297

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/VA-86/3		

4. Title and Subtitle	5. Report Date
Survey of Bridge Decks with Ground-Penetrating Radar -- A Manual	July 1985
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Gerardo G. Clemeña	VHTRC 86-R3
9. Performing Organization Name and Address	10. Work Unit No.
Virginia Highway & Transportation Research Council P. O. Box 3817, University Station Charlottesville, Virginia 22903	11. Contract or Grant No. HPR 2098-202
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Virginia Department of Highways & Transportation 1221 E. Broad Street Richmond, Virginia 23219	Final September 1983 - July 1985
	14. Sponsoring Agency Code

15. Supplementary Notes

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

16. Abstract

This manual has been prepared to facilitate the use of ground-penetrating radar (GPR) in the bridge inspection program of the Virginia Department of Highways and Transportation. It briefly discusses the basic principle of GPR, and its application in the nondestructive inspection of bridge decks for delaminations in the reinforced concrete. It then provides guides on the survey procedure, the operation of a microwave radar system, and the interpretation and the quantification of radar results.

17. Key Words	18. Distribution Statement
Ground-penetrating radar, bridge decks, delamination in concrete	No restrictions. This document is available through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	58	

Form DOT F 1700.7 (8-69)

SURVEY OF BRIDGE DECKS WITH GROUND-PENETRATION RADAR -- A MANUAL

by

Gerardo G. Clemena
Research Scientist

Virginia Highway & Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia
Department of Highways & Transportation and
the University of Virginia)

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

July 1985
VHTRC 86-R3

300

BRIDGE RESEARCH ADVISORY COMMITTEE

L. L. MISENHEIMER, Chairman, District Bridge Engineer, VDH&T

J. E. ANDREWS, Bridge Design Engineer Supervisor, VDH&T

C. L. CHAMBERS, Division Bridge Engineer, FHWA

C. D. GARVER, JR., Division Administrator -- Construction Div., VDH&T

M. H. HILTON, Senior Research Scientist, VH&TRC

J. G. G. MCGEE, Assistant Construction Engineer, VDH&T

M. F. MENEFEE, JR., Structural Steel Engineer, VDH&T

R. H. MORECOCK, District Bridge Engineer, VDH&T

C. A. NASH, JR., District Engineer, VDH&T

F. L. PREWOZNIK, District Bridge Engineer, VDH&T

W. L. SELLARS, District Bridge Engineer, VDH&T

F. G. SUTHERLAND, Bridge Engineer, VDH&T

L. R. L. WANG, Prof. of Civil Engineering, Old Dominion University

C. P. WILLIAMS, District Materials Engineer, VDH&T

FOREWORD

In 1976, the Research Council initiated research on the use of infrared thermography for locating concrete delaminations in bridge decks. In 1978, it reported that under suitable weather conditions, thermography is a faster and more effective method than conventional sounding methods for surveying concrete decks that have not been overlaid with bituminous concrete. For overlaid bridge decks, however, the effectiveness of thermography is at best questionable.

Consequently, in 1980 the focus of the research effort was shifted toward the use of ground-penetrating radar (GPR), which the Council had just shown to be extremely useful for nondestructive surveys of sidewalk undermining that had become a problem in Northern Virginia. Since then, GPR has and is being increasingly recognized across the country as a useful method for surveying both non-overlaid and overlaid concrete decks.

This Manual has been prepared to facilitate the use of this technique by the Virginia Department of Highways and Transportation. An attempt has been made to strike a balance between presenting too much or too little on the basic principle of GPR. It is hoped that by providing some insight into the working principle of GPR, the Manual will prove helpful to the people who use the technique and make them aware of its current limitations. There is no doubt that future improvements of radar systems, such as antennas with narrower pulse widths, systems that simultaneously utilize three or more antennas, etc., will eliminate most of these limitations.

ACKNOWLEDGMENT

Appreciation is extended to F. G. Sutherland, state bridge engineer, for his valuable support. Appreciation is also extended to W. L. Sellars, Lynchburg district bridge engineer, and E. R. Driskill, Jr. of his staff, for their cooperation.

The author thanks those members of the Council who gave valuable assistance with the study, and H. E. Brown for administrative guidance.

TABLE OF CONTENTS

To Convert From	To	Multiply By
Length:		
in	cm	2.54
in	m	0.025 4
ft	m	0.304 8
yd	m	0.914 4
mi	km	1 . 609 344
Area:		
in^2	cm^2	6.451 600 E+00
ft^2	m^2	9.290 304 E-02
yd^2	m^2	8.361 274 E-01
mi^2	Hectares	2.589 988 E+02
acre (a)	Hectares	4.046 856 E-01
Volume:		
oz	m^3	2.957 353 E-05
pt	m^3	4.731 765 E-04
qt	m^3	9.463 529 E-04
gal	m^3	3.785 412 E-03
in^3	m^3	1.638 706 E-05
ft^3	m^3	2.831 685 E-02
yd^3	m^3	7.645 549 E-01

NOTE: $1m^3 = 1{,}000$ L

To Convert From	To	Multiply By
Volume per Unit Time:		
ft^3/min	m^3/sec	4.719 474 E-04
ft^3/s	m^3/sec	2.831 685 E-02
in^3/min	m^3/sec	2.731 177 E-07
yd^3/min	m^3/sec	1.274 258 E-02
gal/min	m^3/sec	6.309 020 E-05
Mass:		
oz	kg	2.834 952 E-02
dwt	kg	1.555 174 E-03
lb	kg	4.535 924 E-01
ton (2000 lb)	kg	9.071 847 E+02
Mass per Unit Volume:		
lb/yd^2	kg/m^2	4.394 185 E+01
lb/in^3	kg/m^3	2.767 990 E+04
lb/ft^3	kg/m^3	1.601 846 E+01
lb/yd^3	kg/m^3	5.932 764 E-01
Velocity: (Includes Speed)		
ft/s	m/s	3.048 000 E-01
mi/h	m/s	4.470 400 E-01
knot	m/s	5.144 444 E-01
mi/h	km/h	1.609 344 E+00
Force Per Unit Area:		
lbf/in^2	Pa	6.894 757 E+03
lbf/ft^2	Pa	4.788 026 E+01
Viscosity:		
cS_t	m^2/s	1.000 000 E-06
P	Pa·s	1.000 000 E-01

Temperature: $°F-32)^5/9 = °C$

1. GLOSSARY

Address -- One of 65,536 locations on a Scotch DC 600HC magnetic tape that can store 1 kilobyte of data.

Attenuation -- The reduction, due to scattering or absorption, in the intensity of an electromagnetic wave as it propagates through a material.

Byte -- A group of 8 bits of digital information.

Conductivity -- A measure of the ability of a material to conduct electrical current. It is the reciprocal of resistivity.

Dielectric constant -- That property of a material that determines the electrostatic energy stored per unit volume, for unit potential gradient; synonymous with permittivity.

Electromagnetic wave -- A disturbance produced by the acceleration or oscillation of an electrical charge. In order of increasing frequency (or decreasing wavelength), the important types of electromagnetic wave are radio waves, infrared radiation, visible light, x-rays, and gamma-rays. Their production can always be ultimately related to the acceleration of electrons, protons, or other charged fundamental particles.

Interface -- The boundary between two materials with different dielectric constants.

Kilobyte -- 1,024 bytes.

LED (light-emitting diode) -- A rectifying semiconductor device that converts electrical energy into light. It is commonly used as a solid-state indicator light.

LCD (liquid-crystal display) -- A display device for electronic instruments; usually consists of a thin film of room-temperature liquid crystal sandwiched between two transparent electrodes. It is desirable because of its comparatively low power consumption and the excellent clarity of the resulting display.

Loss tangent -- Synonymous with dissipation factor, it describes the electrical energy dissipated by an electrical field through molecular collisions in a dielectric material.

Magnetic permeability -- The ability of a material to modify the resulting magnetic induction when the material is subjected to a magnetic field.

3110

Microwave -- An electromagnetic wave whose wavelength is in the range of 10^{-1} to 10^{2} cm. It is bounded by the various kinds of radio waves on the longer wavelength and by infrared radiation on the shorter wavelength side of the spectrum of electromagnetic waves.

Reflection coefficient -- The ratio of the amplitudes, or energy, in the reflected wave to that in the incident wave. Reflection occurs when an electromagnetic wave passes from one medium to another medium with different dielectric constants.

Reflection profile -- A continuous depth, or transit time, profile of various microwave reflections from throughout the cross section of a bridge deck.

Read -- The process of playing back or reproducing digital data from a magnetic tape.

Scan path -- The longitudinal path taken by the microwave antenna as it traverses a bridge deck being inspected.

Write -- The recording of digital data onto magnetic tape.

2. PRINCIPLE OF GROUND-PENETRATING RADAR

NOTE: Users who may not be interested in the following discussion on the behavior of microwave pulses during propagation through a material can proceed directly to Section 2.2 on page 7.

2.1 Basic Principle

During World War II, there was rapid advancement in the technology of radar because of its military significance. Subsequent refinements in the technology made it possible for radar to be used not only for the detection of objects, but also for the recognition of certain details of objects by their electromagnetic (EM) wave reflection and absorption characteristics. Since this technology was also applicable to the transmission of EM waves through solids, in the early 1950s experiments in the use of microwave radar for probing through rocks, soil, etc., were conducted. And, it was quickly recognized that when microwaves were transmitted through solids, their behavior could vary significantly from one material to another, as the following discussion will show.

2.1.1 Behavior of microwaves at the interface of two different materials

Consider first the behavior of microwaves at the interface, or boundary, between two materials of different dielectric properties, as depicted in Figure 2.1. When a wave strikes the interface, some of its energy is reflected, and the remainder penetrates through the interface into the second material. The reflected energy, E_r, is related to the incident energy, E_o, by

$$\rho = \frac{E_r}{E_o} = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \qquad (1)$$

where

ρ = reflection coefficient at the interface, and

η_1, η_2 = the wave impedances of materials 1 and 2, respectively, in ohms.

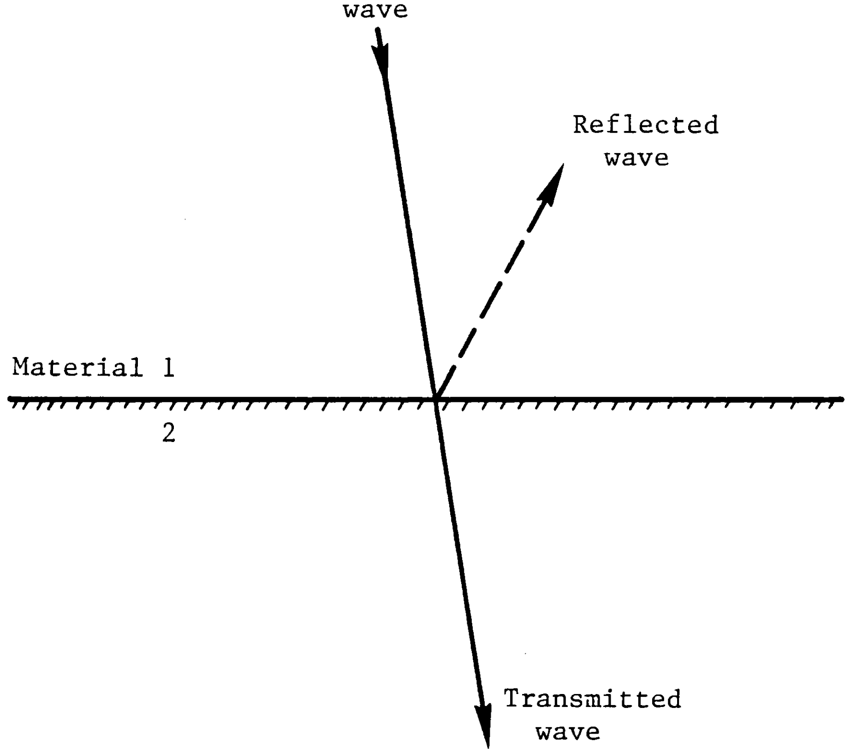


Figure 2.1. Behavior of electromagnetic waves at a dielectric boundary.

For any nonmetallic material such as concrete or soil, the wave impedance is given by

$$\eta = \sqrt{\frac{\mu_o}{\varepsilon}} \tag{2}$$

where

μ_o = the magnetic permeability of free space, which is $4\Pi \times 10^{-7}$ henry/meter, and

ε = the dielectric constant of the materials in farad/meter.

(For a metal, which is a good conductor, the wave impedance is zero, which explains why metals are perfect reflectors.) Since the wave impedance of free space is

$$\eta_o = \sqrt{\frac{\mu_o}{\varepsilon_o}} \tag{3}$$

and if we define the relative dielectric constant, ε_r, of a material as

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_o} \tag{4}$$

where

ε_o = the dielectric constant of free space, which is 8.85×10^{-12} farad/meter, then

we may rewrite equation 2 as

$$\eta = \frac{\eta_o}{\sqrt{\varepsilon_r}} \tag{5}$$

and equation 1 as

$$\rho = \frac{\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}}{\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}} \tag{6}$$

where ε_{r1} and ε_{r2} are the relative dielectric constants of materials 1 and 2, respectively.

Equation 6 implies that when the microwave strikes the interface between two materials of differing dielectric properties, i.e., $\varepsilon_{r1} \neq \varepsilon_{r2}$, the microwave will be reflected in the amount dictated by the value of ρ. And, if material 2 has a larger relative dielectric constant than material 1, then ρ would have a negative value; i.e., the reflected wave will have a polarity opposite that of the incident wave.

2.1.1 Propagation of microwave through a solid

After penetrating the interface and into material 2, the wave propagates through the material with a velocity, V_2, given by

$$V_2 = \frac{C}{\sqrt{\varepsilon_{r2}}} \qquad (7)$$

where C is the propagation velocity of the microwave through free space, which is equivalent to the velocity of light, or 1 ft/ns (0.3 m/ns).

And, as the wave propagates through the material, its energy is attenuated as follows:

$$A = 12.863 \times 10^{-8}\ f \sqrt{\varepsilon_{r2}}\ \{\sqrt{1 + \tan^2 \delta} - 1\}^{1/2} \qquad (8)$$

where the loss tangent is given by

$$\tan \delta = 1.80 \times 10^{10} \frac{\sigma}{f\ \varepsilon_{r2}} \qquad (9)$$

and A = attenuation, in decibel/meter,

f = wave frequency, in Hz, and

σ = electrical conductivity, in mho/meter.

When this wave strikes another interface, it will be partially reflected back (according to equation 6) through material 2. The resulting two-way transit time, t, of this portion of the wave through this material is

$$t = \frac{2D}{V_2} = \frac{2D\sqrt{\varepsilon_{r2}}}{C} \qquad (10)$$

where D is the thickness of material 2.

2.2 Applied Principle in the Survey of Bridge Decks

In this section, the basic principle is applied in the nondestructive survey of bridge decks.

