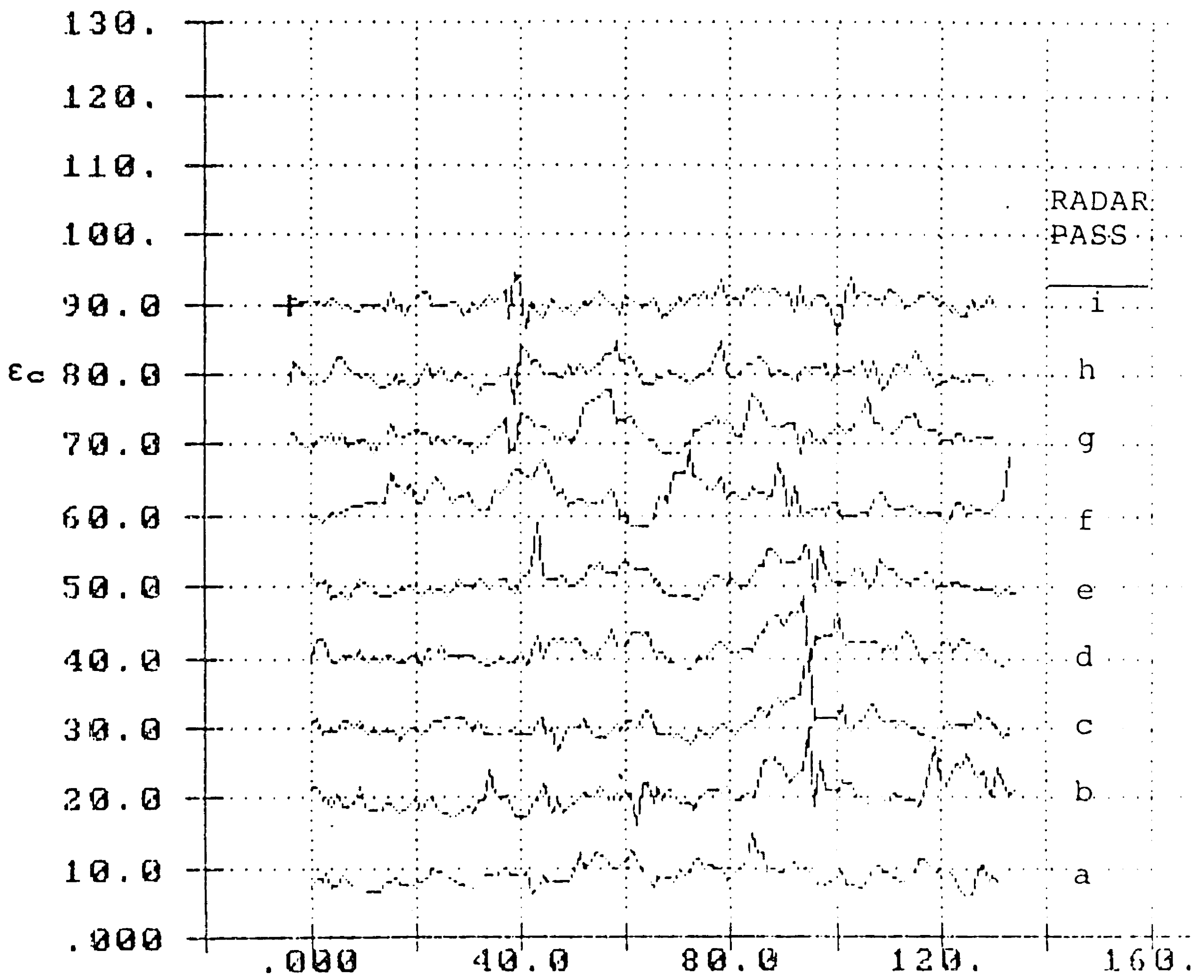
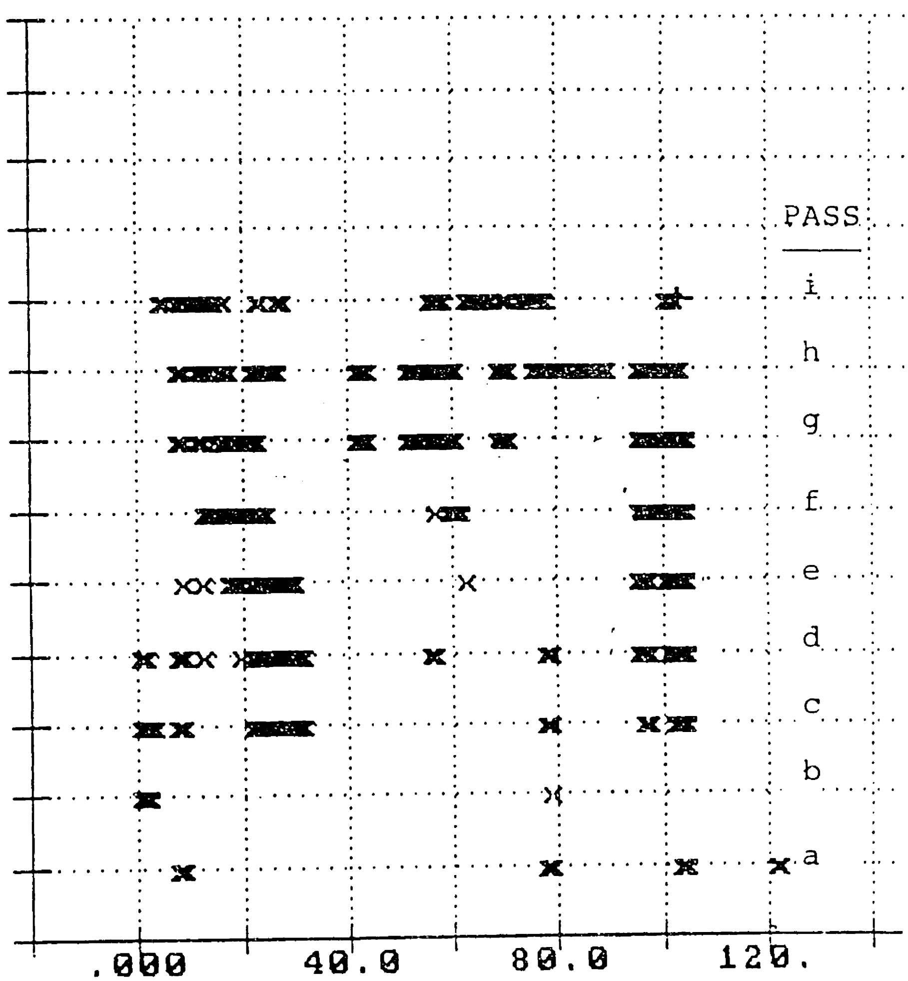


Figure 8-3: ε_c Values for Deck Maine 1



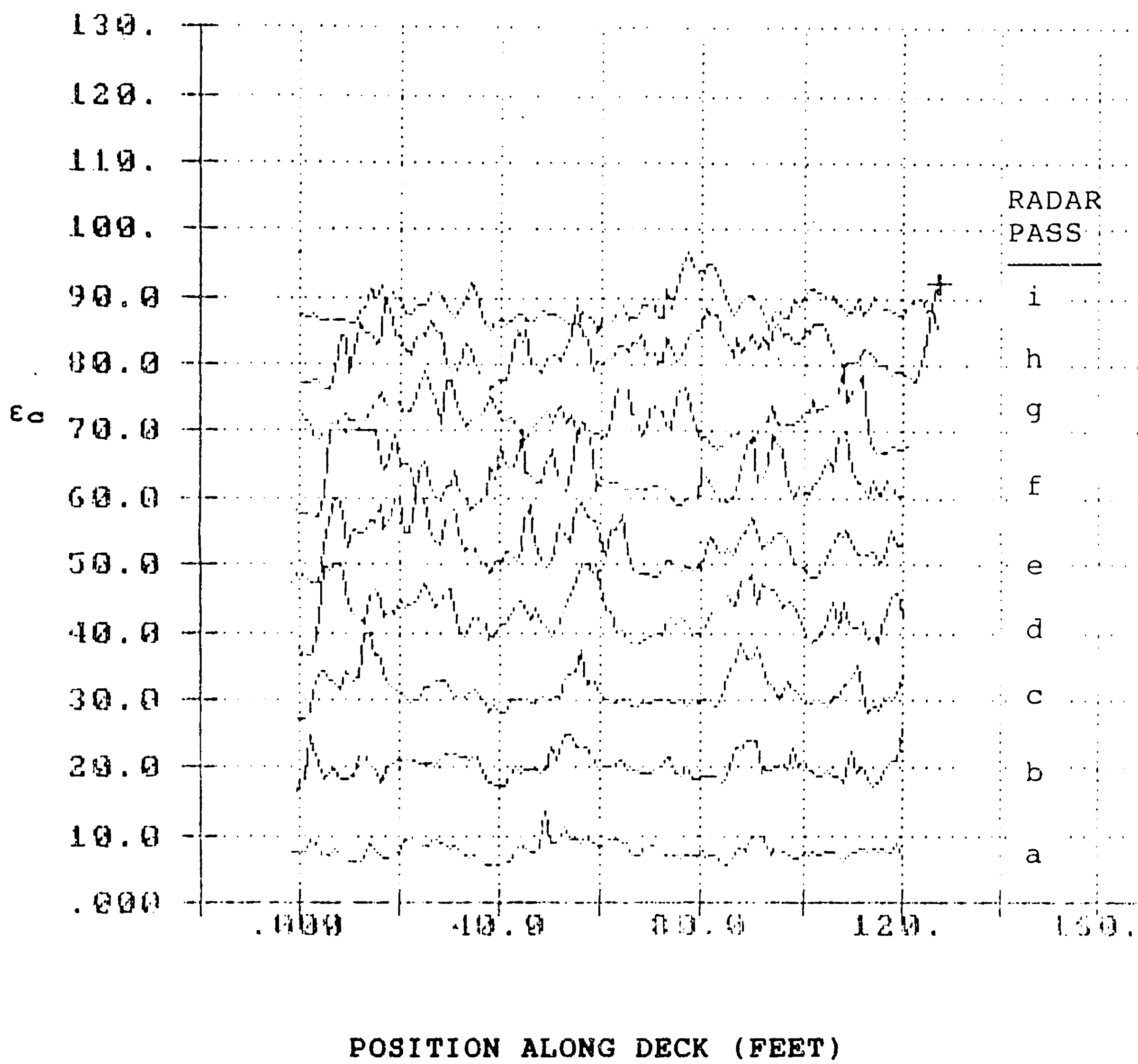
Note: ε_c values are plotted one pass over another, in intervals of 10. To read ε_c values for pass b, subtract 10 from ordinate value. To read values for pass c, subtract 20, etc.

Figure 8-4: Actual "Punky" Areas for Deck Maine 1



POSITION ALONG DECK (FEET)

Figure 8-5: ε_c Values for Deck New Hampshire 2



Note: ε_c values are plotted one pass over another, in intervals of 10. To read ε_c values for pass b, subtract 10 from ordinate value. To read values for pass c, subtract 20, etc.

Figure 8-6: Actual "Punky" Areas for Deck New Hampshire 2

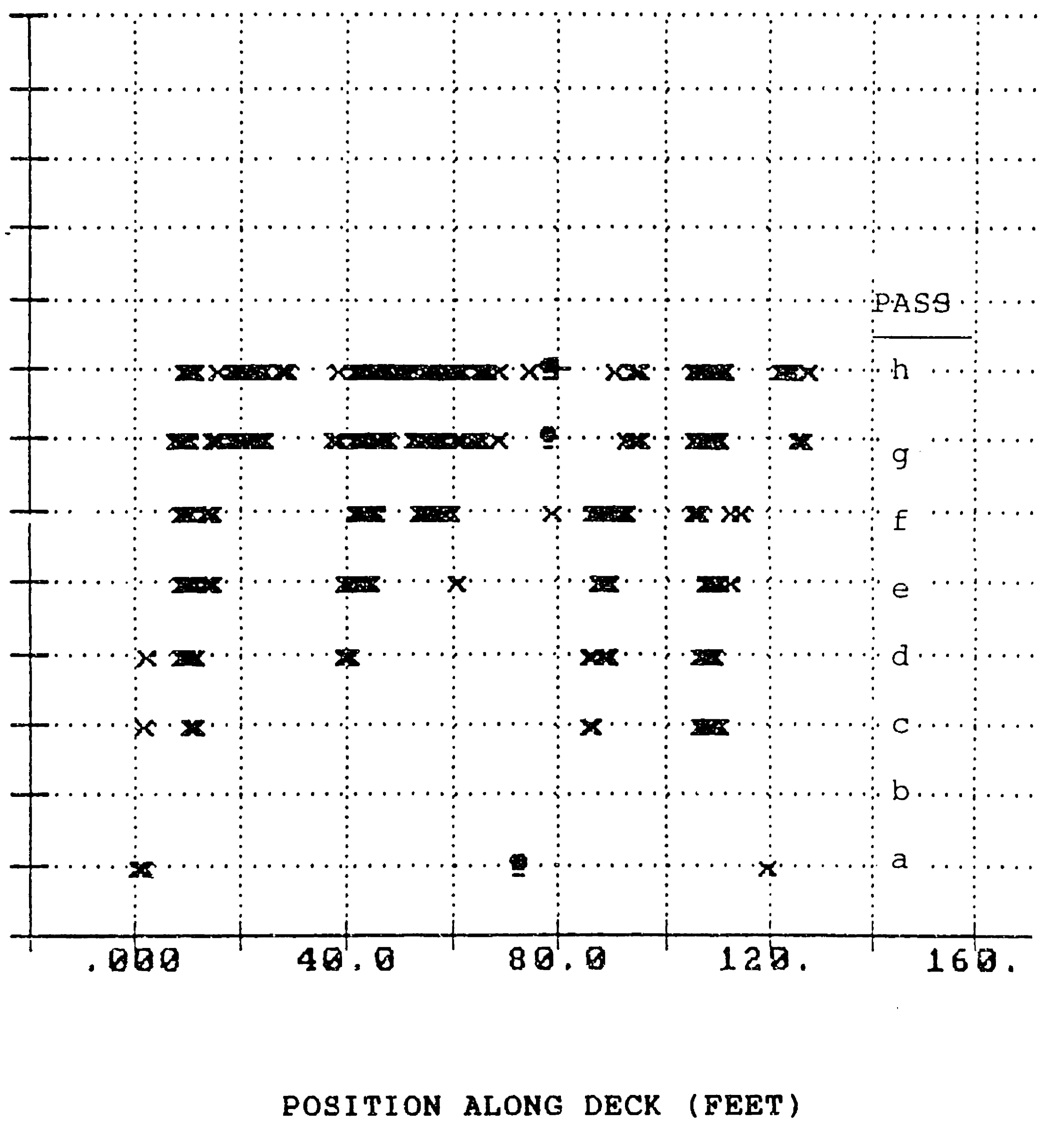


Figure 8-7: Flowchart of Top Cover Algorithm

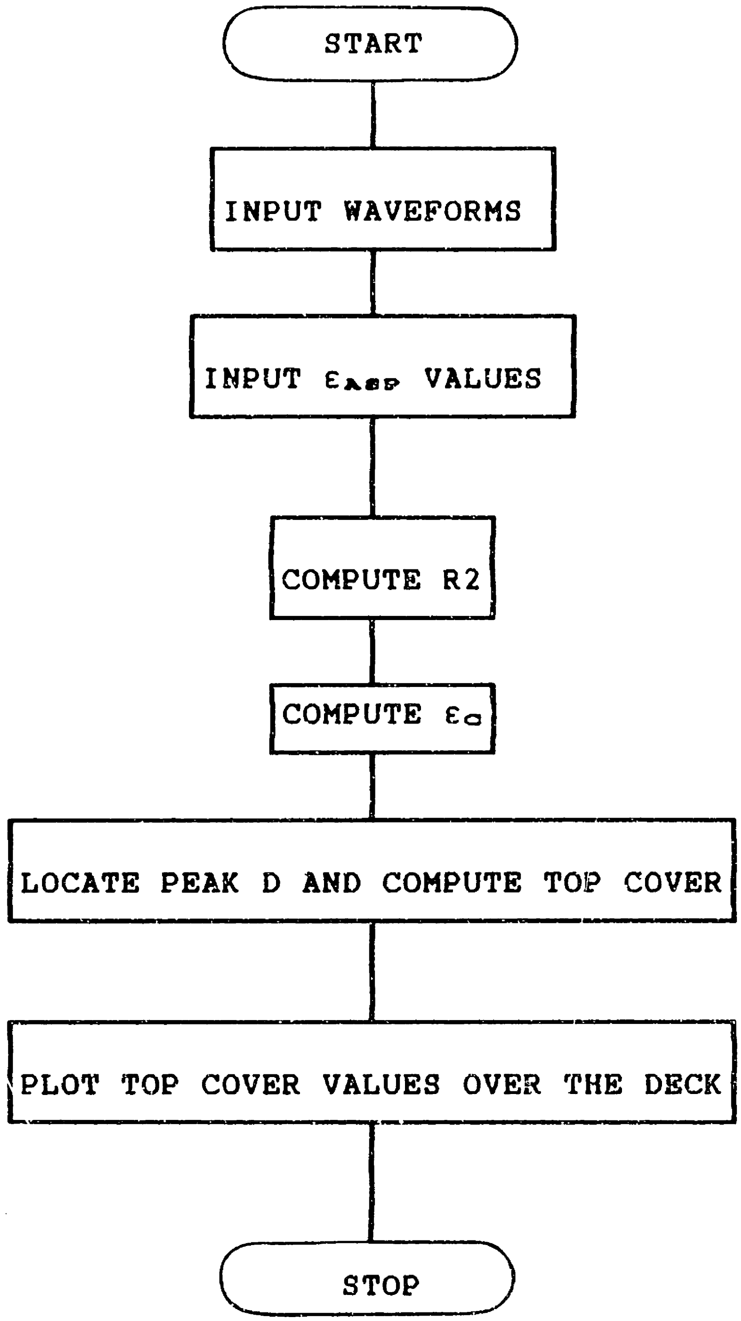
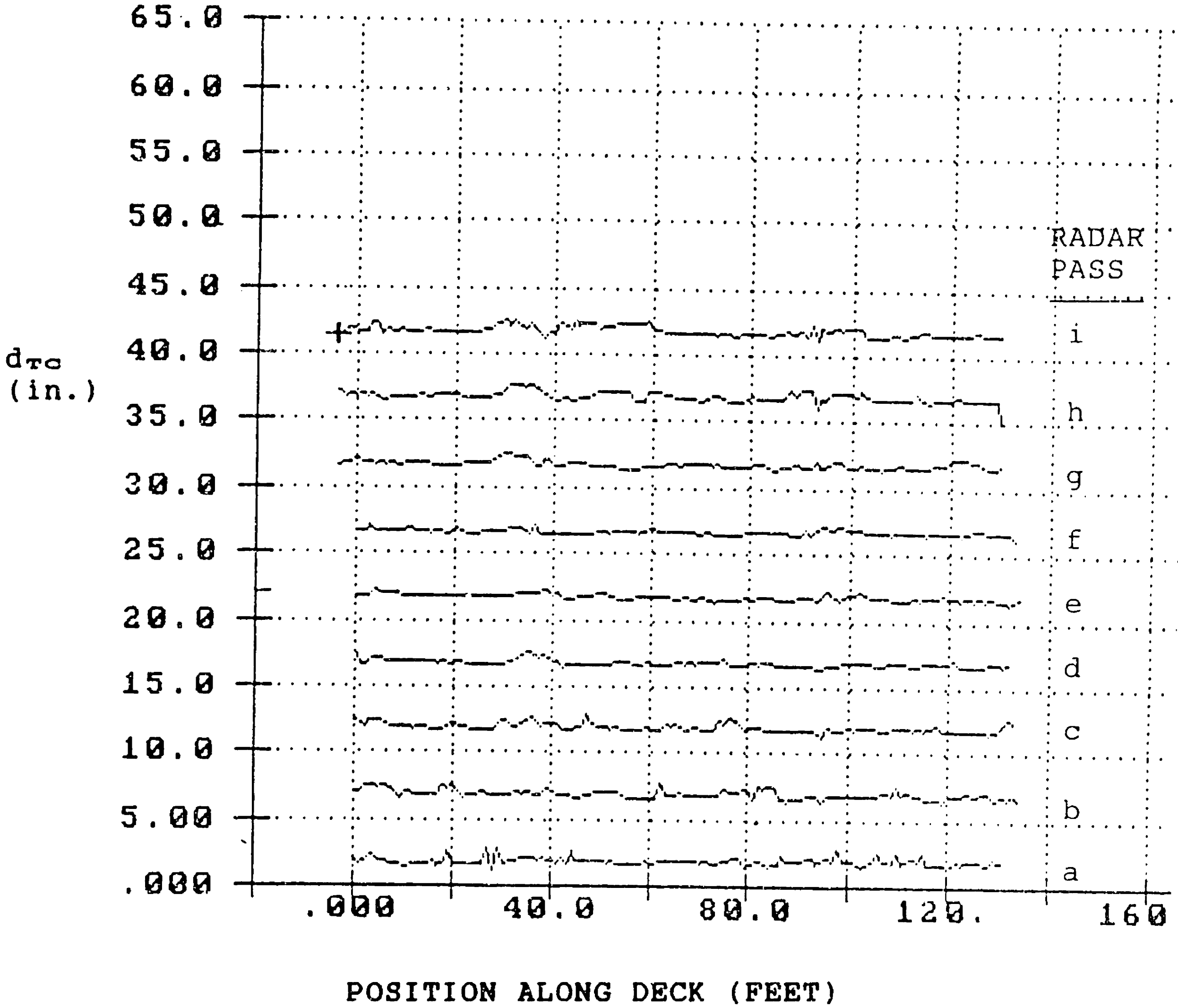


Figure 8-8: Top Cover Thicknesses



Note: d_{TC} values are plotted one pass over another, in intervals of 5. To read d_{TC} values for pass b, subtract 5 from ordinate value. To read values for pass c, subtract 10, etc.

to correlate top cover values to areas of deterioration or delamination, but further research in this area may be useful. This research should examine the effects of top cover thickness on the rate of cracking and rebar corrosion. Deck core samples may also be used to verify top cover measurements and delamination estimates.

