FINAL TECHNICAL REPORT

EVALUATION OF GROUND–PROBING RADAR
FOR
RAPID DELAMINATION DETECTION

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16. Abstract
This report covers an assessment of ground-probing radar technology as a rapid, nondestructive technique for the evaluation of the structural integrity of portland cement concrete bridge decks. Delaminations normally occur at the plane of the top mat of reinforcing steel within reinforced decks. This delamination is not evidenced by surface manifestations of deterioration until it has progressed to the point that major repairs to, if not replacements of, the deck are necessary. Engineers would welcome a nondestructive technique for deck evaluation to detect the existence of delaminations at an early stage in their development when repair is less extensive and less disruptive to traffic flow. Ground-probing radar has shown promise for such an application in that with this technology, internal conditions of the deck can be recorded, and perhaps the data anlayzed and interpreted to yield information concerning the decks internal integrity as a load-carrying structure. Additional controlled measurements will be required to develop an algorithm or pattern-recognition based analysis to allow dynamic data to be interpreted for the detection of small delaminations.

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Delaminations, bridge decks, ground-probing radar, nondestructive testing

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SECTION ONE

INTRODUCTION

This research concerning the detection of delaminations within bridge decks, both bare portland cement concrete and asphaltic concrete overlaid was performed in response to a seemingly accelerating problem of highway infrastructure deterioration, particularly structural bridge decks. Federal mandates require that States maintain a program of regular bridge structure inspections and maintain the structures in such a manner that they serve to adequately support design loads. To this end, methods for condition evaluations are constantly in a state of development with the hope that reliable, non-destructive evaluation techniques can be perfected to such an extent as to minimize interruption to normal traffic flow on the structure.

Ground-penetrating radar technology holds promise as an investigative technique for the determination of internal conditions within bridge deck structures. The objectives of this research were to (1) assemble a modified and improved version of a radar field instrumentation system developed in an earlier FHWA contract, and (2) evaluate the field performance of the improved system.

SECTION TWO

PROBLEM BACKGROUND

Introduction

The deterioration of steel reinforced portland cement concrete (PCC) bridge decks is of major concern to those agencies shouldered with the responsibility of providing a safe and pleasing transportation network for the general public. The deterioration of these decks can be manifest in many forms such as cracking, spalling, scaling, or delamination. This latter type of deterioration is perhaps of most concern to transportation agencies since it often goes undetected for some period of time, and can reduce the ability of the structural deck to adequately support the design loads.

Deck Construction

Portland cement concrete utilized as a structural material in bridge deck construction may serve as the riding surface or may be overlayed with either a PCC riding surface or an asphaltic concrete overlay. The case involving overlayed decks is of particular concern since visual evidence of internal deterioration of the structural PCC deck can remain undetected until the deterioration has progressed to the extent that major repairs, or perhaps complete replacement, of the structural deck is necessary. Structural PCC decks usually are reinforced with deformed reinforcing steel bars at two levels or depths within the deck structure. Normally, the top layer of reinforcing steel is between two and four inches below the surface of non-overlayed PCC decks, but may be two to three times that deep in decks with either a PCC overlay or with one or more asphaltic concrete overlay(s).

Portland cement concrete provides a protective environment for reinforcing steel unless it becomes distressed or contaminated. Cracks can provide a path for moisture and salt to migrate to the reinforcing steel and initiate corrosion. Similarly, portland cement concrete that has been contaminated with deicing salts ($CaCl_2$ and/or NaCl) provides an environment conducive to rebar corrosion because of the alteration of the naturally protective, high pH condition provided by the portland cement concrete.

The corrosion of reinforcing steel necessarily results in the formation of oxides and/or hydrated oxides of iron and the various alloying elements present in the steel. These oxides/hydrated oxides corrosion products occupy a greater volume than do the elemented iron and alloying materials, thus the formation of these corrosion products results in a tensile stress in the portland cement concrete surrounding the reinforcing steel. With continued active corrosion, this stress eventually exceeds the tensile strength of the concrete resulting in a fracture of the structure. This fracture often manifests itself as a crack roughly perpendicular to the surface above the reinforcing steel between the surface and the steel, but can manifest itself as relatively widespread cracking in the plane of the reinforcing steel parallel to the surface of the structure. This latter type of fracture results in the localized or overall delamination of the deck structure with the resultant loss of load-carrying capability.