When microwave pulses are transmitted from an antenna into an overlaid concrete deck, as depicted in Figure 2.2, some pulses (p_1) will be reflected at the surface of the asphalt overlay. This reflection, of course, is due to the difference in the dielectric constants of air and asphalt (Tables 2.1 and 2.2).

The remaining pulses will travel through the layer of asphalt concrete at a velocity and attenuation corresponding to the dielectric constant of the material. When these pulses reach the asphalt/concrete interface, another reflection occurs and causes some pulses (p_2) to be reflected back.

The unreflected pulses penetrate into the reinforced concrete slab and continue on with the propagation process, unless these pulses strike rebars and are reflected. And if the concrete slab is sound, there will be one last reflection (p_4) at the bottom of the slab, with some pulses eventually penetrating through the deck.

However, if the slab is delaminated, there will be an additional reflection (p_3), and probably attenuation, at some complex "sound concrete/bad concrete/sound concrete" interface. This additional reflection, therefore, serves as an indicator of the presence of a delamination in the concrete slab. (All the reflected pulses will arrive at the antenna at transit times dictated by the dielectric constants and thicknesses of the materials they are propagated in, as governed by equation 10.)

It must be emphasized that this same principle applies for bridge decks that have not been overlaid, or clear concrete decks, and that ground-penetrating radar (GPR) can also be used to rapidly inspect such decks.

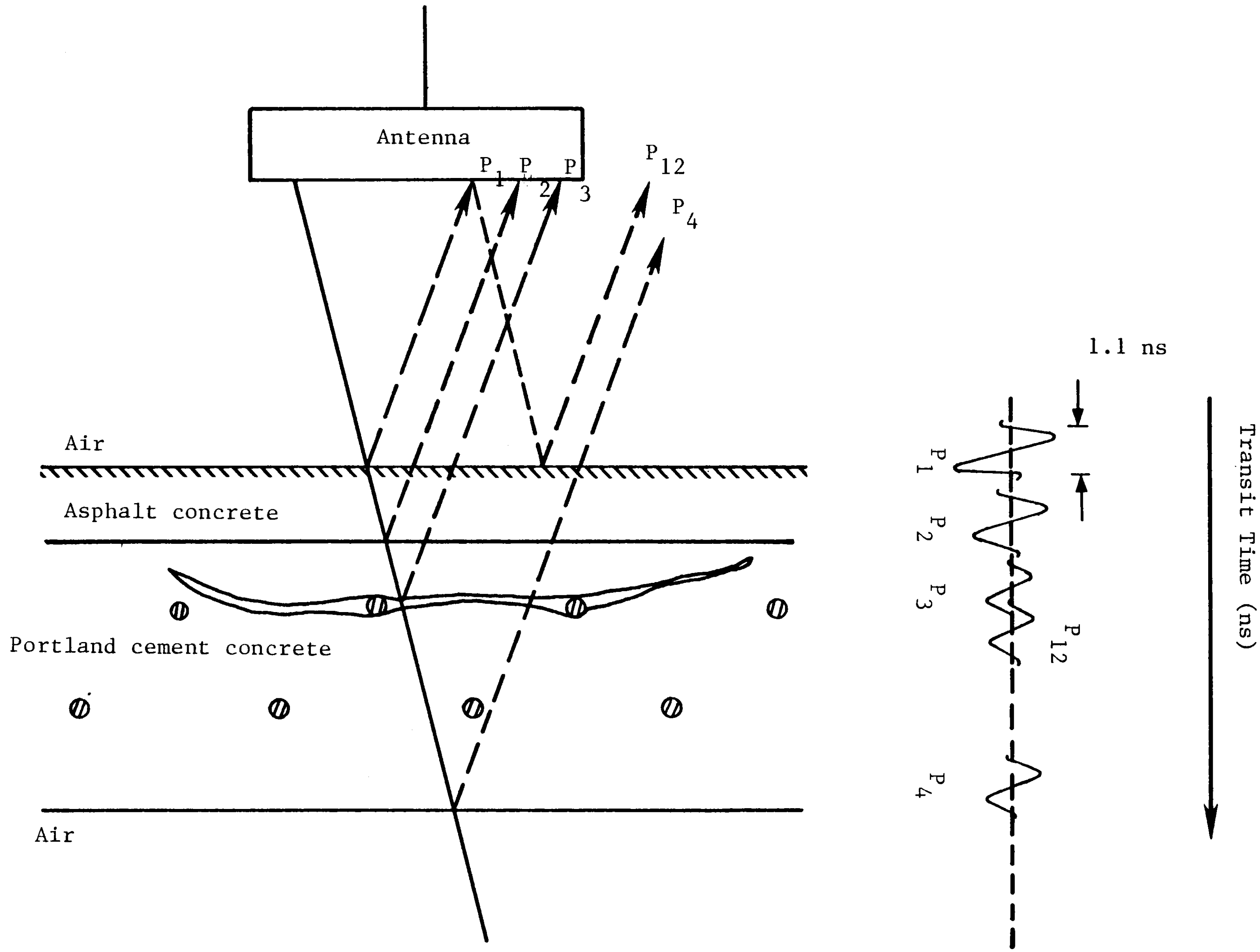


Figure 2.2. Transmission of microwave pulses through an overlaid bridge deck.

TABLE 2.1

Dielectric Properties of Materials Relevant to Bridge Decks

Materials	Approx. Relative Dielectric Constant, ε_r	Approx. Two-Way Transit Time of EM Wave
Air	1	0.07 ns/cm (0.17 ns/in)
Asphalt	3-4	0.12-0.13 ns/cm (0.29-0.34 ns/in)
Concrete	8-12	0.19-0.23 ns/cm (0.48-0.58 ns/in)

TABLE 2.2

Estimated Reflection Coefficients at Interfaces Relevant to Bridge Decks

Interface	Approx. Reflection Coefficient
Air/Asphalt	-0.3
Asphalt/Concrete	-0.2 to 0.3
Sound Concrete/Bad Concrete/ Sound Concrete	---
Concrete/Air	+0.5 to + 0.6

3. SURVEY PROCEDURE

NOTE: Unless the engineer (or inspector) is extremely familiar with the bridge deck to be surveyed, it is recommended that a set of plans of the deck be secured before the survey to aid in planning the survey. The plans would also be useful during the interpretation of the radar output after the survey.

The survey procedure consists essentially of setting up the radar antenna at an optimum height from the surface of the deck to be inspected, then passing the antenna from one end of the deck to the other while continuously recording the reflection pattern on either a graphic recorder or a high-speed tape recorder.

However, every antenna has a finite "field of view," or area of coverage, which depends on the height of the antenna. (Example, for the 101c antenna the coverage is approximately 15 in x 12 in when it is set at a height of 12 in, as shown in Figure 3.1.) This means that to get an adequate representation of the locations and sizes of all deteriorated areas in a deck the antenna would have to make several longitudinal passes, or scans, over the deck. During each scan a different point across the width of the deck is covered, so that a composite mapping of the delaminated concrete in the deck can be assembled.

3.1 Height of the Antenna

3.1.1 When surveying overlaid decks

Since each type of antenna has a characteristics pulse width (for 101C, it's 1.1 nsec), the pulse P_{12} shown in Figure 2.2 can be a source of interference when surveying an overlaid deck for deteriorated concrete. This pulse may arrive at the antenna at the same time as the pulse reflected from a concrete delamination, P_3, depending upon the thickness of the overlay, the depth of concrete over the top mat of rebars, and the height of the antenna. If this occurs, that delamination may not be located clearly, depending upon how much P_3 is masked by P_{12}.

As a rule, the larger the difference (Δt) in the transit, or arrival, times of these two pulses, the less is the interference. The calculated Δt based on the assumption of reasonable dielectric constants for the overlay and concrete shows that the optimum height of the antenna varies according to the thickness of the overlay and the depth of concrete cover on the deck (Figure 3.2). Examination of this illustration reveals that if we consider a difference of at least 0.55 nsec (which is a half of the pulse width of the 101C antenna) to be sufficient separation of P_{12} from P_3, then an antenna height of approximately 5 in would be acceptable in most cases.

However, it is safer for the antenna to be set higher if possible. Therefore, it is recommended that an effort be made to determine (or estimate) as well as possible the thickness of the overlay and the depth of concrete cover, so that it can be decided from Figure 3.2 whether the antenna can be set higher for a particular deck.

3.1.2 When surveying non-overlaid decks

The same interference posed by P_{12} on P_3 can occur when inspecting a non-overlaid deck. However, the situation is simpler than with overlaid decks, since the thickness of an overlay is not a factor.

Similar calculations of Δt, when a reasonable dielectric constant is assumed for concrete, have shown that an antenna height of 12 in or more is very acceptable (Figure 3.3).

3.2 Survey Speed

Depending upon the user's preference and circumstances, the radar scans of a deck can be carried out at two different speeds.

3.2.1 5 to 10 miles per hour

The antenna can be mounted on the bumper of a survey vehicle through a rack that allows the antenna to be manually moved across it (Figure 3.4). The vehicle then makes at least a few passes over each traffic lane, and during each pass the antenna is positioned at a different point along the rack.

It is desirable for the survey vehicle to be equipped with a "fifth-wheel" device, such as the kind used on skid trailers, so that any point on the recorder radar reflection pattern can be precisely correlated to a location on the bridge deck. However, for most bridge decks, which are less than several hundred feet long, such a device is not absolutely necessary, provided all scans are maintained at a constant speed so that the interpolation is reasonably valid.

Lane closure is not required at this survey speed; however, on heavily-travelled bridge decks, it is necessary to have caution vehicles leading and trailing the survey vehicle for safety purposes.

It is not yet known how much accuracy is sacrificed when surveying a deck at this speed, as no study has been reported.

3.2.2 Walking pace

When a more detailed and precise survey is desired and circumstances allow, a traffic lane can be briefly closed so that the antenna can be manually towed (or pushed) over the lane. The antenna can be mounted on a small, light dolly such as that shown in Figure 3.5.

The deck, of course, has to be grided first.

3.3 Layout of Grid System

When it is decided that the survey will be conducted at the slower speed, a grid system should be laid out over the deck so that the locations and, in particular, the sizes of any delaminations that are located can be precisely determined.

An example of an effective grid layout for bridge decks is shown in Figure 3.6. Note that the grid consists of several parallel, longitudinal scan paths 2 ft apart and running in the direction of the traffic. Each scan path is marked with points 10 ft apart (a closer spacing, such as 5 ft, can be used if preferred). On a clear concrete deck, where a grid, usually 5-ft squares, might already have been laid out for the survey of rebar corrosion activity, the radar scan paths may be separated 2.5 ft apart so that the existing grid can be used with only minor additional point markings.

When surveying at a walking pace it is convenient to scan from joint-to-joint and on one span at a time. During each scan, whenever the antenna is directly over a grid point or a joint, a reference (or tick) mark should be remotely triggered by the operator on the recording for locational purposes (see RADAR OPERATING PROCEDURE).

At the faster survey speed of 5 to 10 mph, a grid system is obviously not as beneficial, since it is extremely difficult to maneuver a survey vehicle so that the antenna is directly above a desired scan path during the entire pass, which would be from abutment to abutment. The best that one can achieve is probably within ±1 foot of any given desired scan path. Therefore, 3 scan paths -- one on each wheel path and one between these two paths -- for each traffic lane would be reasonable.

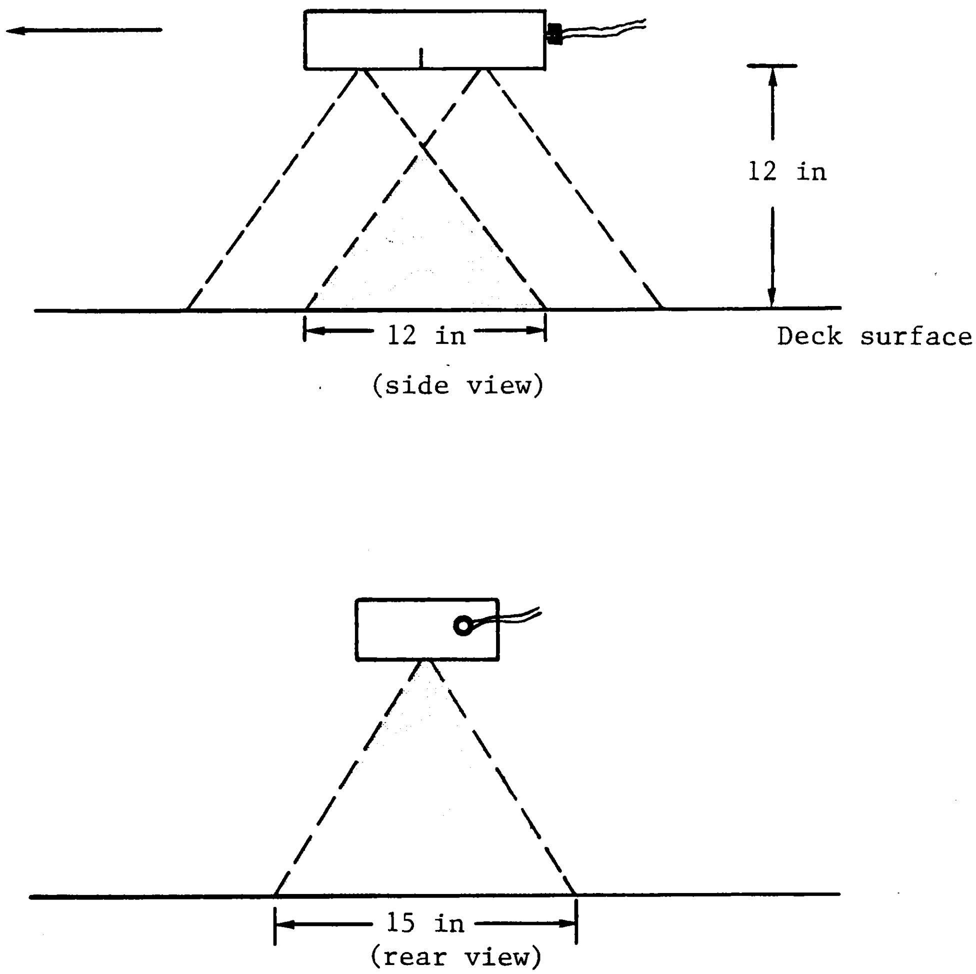


Figure 3.1. "Field of view" of the radar antenna.