8.5 Analysis of Rebar Reflections

Expressions have also been derived to compute rebar reflections in order to identify corrosion induced delaminations. Thin vertical cracks in the asphalt and concrete and failure of the waterproof membrane allow water and chlorides from deicing salts to penetrate the deck and reach the rebar. Concrete with a high chloride content can produce rebar corrosion and delaminations, and an analysis of the reflections from cylindrical rebars may help to identify rebar corrosion. From Maser's derivation,[15] the reflection resulting from cylindrical rebar is proportional to

$$1/2d_{TC}\ [\ K - \ln D/A\ ] \qquad (8-2)$$

where,

d_{TC} = top cover thickness
K = -1.46
D = concrete/rebar reflection
A = air/asphalt reflection

Since we expect rebar corrosion to affect the rebar

[15] Kenneth Maser and Udaya Halabe, "Assessment of In-Situ Conditions Using Wave Propagation Techniques" (Massachusetts Institute of Technology Report to the U.S. Army Research Office, 1987), pp. 3-5.

reflection, we should see a change in the value of $(1/d_{TC})(-\ln D/A)$ at delaminated locations along a deck due to a change in the magnitude of peak D. Figure 8-9 is a flowchart of a program to compute this measure of reflection and Figure 8-10 provides an example of the output.

Chloride, moisture content, and $(1/d_{TC})(-\ln D/A)$ values for locations along several decks are provided in Table 8-2. A link between delaminated areas and rebar reflection values has not been discovered from this limited data set; however, the approach, derived from a physical model of the deck and electromagnetic theory, remains interesting and worthy of further study. With a larger data set, more statistical analyses can be applied and results may prove a correlation to actual delaminated areas. In this way, the effectiveness of radar as an all-purpose inspection tool can be improved.

8.6 Summary

The ε_C algorithm proposed in this chapter, derived directly from the reflection and transmission coefficient models of Chapter 6, uses timing calibration factors and bridge deck core sample data to obtain best estimates of ε_{AMP}, and, as will be shown in the next chapter, provides more meaningful "punky" concrete estimates than any of the other algorithms presented in this thesis. However, the attempt to locate delaminations by analyzing the rebar reflections has been unsuccessful, even though this latest algorithm is also derived from the laws of electromagnetics.

Figure 8-9: Flowchart of Rebar Reflection Algorithm

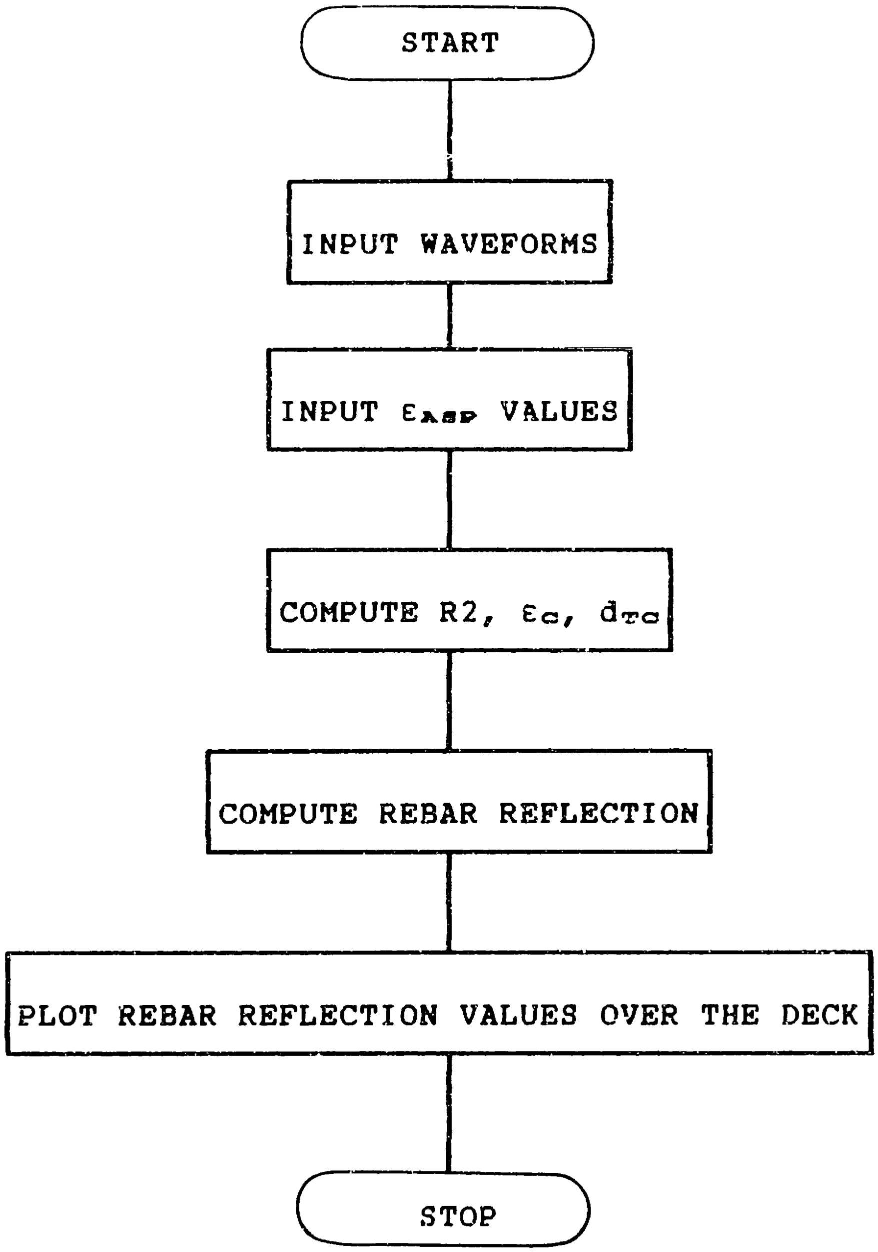
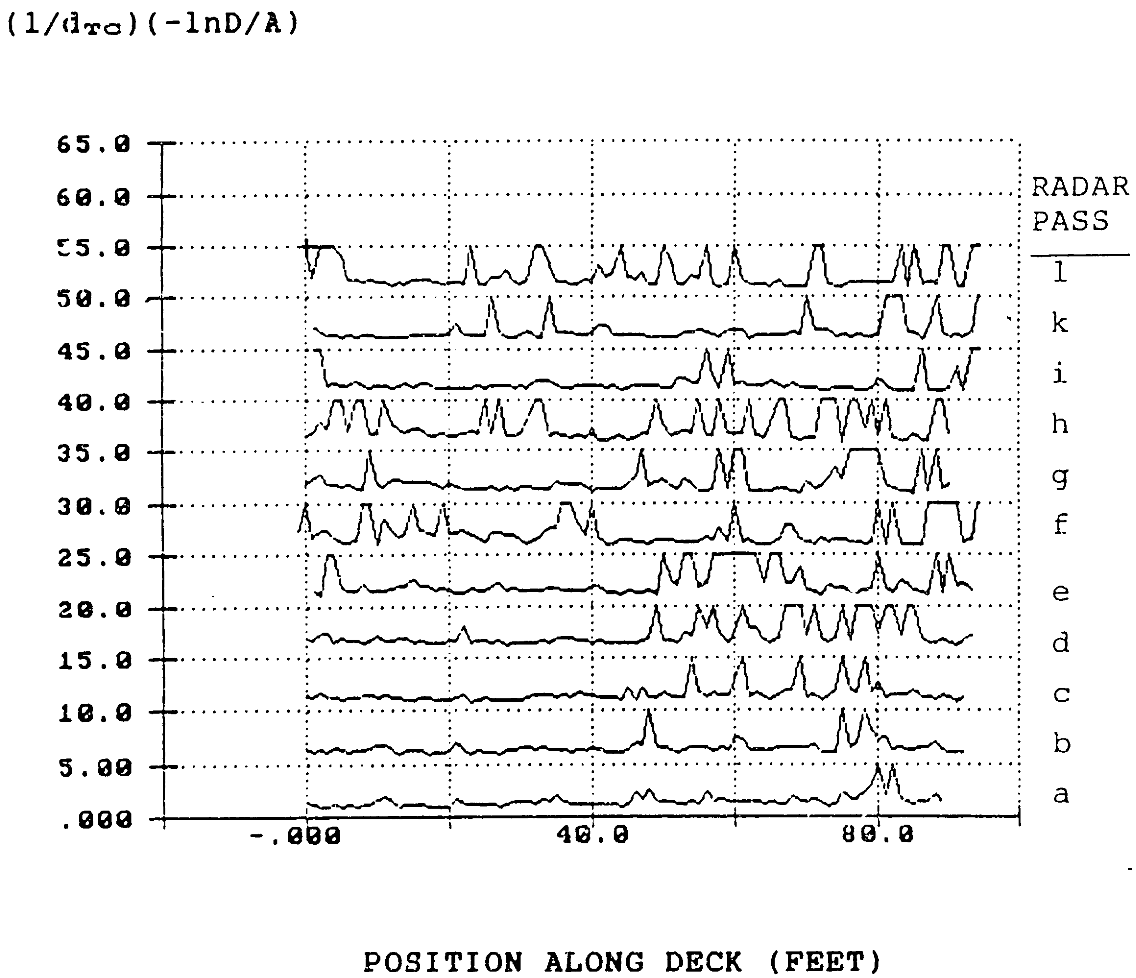


Figure 8-10: Rebar Reflection Values

RHODE ISLAND 1



Note: Reflection values are plotted one pass over another, in intervals of 5. To read values for pass b, subtract 5 from ordinate value. To read values for pass c, subtract 10, etc.

Table 8-2: Chloride, Moisture Content and Rebar Reflections

BRIDGE	LOCATION	AV. Cl- (% by wt.)	AV. MC (% by wt.)	RADAR SIGNATURE ($-1/d_{TC}$ lnD/A)
V1	D-53	0.07	1.7	2
V1	D-69	0.034	3.3	5
V1	D-70	0.022	3.0	5
V1	D-71	0.052	3.3	5
V1	F-89	0.233	5.8	4
NH2	C-54	0.02	3.91	1.5
NH2	E-116	0.013	3.96	2.5
NH2	F-13	0.16	2.96	2
NH2	F-34	0.09	3.16	5
NH2	H-109	0.26	8.34	1.5
M3	C-41	0.006	0.94	2
M3	C-49	0.094	3.4	2
M3	C-50	0.063	3.36	1.75
M3	C-51	0.044	5.20	1.75
M3	C-99	0.19	2.44	1.5
M3	C-101	0.001	1.31	1.25
M3	C-103	0.0057	3.65	1.25
M3	C-105	0.020	3.26	1.5
M3	C-107	0.080	3.58	2
M3	C-129	0.080	6.56	2.5
M3	C-131	0.062	7.41	1.5
M3	C-132	0.062	7.46	1.25
M3	C-133	0.064	7.54	1.5
M3	I-105	0.023	1.84	2
M3	I-111	0.004	0.80	1
M3	I-119	0.005	1.49	0.75
RI1	D-5	0.14	2.55	1.5
RI1	D-8	0.136	3.7	1.5
RI1	D-12	0.08	1.7	2
M1	D-231	0.15	1.3	4
M1	G-165	0.18	1.0	1
M1	H-93	0.15	3.6	2
M1	H-170	0.19	2.0	5
Mi1	F-16	0.17	3.6	2.5
Mi1	F-20	0.12	2.2	3.5
Mi1	F-70	0.037	0.6	2

Therefore, radar has not been an effective tool for locating delaminations. The gain and timing problems with the radar that have been described in Chapter 7 and in this chapter may contribute to radar's inability to locate the delaminations and may also explain errors in "punky" concrete detection and thickness calculations.

Chapter 9

Results and Conclusions

9.1 Introduction

The moisture content data obtained from core samples of several decks, and the output from the ε_c and R2 algorithms is compared to the theoretical relationships between moisture, ε_c and R2, derived in Chapter 6. A basic regression shows that ε_c and R2 are useful techniques for predicting the moisture content of concrete. The output from the ε_c program of Chapter 8 has been analyzed to produce measurements of deck deterioration and maps of "punky" concrete locations. Although field and laboratory experiments have shown that radar is not an effective tool for locating thin, air-filled delaminations, other non-destructive testing methods, such as infrared thermography, may be used for locating delaminations.

This thesis concludes that by combining radar predictions of "punky" concrete areas with the results of infrared thermography surveys, the total bridge deck deterioration as a percent of bridge deck area can be estimated to within five percent of actual deterioration. The analysis of ε_c and R2 versus moisture content provides a theoretical basis for prediction of "punky" concrete from radar reflections, and the ε_c algorithm, which can be modified for differences in the dielectric constant of asphalt, computes the dielectric permittivity of the concrete over entire decks so that high moisture areas can be identified as "punky".

This chapter presents deck deterioration maps for four New England bridges that have been analyzed with radar, infrared thermography, visual underside surveys. These decks were repaired by the state transportation departments and actual deck deterioration maps were produced as the construction was performed. These maps are used for the comparison with radar and infrared predictions of deterioration.

9.2 ε_a and R2 Versus Moisture Content

Plots of calculated ε_a and R2 values versus moisture content for six bridge decks, Figures 9-1 and 9-2, are compared to the theoretical relationships of ε_a and R2 versus moisture content, Figures 6-3 and 6-4. The results of straight line regressions of ε_a and R2 versus moisture content are shown in Tables 9-1 and 9-2. Figures 9-3 and 9-4 are the linear plots of ε_a and R2 versus moisture content that are obtained from these regressions. The theoretical relationships between these variables are also displayed in these graphs. The similarity between the experimental and theoretical trend lines suggests that radar can be used to predict moisture content of concrete and this information can be used in estimating the condition of decks.