The above described delamination phenomenon should be detected before major repairs are necessary. In order to accomplish this task, a non-destructive testing technique must be utilized that can provide data concerning the internal condition of a structural PCC bridge deck. Ground penetrating radar technology has been successfully utilized to provide subsurface data from pavement systems and bridge decks.(1) This report summarizes GAR's further development and evaluation of this subsurface radar technology for use in nondestructively assessing the internal condition of bridge decks specifically.

Electromagnetic Theory

The propagation of electromagnetic energy in a steel reinforced portland cement concrete bridge deck is not an easily characterized phenomenon. The multiplicity of construction materials leads to large signal attenuation as well as frequency dispersion. Even if a sought for signal return can be detected, multiple reflections, system internal reflections, and reflections from unwanted targets can lead to high levels of interference or clutter. The existence of this attendant clutter with target returns makes identification and characterization of the target return difficult at best, if not at times impossible. Following is a discussion of the effects of attenuation on delamination detection by electromagnetic techniques.

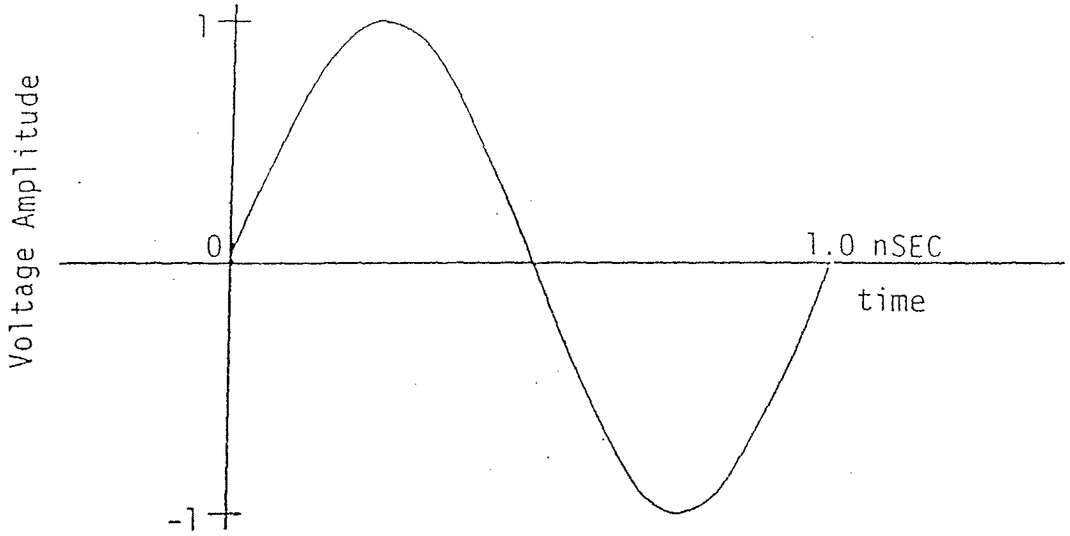
The effect of attenuation on the return signal is twofold. The attenuation reduces the returning signal relative to the interference level and thus signal-to-interference ratio may be insufficient for proper detection, or the peak-to-peak amplitude of the returning signal is reduced, making it difficult to estimate characteristics based on amplitude. The second effect of attenuation is to modify the frequency content of the signal and lengthen the return pulse so as to distort the return signal. For these reasons, it is important to understand the effects of attenuation and how it comes about and under what conditions it exists.

The major source of attenuation in this application is the concrete slab.(1) Unfortunately, very little information on the attenuation characteristics of concrete at the frequency of the short-pulse radar seems to be available. However, some inferences can be made based on existing data.