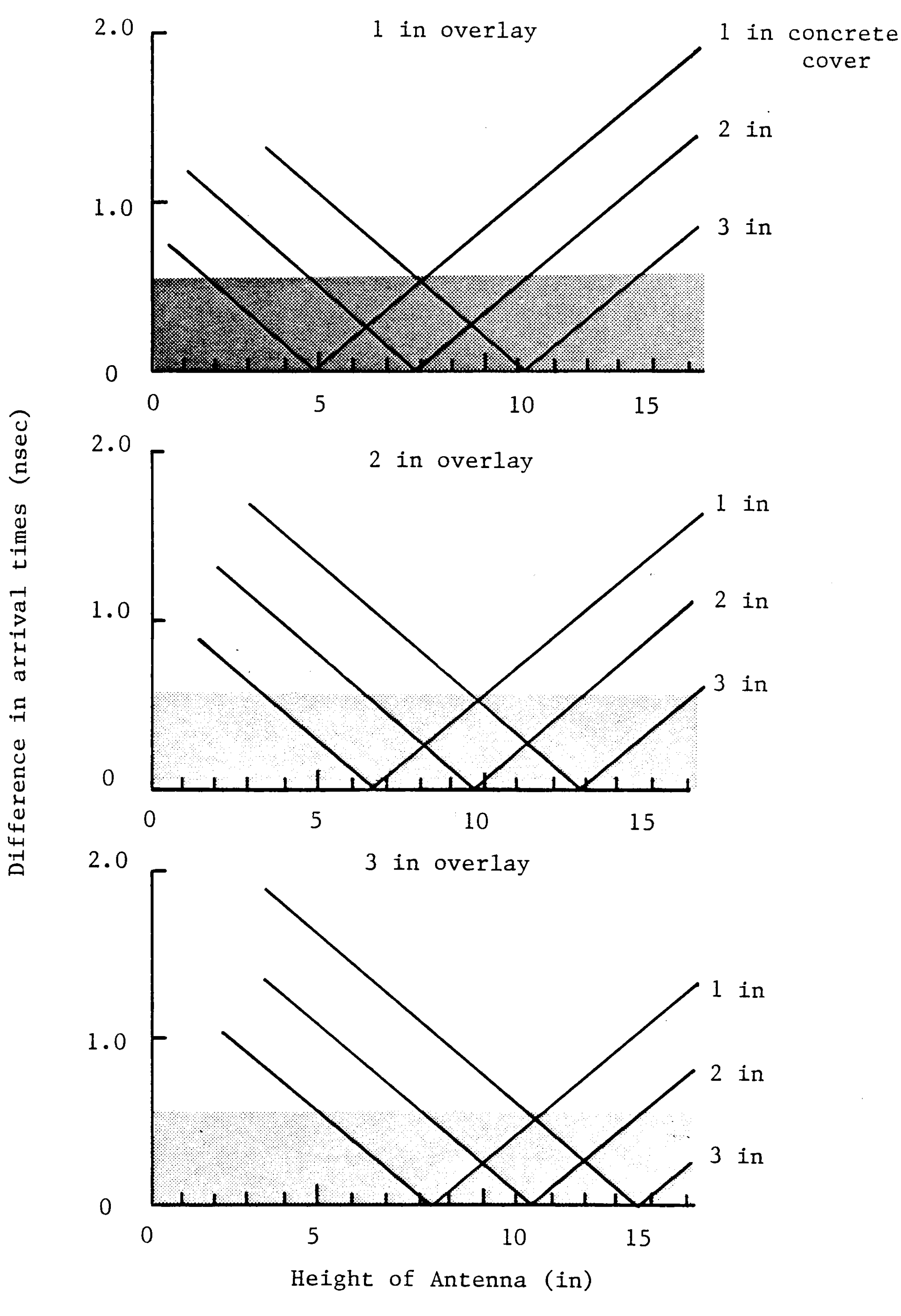


Figure 3.2. Relationships between height of antenna and the difference in the arrival times of P_{12} and P_3 for various thicknesses of overlay and depths of concrete cover over the top mat of the rebars in an overlaid deck.

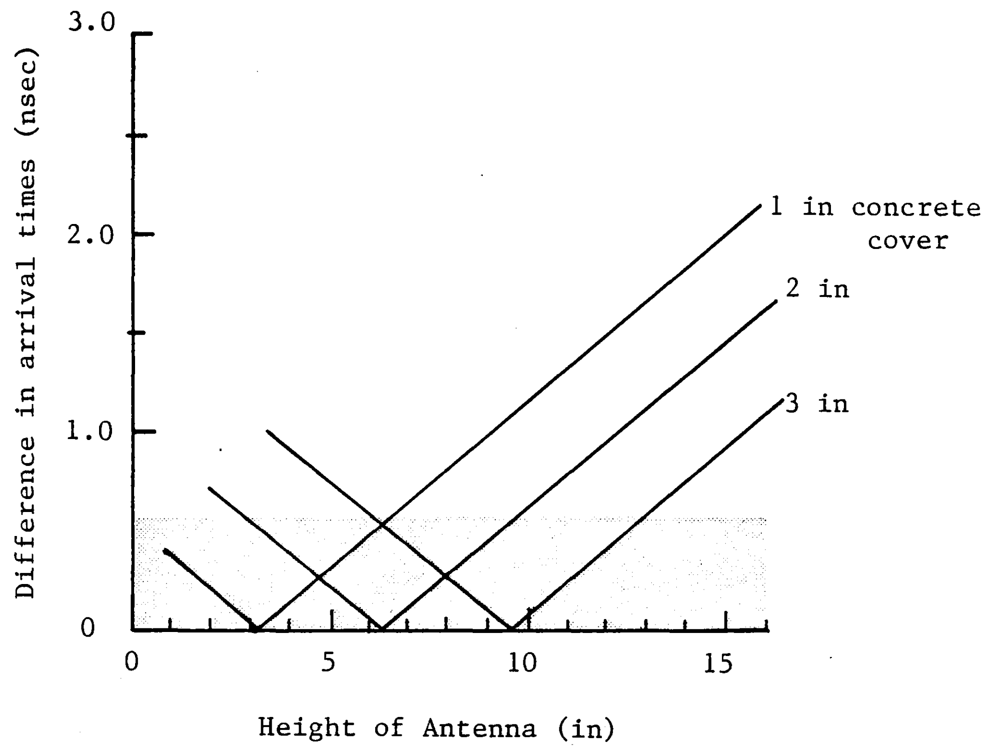


Figure 3.3. Relationship between height of antenna and the difference in the arrival times of P_{12} and P_3 for various depths of concrete cover of the top mat of rebars in a non-overlaid deck.

324

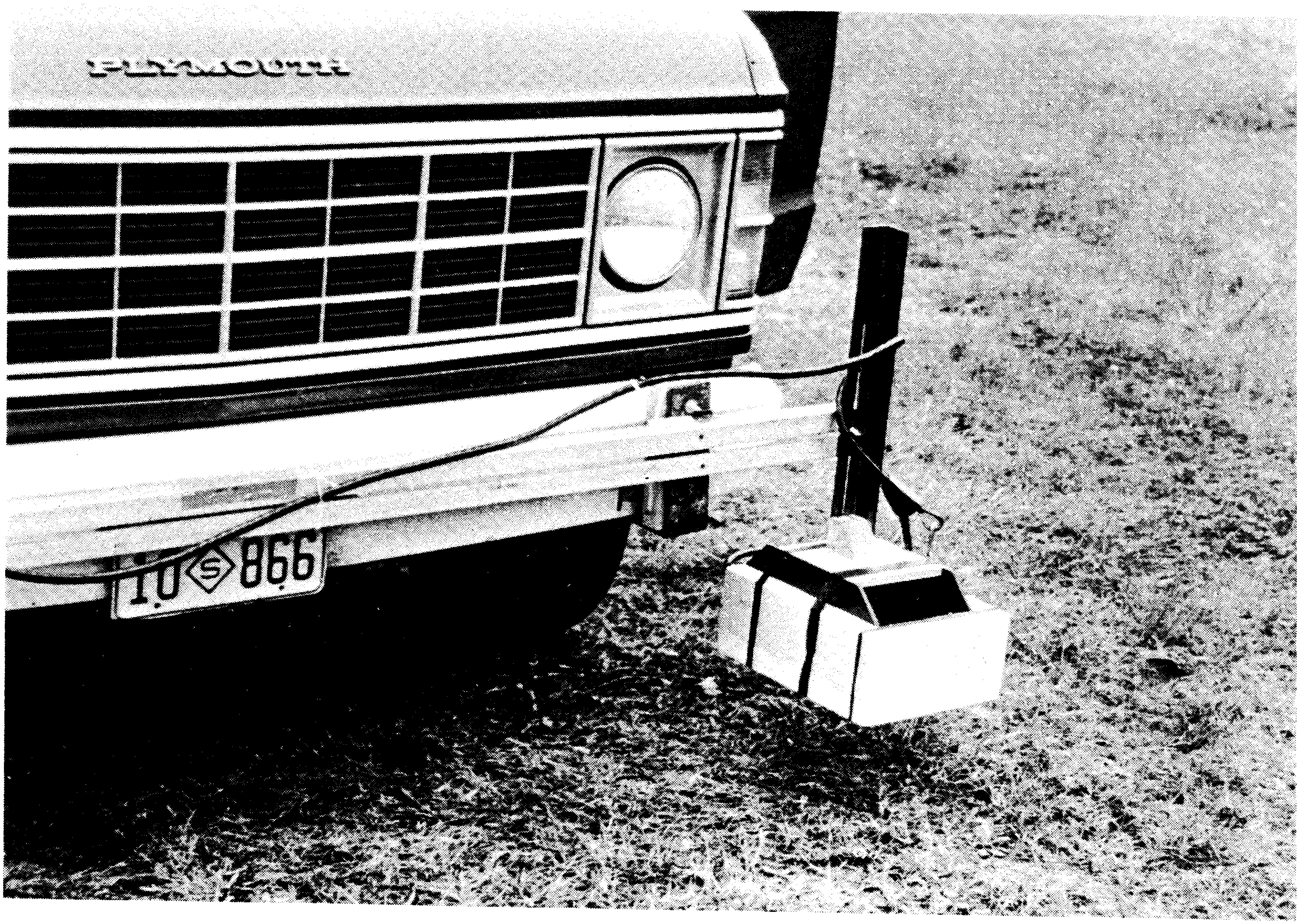


Figure 3.4. Radar antenna mounted on the front bumper of a vehicle through a rack that allows for manual adjustment of the horizontal position of the antenna.

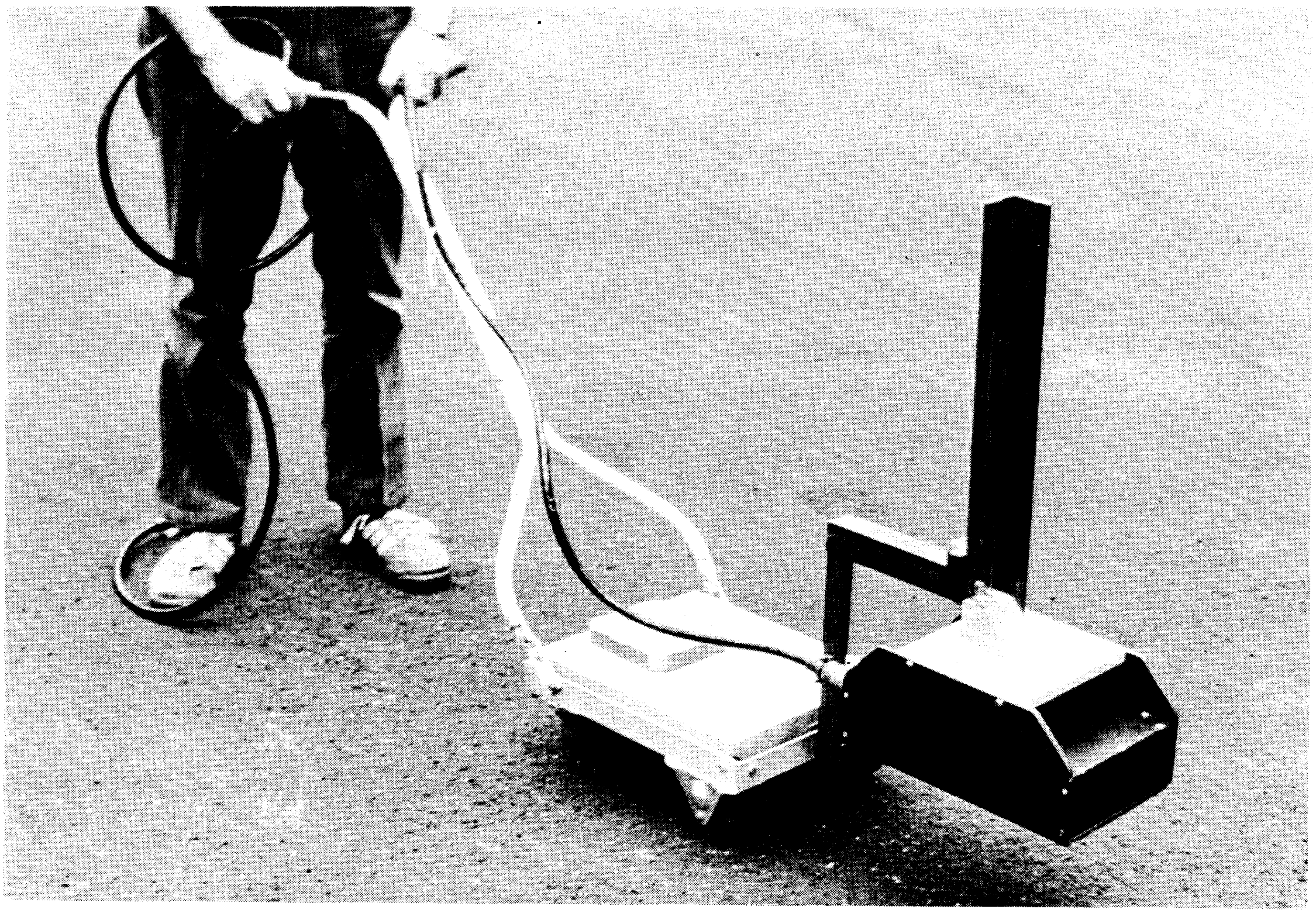


Figure 3.5. The 101c antenna mounted on a dolly.