Figure 9-1: ε_o Versus Moisture Content (Experimental)

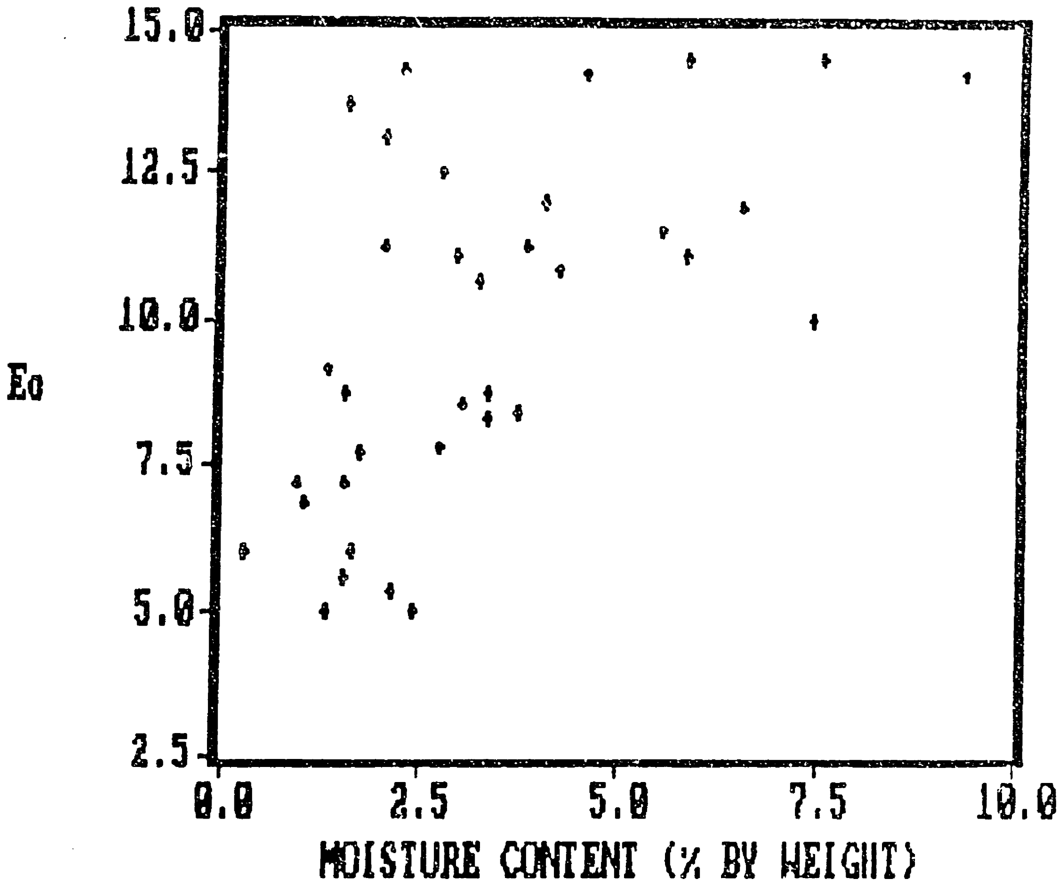


Figure 9-2: R2 Versus Moisture Content (Experimental)

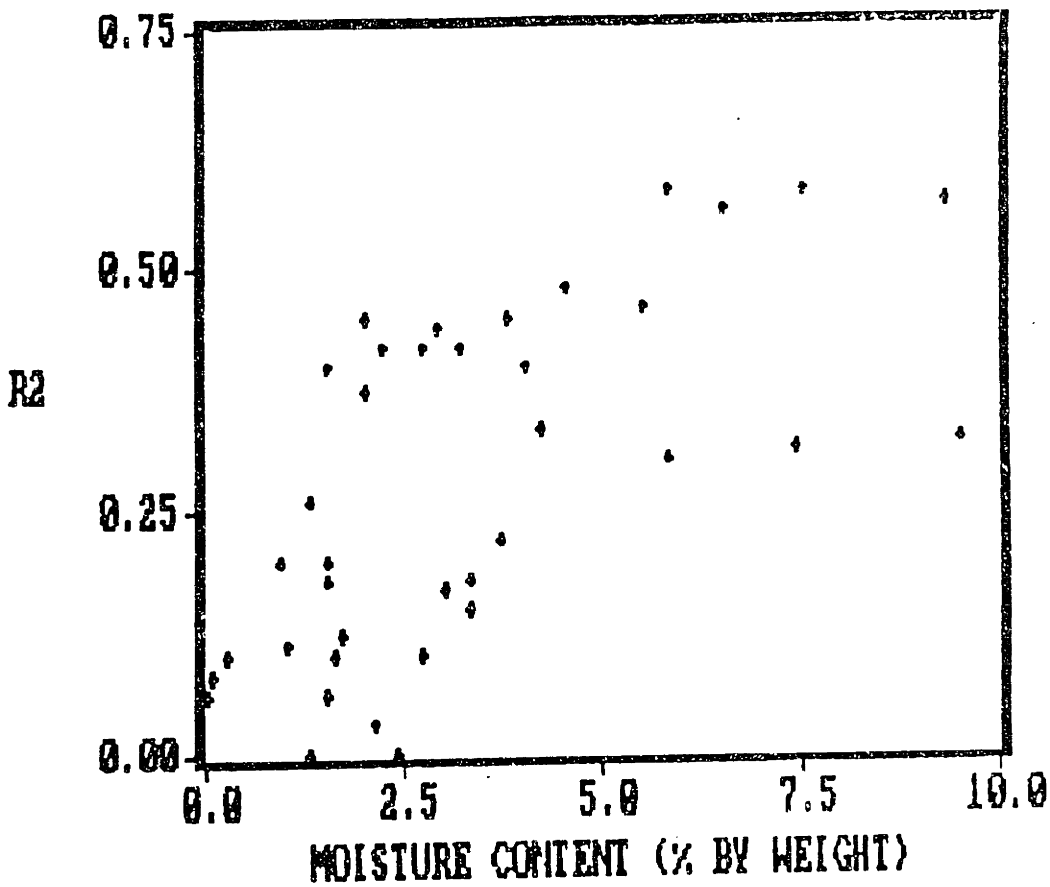


Table 9-1: Regression of ε_a Versus Moisture Content

LS // Dependent Variable is ECB
Date: 1-15-1989 / Time: 0:55
SMPL range: 1 - 35
Number of observations: 35

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	7.0911155	0.7662603	9.2541857	0.000
MCB	0.8415543	0.1976552	4.2576889	0.000

R-squared	0.354560	Mean of dependent var	9.828571
Adjusted R-squared	0.335001	S.D. of dependent var	3.024272
S.E. of regression	2.466217	Sum of squared resid	200.7134
Durbin-Watson stat	1.205342	F-statistic	18.12791
Log likelihood	-80.22712		

Table 9-2: Regression of R2 Versus Moisture Content

```
LS // Dependent Variable is R2A
Date: 1-15-1989 / Time: 0:57
SMPL range:     1  -    38
Number of observations: 38
```

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	0.1261616	0.0382460	3.2986858	0.002
MCA	0.0468794	0.0094971	4.9361985	0.000

R-squared	0.403638	Mean of dependent var	0.278421
Adjusted R-squared	0.387073	S.D. of dependent var	0.178045
S.E. of regression	0.139391	Sum of squared resid	0.699476
Durbin-Watson stat	1.229581	F-statistic	24.36606
Log likelihood	21.98553		

Figure 9-3: ε_o Versus Moisture Content (Theoretical and Regression Line of Experimental Data)

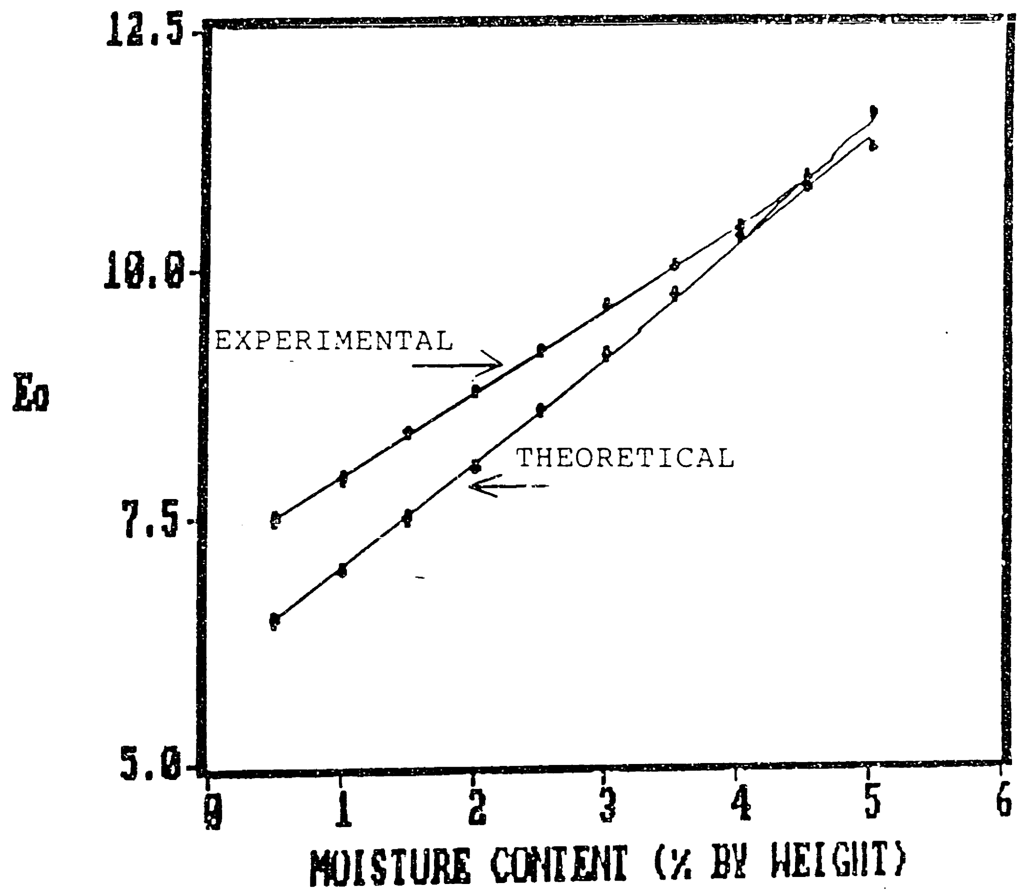
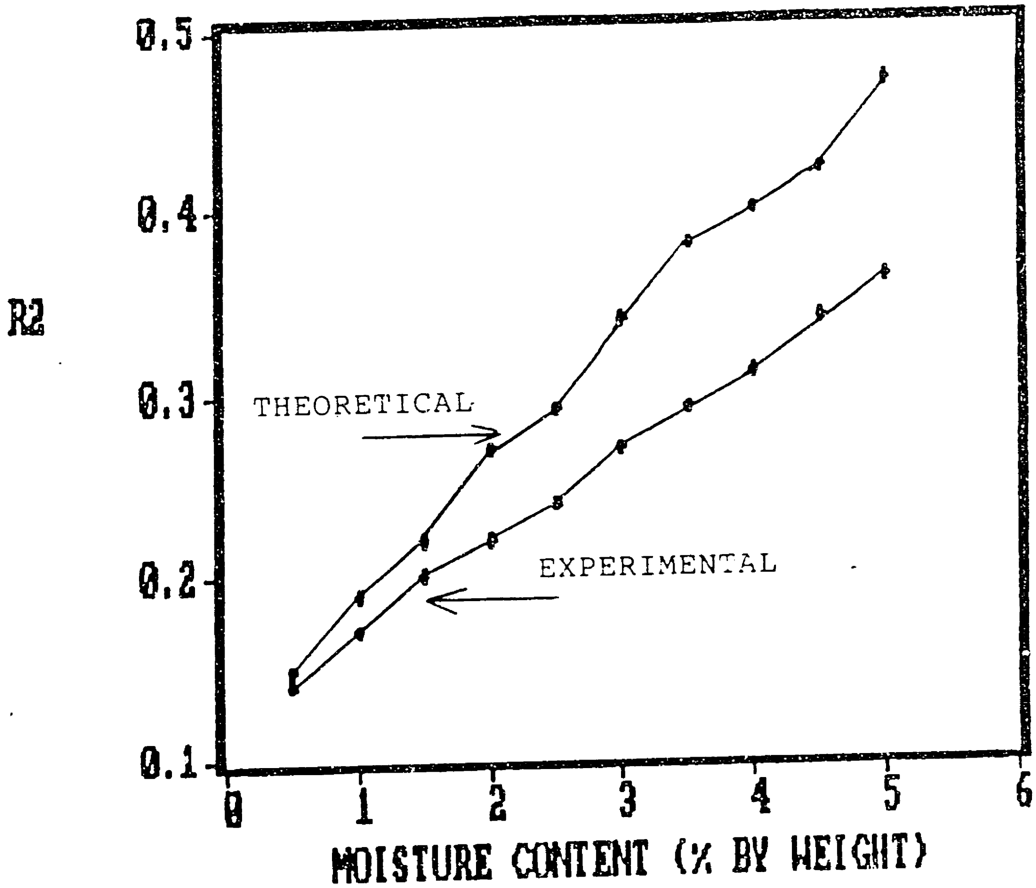


Figure 9-4: R2 Versus Moisture Content (Theoretical and Regression Line of Experimental Data)



9.3 Threshold and Statistical Analyses of ε_c Data

Several data analysis techniques were employed to produce measurements of deterioration. By setting threshold limits for ε_c values and searching for locations where the threshold is exceeded, and by examining the variation of the ε_c values, measurements of moisture induced deterioration, or "punky" concrete are obtained.

9.3.1 $\varepsilon_c > 12$

The fraction of points along the deck where calculated ε_c values are greater than twelve was investigated as a measure of deck deterioration. However, Equation 6-6 shows that the dielectric constants of structurally sound decks may vary if the concrete volume fractions of air, water or aggregate are not uniform. Therefore, using a single threshold value is inappropriate since physical conditions besides moisture-induced deterioration may be responsible for variations in dielectric constants.

9.3.2 $\varepsilon_c > \varepsilon_c$MEAN + 2

By taking the mean of the dielectric constant of concrete over a deck and looking for large deviations from this mean, a more accurate appraisal of isolated moisture effects on the radar was obtained. To identify changes that are the result of moisture saturation, ASYST is used to search the ε_c data files for points where the concrete dielectric constant is greater than the mean ε_c value plus two. The total percentage of deck deterioration is determined from the fraction of data points that have calculated dielectric values greater than the mean of the dielectric constant plus two.

9.3.3 Standard Deviation of ε_c

The standard deviation of the dielectric constant over a deck provides a measurement of the variability of the ε_c values and can be used to estimate deck condition. Table 9-3 presents the results of these statistical operations. The relationship between percent deterioration (from $\varepsilon_c > \varepsilon_c$MEAN + 2) and standard deviation is shown in Figure 9-5.

Since the standard deviation appears to be linearly related to the percent deterioration predictions, the standard deviation of the ε_c values also provides an indication of the deck condition.

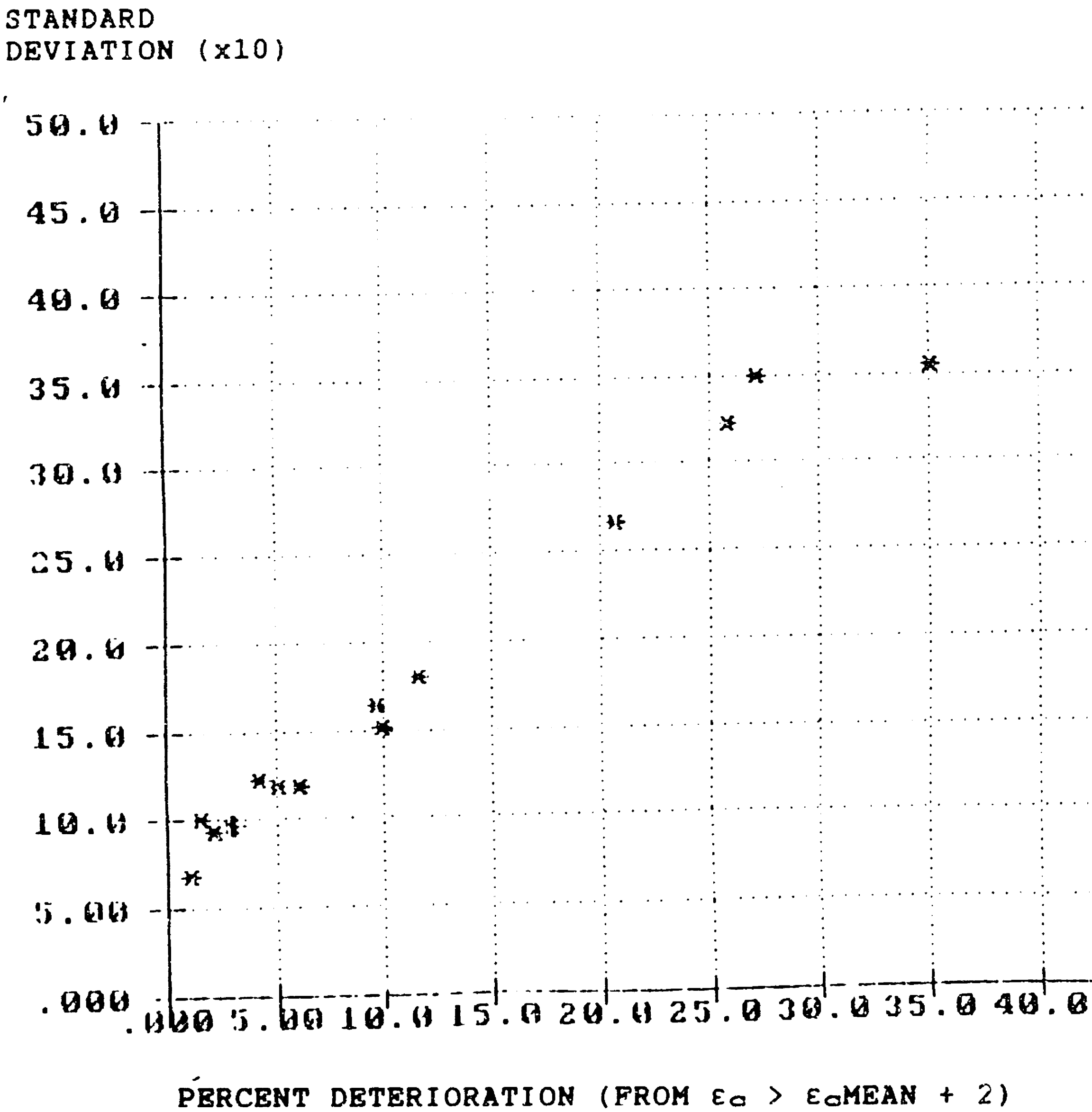
9.4 A Combination of Inspection Techniques

Although the M.I.T. bridge deck project team was unsuccessful in using radar to predict delaminations, other technologies employed in conjunction with radar provided improved measurements of overall deck deterioration. When infrared thermography data, compiled by the New England Surface Transportation Infrastructure Consortium, is also used to provide delamination predictions, total deck deterioration is estimated to within five percent of actual deterioration. Estimates of overall deck deterioration from

Table 9-3: Percent Deterioration Estimates

BRIDGE DECK	PERCENT DETERIORATED $\varepsilon_a > 12$	$\varepsilon_a > \varepsilon_a$MEAN + 2	STANDARD DEVIATION
Maine 1	20.9	11.7	1.8
Massachusetts 1	22.5	9.7	1.6
Massachusetts 3	22.5	25.9	3.2
Massachusetts 4	12.0	4.3	1.2
New Hampshire 1	38.0	27.2	3.5
New Hampshire 2	36.5	20.7	2.7
New Hampshire 3	9.9	1.2	0.69
New Hampshire 4	27.5	15.6	2.1
Rhode Island 1	0.87	6.1	1.2
Rhode Island 2.1	9.2	10.0	1.5
Rhode Island 2.2	0.49	1.6	1.0
Rhode Island 3	1.3	2.3	0.93
Vermont 1	2.3	5.2	1.2
Vermont 2	0.34	3.0	0.98

Figure 9-5: Standard Deviation of ε_c Versus % Deterioration



radar and infrared surveys and actual amounts of deck deterioration are provided in Table 9-4.

The results of radar and infrared surveys are plotted onto small scale maps of the bridge decks and compared to mappings of actual deterioration locations obtained when the bridge decks were opened. The results of visual underside surveys of the decks are also mapped on the same scale. Total areas of deterioration predicted by radar, infrared, and underside surveys were calculated and compared to actual deteriorations. This approach makes use of the complementary technologies of radar and infrared thermography and in this way the best measure of concrete deterioration and delamination is obtained. This final graphical output is easy to read and although all predicted areas of deterioration do not exactly correspond to actual deteriorations, estimates of overall percent deteriorations are still within five percent, a significant improvement over previous inspection techniques. Complete data sets for four bridge decks were compiled and the maps of predicted and actual deteriorations are displayed in Figure 9-6.