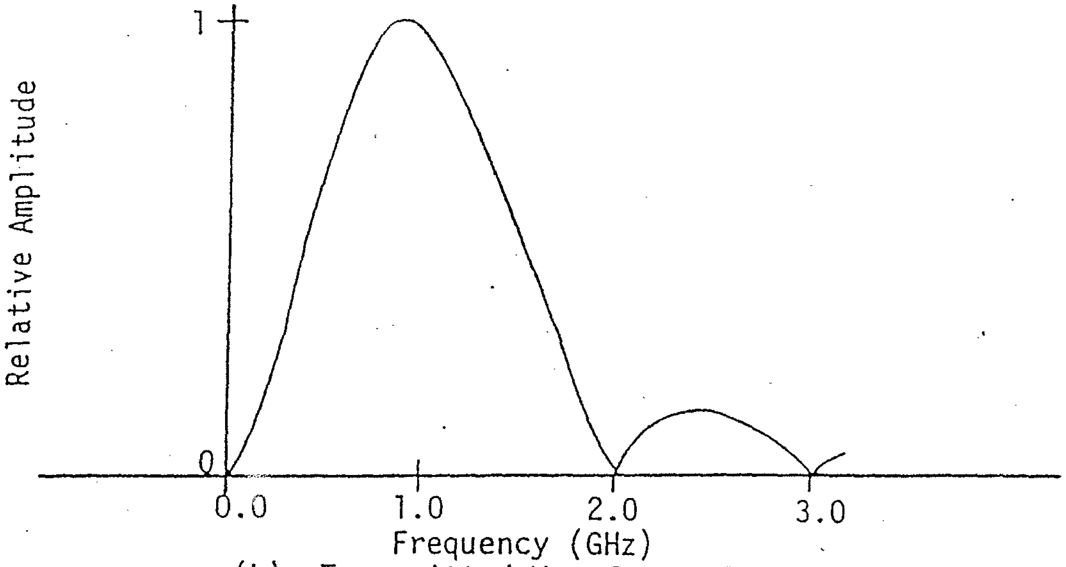
Attenuation characteristics of materials are very dependent on the frequency of the electromagnetic energy impinging on them. The time-domain signal generated by the radar transmitter is approximately that shown in figure 1 (a). The frequency spectrum of this transmitted signal is calculated to be that shown in figure 1 (b). The antenna frequency characteristics will modify this spectrum somewhat. However, because the antenna is very wideband, it does not significantly alter the spectrum shown. Most of the energy in the transmitted signal is located between the "one-half-power" frequencies, defined where the voltage spectrum is down 0.707 from the peak value. For the spectrum shown, these frequencies are approximately 0.6 and 1.4 GHz with a mean of about 1.0 GHz. Thus, the attenuation characteristics of concrete over this frequency band are of major interest.

The attenuation of EM waves in a dielectric material is given by:

$$\text{Attn} = e^{-ax} \qquad (1)$$



(a) Transmitted Temporal Waveform



(b) Transmitted Waveform Voltage Spectrum

Figure 1. Characteristics of short-pulse radar signal

where

$a = (2\ f/c)\ e_r\ \tan d$

f = frequency

c = velocity of light

e_r = the relative dielectric constant

$\tan d$ = the loss tangent

x = the distance EM waves travel through the dielectric material.

The attenuation in decibels (dB) per inch of a two-way travel is given by:

$$\text{Attn (dB/in.)} = 2.31 \times 10^{-9}\ f\ \ e_r\ \ \tan d \tag{2}$$

with the terms as previously defined. Thus, there are two dielectric properties that contribute to a material's attenuation characteristics: the relative dielectric constant and the loss tangent. Tables of these two characteristics for a large variety of materials exist (2, 3, 4). However, they are usually given for widely separated discrete frequencies (e.g., 0.3 and 3.0 GHz). The values of these parameters for frequencies between 0.6 and 1.4 GHz appear not to be available for concrete over an appropriate range of temperature and moisture conditions. One paper (4) discusses concrete but not in the frequency range of interest for this application. The dielectric constant and loss tangent for a frequency of 3.0 GHz is $e_r = 9$, and $\tan d = .3$. If we assume these values are valid at 1 GHz, then the corresponding two-way attenuation is 2 dB/inch (0.8dB/cm). Actual attenuation in concrete at 1 GHz will probably not be this large, but will be significant.

Hoekstra and Delaney(3) indicate that many types of soils are characterized by a "dielectric relaxation" at certain frequencies. The dielectric constant decreases with increasing frequency and the dielectric loss factor (loss tangent) goes through a maximum at a certain frequency. They indicate that the relaxation observed can be attributed to the presence of bound water. Also, the frequency of maximum loss is dependent on temperature. In general, lower temperature yields a lower attenuation and a higher frequency of maximum loss. Apparently, the so-called "bound water" consists of a thin layer of water molecules intimately bonded to polar sites in the host medium. This bonding reduces the rotational polarizability of the water molecules and thus lowers their relaxation frequency.(5) It is postulated that concrete at lower temperatures (e.g., freezing) will exhibit considerably lower attenuation.