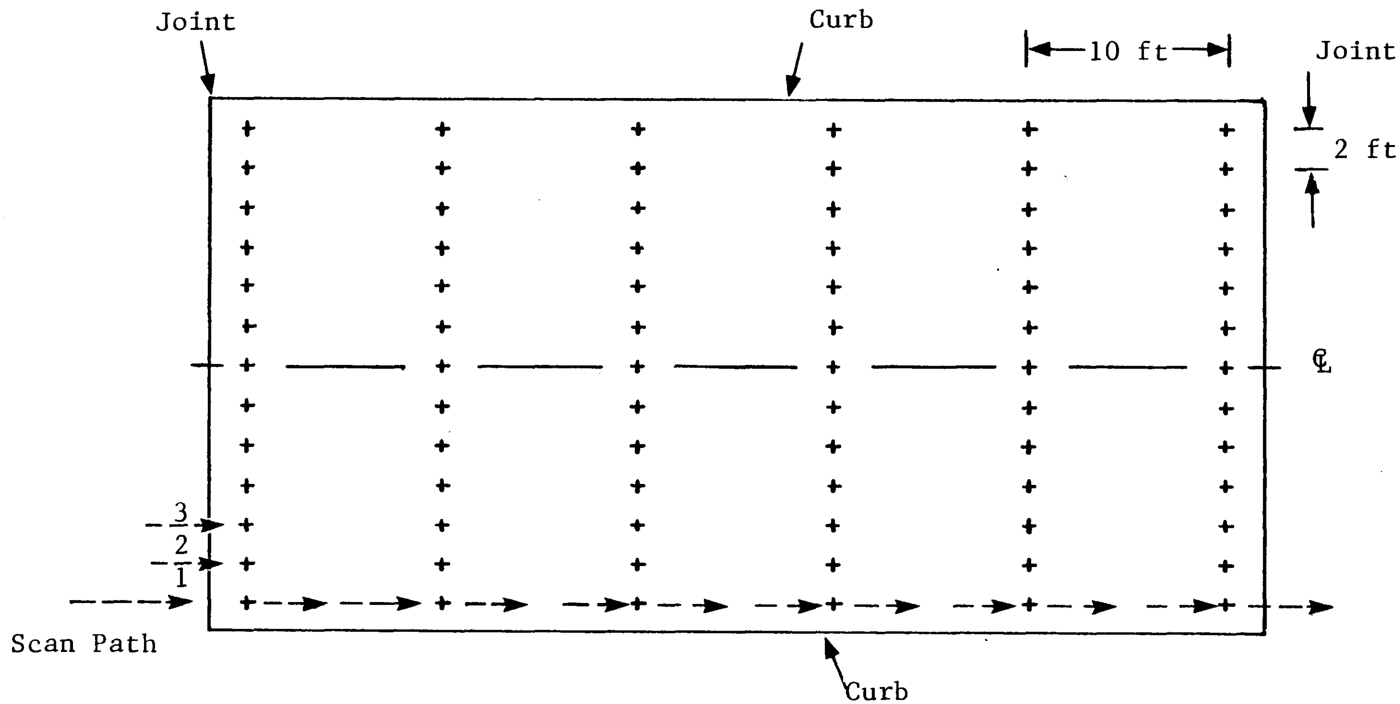


Figure 3.6. A grid laid out on a span before scanning with radar.

4. RADAR OPERATING PROCEDURES

NOTE: The following procedures are for the SIR System 4800 manufactured by the Geophysical Survey Systems, Inc., Hudson, New Hampshire.

The radar system consists of the following components:

1. Control unit (4800)
2. Digital cassette tape recorder (DT-6000)
3. Graphic recorder (SR-8000)
4. Power distribution unit (07)
5. Remote control unit (20)
6. Transducer (101c)

The first three components are shown in Figures 4.1 through 4.3. With the exception of the transducer, the components are mounted in a suitable vehicle and can be arranged in a manner most convenient for the operator. Figure 4.4 shows an example arrangement of these components inside a van. It must be noted that a window or other suitable opening must be available so that the connecting cable from the control unit to the externally located transducer can pass from within the vehicle to the outside.

4.1 Modes of Operation

During a survey, the radar system is normally operated in such a mode that data are recorded and stored on a tape with the digital cassette tape recorder. This mode provides some advantages: (1) because of the faster response of the cassette recorder as compared to that of the graphic recorder, the survey can be conducted at a faster speed than if the latter recorder is used; and (2) data recorded on the tape can be "played back" at a later convenient time, over and over, directly or through a microprocessor-based signal processor, to the graphic recorder in different ways that may make the anomalies associated with delaminations or other forms of distress easily distinguishable.

In the unfortunate event that the tape recorder is temporarily out of order, the data must be recorded with the graphic recorder. In such case, it is recommended that the survey speed be no more than 5 mph to minimize the possible loss of data.

- 328

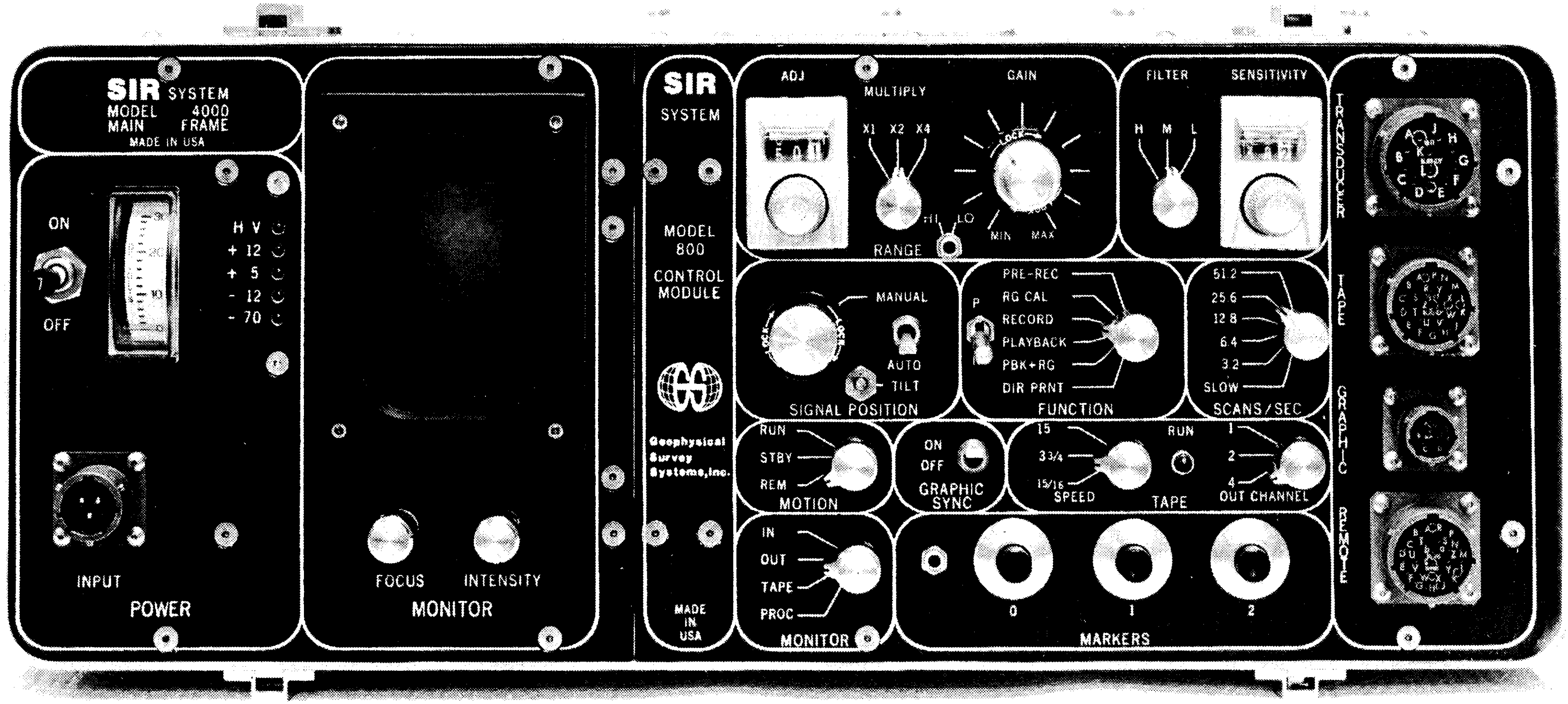


Figure 4.1. The SIR 4800 control unit.

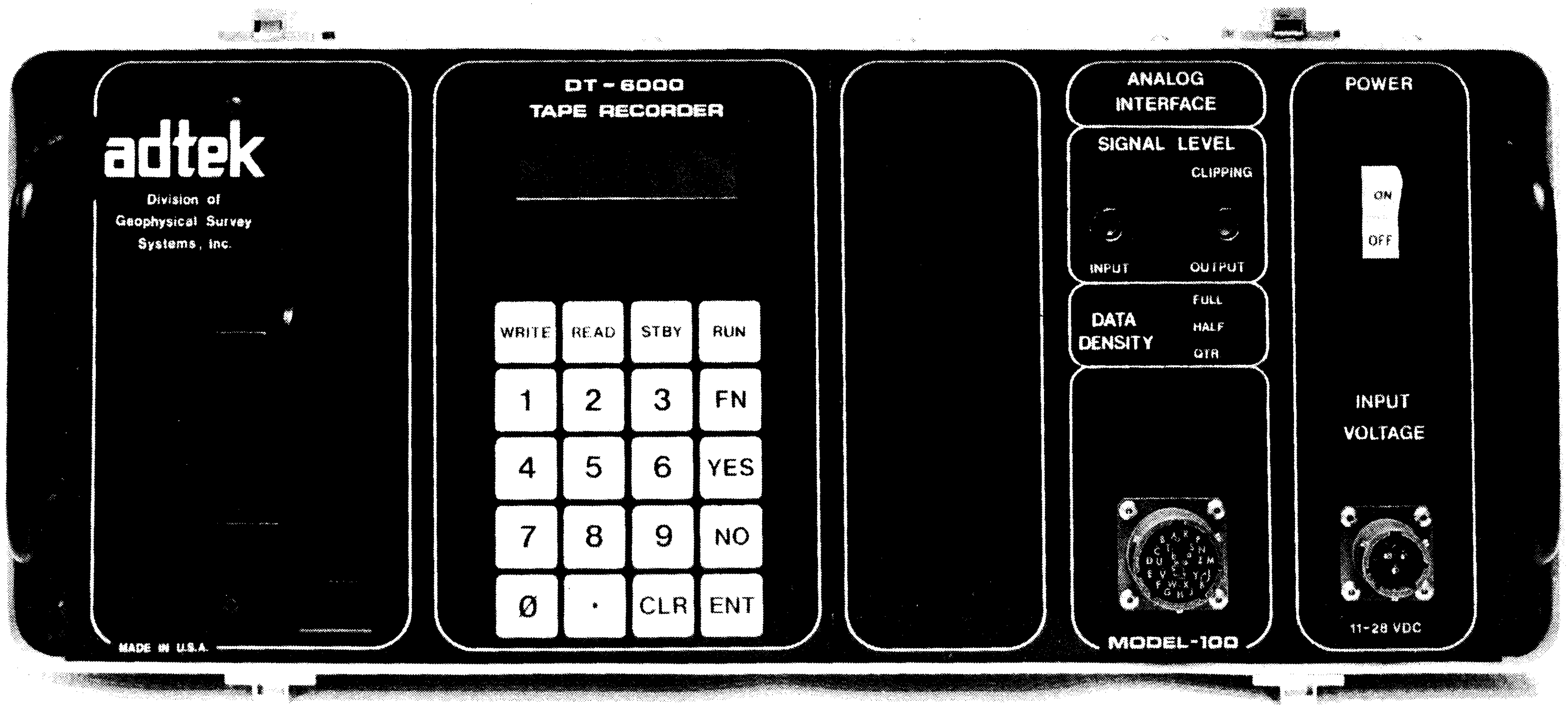


Figure 4.2. The DT-6000 tape recorder.

320

330

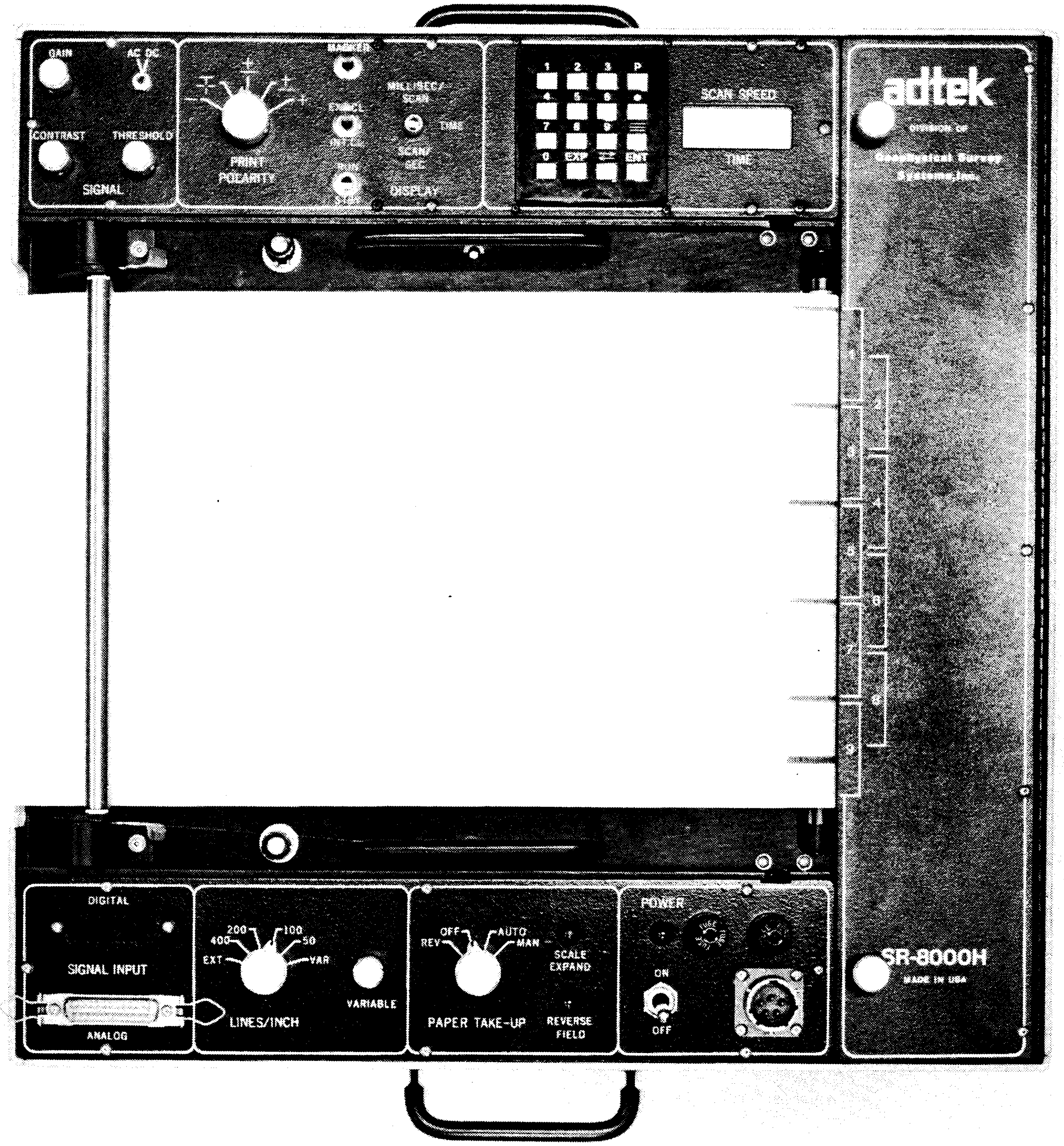


Figure 4.3. The SR-8000 graphic recorder.