Table 9-4: Percent Deterioration Prediction Versus Actual

BRIDGE DECK	% Deterioration Predicted	Actual % Deterioration
Maine 1	18.0	21.0
Massachusetts 1	12.0	9.0
New Hampshire 2	20.0	20.5
New Hampshire 3	1.0	0.0
Vermont 1	4.0	3.6
Vermont 2		
Span 1	2.0	7.0
Span 2	3.0	7.0
Span 3	1.0	4.0
Span 4	5.0	12.0
Span 5	7.0	12.0
Total	4.0	9.0

Figure 9-6: Bridge Deck Deterioration Maps

Key

= Radar Predictions

= Infrared Predictions

= Visual Underside Survey

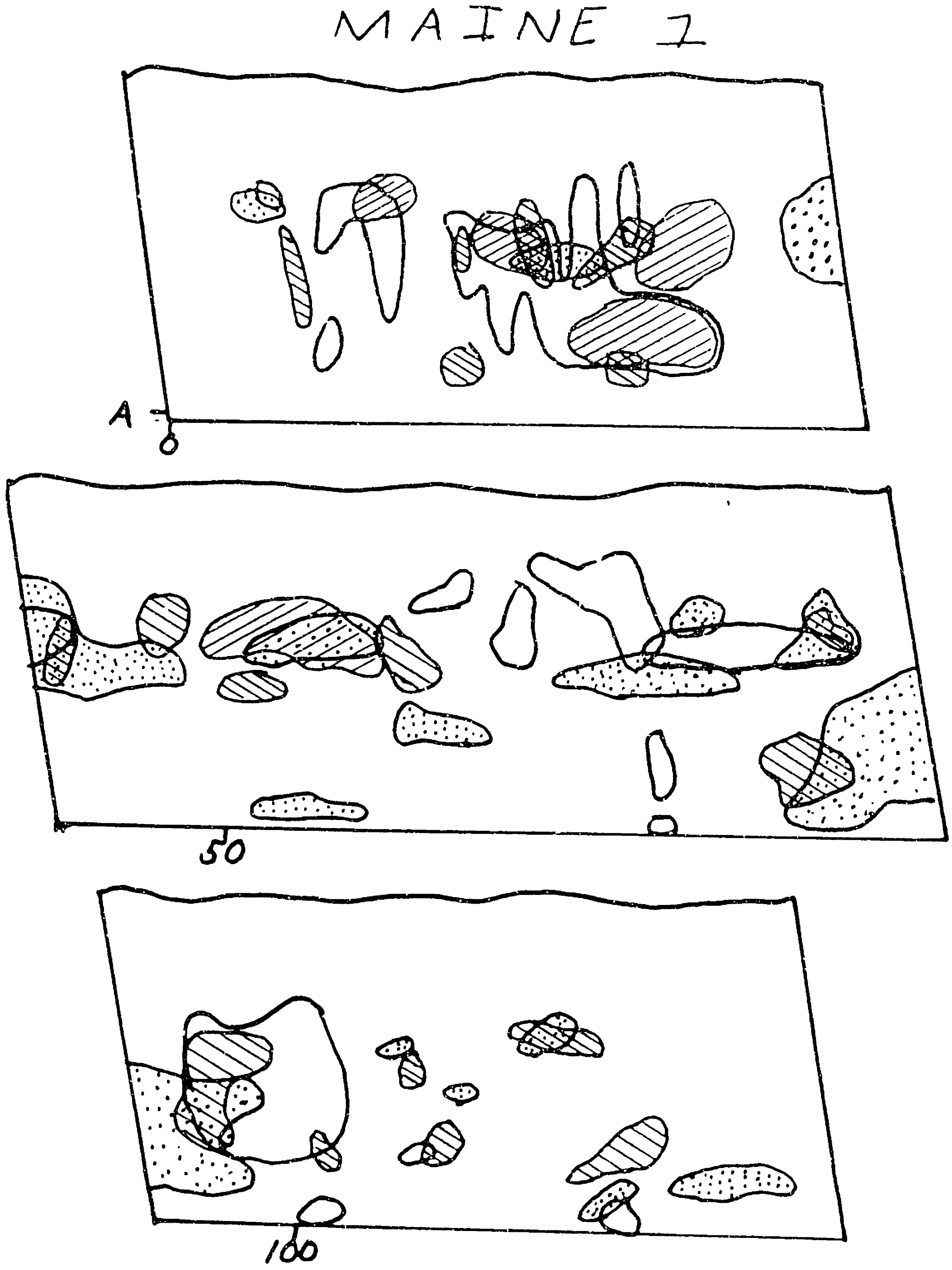
= Actual Deterioration

Scale

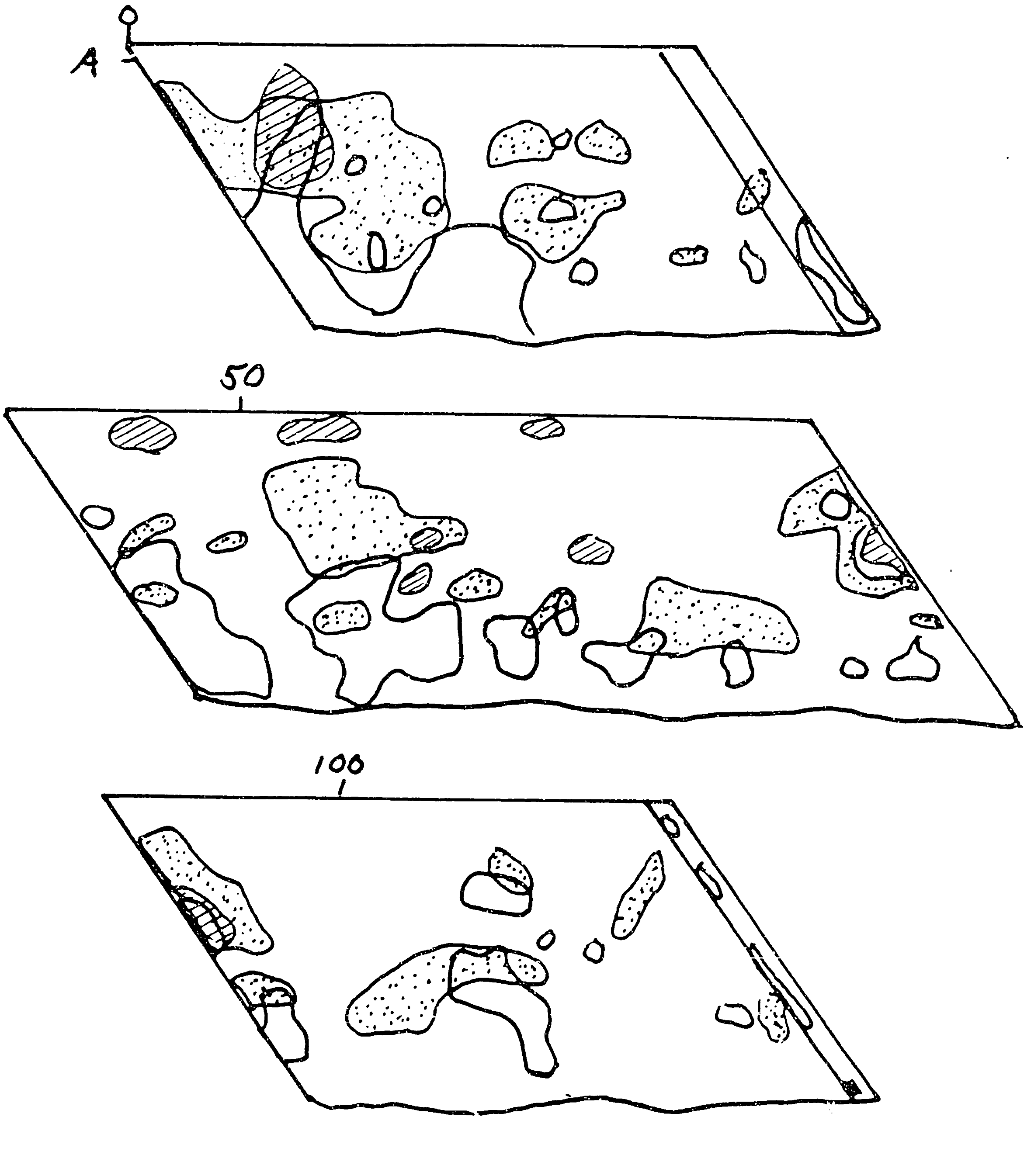
1 inch = 10 feet

DETERIORATION SUMMARY

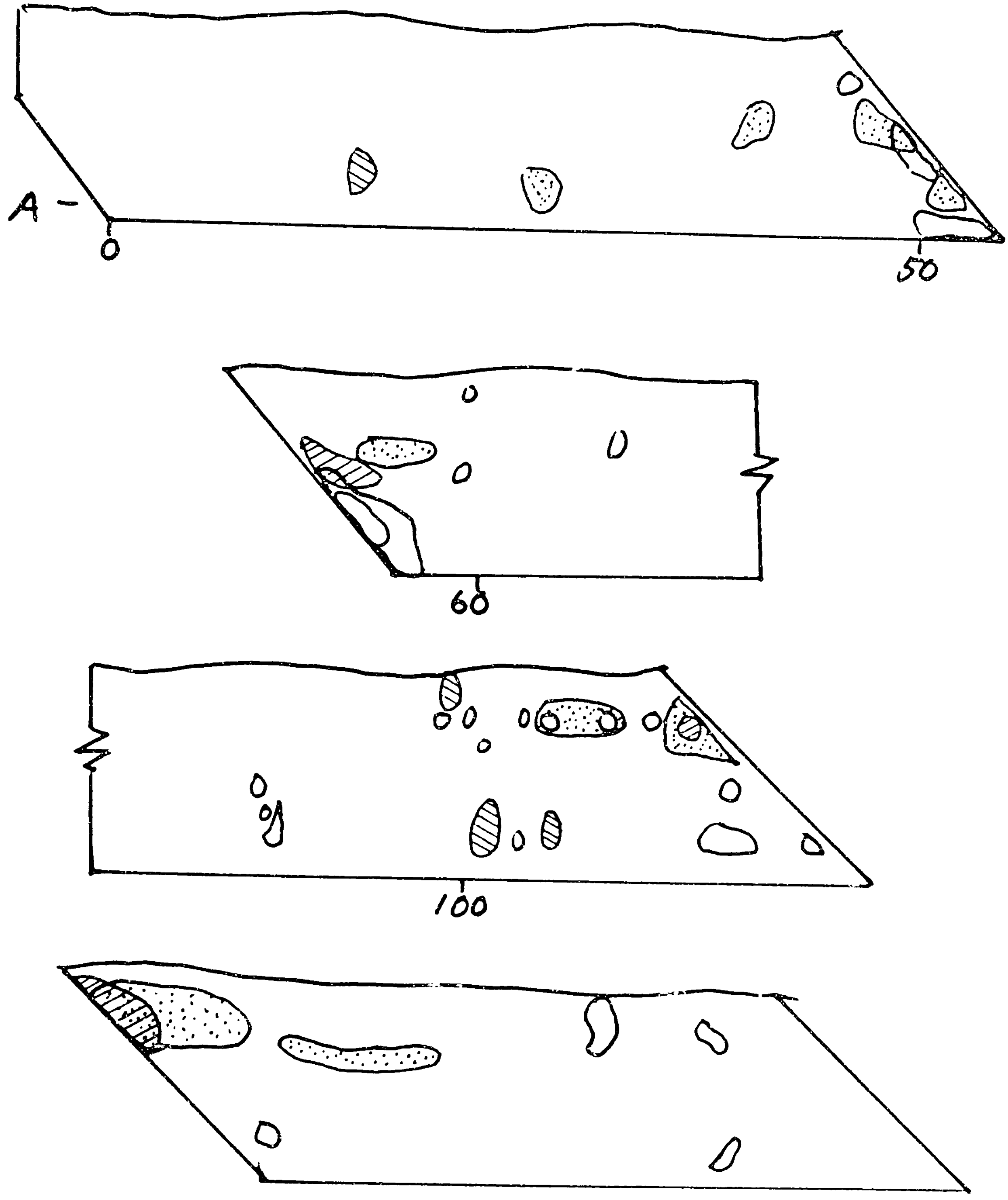
DECK	AREA (SQ.FT.)	PREDICTED DETERIORATION AREA: RADAR + INFRARED (SQ. FT.)	(%)	RADAR + INFRARED + UNDERSIDE (SQ. FT.)	(%)	ACTUAL (SQ. FT.)	(%)
mil	1,950	347	18	417	21	410	21
n2	2,040	400	20	-	-	418	20
v1	2,535	96	4	105	4	67	3
v2 span1	1,596	30	2	74	5	112	7
v2 span2	1,610	46	3	87	5	105	7
v2 span3	1,288	18	1	50	4	56	4
v2 span4	1,610	74	5	121	8	187	12
v2 span5	1,596	111	7	226	14	195	12