A second effect of attenuation on the radar return is to distort the shape of the returning signal, making it more difficult to recognize. High frequencies in the band of interest are attenuated more than the low frequencies. Thus, the spectrum of the radar return is distorted causing the radar signal itself to be changed. The general effect is to make the spectrum narrower in bandwidth and, thus, make the radar return signal of longer time duration. However, this effect is not as serious as the attenuation of signal amplitude. The signal is likely to be attenuated below the interference level before any major distortion of signal shape can be observed.

Thus, the main concern is the attenuation of the signal below the interference level where detection is impossible, with the second effect being to corrupt the estimate of delamination size, where the peak signal values are used in the estimation.

In terms of the actual expected signal return when delaminations are present, consider the model of a concrete slab as shown in figure 2. The model was deliberately kept simplistic so that the associated mathematics are tractable. The source and receiver of the electromagnetic (EM) waves are located above the slab, and the waves are directed into the slab by an appropriate antenna. A portion of the EM wave is reflected by the slab surface and discontinuities in the slab. If there is no delamination in the slab, the only dielectric discontinuity is beneath the slab surface and the incident EM waves will be reflected from it. If a delamination does exist, each of the boundaries will reflect a portion of the incident EM waves.

Consider for a moment the behavior of electromagnetic waves at the delamination. The reflection coefficient, p, is given by:

$$p = \frac{\sqrt{e_{r1}} - \sqrt{e_{r2}}}{\sqrt{e_{r1}} + \sqrt{e_{r2}}}, \tag{3}$$