331

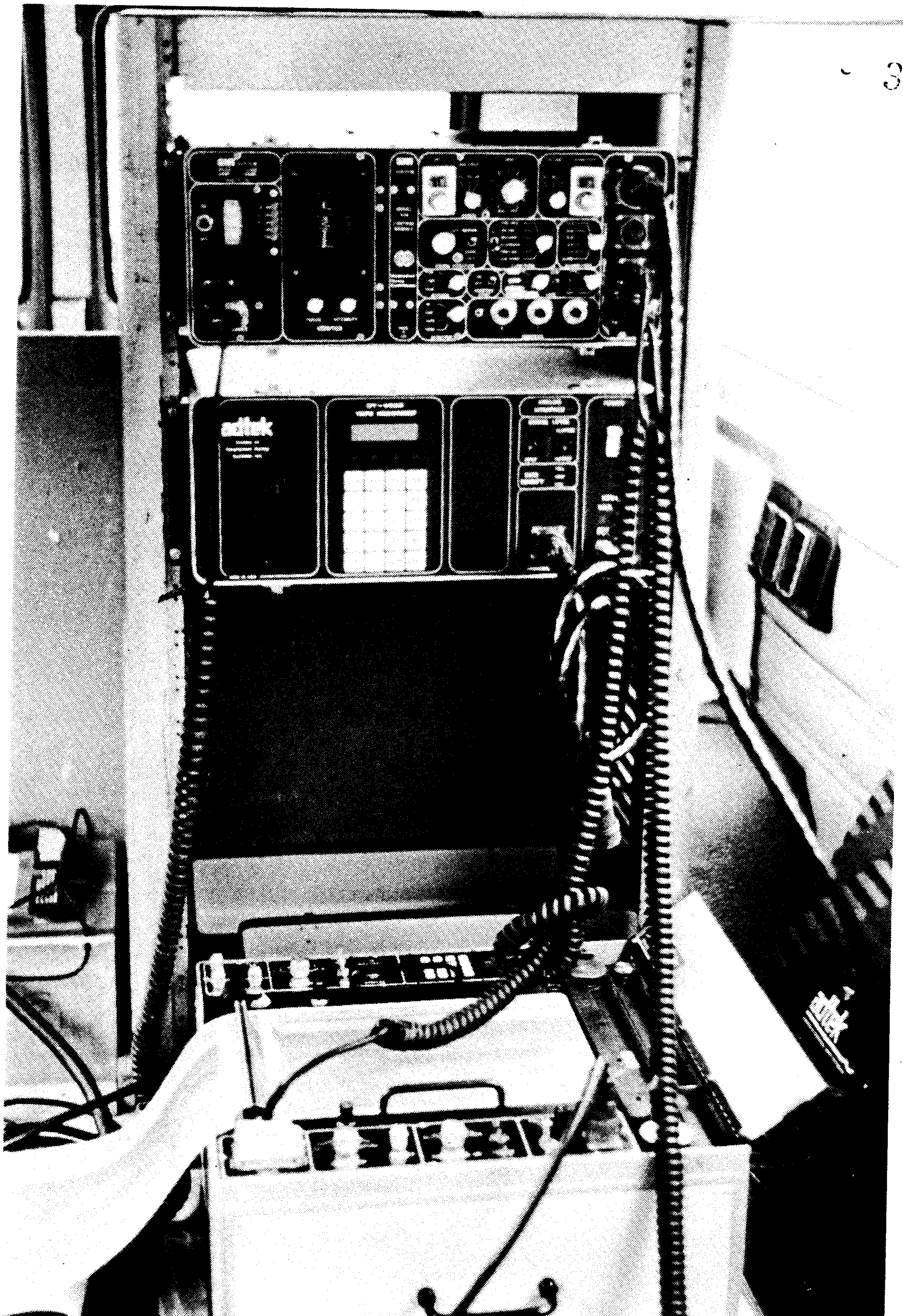


Figure 4.4. The radar system mounted in a van.

- 332

4.1.1 Recording date on tape

1. Insure that all cable connections are completed as shown in Figure 4.5.

2. Set the control unit (CU) as follows:

POWER	OFF
RANGE ADJ	050
MULTIPLY	X1
GAIN	60^{o} - 90^{o} (CW)
FILTER	L
SENSITIVITY	0014-0025
SIGNAL POSITION	MANUAL
FUNCTION	RECORD
SCANS/SEC	51.2
MOTION	STBY
GRAPHIC SYNC	OFF
DATA DENSITY	HALF
MONITOR	OUT

3. Start up the tape recorder as follows:

(1) Turn on the recorder.

Upon which the LED indicators will indicate the default status of READ and STBY. And the LCD display will prompt.

Insert DC 600HC

Tape Cartridge

(2) Insert a DC 600HC cartridge, with the metal side facing the cartridge eject lever.

The LCD will then show

Initializing

Tape .... Wait

and after approximately 90 seconds, the LCD will prompt

Select Mode:

Write or Read

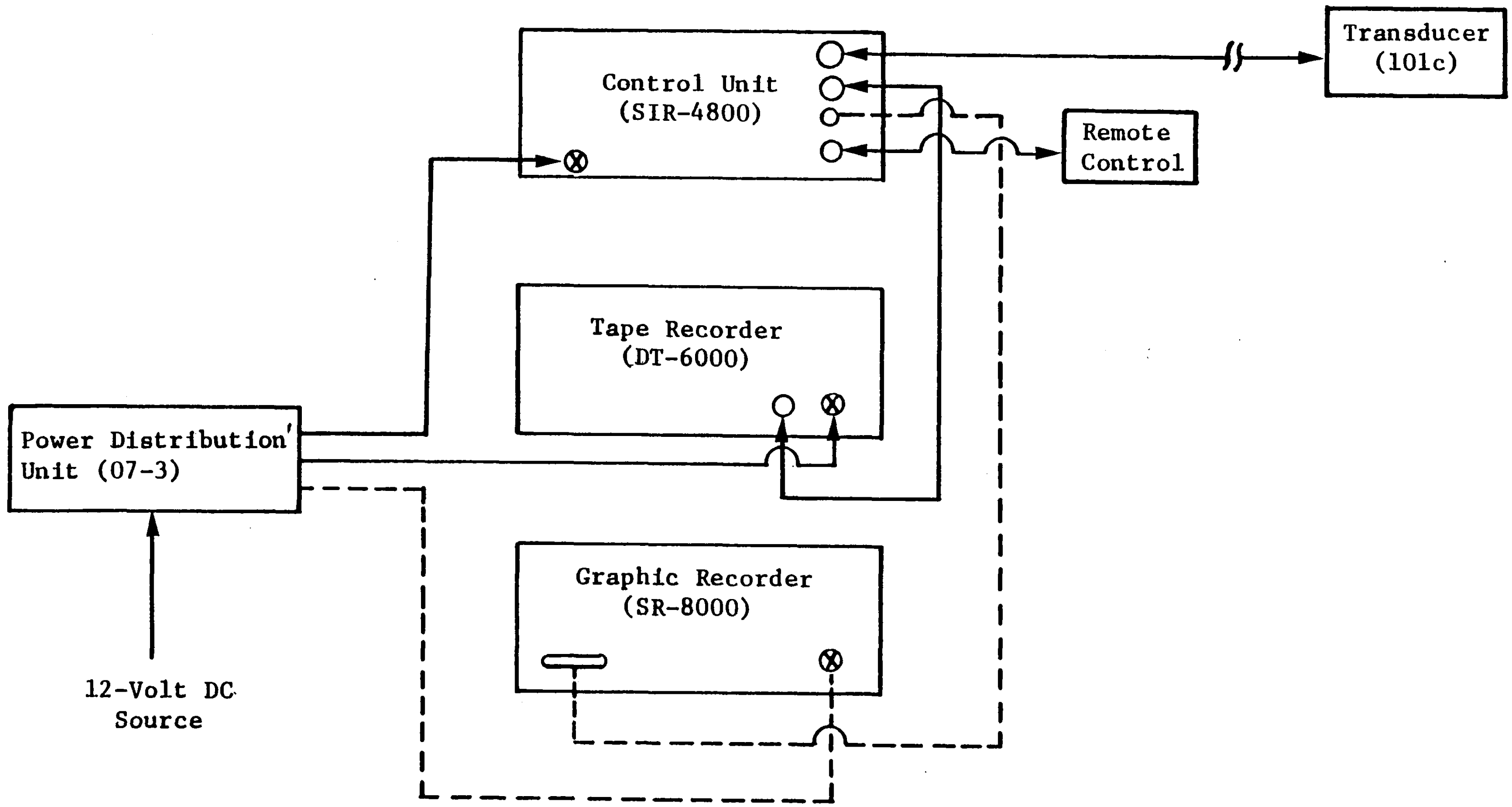


Figure 4.5. Recording data on tape. Notice that it is not necessary for the graphic recorder to be connected.

(3) Press the WRITE key.

The LED will indicate WRITE and STBY. Then the LCD will display the default scan rate and prompt for any change, if desired.

Scans/Sec: 51.2

Change? (Y/N)

(4)(a)(1) If the scan rate isn't 51.2 scans/sec (or any other desired rate), press the YES key; Otherwise proceed to step (4)(b)(1).

The LCD will then display

Enter Scan/Sec:

(0.4 - 128):

(4)(a)(2) Key in 51.2 (or any other desired rate), and then press the ENTER key. (If any error is made, use CLEAR key to erase.)

The LCD will display the chosen scan rate and prompt for any changes.

Scan/Sec: 51.2

Change? (Y/N)

(4)(b)(1) If satisfied with the scan rate, press the NO key.

The LCD will display

Address: 0

Change? (Y/N)

(The tape recorder uses a formatted data cartridge that can be addressed from 0 to 65,535. If the cartridge is blank, the user can write data from 0, or any other address, to 65,535.)

(5)(a)(1) To write from 0, press the NO key.

The display will show

S = 51.2 A = 0

Searching..........

then

S = 51.2 A = 0

Ready to Run

(5)(b)(1) To continue writing from a previous address, press the YES key.

The LCD will prompt

Enter Address

(0 - 65,535)

For example, let's say the desired previous address is 20,500. Therefore,

(5)(b)(2) Key in 20,500, then press the ENTER key.

The LCD will ask

Address: 20,500

Change? (Y/N)

If not satisfied, then press YES key and proceed again from step (5)(b)(2); otherwise

(5)(b)(3) Press the NO key.

The LCD will then display

S = 51.2 A = 20,500

Searching..........

after which

S = 51.2 A = 20,500

Ready to Run

(5)(b)(4) Log down this initial address.

4. Turn the CU power on.

5. Wait approximately 5 minutes for warm-up and stabilization.

6. To start recording survey, turn MOTION switch on the CU to RUN. (If desired, recording can be remotely started by turning this switch to REM instead, followed by turning the MOTION switch on the remote control device from STBY to RUN.)

7. To stop recording when survey (or a pass) is finished, turn MOTION switch to STBY.

8. Log down the final tape address.

9. To restart recording, simply repeat step 6.

10. To extract the tape after the survey has been completed, press the function key FN.

The display will show

Release Tape

Cartridge? (Y/N)

11. Press YES.

The display will respond

Rewinding

Tape.........

followed by

Remove

Tape.........

12. Press down on the cartridge eject lever, then pull tape out.

13. Turn both CU and tape recorder off.

4.1.2 Recording data with graphic recorder

1. Insure that all cable connections are completed as shown in Figure 4.6.

2. Set the graphic recorder as follows:

POWER	ON
GAIN	90°CW (or as required)
CONTRAST	270°CW (or as required)
THRESHOLD	MINIMUM
PRINT POLARITY	±
CLOCK	EXTERNAL
RUN/STBY	RUN
DISPLAY	SCAN/SEC
SCAN/SEC	12.8 to 25.6 (see notes)
LINES/INCH	100 (or as required)
PAPER TAKEUP	AS REQUIRED

NOTE: If the scan rate indicated by the LCD display is not as desired, key in "12.8" (or "25.6") and "ENT".

3. Set the CU as follows:

POWER	ON
RANGE ADJ	050
MULTIPLY	X1
GAIN	90°
FILTER	L
SENSITIVITY	0025
SIGNAL POSITION	MANUAL
P/N	P
FUNCTION	DIR. PRINT
SCANS/SEC	12.8 (or 25.6)
MOTION	STBY
GRAPHIC SYNC	ON
DATA DENSITY	1/4 (or as required)
MONITOR	OUT

4. Wait approximately 5 minutes for warm-up.

5. To start recording, turn MOTION switch on the CU to RUN. (If desired, recording can be remotely started by turning the switch to REM instead, followed by turning the MOTION switch on the remote control device from STBY to RUN.)

6. To stop recording, turn the switch to STBY.

7. To restart recording, turn switch to RUN again.

8. When the survey is complete, turn CU and graphic recorder power off.

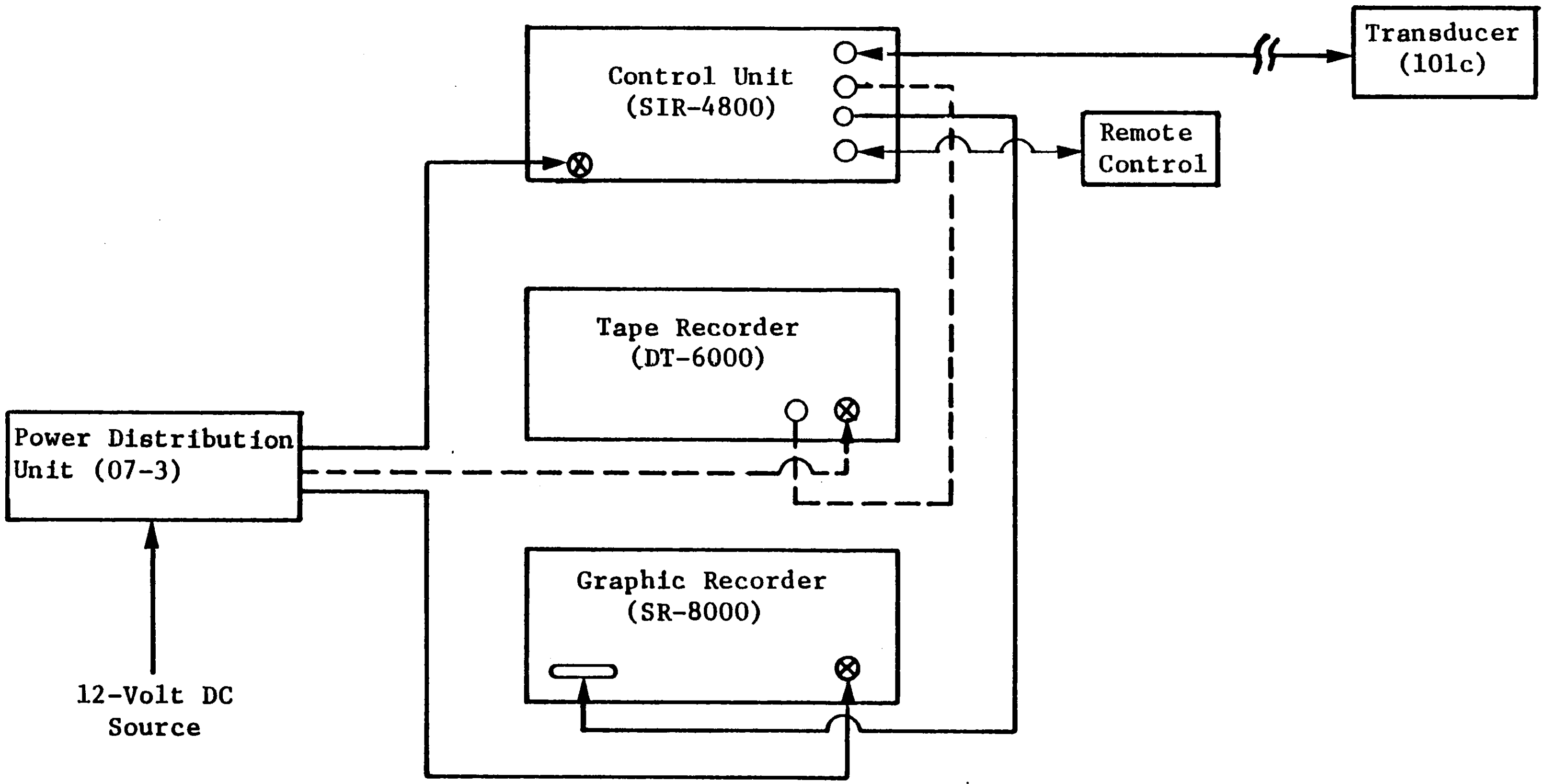


Figure 4.6. Recording data with the graphic recorder. Notice that it is not necessary for the tape recorder to be connected.