MAINE 1
A
0
50
100

NEW HAMPSHIRE 2

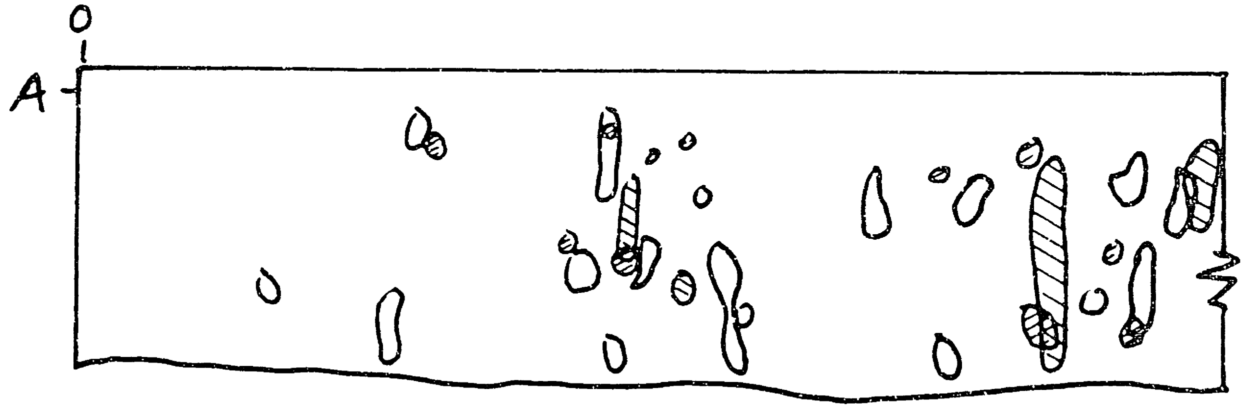


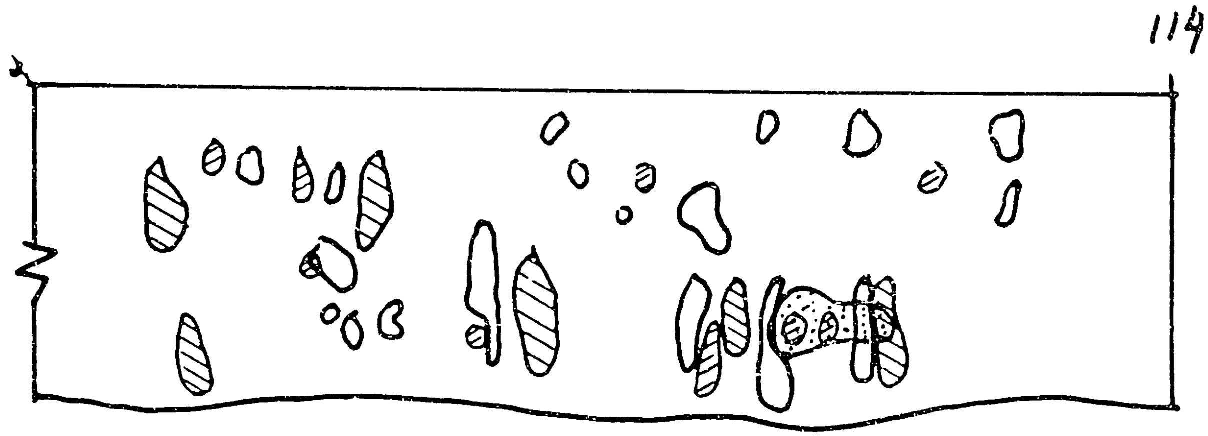
VERMONT 1



VERMONT 2

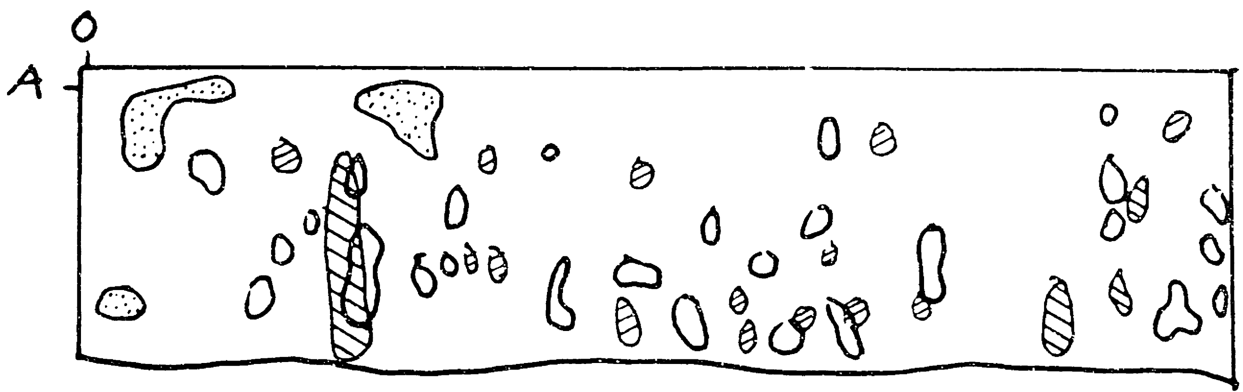
SPAN 1

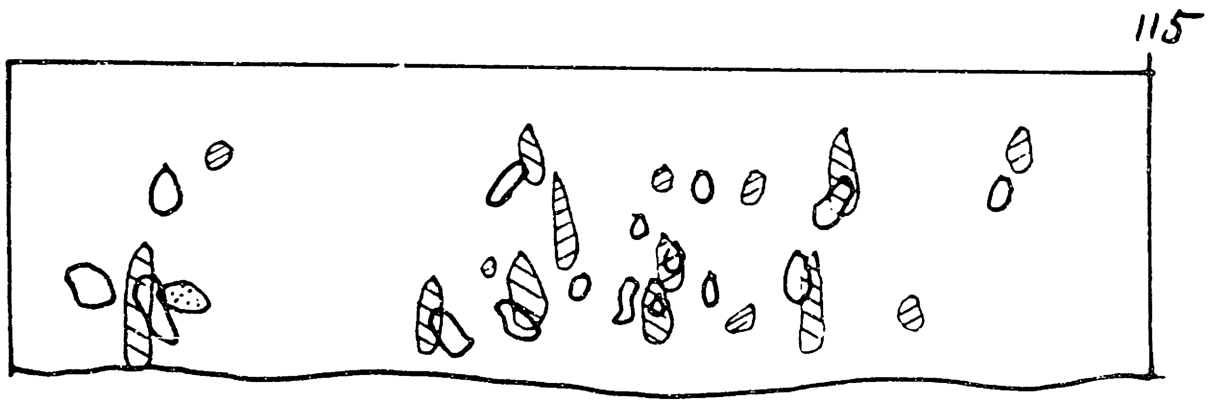




VERMONT 2

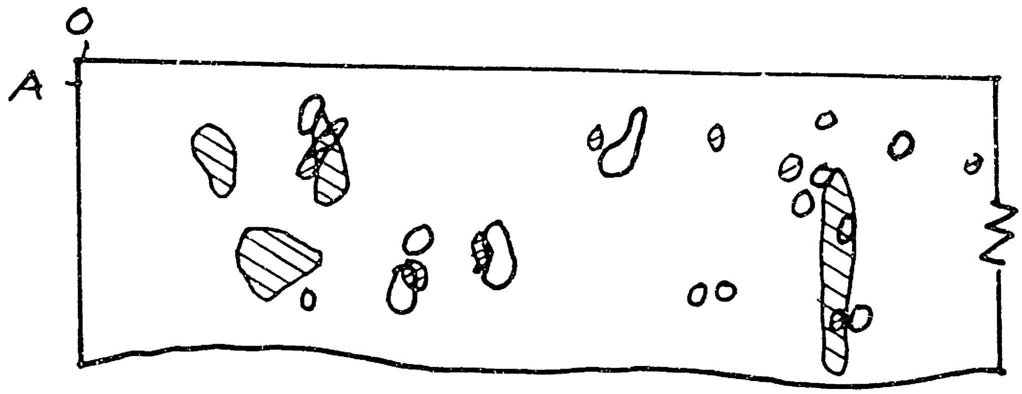
SPAN 2

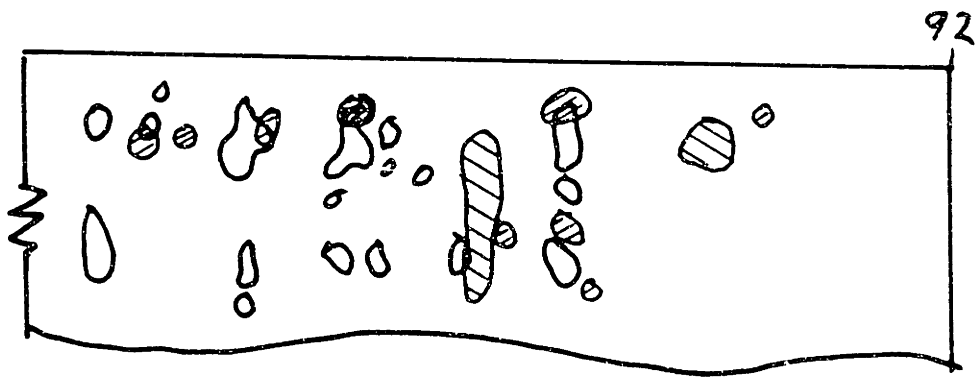




VERMONT 2

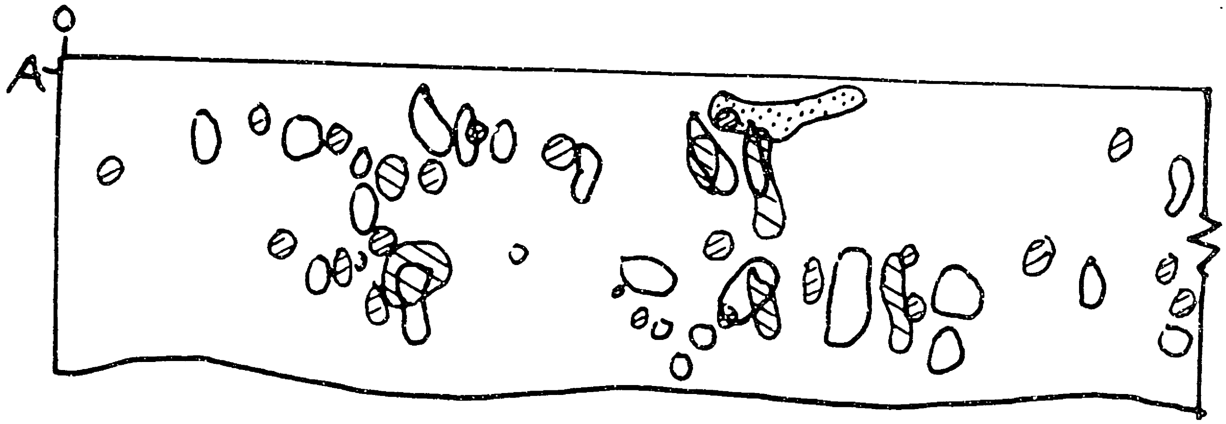
SPAN 3

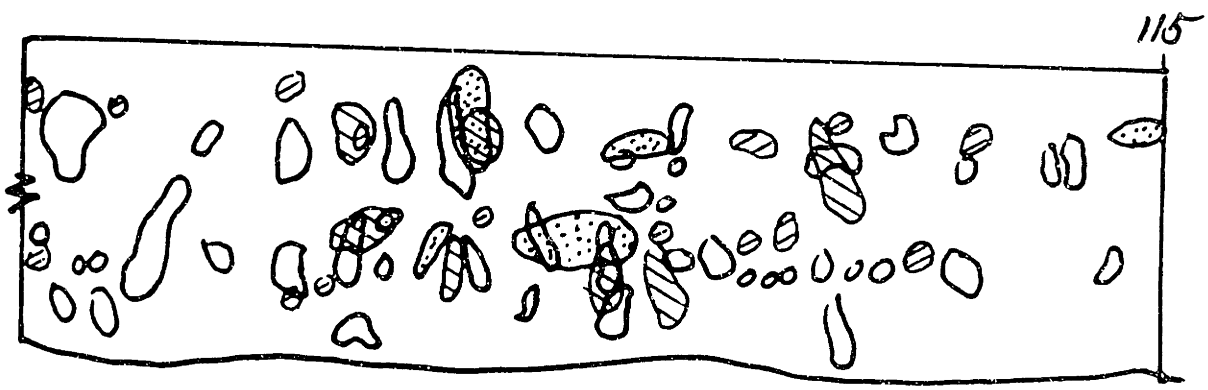




VERMONT 2

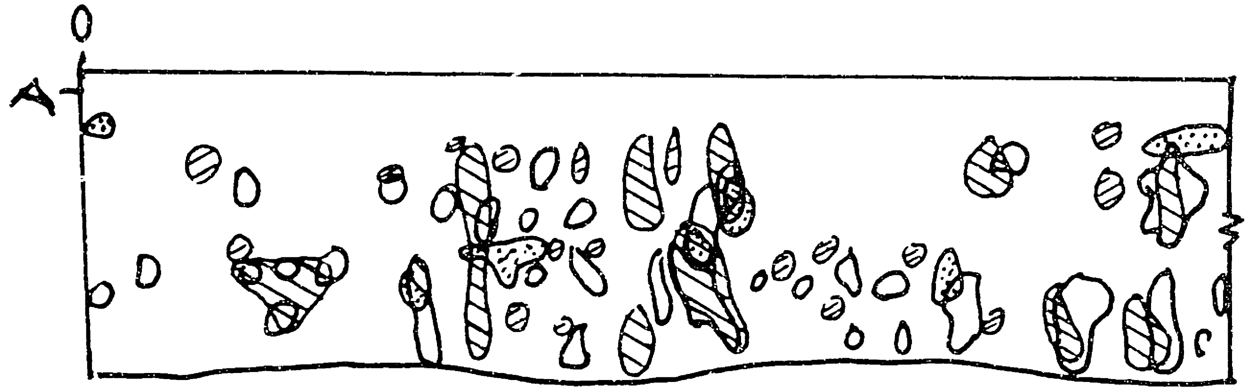
SPAN 4

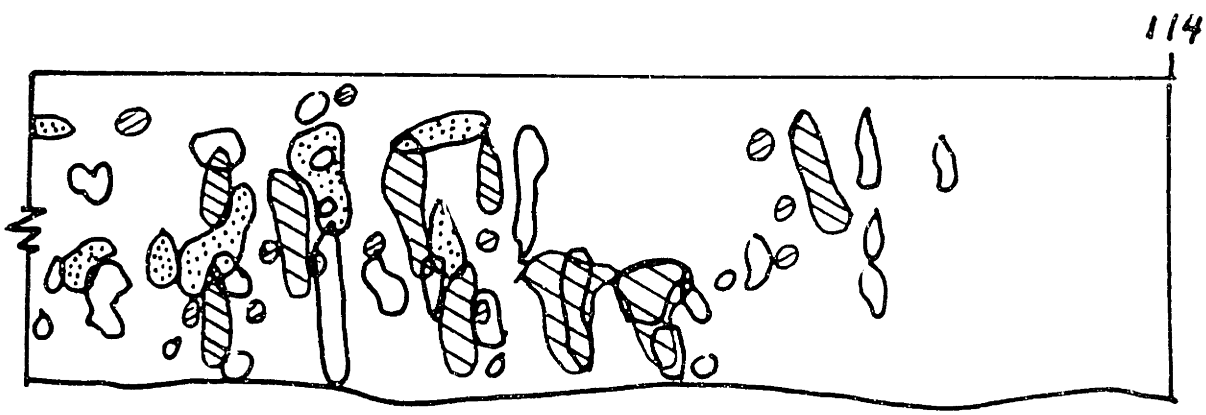




VERMONT 2

SPAN 5





Chapter 10

Recommendations

The analyses presented in this thesis may be further developed in several ways. For example, expert computer systems may be developed for the digital signature analysis of radar reflections. The system's knowledge base could include historical, theoretical and experimental data that could be used to improve this thesis' waveform peak detection techniques and calculations of asphalt dielectric constants by eliminating operator input of certain parameters. Also, technical improvements to radar equipment will improve the quality of the data and new experimental studies with radar may improve our understanding of radar propagation through concrete.

10.1 Peak Detection Techniques

The computer programs for analyzing radar waveforms have been customized for each bridge deck. Due to the varying asphalt and top cover thicknesses of decks, the waveform windows that are specified for peak detection routines must be modified for many decks and this requires the user to manually inspect the recorded waveforms. As the radar waveforms of Figures 7-3 and 7-4 show, a general knowledge of asphalt thickness is important for the identification of waveform peaks. Knowledge of other construction dimensions of the decks may also be needed for analyses of concrete and rebar reflections. Therefore, development of an expert system may be a goal of future bridge deck research. Maser[16] has proposed an expert system for the Automated Interpretation of Sensor Data that analyzes large quantities of sensor data and also includes multi-disciplinary knowledge of bridge deck design, construction, radar signal processing and concrete deterioration. The efficiency of radar analysis will be increased by the automatic application of the knowledge of an expert system to the important task of window selection for waveform peak detection.

10.2 Adjustments for ε_{asp} Variations on a Deck

The algorithm that determines the dielectric constant of the top cover of concrete is based on a physical model of radar reflections from the deck, but also requires the user to input an appropriate value for the dielectric constant of asphalt. This is accomplished by taking core or dust samples to determine asphalt thickness and by following the procedure summarized in Table 8-1. However, if this knowledge is part of a bridge deck expert system, drilling will be unnecessary and bridge inspection can be completed more rapidly. In addition, the program presented in Section 7.3.3, which computes the dielectric constant of asphalt at each data location along the deck, will be a useful analysis tool if

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[16]Kenneth Maser, "Automated Interpretation for Sensing In-Situ Conditions," <u>ASCE Journal of Computing in Civil Engineering</u>, Volume 2, Number 3 (July, 1988), p. 4.

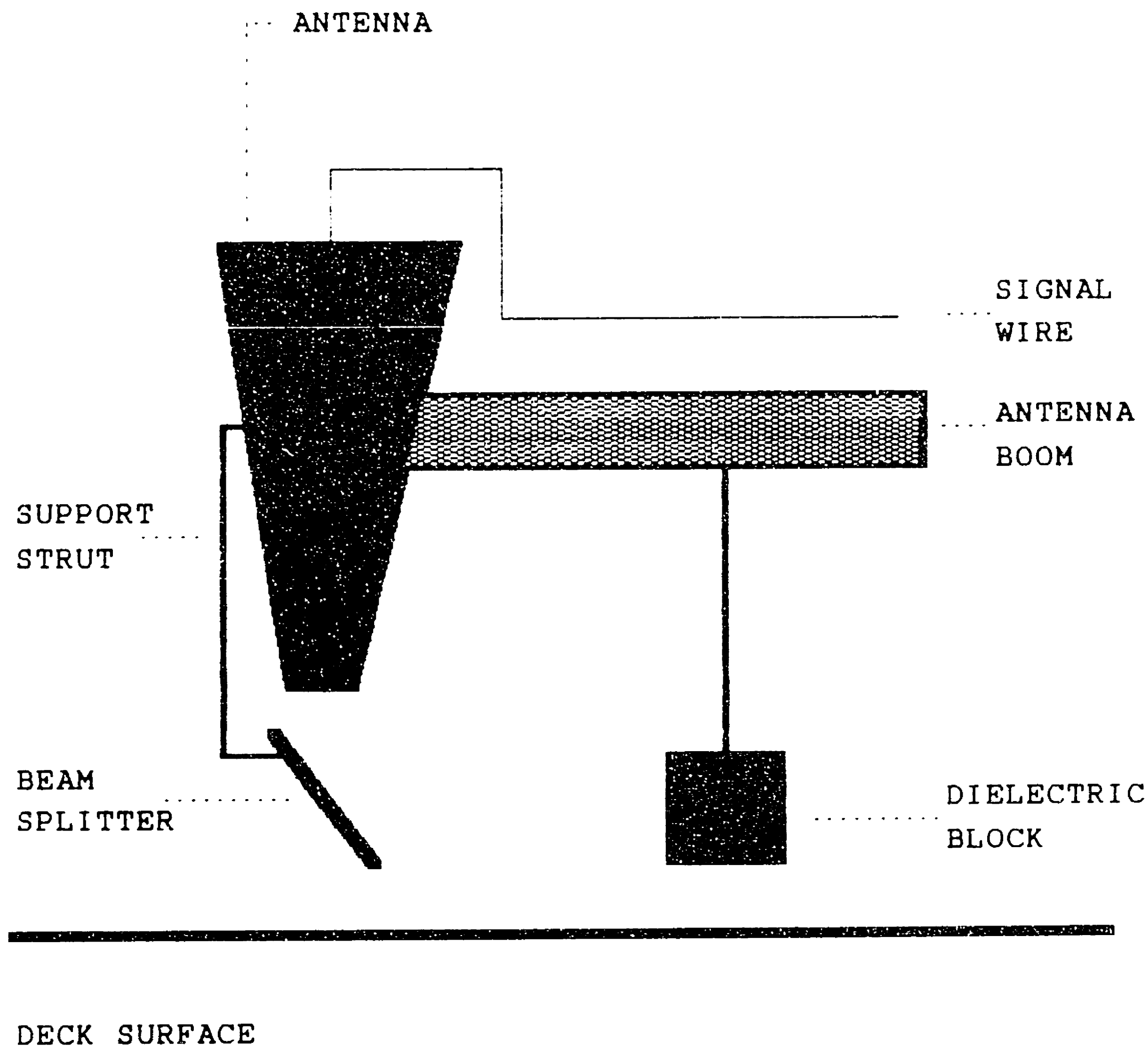
radar equipment can be improved so that the gain instability which distorted these calculations is corrected.

10.3 Real-Time Calibration

In addition to technical improvements to the radar equipment, the radar system may be modified so that a calibration test can be performed as the van travels over the deck. This test will produce a measurement of the incident radar wave magnitude for each data point along the deck so that the ε_{asp} calculations of Section 7.3.3 are unaffected by changes in the radar gain. The calibration test will also yield timing factors, described in Section 8.1, that are modified for each data point. These factors will produce more accurate thickness values.

The calibration test (Figure 10-1) uses a radar beam splitter to send part of the incident radar wave to a calibration block of known dielectric permittivity and thickness. Wire screens can be used to split radar beams in the similar way that silvered glass surfaces can be used to split light beams. For radar, the spacing between the wires in the screen should be on the order of one-half a wavelength, or about six inches. Part of the radar wave will travel through the screen to the deck and the other part will travel toward the calibration block. Two radar reflections will be returned from the block. The first reflection will be from the radar passing from the air to the block. The second reflection is produced when the radar passes from the

Figure 10-1: Real-Time Calibration Test



other end of the block to the air. Since the dielectric constant of the block is known, the first block reflection can be used in Equation 6-2 to compute ε_{ASD} for each location along the deck. Since the block has a known thickness, both reflections can be used to compute time scale factors for each data point. Therefore, the analysis program of Section 7.3.3 and the programs in Chapter 8 may be modified to use the results of the calibration tests to adjust for gain or timing changes.

10.4 Larger Data Sets

Although programs to determine locations of delaminations and correlations to chloride content values have not produced meaningful results, more decks should be tested in order to obtain a larger data set. If future analysis proves that radar can be used to identify delaminations, other inspection technologies will not have to be used to supplement the radar analysis. Thus, the rebar attenuation algorithm of Section 8.5 should not be abandoned, and the thickness and dielectric constant algorithms of Chapter 8 should be further tested with data from additional bridge decks.

10.5 Radar Attenuation in Concrete

As indicated in Chapter 2, the radar models described in this thesis have been simplified by eliminating the effects of radar signal attenuation through concrete. Since no detailed studies of the dielectric permittivity and loss tangent of concrete at high frequencies have been performed, researchers have estimated attenuation from soil and clay models. If high frequency measurements of dielectric permittivity and loss tangent can be performed for a wide range of concrete compositions, all the models presented in this thesis may be modified to incorporate attenuation factors. In this way, the radar models and algorithms will more thoroughly conform to the electromagnetic principles of radar propagation. Attenuation is likely to be low, making values for reflection and transmission coefficients from material interfaces slightly higher than those in the models that ignore attenuation. This may require altering the threshold levels for identifying deterioration in ratio-based analyses, such as the ε_a algorithm.