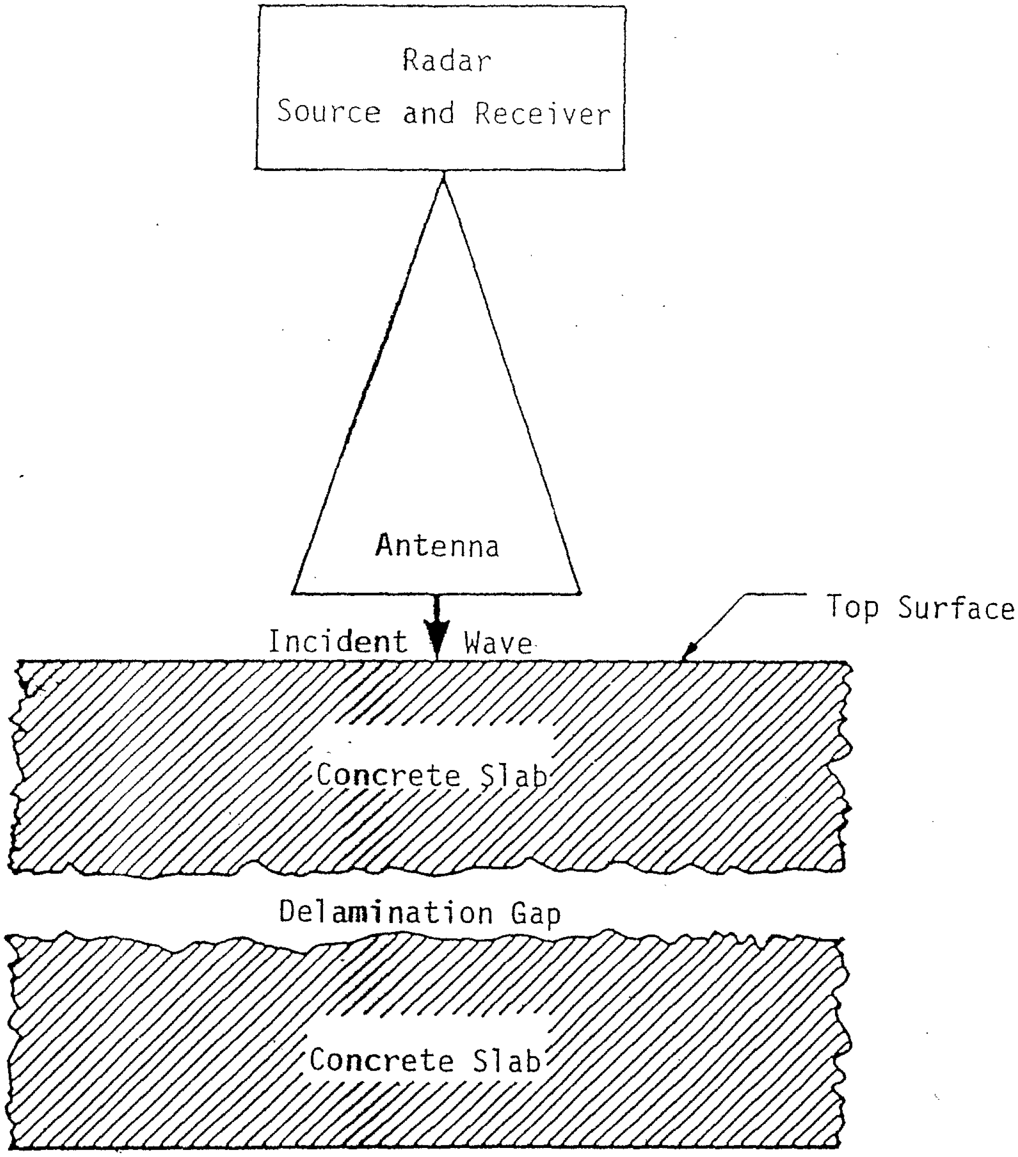


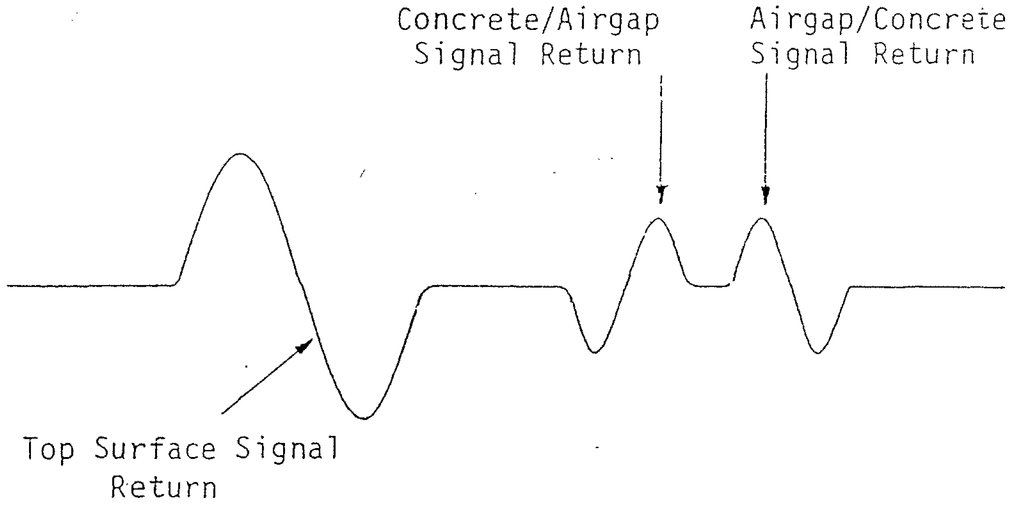
Figure 2. Model of bridge deck delamination problem

where e_r is the relative dielectric constant of the medium. Note that if medium 1 has a smaller relative dielectric constant than medium 2, p has a negative value. On the other hand, if medium 1 has a larger relative dielectric constant than medium 2, p is positive.