339

340

4.1.3 Playback of data recorded on Tape (without signal processing)

1. Insure that all cable connections, shown in Figure 4.7, are complete.

2. Set the graphic recorder as follows:

POWER	ON
GAIN	90^{o}
CONTRAST	270^{o}
PRINT POLARITY	± (or as desired)
CLOCK	EXTERNAL
RUN/STBY	RUN
DISPLAY	SCAN/SEC
SCAN/SEC	6.4 (or as required)
LINES/INCH	100
PAPER TAKEUP	AS REQUIRED

3. Start up tape recorder as follows:

(1) Turn on the recorder.

Upon which the LED indicators will indicate the default status of READ and STBY. And the LCD display will prompt.

Insert DC 600HC

Tape Cartridge

(2) Insert a DC 600HC cartridge, with the metal side facing the cartridge eject lever.

The LCD will then show

Initializing

Tape .... Wait

and after approximately 90 seconds, the LCD will prompt

Select Mode:

Write or Read

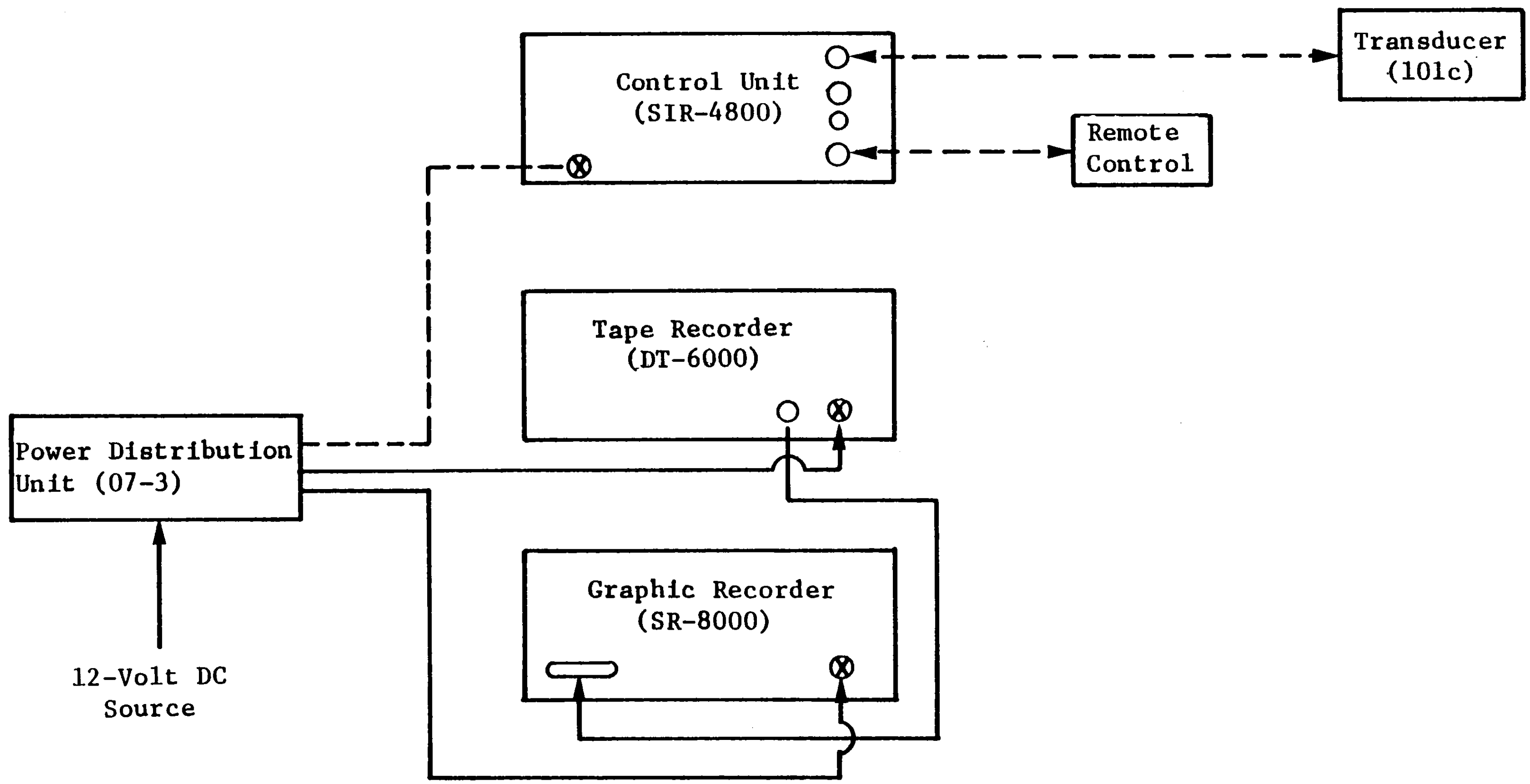


Figure 4.7. Playback of data previously recorded on tape to the graphic recorder. Notice that it is not necessary for the control unit, transducer, nor remote control unit to be connected.

(3) Press the READ key.

The LED will indicate READ and STBY. Then the LCD will prompt for any change, if desired.

Scans/Sec:	25.6
Change?	(Y/N)

(4) Press the YES key.

The LCD will prompt

Enter Scan/Sec:

(0.4 - 128):

(5) Key in 6.4 (or any other desired rate), then press ENTER key.

The LCD will display the chosen scan rate and prompt for any changes.

Scan/Sec:	6.4
Change?	(Y/N)

(6) If satisfied with the scan rate, press the NO key.

The LCD will display

Address	0
Change?	(Y/N)

(7)(a)(1) To read from 0, press the NO key; otherwise proceed to step (7)(b)(1)

The display will show

S = 6.4 A = 0

Searching..........

then

S = 6.4 A = 0

Ready to Run

(7)(a)(2) Then go to step 8.

(7)(b)(1) To read from a previous address, say 20,000, press the YES key.

The LCD will prompt

Enter Address

(0 - 65,535):

(7)(b)(2) Key in 20,000, then press ENTER key.

The LCD will display

Address: 20,000

Change? (Y/N)

If not satisfied, go back to step (7)(B)(1); otherwise

(7)(b)(3) Press the NO key.

The LCD will display

S = 6.4 A = 20,000

Searching..........

then

S = 6.4 A = 20,000

Ready to Run

8. To start playback, press RUN key on the tape recorder.

9. To stop playback, press STBY key.

10. To restart playback, simply press RUN again.

11. To extract the tape after the playback has been completed, press the function key FN on the tape recorder.

The LCD will show

Release Tape

Cartridge? (Y/N)

12. Press YES

The LCD will respond

Rewinding

Tape.........

then

Remove

Tape.........

13. Press down on the eject lever, then pull tape out.

14. Turn both recorders off.

- 346

5. INTERPRETATION OF RADAR OUTPUT

5.1 Reflection Profiles -- The Output

Each of the reflected pulses illustrated in Figure 2.2 and other pulses arrive back at the receiving antenna at different times that are governed by the depth of the reflection interface and the dielectric constants of the materials involved. These pulses, or waveforms, are then fed to a receiver circuit that electronically translates them to the audio frequency range by a time-domain sampling technique. The resulting low-frequency replicas of the received signals are then sent to the CU for amplification and further conditioning before being fed to an output recorder. The output is a composite waveform that is displayed on an oscilloscope in the CU, as illustrated in Figure 5.1a.

A more useful output is the one recorded, either directly or by playback from the tape recorder, on the facsimile graphic recorder as a reflection profile (Figure 5.1b). It represents an array of individual composite waveforms that continuously change in the direction of travel as the antenna traverses a scan path on the deck.

Note that the main feature of the profile is the display of groups of closely related dark bands at varying depths. Each group is caused by oscillations in a reflected pulse. Notice also that the dark bands correspond to the positive and negative peaks, and the narrow white lines are the zero crossings between peaks.

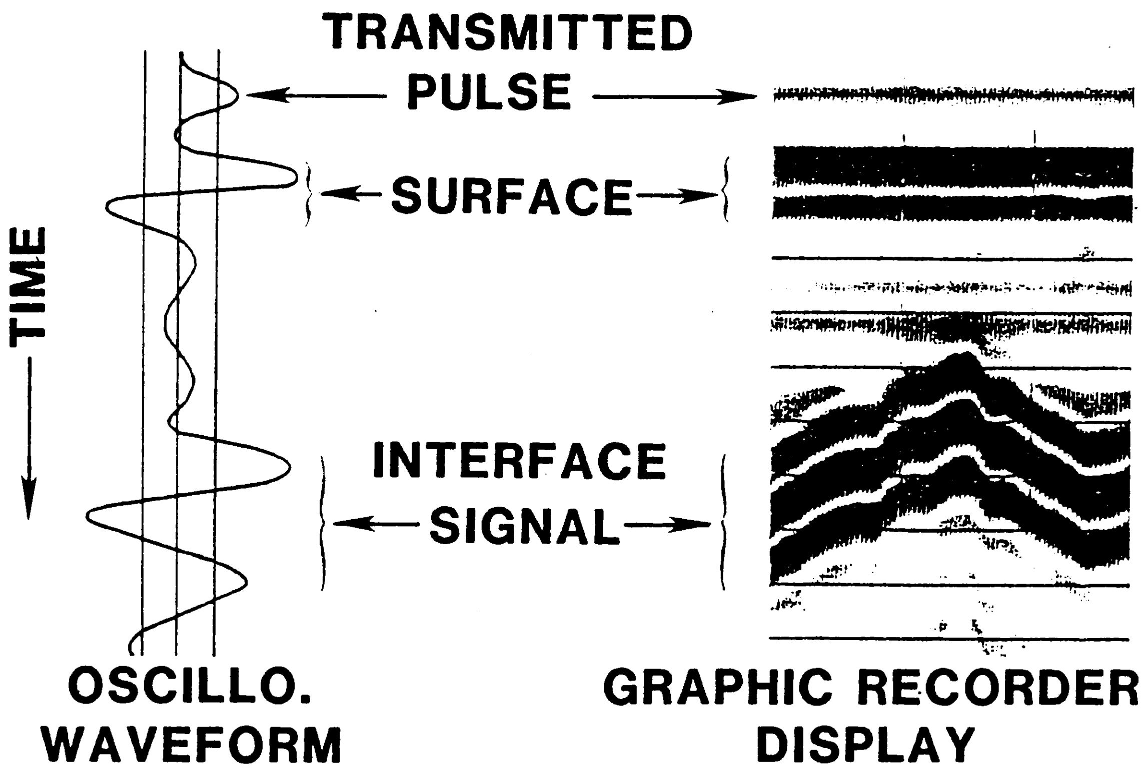
5.2 Identification of Delaminated Concrete

In the interpretation of each radar reflection profile, it is necessary to first identify which group of reflection bands came from the top mat of rebars, where most concrete delaminations originate. This step is then followed by a search for irregularities just above and below these identified bands that may represent reflections from unsound concrete.

5.2.1 Reflection from rebars

Fortunately, the identification of reflection bands from the top mat of rebars is made relatively easy by the small cross sections of rebars.

The beam of microwave pulses radiated from the antenna assumes a semi-elliptical cone that spreads 60^{o} and 90^{o} along the width and length of the antenna, respectively. When this beam traverses a deck, simultaneous reflections from neighboring rebars occur and the resulting reflection pattern resembles that shown in Figure 5.2. Note that this rendition of an idealized reflection pattern shows good agreement with the actual recording of such a pattern shown in Figure 5.3.



5.1(a) 5.1(b)

Figure 5.1 Data presentation of GPR.

If the scan path happens to be directly above a girder, then the zigzag feature of the rebar reflection pattern is rendered less distinct by additional reflections from steel in the girder.

At times, especially when a survey is conducted at a walking pace, the zigzag feature can become sharper and assume the appearance of spikes. Figure 5.4 shows an example of these spikes that indicate reflections from rebars. This probably depends on such factors as the distance of the antenna from the surface of the deck, the thicknesses of the overlay and concrete cover over the top mat of the rebars, etc.

5.2.2 Reflection from delaminated concrete

To conceptualize how the reflection pattern for delaminated concrete can look, consider a delamination with well-defined planes of distress such as that depicted in Figure 5.5a.

As the antenna moves over the delamination, the major reflection from this delamination at any instant would be that part of the beam that is perpendicular to the nearest plane of distress. This causes the typical reflection pattern, or signature, of the delamination to assume the shape of a depression, as illustrated in Figure 5.5b.

In fact, a reflection pattern in this shape has been observed to correspond to delaminations in profiles recorded for both clear and overlaid concrete decks. Figures 5.3, 5.4, 5.6, and 5.7 show examples of these profiles wherein the signatures of delaminations were usually in the shape of a depression with occasional ill-defined, blurred reflections.

Note that profiles for one deck can be noticeably different from those of another deck. Consequently, reflection profiles for some decks can be more difficult to interpret than those from other decks. Such situations may be minimized by giving adequate consideration to the thickness of the overlay on the deck to be surveyed when deciding on the appropriate height of the antenna.

5.2.3 Concomitant reflections

Reflections from joints and struts also accompany the above mentioned reflections. These reflections can easily be identified by examining the plans for the structure being inspected.