Appendix A

Sample Theoretical Calculations of ε_c and R2 Versus Moisture Content

Assume concrete has 0.12 volume fraction of air and water and 0.88 volume fraction of aggregate. Moisture content by weight is converted to volume fraction by:

$$\text{M.C. by weight} \times \frac{\text{vol. / wt. water}}{\text{vol.. / wt. concrete}} = \text{M.C. by volume}$$

$$\text{M.C. by weight} \times 150/62.5 = \text{M.C. by volume}$$

Therefore, for a 0.12 air and water void:

M.C. by wt.	Vol fraction of water	Volume fraction of air (0.12 - vol. fr. water)
0.01	0.024	0.096
0.02	0.048	0.072
0.03	0.072	0.048
0.04	0.096	0.024
0.05	0.120	0.000

Use Equations 6-5 and 6-6 and assume $\varepsilon_{AGGREGATE}=7$, $\varepsilon_{AIR}=1$, $\varepsilon_{WATER}=81$:

M.C. by weight	ε_c	R2
0.01	6.97	0.19
0.02	8.02	0.27
0.03	9.14	0.34
0.04	10.34	0.40
0.05	11.61	0.47

Appendix B

Computer Programs for Bridge Deck Data Analysis

PROGRAM TITLE	REFERENCES	PAGE
Area Coefficient	Eq. 7-1, Fig. 7-1	129
R2 and Asphalt Thickness	Fig. 7-4	132
R3 and Top Cover	Fig. 7-5	135
D/C and Top Cover for Bridge Mass2		138
Asphalt and Top Cover Analysis	Eqs. 7-2, 7-3 Figs. 7-6, 7-7	141
ε_c	Eq. 8-1, Figs. 8-2, 8-3	147
ε_cSTAT	Table 9-1	151
TC (Top Cover)	Figs. 8-5, 8-6	153
TC for Bridge M2		156
LN (rebar reflection algorithm)	Eq. 8-2 Figs. 8-7, 8-8	158
LN for Bridge M2		162

Area Coefficient

```
\
```

\   This program calculates the correlation factor $\int_{t-.4}^{t+.4} w_i \times w_b \, dt \Big/ \int_{t-.4}^{t+.4} w_b^2 \, dt$
\ at each position along a pass. The array wb represents a
\ 1 ns part of a user selected base wave and wi represents a 1 ns part
\ of any wave along a pass.

```
\      These statements define graphic areas.

 vuport big
 big 0.0 0.0 vuport.orig 1.0 1.0 vuport.size
 vuport corplot
 corplot 0.0 0.0 vuport.orig 1.0 1.0 vuport.size

\      The following statements declare the variables and arrays used
\ by the program.

real scalar wave#                \ wave# is the user selected base wave
30 wave# :=                      \ ( in this case the 30th wave is selected )

real scalar owave                \ owave is used to access wave#
integer dim[ 300 ] array feet
integer scalar a
integer scalar c
integer scalar d
integer scalar num
integer dim[ 500 ] array w1
real dim[ 150 ] array wave
real dim[ 50 ] array wb          \ a 1 ns part of the base wave
real dim[ 50 ] array w2          \ contains wb*wb
real dim[ 50 ] array wi          \ a 1ns part of any wave along a pass
real dim[ 50 ] array w3          \ contains wb*wi
real scalar denom
real scalar numer
real dim[ 300 ] array out

300 integer ramp feet :=

30 string file
1 set.#.optima
17 set.#.points

wave# 1 - owave :=

\      This is the main routine.

: ont

     num :=
     " random.open "  file "cat "exec
        owave 1000 * random.lseek              \ looks at the base wave
        wi random.get                          \      to calculate the
```

```
                                                        \      denominator

 \ NOTE:  since the waveforms for bridge V1 are inverted, the following
 \      statement should be included for this bridge:
 \                Ø w1 - w1:=

      w1 sub[ 1 , 155 ] local.maxima
      swap
      a :=
      w1 sub[ a , 15Ø ] wave :=
      wave sub[ 15 , 135 ] local.maxima   \ NOTE: change 15 to 4Ø and 135 to
      swap                                \       1ØØ for bridge Mil
      a + 15 + c :=                       \
      2Ø c + d :=                         \ point d is .4 ns after peak c
      w1 sub[ d , 5Ø ] wb :=              \ wb is from c+.4ns to c+1.4ns
      wb wb * w2 :=                       \ wb is squared and set equal to w2
      w2 integrate.data                   \ a running integral of w2 is
      [ 5Ø ] denom :=                     \       obtained and the final value
      denom .                             \       is extracted and printed
      stack.clear

 num Ø do i 1 + .                         \ to calculate the numerator we
      i 1ØØØ * random.lseek               \       access every wave along
      w1 random.get                       \       the deck

      \ NOTE:  since the waveforms for bridge V1 are inverted, the following
      \      statement should be included for this bridge.
      \                Ø w1 - w1 :=

      w1 sub[ 1 , 155 ] local.maxima
      swap
      a :=
      w1 sub[ a , 15Ø ] wave :=
      wave sub[ 15 , 135 ] local.maxima   \ NOTE:  change 15 to 4Ø and 135 to
      swap                                \       1ØØ for bridge Mil
      a + 15 + c :=                       \
      2Ø c + d :=
      w1 sub[ d , 5Ø ] wi :=              \ wi is from c+.4ns to c+1.4ns
      wi wb * w3 :=                       \ multiply wi by wb, take a
      w3 integrate.data                   \       running integral and
      [ 5Ø ] numer :=                     \       extract the final value
      numer denom / out [ i 1 - ] :=      \ calculate the correlation
      numer denom / .                     \       factor and print
      stack.clear
 loop

    These statements display and plot the results in graphic vuports.

graphics.display
 big
 normal.coords
      Ø.Ø15 .2 position 9Ø char.dir 9Ø label.dir
```

```
          " correlation factor " label
     .3 .03 position 0 char.dir 0 label.dir
          " position along deck (feet) " label
     .4 .95 position file label
     .6 .2 position " denom " label
     .7 .2 position denom "." label
     .2 .2 position " wave# " label
     .3 .2 position wave# "." label
     .2 .3 position " integral from c+.4ns to c+1.4ns " label

 corplot
 vertical linear
 vertical axis.fit.off
 horizontal axis.fit.off
 horizontal 0 200 world.set      \ NOTE:  change 200 to 300 for bridges M1 and M2
 vertical -1. 1.5 world.set
 corplot xy.axis.plot
 corplot solid
 feet sub[ 1 , num ] out sub[ 1 , num ] xy.data.plot
pause
screen.print
random.close
stack.clear
normal.display

;
```

```
\                      R2 and Asphalt Thickness
\                  ( for all bridges except Mass2 )

\      This program calculates and plots values for R2 ( the magnitude
\ of peak c divided by the magnitude of peak a ) and the asphalt thickness.


\      These statements define the graphic areas.

vuport big                                          \ this large area holds the
big 0.0 0.0 vuport.orig 1.0 1.0 vuport.size         \      graphics labels
vuport r2                                           \ this window is for the R2 plot
r2 0.0 0.5 vuport.orig 1.0 .5 vuport.size
vuport thick                                        \ this is for the asphalt
thick 0.0 0.0 vuport.orig 1.0 .5 vuport.size        \      thickness plot


\      The following statements declare the variables and arrays used
\ by this program.

integer dim[ 500 ] array w1     \ this array holds raw waveforms
real dim[ 150 ] array wave      \ a sub-array of w1
real dim[ 300 ] array out2      \ contains R2 values
real dim[ 300 ] array asph      \ contains asphalt thicknesses
integer dim[ 300 ] array feet   \ contains the location along the deck


integer scalar num              \ represents the length of the pass
real scalar amag                \ represents the magnitude of peak a
real scalar cmag                \ represents the magnitude of peak c
integer scalar a                \ represents the location of peak a
integer scalar c                \ represents the location of peak c


300 integer ramp feet :=       \ this function assigns values for location
                               \      along the deck from 1 to 300 feet


30 string file      \ file is a string variable that holds the name of the
                    \      dos file which contains the waveforms
1 set.#.optima      \ tells asyst to look for the steepest local maxima
17 set.#.points     \ tells asyst to use 17 points at a time in its search
                    \      for a local maxima


\      The main routine of the program is called ont.  To run this
\ routine, the user must place a value for the length of the pass on
\ top of the stack and put the name of the dos file to be used into
\ the variable file.  For example:
\          122 " d: \nh\n2-v-c.dat " file ":= ont


ASYST Version 2.00
Page 1     \JEFF\ONT.DMO    01/29/88    15:12:15.56
```

```
: ont

    num :=              \ loads length of pass from top of the stack
    Ø out2 :=           \ initializes arrays to zero
    Ø asph :=
    " random.open "  file "cat "exec      \ opens dos file to read waveforms

    num Ø do i 1 + .                      \ this loop operates on one wave
                                          \      at a time
         i 1ØØØ * random.lseek            \ locks for and loads a wave from
         w1 random.get                    \      1 through num

    \ NOTE: since the waveforms for bridge V1 are inverted, the following
    \      statement should be included for this bridge:
    \               Ø w1 - w1 :=


         w1 sub[ 1 , 155 ] local.maxima   \ finds magnitude and location of
         amag := a :=                     \      the steepest peak ( a )

         w1 sub[ a , 15Ø ] wave :=        \ wave is the region from peak a
                                          \      to peak a + 3 ns
                                          \ REMEMBER each point in a waveform
                                          \      array equals .Ø2 ns

         wave sub[ 15 , 135 ] local.maxima   \ finds the location of peak c
         cmag := a + 15 + c :=                  \ NOTE:  for bridge Mil change
                                             \      15 to 4Ø and 135 to 1ØØ

            cmag amag / out2 [ i 1 + ] :=    \ calculates R2 and asphalt
            c a - .Ø5Ø6 * asph [ i 1 + ] :=  \      and places these in the
                                             \      appropriate array


\      The following statements limit the R2 values and asphalt thickness
\ to 1 and 5 for properly scaled plots.

              out2 [ i 1 + ] abs 1. > if 1. out2 [ i 1 + ] := then
              asph [ i 1 + ] abs 5. > if 5. asph [ i 1 + ] := then
         stack.clear

     loop     \ now load the next waveform along the deck


\      These statements display and plot the results in graphic vuports.

     graphics.display
     big
     normal.coords
          .Ø15 .7 position 9Ø char.dir 9Ø label.dir
               " r 2 " label
          .Ø15 .1 position 9Ø char.dir 9Ø label.dir
               " asphalt (inches) " label
```

```
     .4 .95 position Ø char.dir Ø label_dir
        file label
     .3 .Ø3 position " position along deck (feet) " label
r2
vertical linear
vertical axis.fit.off
horizontal Ø 2ØØ world.set    \ NOTE:  since bridges M1 and M2 are longer,
                              \      change 2ØØ to 3ØØ for M1 and M2
vertical Ø 1. world.set
r2 xy.axis.plot
r2 solid
feet sub[ 1 , num ] out2 sub[ 1 , num ] xy.data.plot
thick
vertical 1.Ø 5.Ø world.set
horizontal Ø 2ØØ world.set     \ NOTE: change 2ØØ to 3ØØ for M1 and M2
thick xy.axis.plot
thick feet sub[ 1 , num ] asph sub[ 1 , num ] xy.data.bar
pause
screen.print
random.close
stack.clear
stack.display
```

```
\                          R3 and Top Cover
                 ( for all bridges except Mass2 )


\      This program calculates and plots values for R3 ( the magnitude
\ of peak d divided by the magnitude of peak a ) and the depth of the
\ top cover of concrete.
\      The program first determines points a and c of the waveform as
\ in the program ont.dmo then locates point d to determine R3 and top
\ cover.


\      These statements define the graphic areas.

vuport big                                      \ this large area holds the
big 0.0 0.0 vuport.orig 1.0 1.0 vuport.size     \      graphics labels
vuport r3                                       \ this window is for the R3 plot
r3 0.0 0.5 vuport.orig 1.0 .5 vuport.size
vuport thick                                    \ this is for the top
thick 0.0 0.0 vuport.orig 1.0 .5 vuport.size    \      cover plot


\      The following statements declare the variables and arrays used
\ by this program.

integer dim[ 500 ] array w1    \ this array holds raw waveforms
  al dim[ 150 ] array wave     \ a sub-array of w1
real dim[ 300 ] array out3     \ contains R3 values
real dim[ 300 ] array conc     \ contains top cover values
integer dim[ 300 ] array feet  \ contains the location along the deck


integer scalar num             \ represents the length of the pass
real scalar amag               \ represents the magnitude of peak a
real scalar dmag               \ represents the magnitude of peak d
integer scalar a               \ represents the location of peak a
integer scalar c               \ represents the location of peak c
integer scalar e               \ used to determine peak d
integer scalar d               \ represents the location of peak d


300 integer ramp feet :=      \ this function assigns values for location
                              \      along the deck from 1 to 300 feet


30 string file     \ file is a string variable that holds the name of the
                   \      dos file which contains the waveforms
1 set.#.optima     \ tells asyst to look for the steepest local maxima
17 set.#.points    \ tells asyst to use 17 points at a time in its search
                   \      for a local maxima
```

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Page 1   \JEFF\R3.DMO   01/28/88   18:12:33.97

```
\      The main routine of the program is called ont.  To run this
\ routine, the user must place a value for the length of the pass on
  top of the stack and put the name of the dos file to be used into
\ the variable file.  For example:
\           122 " d: \nh\n2-v-c.dat " file ":= ont


: ont

     num :=              \ loads length of pass from top of the stack
     Ø out3 :=           \ initializes arrays to zero
     Ø conc :=
     " random.open "  file "cat "exec        \ opens dos file to read waveforms

     num Ø do i 1 + .                        \ this loop operates on one wave
                                             \      at a time
          i 1ØØØ * random.lseek              \ looks for and loads a wave from
          w1 random.get                      \      1 through num

     \ NOTE: since the waveforms for bridge V1 are inverted, the following
     \      statement should be included for this bridge:
     \                Ø w1 - w1 :=


          w1 sub[ 1 , 155 ] local.maxima     \ finds magnitude and location of
          amag := a :=                       \      the steepest peak ( a )

          w1 sub[ a , 15Ø ] wave :=          \ wave is the region from peak a
                                             \      to peak a + 3 ns
                                             \ REMEMBER each point in a waveform
                                             \      array equals .Ø2 ns


          wave sub[ 15 . 135 ] local.maxima     \ finds the location of peak c
          swap a + 15 + c :=                    \ NOTE:  for bridge Mil change
                                                \      15 to 4Ø and 135 to 1ØØ

          5 c + e :=                           \ point e is defined as c + .1 ns

          w1 sub[ e , 55 ] local.maxima         \ looks for peak d in the region
                                                \ from e to e + 1.1 ns
                                                \ NOTE:  for bridges NH2 and RI1
                                                \   change 55 to 65 (1.3 ns)
          if                                    \ if a peak is found, location and
             dmag := e + d :=                   \      magnitude is saved
             dmag amag / out3 [ i 1 + ] :=      \ calculates R3 and top cover
             d c - .Ø4 * conc [ i 1 + ] :=      \      and places these in the
                                                \      appropriate array

            else                                 \ if the program cannot find peak
             i Ø > if                            \      d it sets R3 and top cover
             out3 [ i ] out3 [ i 1 + ] :=        \      to the previous values
             conc [ i ] conc [ i 1 + ] := then
             i Ø = if                            \ if the program cannot find peak
             Ø.Ø out3 [ i 1 + ] :=               \      d of the first wave it
```

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Page 2   \JEFF\R3.DMO   Ø1/28/88   18:12:38.41

```
            0.0 conc [ i 1 + ] := then          \     sets R3 and top cover = 0
        then
   ;

\      The following statements limit the R3 values to between .21 and
\ -.11 for properly scaled plots.
             out3 [ i 1 + ] .21 > if .21 out3 [ i 1 + ] := then
             out3 [ i 1 + ] -.11 < if -.11 out3 [ i 1 + ] := then
        stack.clear

    loop     \ now load the next waveform along the deck

\      These statements display and plot the results in graphic vuports.

    graphics.display
    big
    normal.coords
         .015 .7 position 90 char.dir 90 label.dir
              " r 3 " label
         .015 .1 position 90 char.dir 90 label.dir
              " top cover (inches) " label
         .4 .95 position 0 char.dir 0 label.dir
              file label
         .3 .03 position " position along deck (feet) " label
    r3
    vertical linear
    vertical axis.fit.off
    horizontal 0 200 world.set     \ NOTE:  since bridges M1 and M2 are longer,
                                   \        change 200 to 300 for M1 and M2
    vertical -.1 .2 world.set
    r3 xy.axis.plot
    r3 solid
    feet sub[ 1 , num ] out3 sub[ 1 , num ] xy.data.plot
    thick
    vertical 0.0 3.0 world.set
    horizontal 0 200 world.set     \ NOTE: change 200 to 300 for M1 and M2
    thick xy.axis.plot
    thick feet sub[ 1 , num ] conc sub[ 1 , num ] xy.data.bar
    pause
    screen.print
    random.close
    stack.clear
    stack.display

  ;
```

```
\                 D/C and Top Cover for Bridge Mass2

\       This program is a modification of r3.dmo that is to be used for
\ only bridge M2.  Since M2 has no asphalt, D/C represents the reflection
\ from the concrete-rebar interface divided by the reflection from the
\ air-concrete interface.


\       This program calculates and plots values for D/C and the depth of
\ the top cover of concrete.  In this modification, the air-concrete
\ interface is the first peak and is represented by c, and the concrete-
\ rebar interface is the second peak and is noted as d.


\       These statements define the graphic areas.

vuport big                                     \ this large area holds the
big 0.0 0.0 vuport.orig 1.0 1.0 vuport.size    \       graphics labels
vuport r3                                      \ this window is for the D/C plot
r3 0.0 0.5 vuport.orig 1.0 .5 vuport.size
vuport thick                                   \ this is for the top
thick 0.0 0.0 vuport.orig 1.0 .5 vuport.size   \       cover plot


\       The following statements declare the variables and arrays used
\ by this program.

integer dim[ 500 ] array w1       \ this array holds raw waveforms
real dim[ 150 ] array wave        \ a sub-array of w1
real dim[ 300 ] array out3        \ contains D/C values
real dim[ 300 ] array conc        \ contains top cover values
integer dim[ 300 ] array feet     \ contains the location along the deck


integer scalar num                \ represents the length of the pass
real scalar cmag                  \ represents the magnitude of peak c
real scalar dmag                  \ represents the magnitude of peak d
integer scalar c                  \ represents the location of peak c
integer scalar d                  \ represents the location of peak d


300 integer ramp feet :=         \ this function assigns values for location
                                 \       along the deck from 1 to 300 feet


32 string file     \ file is a string variable that holds the name of the
                   \       dos file which contains the waveforms
1 set.#.optima     \ tells asyst to look for the steepest local maxima
17 set.#.points    \ tells asyst to use 17 points at a time in its search
                   \       for a local maxima


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Page 1    \JEFF\R3MASS2.DMO   01/28/88    17:37:16.49
```

```
\       The main routine of the program is called ont.  To run this
\ routine, the user must place a value for the length of the pass on
\ top of the stack and put the name of the dos file to be used into
\ the variable file.  For example:
\           122 " d: \nh\n2-v-c.dat " file ":= ont


: ont

    num :=             \ loads length of pass from top of the stack
    0 out3 :=          \ initializes arrays to ze
    0 conc :=
    " random.open "  file "cat "exec        \ opens dos file to read waveforms

    num 0 do i 1 + .                        \ this loop operates on one wave
                                            \      at a time
         i 1000 * random.lseek              \ looks for and loads a wave from
         w1 random.get                      \      1 through num

         w1 sub[ 1 , 155 ] local.maxima     \ finds magnitude and location of
         cmag := c :=                       \      the steepest peak ( c )

         w1 sub[ c , 150 ] wave :=          \ wave is the region from peak c
                                            \      to peak c + 3 ns
                                            \ REMEMBER each point in a waveform
                                            \      array equals .02 ns


         wave sub[ 15 , 60 ] local.maxima       \ looks for peak d in the region
                                                \      from c + .3 ns to c + 1.5 ns
         if                                     \ if a peak is found, location and
            dmag := c + 15 + d :=               \      magnitude is saved
            dmag cmag / out3 [ i 1 + ] :=       \ calculates D/C and top cover
            d c - .04 * conc [ i 1 + ] :=       \      and places these in the
                                                \      appropriate array

           else                                   \ if the program cannot find peak
            i 0 > if                              \      d it sets D/C and top cover
            out3 [ i ] out3 [ i 1 + ] :=          \      to the previous values
            conc [ i ] conc [ i 1 + ] := then
            i 0 = if                              \ if the program cannot find peak
            0.0 out3 [ i 1 + ] :=                 \      d of the first wave it
            0.0 conc [ i 1 + ] := then            \      sets D/C and top cover = 0
         then

\      The following statements limit the D/C values to between .21 and
\ -.11 and top cover values to under 3 inches for properly scaled plots.

              out3 [ i 1 + ] .21 > if .21 out3 [ i 1 + ] := then
              out3 [ i 1 + ] -.11 < if -.11 out3 [ i 1 + ] := then
              conc [ i 1 + ] 3. > if 3. conc [ i 1 + ] := then
         stack.clear
```

```
loop      \ now load the next waveform along the deck

\      These statements display and plot the results in graphic vuports.

graphics.display
big
normal.coords
     .Ø15 .7 position 9Ø char.dir 9Ø label.dir
          " d/c " label
     .Ø15 .1 position 9Ø char.dir 9Ø label.dir
          " top cover (inches) " label
     .4 .95 position Ø char.dir Ø label.dir
          file label
     .3 .Ø3 position " position along deck (feet) " label
r3
vertical linear
vertical axis.fit.off
horizontal Ø 3ØØ world.set
vertical -.1 .2 world.set
r3 xy.axis.plot
r3 solid
feet sub[ 1 , num ] out3 sub[ 1 . num ] xy.data.plot
thick
vertical Ø.Ø 3.Ø world.set
horizontal Ø 3ØØ world.set
thick xy.axis.plot
thick feet sub[ 1 , num ] conc sub[ 1 . num ] xy.data.bar
pause
screen.print
random.close
stack.clear
stack.display
```

```
\                       Asphalt and Top Cover Analysis
\


\     This program calculates and plots values for asphalt thickness, top
\ cover of concrete, dielectric constants of asphalt and top cover and
\ determines the value of the reflection from peak d divided by the reflection
\ from peak c and R2.


\       These statements define the graphic areas.

vuport big                                        \ this large area holds the
big Ø.Ø Ø.Ø vuport.orig 1.Ø 1.Ø vuport.size       \      graphics labels
vuport deck                                       \ this is for the deterioration
deck Ø.Ø .9 vuport.orig 1.Ø .Ø7 vuport.size       \      map
vuport thick                                      \ this window is for the
thick Ø.Ø Ø.59 vuport orig 1.Ø .3 vuport.size     \      thickness plots
vuport diel                                       \ this is for the plot of
diel Ø.Ø Ø.32 vuport.orig 1.Ø .3 vuport.size      \       dielectric constants
vuport d/c&r2                                     \ this is for the R2 and the
d/c&r2 Ø.Ø Ø.Ø5 vuport.orig 1.Ø .3 vuport.size    \       d/c plots

\       The following statements declare the variables and arrays used
\ by this program.

integer dim[ 3ØØ ] array actual
integer dim[ 5ØØ ] array w1      \ this array holds raw waveforms
real dim[ 15Ø ] array wave       \ a sub-array of w1
real dim[ 3ØØ ] array ea         \ contains dielectric constant of asphalt
real dim[ 3ØØ ] array asph       \ contains asphalt values
real dim[ 3ØØ ] array out2       \ contains r2
real dim[ 3ØØ ] array outdc      \ contains d/c
real dim[ 3ØØ ] array ec         \ contains dielectric constant of top cover
real dim[ 3ØØ ] array conc       \ contains top cover values
integer dim[ 3ØØ ] array feet    \ contains the location along the deck
35 string act
integer dim[ 3ØØ ] array zero
integer dim[ 3ØØ ] array x
integer dim[ 3ØØ ] array l
integer dim[ 3ØØ ] array corr

integer scalar num               \ represents the length of the pass
real scalar amag                 \ represents the magnitude of peak a
real scalar cmag                 \ represents the magnitude of peak c
real scalar dmag                 \ represents the magnitude of peak d
integer scalar a                 \ represents the location of peak a
integer scalar c                 \ represents the location of peak c
integer scalar e                 \ used to determine peak d
integer scalar d                 \ represents the location of peak d


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```