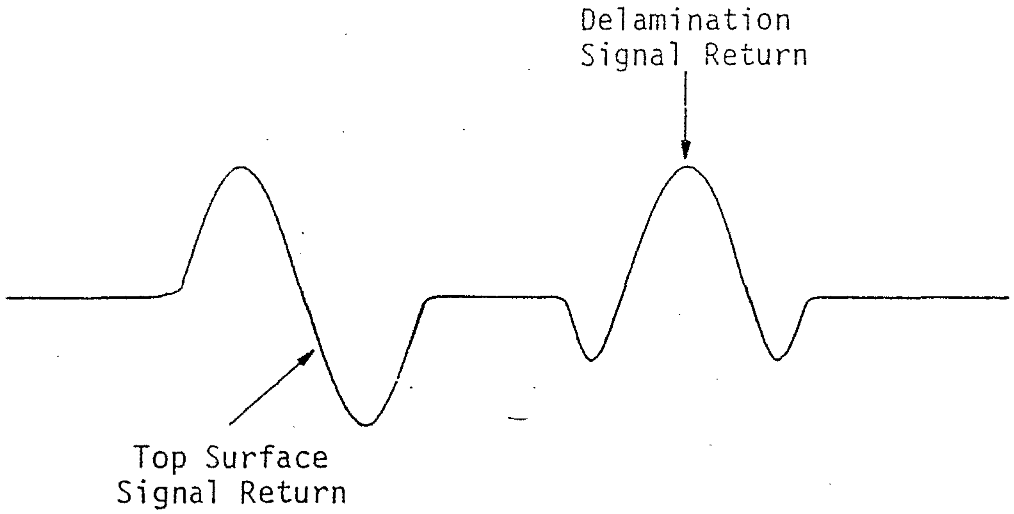
In the analysis of the case where a delamination exists, the reflected EM waves (radar returns) are as shown in figure 3(a). Because the dielectric constant of concrete is greater than that of air, the reflection coefficient at the concrete-air interface is positive. However, the reflection coefficient at the air-concrete interface is negative. Thus, the reflected pulses from these two boundaries are of different polarities as shown. As indicated in figure 3(b), the smaller the delamination air gap, the more the two interface returns interact together. Thus, the amplitude and shape of the signal return gives an indication of the air gap size in the direction of the incident EM wave propagation.

Calibration

To collect meaningful data from a PCC bridge deck with the attendant difficulties described in the preceeding paragraphs, one must assume that the ground penetrating radar equipment is always in peak condition and operating in a consistent manner so data gathered at different locations, at different times, and under dissimilar conditions (temperature, humidity, etc.) can be compared. To this end, the equipment must be maintained in a calibrated condition and consistent data gathering methods and procedures be followed. The equipment should be adjusted at the beginning of each day and the calibration checked periodically for stability, particularly if significant temperature changes occur during the measurement period. To facilitate this calibration, a calibration test fixture can be constructed as shown in figure 4. The fixture is utilized by first illuminating the foam block without either aluminum plate in the beam of the electromagnetic energy. The large plate is then inserted at the block face farthest from the antenna, and the location of the return from the plate is noted on the oscilloscope. With the large plate in place under the block, the small aluminum plate is slowly inserted into the path of the radiation until one also witnesses a return from that small plate. With returns from both plates present on the oscilloscope, the potentiometer on the sampler sweep board of the transducer is slowly adjusted



(a) Large delamination gap.



(b) Small delamination gap.