It is suspected that disbondment of the overlay can affect the reflection from the asphalt/concrete interface, particularly if the surface of the concrete has deteriorated because of frequent trapping of moisture between the overlay and the concrete. Therefore, when localized abnormal reflections from this interface are observed, it may be assumed that at least superficial repair of the concrete at that spot would be necessary.

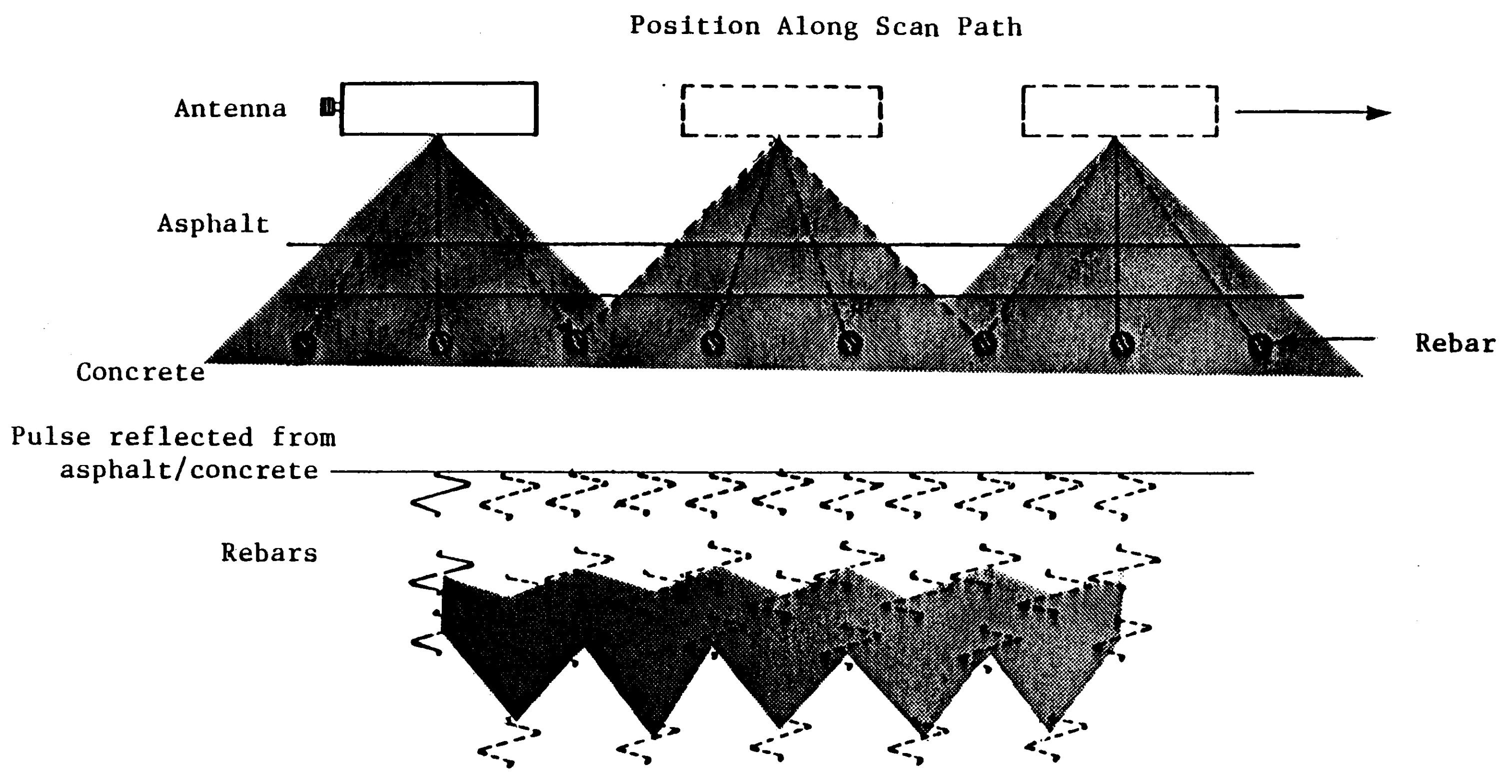


Figure 5.2. Idealized reflection pattern for rebars.

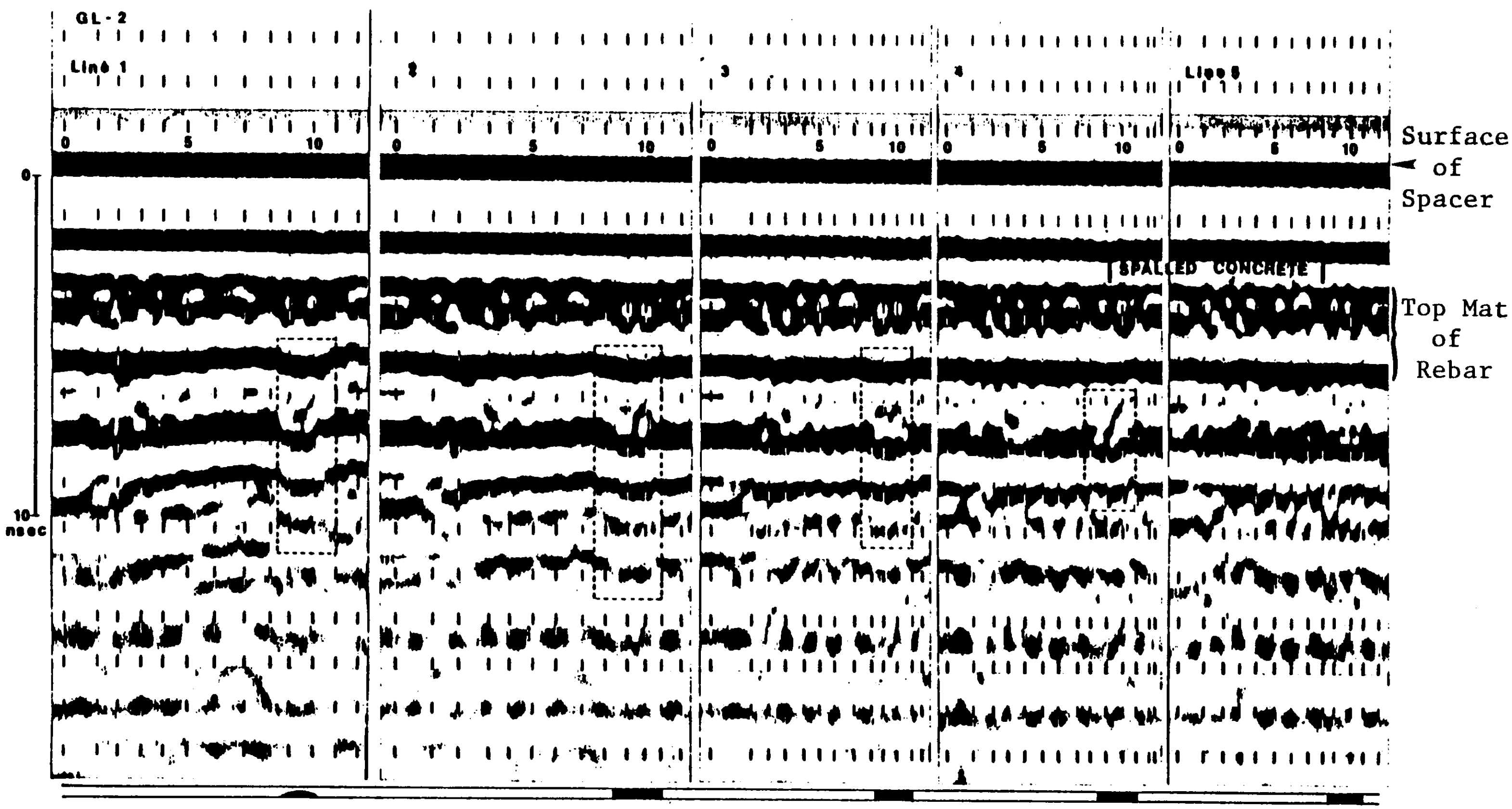


Figure 5.3. Some microwave reflection profiles for a clear concrete deck.

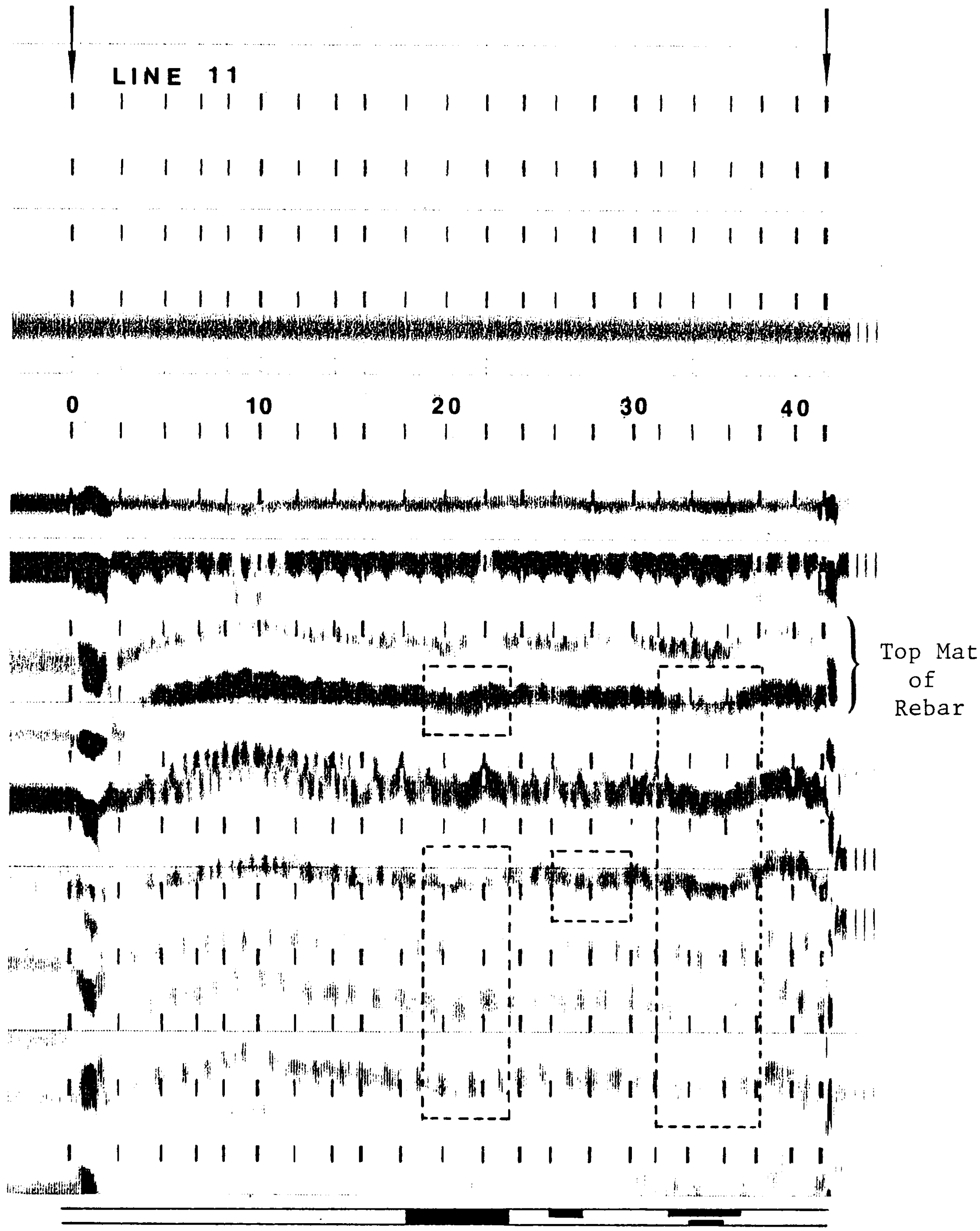


Figure 5.4. An example reflection profile from an overlaid deck.

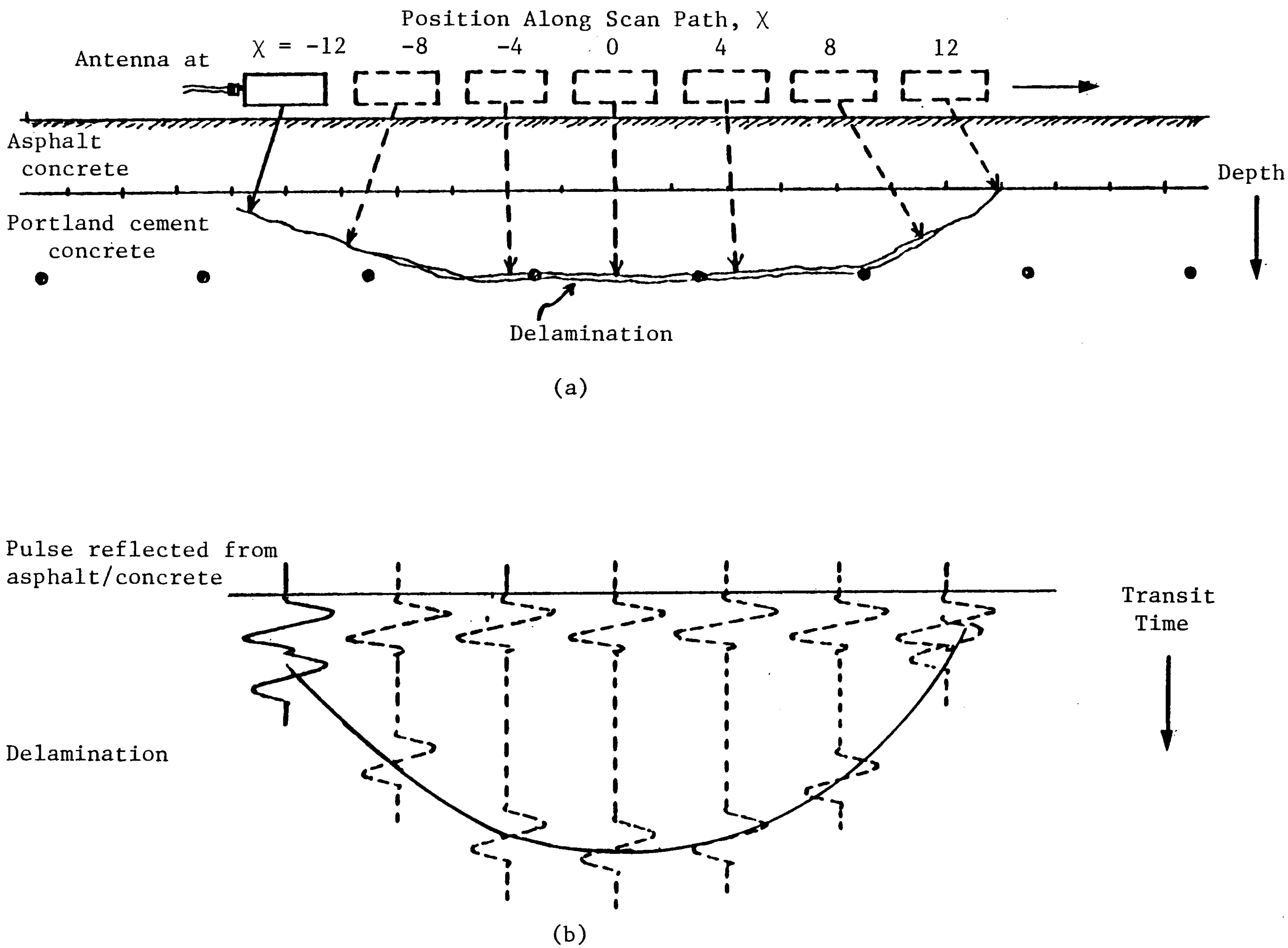


Figure 5.5. Illustration of the development of an idealized reflection pattern for a delamination. Not shown is the reflection from the rebars.