```
real scalar apl                 \ represents plate reflection
real scalar r12                 \ asphalt reflection / apl
real scalar eas                 \ square root of ea
real scalar ca                  \ used to calculate ecs
real scalar k                   \ used to calculate ecs
real scalar ecs                 \ square root of ec
integer scalar scale            \ represents x-axis length
integer scalar direction        \ represents direction of pass
integer scalar tick             \ used for graphics
integer scalar h
integer scalar h1
integer scalar h2

3Ø string file     \ file is a string variable that holds the name of the
                   \       dos file which contains the waveforms
1 set.#.optima     \ tells asyst to look for the steepest local maxima
17 set.#.points    \ tells asyst to use 17 points at a time in its search
                   \       for a local maxima


\      The main routine of the program is called ont.  To run this
\ routine, the user must place a value for the length of the pass on
\ top of the stack and put the name of the dos file to be used into
\ the variable file.  For example:
\          122 12Ø -1 "  \nh\n2-v-c.dat " file ":= ont


: ont

   " d:\actual" file "cat act ":=

    direction :=     \ loads direction of pass
    feet [ 1 ] :=    \ loads first pass
    num :=           \ loads length of pass
    num Ø do i
      direction feet [ i 1 + ] + feet [ i 2 + ] := \ fills feet array
      stack.clear
    loop

    Ø asph :=        \ initializes arrays to zero
    Ø conc :=
    Ø out2 :=
    Ø outdc :=
    Ø ea :=
    Ø ec :=
    Ø actual :=
    Ø x :=
    Ø l :=
    Ø corr :=
    Ø h :=
    Ø h1 :=
    Ø h2 :=
    1 zero :=
```

```
" random.open "  file "cat "exec      \ opens dos file to read waveforms

num Ø do i 1 + .                         \ this loop operates on one wave
                                         \     at a time
     i 1000 * random.lseek               \ looks for and loads a wave from
     w1 random.get                       \     1 through num

\ NOTE: since the waveforms for bridge V1 are inverted, the following
\      statement should be included for this bridge:
\   .             Ø w1 - w1 :=


     w1 sub[ 1 , 155 ] local.maxima     \ finds magnitude and location of
     amag := a :=                       \      the steepest peak ( a )
\ NOTE: the following value for apl is unique to each deck
                   for Mi1    NH2(2417.4) , M3(2603.04), V1(2313.23)
  2140.97 apl := \
     Ø apl - apl :=                     \ apl is negative  Mi(3768.72)
     amag apl / r12 :=                  \ calcuates r12       A1(1727.8)
     1 r12 - 1 r12 + / eas :=           \ calculates eas
     eas eas * ea [ i 1 + ] :=          \ calculates dielectric constant of
                                        \      asphalt and stores in array


     w1 sub[ a , 150 ] wave :=          \ wave is the region from peak a
                                        \     to peak a + 3 ns
                                        \ REMEMBER each point in a waveform
                                        \     array equals .02 ns


     wave sub[ 15 , 135 ] local.maxima   \ finds peak c
     cmag := a + 15 + c :=               \ NOTE:  for bridge Mi1 change
                                         \       15 to 40 and 135 to 100

     cmag amag / out2 [ i 1 + ] :=       \ calculates r2
     c a - .12 * eas / asph [ i 1 + ] := \ calculates asphalt thickness

     cmag apl / ca :=                    \ calculates ca
     1 eas + 1 eas + * ca * 4. / eas / k :=   \ calculates k
     1 k - eas * 1 k + / ecs :=               \ calculates ecs
     ecs ecs * ec [ i 1 + ] :=           \ calculates dielectric constant
                                         \      of top cover


     5 c + e :=                          \ point e is defined as c + .1 ns

     w1 sub[ e , 55 ] local.maxima       \ looks for peak d in the region
                                         \ from e to e + 1.1 ns
                                         \ NOTE:  for bridges NH2 and FI1
                                         \     change 55 to 65 (1.3 ns)
                                         \ if a peak is found, magnitude
     if                                  \      and location is saved
        dmag := e - d :=

        cmag Ø. = if                     \ if cmag=0. d/c is set to 0
        Ø. outdc [ i 1 - ] :=
        else
```

```
        dmag cmag / outdc [ i 1 + ] :=     \ calculates d/c
        then

        d c - .12 * ecs / conc [ i 1 + ] :=      \ calculates top cover

       else                                  \ if the program cannot find peak
        i Ø > if                             \     d it sets d/c and top cover
        outdc [ i ] outdc [ i 1 + ] :=       \     to the previous value
        conc [ i ] conc [ i 1 + ] := then
        i Ø = if                             \ if the program cannot find peak
        Ø.Ø outdc [ i 1 + ] :=               \     d of the first wave it
        Ø.Ø conc [ i 1 + ] := then           \     sets d/c and top cover = Ø

      then
         asph [ i 1 + ] 5. > if 5. asph [ i 1 + ] := then        \ scales
         conc [ i 1 + ] 5. > if 5. conc [ i 1 + ] := then        \ the
         asph [ i 1 + ] 1. < if 1. asph [ i 1 + ] := then        \ plots
         conc [ i 1 + ] 1. < if 1. conc [ i 1 + ] := then
         ea [ i 1 + ] 2Ø. > if 2Ø. ea [ i 1 + ] := then
         ec [ i 1 + ] 2Ø. > if 2Ø. ec [ i 1 + ] := then
         ea [ i 1 + ] 2. < if 2. ea [ i 1 + ] := then
         ec [ i 1 + ] 2. < if 2. ec [ i 1 + ] := then
         outdc [ i 1 + ] 1. > if 1. outdc [ i 1 + ] := then
         outdc [ i 1 + ] -.2 < if -.2 outdc [ i 1 + ] := then
         out2 [ i 1 + ] 1. > if 1. out2 [ i 1 + ] := then
         out2 [ i 1 + ] -.2 < if -.2 out2 [ i 1 + ] := then
      stack.clear

  loop     \ now load the next waveform along the deck
  random.close

\    These statements display and plot the results in graphic vuports.

  graphics.display
  axis.defaults
  big
  normal.coords
       .Ø2 .9 position 9Ø char.dir 9Ø label.dir
          " det " label
       .Ø15 .7 position 9Ø char.dir 9Ø label.dir
          " tc, ta " label
       .Ø15 .45 position 9Ø char.dir 9Ø label.dir
          " ea, ec " label
       .Ø15 .15 position 9Ø char.dir 9Ø label.dir
          " r2, d/c " label
       .4 .97 position Ø char.dir Ø label.dir
          file label
       .3 .Ø3 position " position along deck (feet) " label

  num 1Ø1 < if 1ØØ scale :=
  else
       num 2ØØ > if 3ØØ scale :=
       else 2ØØ scale := then
  then
```

```
scale 100 = if 6 tick := then
scale 200 = if 11 tick := then
scale 300 = if 16 tick := then

horizontal label.scale.off
vertical label.scale.off
horizontal axis.fit.off
vertical axis.fit.off

deck
" random.open " act "cat "exec
actual random.get
horizontal -20 scale world.set
vertical 0 4 world.set
vertical axis.off
horizontal axis.on
horizontal no.labels
vertical no.labels
horizontal grid.off
vertical grid.off
deck xy.axis.plot
num 0 do
  1 actual [ i 1 + ] = if
  h 1 + h :=
  i 1 + x [ h ] := then
  -1 actual [ i 1 + ] = if
  h1 1 + h1 :=
  i 1 + 1 [ h1 ] := then
  -2 actual [ i 1 + ] = if
  h2 1 + h2 :=
  i 1 + corr [ h2 ] := then
stack.clear
loop
h 1 > if
  deck " x" symbol
  x sub[ 1 , h ] zero sub[ 1 , h ] xy.data.plot then
h1 1 > if
  deck " !" symbol
  1 sub[ 1 , h1 ] zero sub[ 1 , h1 ] xy.data.plot then
h2 1 > if
  deck " c" symbol
  corr sub[ 1 , h2 ] zero sub[ 1 , h2 ] xy.data.plot then
stack.clear


thick
vertical axis.on
horizontal grid.on
vertical grid.on
horizontal -20 scale world.set
vertical 1.2 5.2 world.set
tick 8 axis.divisions
vertical 1 2 label.points
horizontal no.labels
```

```
thick xy.axis.plot
thick " *" solid&symbol
feet sub[ 1 , num ] asph sub[ 1 , num ] xy.data.plot
thick solid
feet sub[ 1 , num ] conc sub[ 1 , num ] xy.data.plot

diel
horizontal -20 scale world.set
vertical 2.0 20.0 world.set
tick 9 axis.divisions
vertical 1 2 label.points
horizontal no.labels
diel xy.axis.plot
diel " *" solid&symbol
feet sub[ 1 , num ] ea sub[ 1 , num ] xy.data.plot
diel solid
feet sub[ 1 , num ] ec sub[ 1 , num ] xy.data.plot

d/c&r2
horizontal -20 scale world.set
vertical -.2 1 world.set
tick 12 axis.divisions
vertical 1 2 label.points
horizontal 1 2 label.points
d/c&r2 xy.axis.plot
d/c&r2 " *" solid&symbol
feet sub[ 1 , num ] out2 sub[ 1 , num ] xy.data.plot
d/c&r2 solid
feet sub[ 1 , num ] outdc sub[ 1 , num ]  xy.data.plot

pause
screen.print
random.close
stack.clear
stack.display
```

```
\
\     This program calculates, plots and saves values for the dielectric
\ constant of the top cover of concrete.  The program locates waveform peaks
\ A and C, computes the R2 ratio, and uses estimated asphalt dielectric
\ constants to compute ec by using the following relationship:



\ These statements define the graphic area.

vuport big
big Ø.2 Ø.Ø vuport.orig Ø.8 1.Ø vuport.size

\ The following statements declare the variables and arays used
\ by this program.

integer dim[ 5ØØ ] array w1          \ this array holds raw waveforms
real dim[ 15Ø ] array wave           \ a sub-array of w1
real dim[ 2ØØ ] array ec             \ contains dielectric constant of top cover
integer dim[ 2ØØ ] array feet        \ contains locations along a pass
                                     \ NOTE:  ec and feet array lengths vary -
                                     \ 6ØØ for V2, 4ØØ for N3 and N4, 3ØØ for M1
                                     \ 6ØØ for V2, 4ØØ for N3 and N4, 3ØØ for M1

real scalar amag                     \ represents the magnitude of peak A
real scalar cmag                     \ represents the magnitude of peak C
integer scalar a                     \ represents the location of peak A
integer scalar c                     \ represents the location of peak C
real scalar r2                       \ represents R2
real scalar ea                       \ represents dielectric constant of asphalt
real scalar eas                      \ square root of ea
real scalar ecs                      \ square root of ec
real scalar aprime                   \ used to compute ecs

integer scalar num                   \ represents length of pass
integer scalar direction             \ represents direction of pass
integer scalar scale                 \ x-axis length for graphic plots
integer scalar tick                  \ x-axis tick marks for graphic plots

real scalar passes                   \ NOTE:  this value represents the number
8. passes :=                         \        of  passes to be printed for a deck
real scalar pass                     \ pass is a counter from 0 to passes
Ø. pass :=

3Ø string file                       \ file is a string variable that holds the
                                     \   name of the DOS file which contains the
                                     \   waveforms
1 set.#.optima                       \ tells ASYST to search for the steepest
                                     \   maxima when the local.maxima command
                                     \   is used
17 set.#.points                      \ tells ASYST to use 17 points in a maxima
                                     \   search
```

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Page 1   A:\EC.DMO   Ø6/1Ø/88   Ø9:59:4Ø.29

```
\ THe following statements plot axes and labels in the graphic vuport.

    graphics.display
    axis.defaults
    big
    normal.coords
        .015 .5 position " ec " label
        .3 .03 position " position along deck (feet) " label
    200 scale :=          \ NOTE:  for M1 change 200 to 300 and 11 to 16
    11 tick :=            \        for M4, N1, R1 change 200 to 100 and 11 to 6
                          \        for V2 change 200 to 580 and 11 to 10
                          \        for N3 and N4 change 200 to 400 and 11 to 14
    horizontal label.scale.off
    vertical label.scale.off
    horizontal axis.fit.off
    vertical axis.fit.off
    horizontal axis.on
    vertical axis.on
    horizontal grid.on
    vertical grid.on
    horizontal -20 scale world.set
    vertical 0 130 world.set
    tick 13 axis.divisions
    horizontal 1 2 label.points
    vertical 0 1 label.points
    big xy.axis.plot

\ The main routine of the program is called ont.  To run this routine, the
\ user must place values for the length of the pass on top of the stack and
\ put the name of the DOS file containing the waveforms on the symbol stack.
\ For example:        122 120 -1 " \nh\n2-v-c.dat " file ":= ont

: ont
    big                                \ results will be plotted in vuport big
    0 feet :=                          \ initialize feet to zero
    0 ec :=                            \ initialize ec to zero

    direction :=                       \ loads direction of pass
    feet [ 1 ] :=                      \ loads location of first radar sample
    num :=                             \ loads length of pass
    num 0 do                                                \ this loop fills the
        direction feet [ i 1 + ] + feet [ i 2 + ] :=       \   feet array with
        stack.clear                                         \   radar sample
    loop                                                    \   locations

    " random.open " file "cat  exec \ opens DOS file to read waveforms

\ This loop operates on one wave at a time.
    num 0 do i 1 + .
        i 1000 * random.lseek          \ searches for a wave
        w1 random.get                  \ loads it into w1

        \ NOTE:  since the waveforms for deck V1 are inverted, the following
```

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```
\         statement must be included for this deck:
\                   Ø w1 - w1 :=

\ The following statements set windows to search for maximas, and
\    determine magnitudes and locations of peaks A and C.
w1 sub[ 1 , 155 ] local.maxima
amag := a :=
w1 sub[ a , 15Ø ] wave :=
wave sub[ 15 , 135 ] local.maxima      \ NOTE:  Window Changes -
if                                     \     for Mi1, N1 change
cmag := a + 15 + c :=                  \         15 to 4Ø and 135 to 1ØØ
                                       \     for R2 change 15 to 5Ø
                                       \         and 135 to 9Ø
                                       \     for R3 change 15 to 8Ø
                                       \         and 135 to 5Ø
                                       \     for N3 change 135 to 5Ø

cmag amag / r2 :=                      \ computes the R2 ratio

\ The following statements use R2 and estimated ea values to compute ec.
    5.5 ea :=    \ NOTE: 5.5 is for M1
                 \       for other bridges use:
                 \       5.Ø M3, 6.Ø Mi1, 5.5 N2, 6.4 R1, 5.Ø N3, 5.5 N4
                 \       6.Ø V1, 6.4 N1, 5.4 V2, 5.5 R2, 5.Ø R3, 5.4 M4

ea Ø.5 ** eas :=
4.Ø eas * 1.Ø ea - / aprime :=
aprime r2 - aprime r2 + / eas * ecs :=
ecs 2.Ø ** ec [ i 1 + ] :=             \ saves the ec values to the ec
                                       \   array
else

\ If the program cannot locate peak C for any location, the previous
\    value for ec is assumed.
i Ø > if ec [ i ] ec [ i 1 - ] := then
i Ø = if 9.Ø ec [ 1 ] := then
then

\ These statements limit ec values to between 2 and 2Ø.
ec [ i 1 + ] 2Ø. > if 2Ø. ec [ i 1 + ] := then
ec [ i 1 + ] 2. < if 2. ec [ i 1 + ] := then
stack.clear
loop

\ The following statements plot the ec values along each pass and save
\    these values to the disk drive.
feet sub[ 1 , num ] ec sub[ 1 , num ] pass 1Ø. * - xy.data.plot
random.close
" random.file.create a:" file "cat "exec
" random.open a:" file "cat "exec
" ec random.put random.close"  exec
1. pass + pass :=
  pass passes = if
  screen.clear
```

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Page 3   A:\EC.DMO   Ø6/1Ø/88   Ø9:59:48.43

```
pause
screen.print
then
;
```