Figure 3. Example of reflected waves from concrete slab

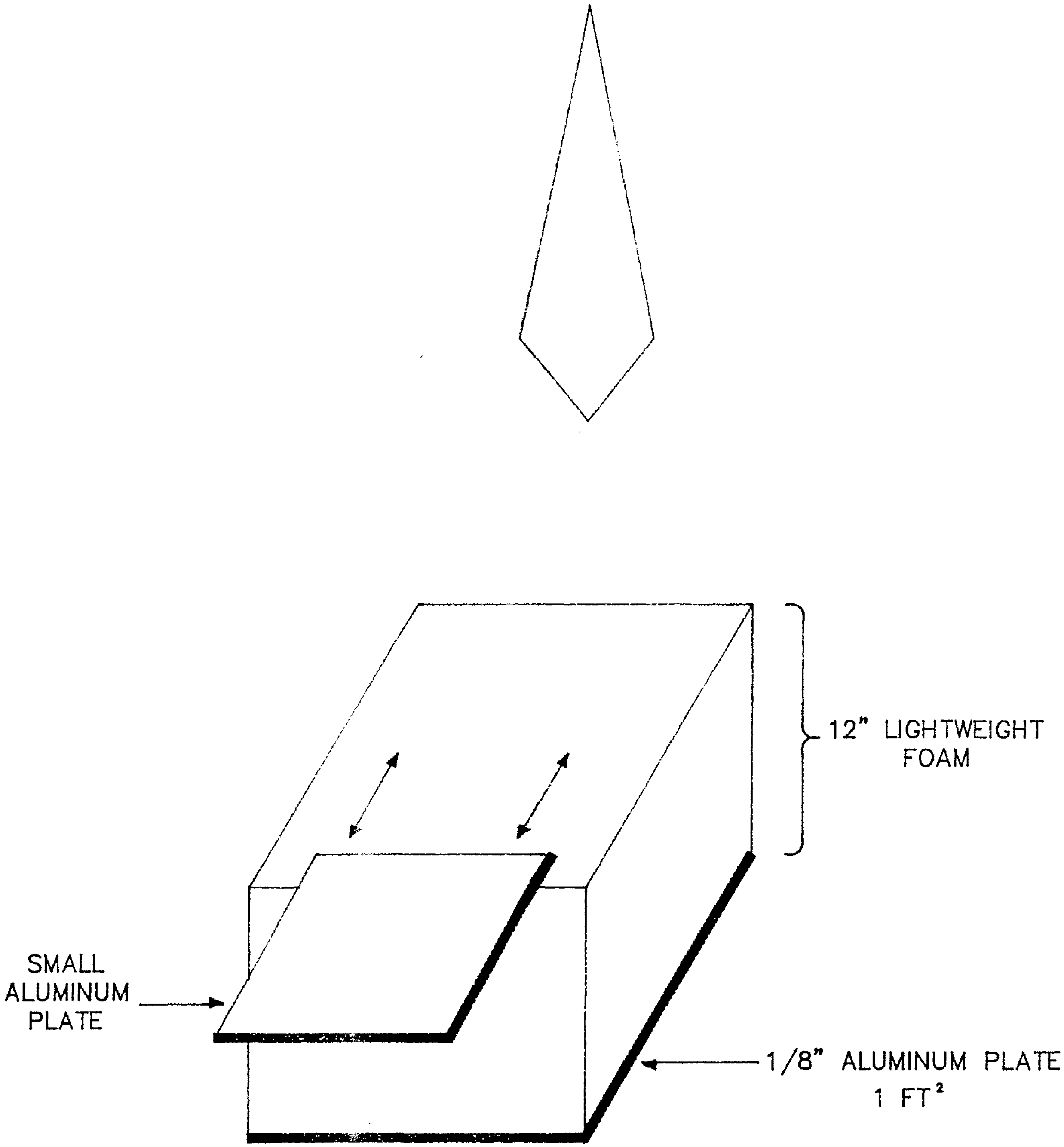


Figure 4. Calibration Fixture

until the two returns exhibit an apparent separation on the oscilloscope of two milliseconds. The use of this procedure insures that the radar equipment, in particular the transducer portion of that equipment, is operating in a consistent manner each time it is utilized.

SECTION THREE

VEHICLE HARDWARE

This section provides a description of the hardware for the radar field instrumentation system that was assembled and modified in this study. Included are the primary components or functional units, the vehicle/instrumentation configuration, the method of assembly, the hardware improvements to the original Penetradar system, and optional equipment. The discussion in each of the following subsections is intended to provide the reader with an understanding of the function(s) of the individual hardware components and their interactions as a fully integrated radar system.

System Description

Block Diagram

Figure 5 is a block diagram of the radar system as assembled by Gulf Applied Research. The racks provided in the vehicle contain the radar control unit, the master control panel, the auxiliary control panel, the four channel frequency modulated reel to reel tape recorder, the oscilloscope, and the power supply units. Also located in the vehicle, but adjacent to the dashboard for the drivers convenience is a digital speedometer/odometer unit. Appropriate cabling/wiring is provided to interconnect the various components into a composite functional radar unit. On the exterior of the vehicle during actual radar data gathering operations are the bumper mounted fifth wheel reference location device, the boom mount and boom, the boom-mounted radar transducer, the radar antenna with appropriate mounting supports, and the optical encoder to mark the beginning of each bridge deck on the recorded data.

General Operation

The fully equipped vehicle is completely self-supporting in its role as a radar data gathering and data display unit. The AC and DC power supplies for the radar equipment and the attendant peripherals are on-board and are independent from