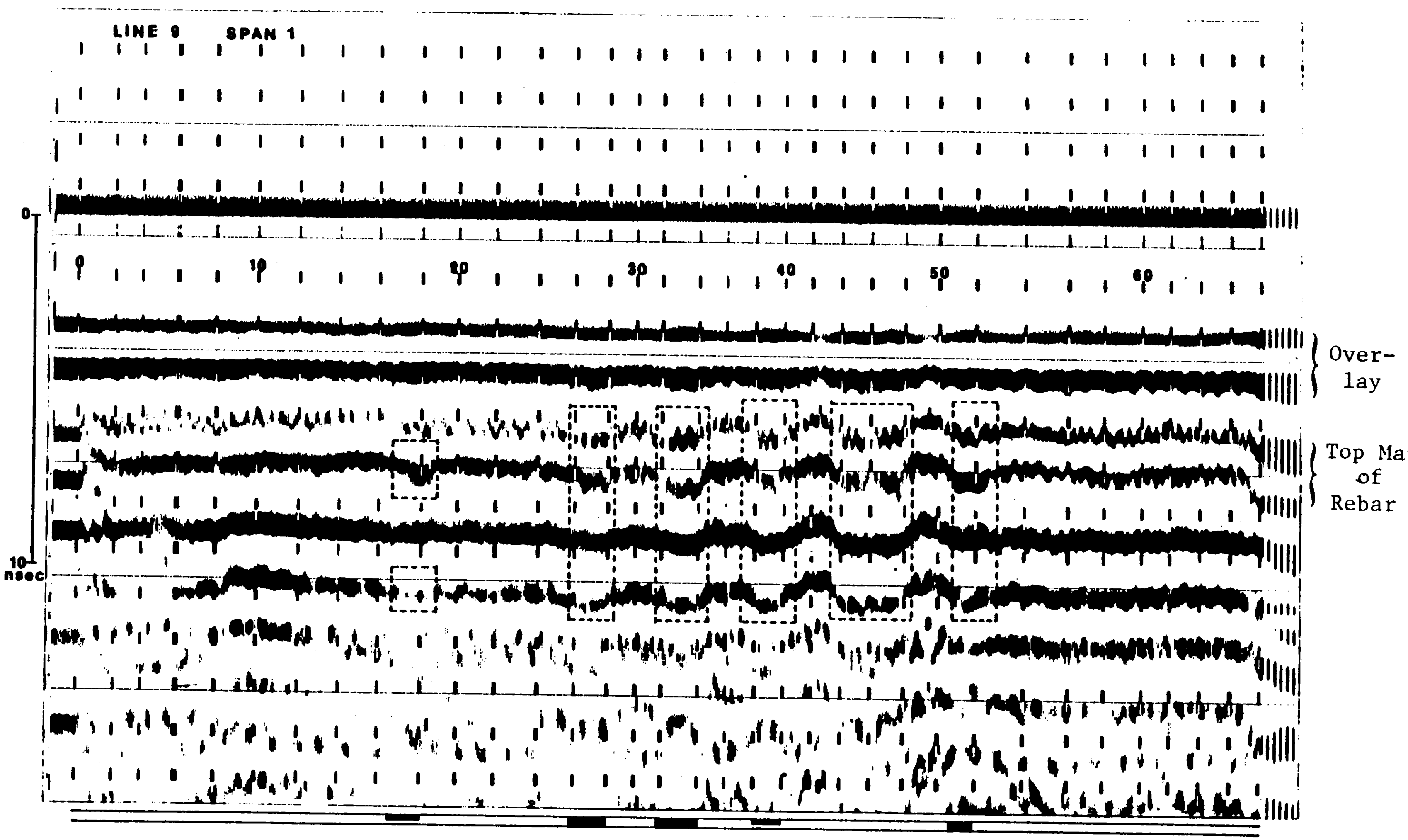


Figure 5.6. An example reflection profile from an overlaid deck.

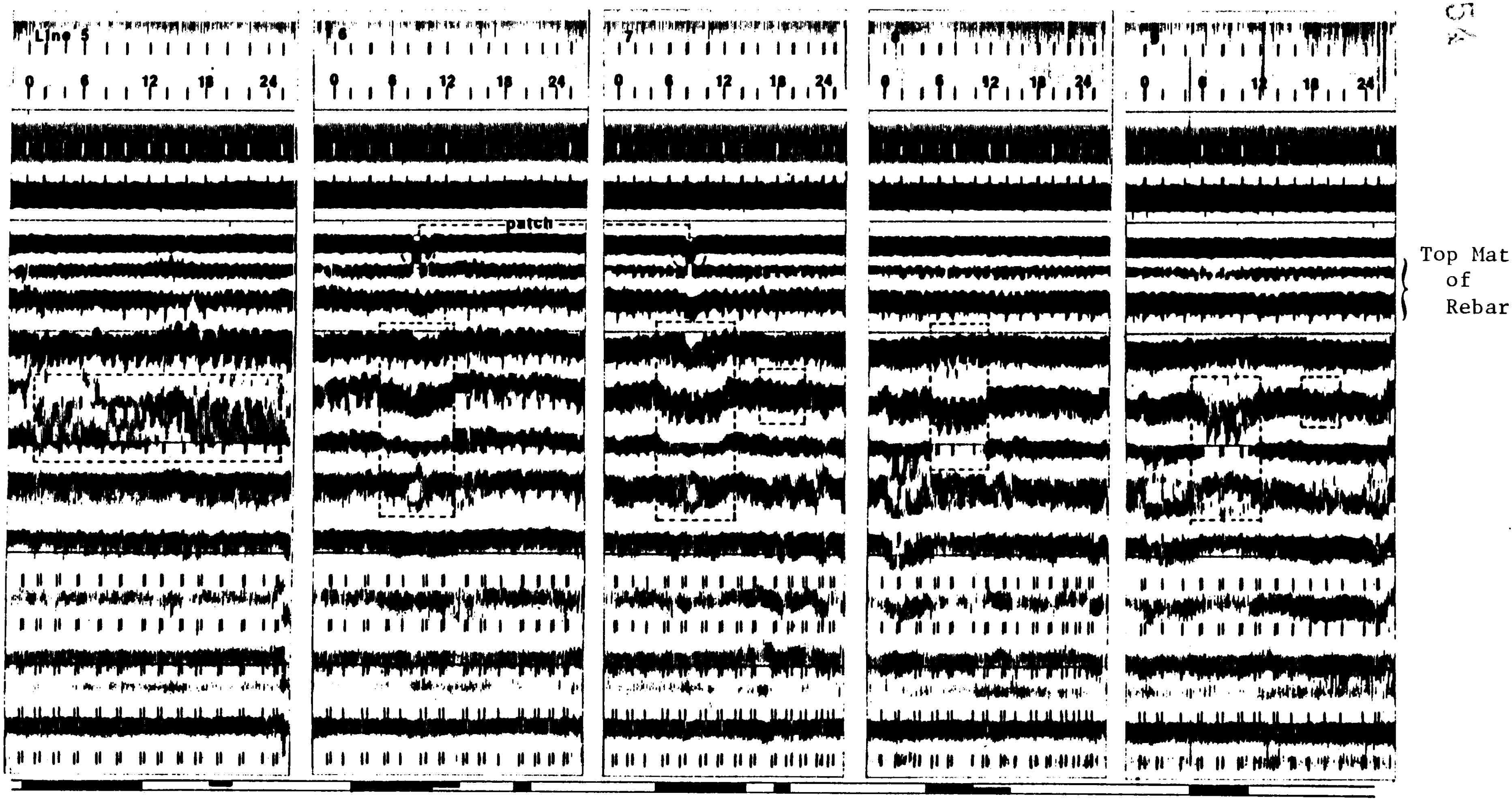


Figure 5.7. An example reflection profile from another non-overlaid deck.

5.3 Accuracy of Radar Survey

Like most survey or testing techniques, radar has limitations, including the following:

1. The intrinsic width of the reflected pulses. For the GSSI Model 101 transducer, this width is 1.1 ns (Figure 2.2). Since the two-way transit time of microwave pulses through typical concrete is 0.48 - 0.58 ns/in (Table 2.1), it follows that pulses reflected from a delaminated area where the concrete cover over the rebars is less than 2 in may be partially masked by the pulses reflected from the bottom of the overlay. Therefore, depending on the size and severity of a delamination, its detection may be adversely affected.

2. Unwanted reflections. Some of the pulses reflected from the surface and the bottom of the overlay may reverberate, or undergo multiple reflections, before eventually reaching the receiving antenna. Depending upon the extent of the reverberations, the thickness of the overlay, etc., these unwanted reflection pulses may arrive at the antenna at a time close enough to mask, or interfere with, the reflection from a delamination.

3. Dependency on the size of delamination. Depending upon their severity, delaminations that are approximately 1 ft across or smaller have at times been missed by the radar.

Consequently, GRP does not provide perfect results. Therefore, it is important for a bridge engineer to know how far off the results can be so that adjustments can be made in estimating the amount of bad concrete that needs to be replaced. To provide a basis for gauging the performance of radar, it was compared against conventional soundings of bare decks (for overlaid decks, this was done after removal of the overlays), assuming that sounding identifies all the delaminations in a test area. As shown in Table 5.1, radar overestimated by approximately 16% and 5% for overlaid and clear decks, respectively. (These values may be updated in the future as more verification is made.) The better performance shown by radar for non-overlaid bridge decks can be expected, since some of the limitations mentioned above would not be applicable.

TABLE 5.1

Performance of GPR

Type of Decks	Overestimation by Radar, %
Overlaid	16
Non-overlaid	5

6. QUANTIFICATION OF DELAMINATED AREAS

Following the identification of all delaminations on the reflection profiles recorded for a deck, the total delaminated areas for the deck can be estimated as follows:

1. Sketch a diagram for each of the spans that make up the deck.

2. On each diagram, mark the delaminations observed in the profiles for the corresponding span to the nearest linear foot as illustrated in Figure 6.1.

3. By lumping adjoining delaminations, outline all the delaminated areas in each span.

4. Determine the size of each delaminated area to the nearest square foot.

5. Sum the sizes of all the individual delaminated areas in each span, and then those for the whole deck.

Note that in the example given in Figure 6.1, the span was scanned along 8 equidistant, parallel paths. From delaminations taken from the 8 resulting reflection profiles and marked on the diagram, it is apparent that there were 8 delaminated areas of varying sizes in this span.

After outlining these 8 areas, with a 0.5-ft allowance on each end of each delamination, it was estimated that the sizes of these delaminated areas were as follows:

Delaminated Area	Size (ft^2)
1	52
2	3
3	70
4	28
5	3
6	4
7	21
8	3

The total area of the delaminations in the span was 184 ft^2, which represents approximately 10% of the span.

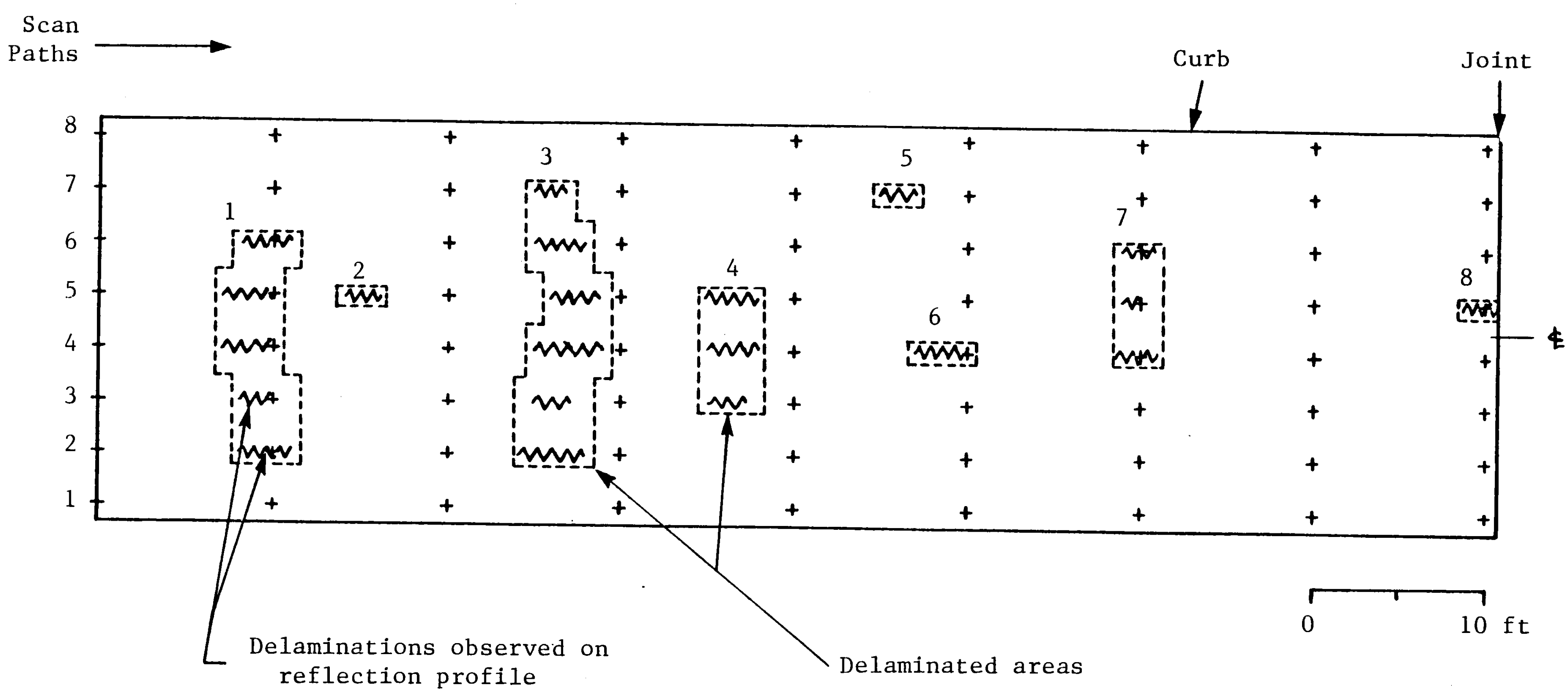


Figure 6.1. Delaminated areas located by GPR in a span of overlaid deck.