ECSTAT

```
\      This program reads values for the dielectric constant of top cover
\ from a floppy disk in drive A.  For each pass on a deck, an average ec is
\ calculated, and the percentage of points where ec 12 and ec>ecmean+2 is
\ computed.  The standard deviation of the ec values for each pass is also
\ calculated.  The percentages and standard deviations for each pass are
\ averaged and then printed.

\ The following statements declare the variables and arrays used by
\ this program.

integer scalar passes        \ represents the number of passes on a deck
8 passes :=
integer scalar pass          \ pass is a counter from 1 to passes
1 pass :=
real dim[ 600 ] array ec     \ this array holds the ec values
real scalar num              \ represents the length of the pass
real scalar ecmean           \ represents the mean of the concrete dielectric c.
real scalar ecvar            \ represents the variance of the concrete diel. c.
real dim[ 15 ] array ecstd   \ this array holds the standard deviation of the
                             \   dielectric constant of concrete for each pass
real scalar level2           \ represents ecmean+2
real scalar count1           \ number of points in a pass where ec>12
real scalar count2           \ number of points in a pass where ec>ecmean+2
real dim[ 15 ] array %det1   \ this array holds the %deterioration values for each
                             \   pass, assuming deterioration is defined as ec>12
real dim[ 15 ] array %det2   \ this array holds the %deterioration values for each
                             \   pass, assuming deterioration is defined as ec>m+2
real scalar ec12             \ average of % deterioration for each pass, where
                             \   deterioration is defined as ec>12
real scalar ecm2             \ average of % deterioration for each pass, where
                             \   deterioration is defined as ec>ecmean+2
real scalar sec              \ average of the standard deviation for each pass

30 string file               \ file is a string variable that holds the name of
                             \   the DOS file which contains the waveforms

integer dim[ 200 ] array feet   \ this array is not used
integer scalar direction        \ this scalar is not used

0 %det1 :=                   \ initialize variables to zero
0 %det2 :=
0 ecstd :=

\ The main routine of the program is called ont.  To run this routine, the
\ user must place values for the length of the pass on top of the stack and
\ put the name of the DOS file containing the waveforms on the symbol stack.
\ For example:        122 122 -1 " nh\n2-v-c.dat " file := ont

: ont
    0 ec :=                  \ initialize variables to zero
```

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Page 1   C:\JEFF\ECSTAT.DMO   26/16/88   10:38:39.16

```
0 count1 :=
0 count2 :=
0 feet :=                 \ not used
direction :=              \ not used
feet [ 1 ] :=             \ not used
num :=                    \ loads length of pass
" random.open a:" file "cat "exec      \ opens the ec file on the floppy
                                       \    disk in drive A
ec random.get                          \ loads the ec array
ec sub[ 1 , num ] mean ecmean :=       \ computes the mean of ec for the pass
ec sub[ 1 , num ] variance ecvar :=    \ computes the variance of ec
ecvar sqrt ecstd [ pass ] :=           \ computes the standard deviation of
                                       \    ec and stores it to the ecstd
                                       \    array
ecmean 2. + level2 :=                  \ computes ecmean+2

\ This loop counts the number of points along a pass where ec>12 and
\ ec>ecmean+2.
num 0 do
    ec [ i 1 + ] 12. > if count1 1 + count1 := then
    ec [ i 1 + ] level2 > if count2 1 + count2 := then
    stack.clear
loop

\ These statements calculate the percentage of points along a pass where
\ ec>12 and ec>ecmean+2.
count1 num / 100. * %det1 [ pass ] :=
count2 num / 100. * %det2 [ pass ] :=
random.close

1 pass + pass :=          \ these statements are part of the pass counter
pass passes > if

%det1 sub[ 1 , passes ] mean ec12 :=    \ averages ec>12 percentages
%det2 sub[ 1 , passes ] mean ecm2 :=    \ averages ec>ecmean+2 percentages
ecstd sub[ 1 , passes ] mean sec :=     \ averages standard deviations
normal.display

\ These statements plot the name of the deck, average percentages of ec>12
\ ec>ecmean+2 areas, and average standard deviation.
cr
out>printer
cr
  Vermont 2          " ec12 ".    cat "      " "cat ecm2 "." "cat
                  " "cat sec ".   cat "type

cr
console
pause
stack.clear

then
;
```

```
vuport tcplot
tcplot 0.2 0.0 vuport.orig 0.8 1.0 vuport.size

integer dim[ 500 ] array w1
real dim[ 150 ] array wave
real dim[ 300 ] array conc
integer dim[ 300 ] array feet

integer scalar num
integer scalar a
real scalar amag
integer scalar c
real scalar cmag
real scalar r2
integer scalar e
integer scalar d
real scalar ea
real scalar aprime
real scalar eas
real scalar ecs

integer scalar direction
integer scalar scale
integer scalar tick

real scalar passes          \ NOTE:   this value represents the # of passes
8. passes :=                \         to be printed
real scalar pass
0. pass :=

30 string file
1 set.#.optima
17 set.#.points

     graphics.display
     axis.defaults
     tcplot
     normal.coords
         .01 .4 position 90 char.dir 90 label.dir
          " top cover" label
         .3 .03 position 0 char.dir 0 label.dir
         " position along deck (feet)" label
     200 scale :=     \ NOTE:   for M1, M2 change 200 to 300 and 11 to 16
     11 tick :=       \      and for RI1, NH1 change 200 to 100 and 11 to 6
     horizontal label.scale.off
     vertical label.scale.off
     horizontal axis.fit.off
     vertical axis.fit.off
     horizontal axis.on
     vertical axis.on
     horizontal grid.on
     vertical grid.on
```

```
    horizontal -20 scale world.set
    vertical 1 40 world.set
    tick 13 axis.divisions
    horizontal 1 2 label.points
    vertical 0 1 label.points
    tcplot xy.axis.plot

: ont
    tcplot
    0 feet :=
    0 conc :=

    direction :=
    feet [ 1 ] :=
    num :=
    num 0 do
        direction feet [ i 1 + ] + feet [ i 2 + ] :=
        stack.clear
    loop

    " random.open " file "cat "exec
    num 0 do i 1 + .
        i 1000 * random.lseek
        w1 random.get

        \ NOTE:  for Vermont add this line:
        \        0 w1 - w1 :=

        w1 sub[ 1 , 155 ] local.maxima
        amag := a :=
        w1 sub[ a , 150 ] wave :=
        wave sub[ 15 , 135 ] local.maxima   \ NOTE:  for Mi1, NH1 change 15 to 40
        cmag := a + 15 + c :=               \        and 135 to 100
        cmag amag / r2 :=
        stack.clear

            5.5 ea :=     \ NOTE:  5.5 is for M1, for other decks use:
                          \ 5.0 M3, 6.0 Mi1, 5.5 NH2, 6.4 RI1, 6.0 Vt1, 6.4 NH1
            ea 2.5 ** eas :=
            4.0 eas * 1.0 ea - / aprime :=
            aprime r2 - aprime r2 + / eas * ecs :=


        5 c + e :=

        w1 sub[ e , 55 ] local.maxima \ NOTE: for NH2, RI1, NH1 change 55 to 65
        if
            swap e + d :=
            d c - .02 * d. * ecs / conc [ i 1 - ] :=   \ NOTE: .02 is a
                                                       \ calibration factor:
                                                       \ .019 M1, .021 M3,
                                                       \ .021 Mi1, .022 NH2,
                                                       \ .02 RI1, .018 Vt1,
                                                       \ .022 NH1
```

```
        else
        i Ø > if conc [ i ] conc [ i 1 + ] := then
        i Ø = if Ø.Ø conc [ 1 ] := then
        then

        conc [ i 1 + ] 5.Ø > if 5.Ø conc [ i 1 + ] := then
        conc [ i 1 + ] Ø.Ø < if Ø.Ø conc [ i 1 + ] := then
        stack.clear
        loop

    feet sub[ 1 , num ] conc sub[ 1 , num ] pass 3. * + xy.data.plot
    random.close
    1. pass + pass :=
        pass passes = if
        screen.clear
        pause
        screen.print
        then
;
```

\ TCM2.DMO

```
vuport tcplot
tcplot 0.2 0.0 vuport.orig 0.8 1.0 vuport.size

integer dim[ 500 ] array wl
real dim[ 150 ] array wave
real dim[ 300 ] array conc
integer dim[ 300 ] array feet

integer scalar num
integer scalar c
integer scalar d

integer scalar direction
integer scalar scale
integer scalar tick

real scalar passes          \ NOTE:  this value represents the # of passes
7. passes :=                \          to be printed
real scalar pass
0. pass :=

30 string file
1 set.#.optima
17 set.#.points

    graphics.display
    axis.defaults
    tcplot
    normal.coords
        .01 .4 position 90 char.dir 90 label.dir
        " top cover" label
        .3 .03 position 0 char.dir 0 label.dir
        " position along deck (feet)" label
    300 scale :=
    16 tick :=
    horizontal label.scale.off
    vertical label.scale.off
    horizontal axis.fit.off
    vertical axis.fit.off
    horizontal axis.on
    vertical axis.on
    horizontal grid.on
    vertical grid.on
    horizontal -20 scale world.set
    vertical 0 65 world.set
    tick 13 axis.divisions
    horizontal 1 2 label.points
    vertical 2 1 label.points
    tcplot xy.axis.plot

: ont
    tcplot
```

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```
Ø feet :=
Ø conc :=

direction :=
feet [ 1 ] :=
num :=
num Ø do
    direction feet [ i 1 + ] + feet [ i 2 + ] :=
    stack.clear
loop.

" random.open " file "cat " exec
num Ø do i 1 + .
    i 1ØØØ * random.lseek
    w1 random.get
    w1 sub[ 1 , 155 ] local.maxima
    swap c :=
    w1 sub[ c , 15Ø ] wave :=
    wave sub[ 15 , 6Ø ] local.maxima

    if
        swap c + 15 + d :=
        d c - .Ø21 * 6. * 3.Ø / conc [ i 1 + ] :=     NOTE: .Ø21 is a
                                                      \ calibration factor:
                                                      \ Assume ecs=3.Ø

    else
    i Ø > if conc [ i ] conc [ i 1 + ] := then
    i Ø = if Ø.Ø conc [ 1 ] := then
    then

    conc [ i 1 + ] 5.Ø > if 5.Ø conc [ i 1 + ] := then
    conc [ i 1 + ] Ø.Ø < if Ø.Ø conc [ i 1 + ] := then
    stack.clear
    loop

feet sub[ 1 , num ] conc sub[ 1 , num ] pass 5. * + xy.data.plot
random.close
1. pass + pass :=
    pass passes = if
    screen.clear
    pause
    screen.print
    then
;
```

\ LN.DMO

```
\       This program calculates and plots values for the expression
                        (-1/tc)(lnD/A).
\
\ The program locates waveform peaks A, C, and D, computes the R2 and
\ R3 ratios, and uses estimated asphalt dielectric constants to compute
\ the dielectric constant of concrete by using the following relationship:



\ The program then computes the top cover thickness of concrete and calculates
\ and plots the values for (-1/tc)(lnD/A).

\ These statements define the graphic area.

vuport lnplot
lnplot 0.2 0.0 vuport.orig 0.8 1.0 vuport.size

\ The following statements declare the variables and arrays used
\ by this program.

integer dim[ 500 ] array w1          \ this array holds raw waveforms
real dim[ 150 ] array wave           \ a sub-array of w1
real dim[ 300 ] array value          \ holds values for (-1/tc)(lnD/A)
integer dim[ 300 ] array feet        \ contains locations along a pass

real scalar amag                     \ represents the magnitude of peak A
real scalar cmag                     \ represents the magnitude of peak C
integer scalar a                     \ represents the location of peak A
integer scalar c                     \ represents the location of peak C
real scalar r2                       \ represents R2
integer scalar e                     \ used in window specification
integer scalar d                     \ represents location of peak D
real scalar dmag                     \ represents magnitude of peak D
real scalar da                       \ represents D/A or R3
real scalar ea                       \ dielectric constant of asphalt
real scalar aprime                   \ used to compute ecs
real scalar eas                      \ square root of ea
real scalar ecs                      \ square root of dielectric constant
                                     \    of top cover of concrete
real scalar conc                     \ top cover thickness in inches


integer scalar num                   \ represents length of pass
integer scalar direction             \ represents direction of pass
integer scalar scale                 \ x-axis length for graphic plots
integer scalar tick                  \ x-axis tick marks for graphic plots

real scalar passes                   \ NOTE:  this value represents the number
5. passes :=                         \        of passes to be printed for a deck
real scalar pass                     \ pass is a counter from 0 to passes
```

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```
0. pass :=

30 string file                              \ file is a string variable that holds the
                                            \   name of the DOS file which contains the
                                            \   waveforms
1 set.#.optima                              \ tells ASYST to search for the steepest
                                            \   maximawhen the local.maxima command
                                            \   is used
17 set.#.points                             \ tells ASYST to use 17 points in a maxima
                                            \   search

\ The following statements plot axes and labels in the graphic vuport.

    graphics.display
    axis.defaults
    lnplot
    normal.coords
        .01 .4 position 90 char.dir 90 label.dir
        " -1/tc ln d/a" label
        .3 .03 position 0 char.dir 0 label.dir
        " position along deck (feet)" label
    200 scale :=             \ NOTE:  for M1 change 200 to 300 and 11 to 16
    11 tick :=               \        for R1, N1 change 200 to 100 and 11 to 6
    horizontal label.scale.off
    vertical label.scale.off
    horizontal axis.fit.off
    vertical axis.fit.off
    horizontal axis.on
    vertical axis.on
    horizontal grid.on
    vertical grid.on
    horizontal -20 scale world.set
    vertical 0 65 world.set
    tick 13 axis.divisions
    horizontal 1 2 label.points
    vertical 0 1 label.points
    lnplot xy.axis.plot

\ The main routine of the program is called ont.  To run this routine, the
\ user must place values for the length of the pass on top of the stack and
\ put the name of the DOS file containing the waveforms on the symbol stack.
\ For example:       120 120 -1 " \nh\n2-v-c.dat " file ":= ont

: ont
    lnplot                                  \ results will be plotted in vuport lnplot
    0 feet :=                               \ initialize feet to zero
    0 value :=                              \ initialize value to zero

                                            \ loads direction of pass
    direction :=                            \ loads direction of first radar sample
    feet [ 1 ] :=                           \ loads length of pass
    num :=                                           \ this loop fills the
    num 0 do                                         \   feet array with
        direction feet [ i 1 + ] + feet [ i 2 + ] := \   radar sample
        stack.clear

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Page 2    A:\LN.DMO    06/10/88    10:20:03.40
```

```
                                                        \    locations
  loop

  " random.open "- file 'cat 'exec \ opens DOS file to read waveforms

\ This loop operates on one wave at a time.
  num Ø do i 1 + .
      i 1ØØØ * random.lseek           \ searches for a wave
      w1 random.get                   \ loads it into w1

      \ NOTE:  since the waveforms for deck V1 are inverted, the following
      \           statement must be included for this deck:
      \                    Ø w1 - w1 :=

      \ The following statements set windows to search for maximas, and
      \    determine magnitudes and locations of peaks A and C.
      w1 sub[ 1 , 155 ] local.maxima
      amag := a :=
      w1 sub[ a , 15Ø ] wave :=
      wave sub[ 15 , 135 ] local.maxima   \ NOTE:   for Mi1, N1 change 15 to 4Ø
      cmag := a + 15 + c :=               \         and 135 to 1ØØ

      cmag amag / r2 :=              \ computes the R2 ratio
      stack.clear

     \ The following statements use R2 and estimated ea values to compute ecs.
          5.5 ea :=          \ NOTE:  5.5 is for M1, for other decks use:
                             \        5.Ø M3, 6.Ø Mi1, 5.5 N2, 6.4 R1, 6.Ø V1
                             \        6.4 N1

          ea Ø.5 ** eas :=
          4.Ø eas * 1.Ø ea - / aprime :=
          aprime r2 - aprime r2 + / eas * ecs :=

      \ These statements set a window to search for peak D, and determine
      \    the location and magnitude and location of peak D.
      5 c + e :=
      w1 sub[ e , 55 ] local.maxima \ NOTE:  for N2, R1, N1 change 55 to 65
      if
          dmag :=  e + d :=
          dmag amag / da :=                           \ computes D/A or R3

          d c - .02 * 6. * ecs / conc :=              \ computes top cover
                                                      \ NOTE: .Ø2 ns/pt is a
                                                      \ calibration factor:
                                                      \ .019 M1, .021 M3,
                                                      \ .Ø21 Mi1, .022 N2,
                                                      \ .02 R1, .018 V1
                                                      \ .022 N1

          da 0.0 > if                                 \ computes -1.tc (lnD/A)
          0.Ø da ln conc / - value [ i 1 + ] :=       \
          else 0.0 value [ i 1 - ] := then            \
      else

      \ If the program cannot locate peak D for any location, the previous
```

```
    \   value for ec is assumed.
    i 0 > if value [ i ] value [ i 1 + ] := then
    i 0 = if 5.0 value [ i ] := then
    then

    \ This statement limits value to less than 5.
    value [ i 1 + ] 5.0 > if 5.0 value [ i 1 + ] := then
    stack.clear
  loop

\ The following statements plot the (-1/tc)(lnD/A) values along each pass.
feet sub[ 1 , num ] value sub[ 1 , num ] pass 5. * + xy.data.plot
random.close
1. pass + pass :=
    pass passes = if
    screen.clear
    pause
    screen.print
    then
;
```

```
vuport lnplot
lnplot 0.2 0.0 vuport.orig 0.8 1.0 vuport.size

integer dim[ 500 ] array w1
real dim[ 150 ] array wave
real dim[ 300 ] array value
integer dim[ 300 ] array feet

integer scalar num
integer scalar c
real scalar cmag
integer scalar d
real scalar dmag
real scalar dc
real scalar conc

integer scalar direction
integer scalar scale
integer scalar tick

real scalar passes          \ NOTE:  this value represents the # of passes
7. passes :=               \          to be printed
real scalar pass
0. pass :=

30 string file
1 set.#.optima
17 set.#.points

     graphics.display
     axis.defaults
     lnplot
     normal.coords
          .01 .4 position 90 char.dir 90 label.dir
          " -1/tc ln d/c" label
          .3 .03 position 0 char.dir 0 label.dir
          " position along deck (feet)" label
     300 scale :=
     16 tick :=
     horizontal label.scale.off
     vertical label.scale.off
     horizontal axis.fit.off
     vertical axis.fit.off
     horizontal axis.on
     vertical axis.on
     horizontal grid.on
     vertical grid.on
     horizontal -20 scale world.set
     vertical 0 65 world.set
     tick 13 axis.divisions
     horizontal 1 2 label.points
     vertical 0 1 label.points
     lnplot xy.axis.plot

  : ont
     lnplot
     0 feet :=
     0 value :=

     direction :=
     feet [ 1 ] :=
     num :=
     num 0 do
```

```
        direction feet [ i 1 + ] + feet [ i 2 + ] :=
        stack.clear
    loop

    " random.open " file "cat "exec
    num Ø do i i + .
        i 1ØØØ * random.lseek
        w1 random.get
        w1 sub[ 1 , 155 ] local.maxima
        cmag := c :=
        w1 sub[ c , 15Ø ] wave :=
        wave sub[ 15 , 6Ø ] local.maxima
        if
            dmag := c + 15 + d :=
            dmag cmag / dc :=
            d c - .Ø21 * 6. * 3.Ø / conc :=           \ NOTE: .Ø21 is a
                                                      \ calibration factor:
                                                      \ Assume ecs=3.Ø

            dc Ø.Ø > if
            Ø.Ø dc ln conc / - value [ i 1 + ] :=
            else 5.Ø value [ i 1 + ] := then

        else
        i Ø > if value [ i ] value [ i 1 + ] := then
        i Ø = if 5.Ø value [ 1 ] := then
        then

        value [ i 1 + ] 5.Ø > if 5.Ø value [ i 1 + ] := then
        stack.clear
        loop

    feet sub[ 1 , num ] value sub[ 1 , num ] pass 5. * + xy.data.plot
    random.close
    1. pass + pass :=
        pass passes = if
        screen.clear
        pause
        screen.print
        then
;
```

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