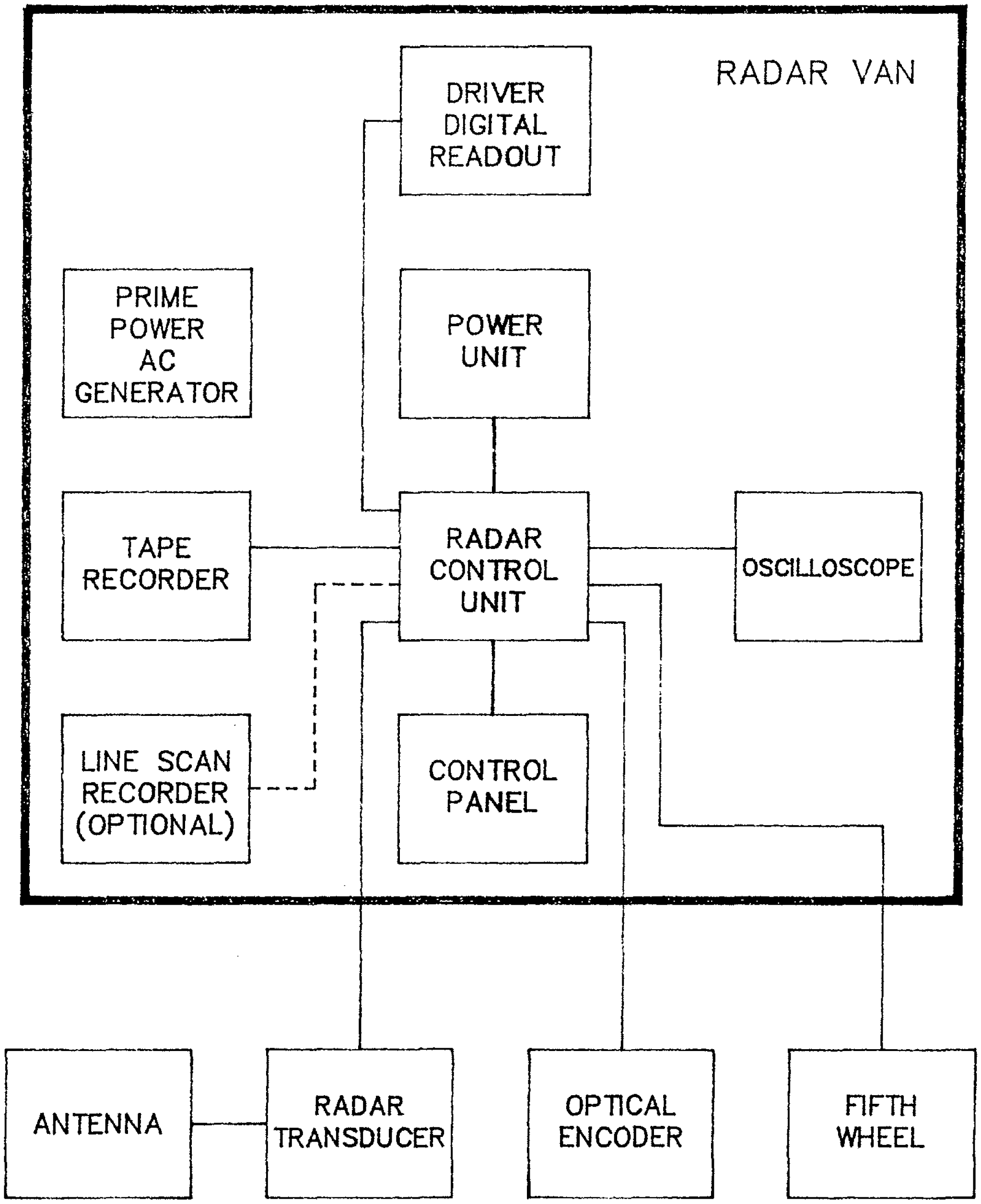


Figure 5. Block diagram, radar field instrumentation system

the vehicle eletrical system. The radar functions and recording functions (fm) are synchroneously controlled from the master control panel to minimize operator error or confusion inherent with a system with a multiplicity of switch function locations. The fifth wheel supplies the speed indications (accurate to 0.1 mi/h) (0.19km/h) and distance (in 1-foot (0.3 m) increments) to the drivers digital display. The optical encoder marks the beginning of a bridge deck both on the magnetically recorded data and on the optional line scan recording.

Radar System

Transmitter

The transmitter is a part of the radar transducer assembly as shown in figure 6. The drive consists of a snap-off, step recovery diode that generates a transition across a coaxial pulse forming network, thereby generating a fast transition pulse. Amplification is then achieved by a transistor operated in the avalanche mode for high-speed-switching. This solid-state transmitter directly couples to the antenna. The high voltage supply is a dc-to-dc converter that takes +12 Vdc and chops it through a transformer to generate the transmitter high voltage.

Receiver

Returning rf is sampled by a Schottky barrier diode that is strobed by a snap-off, step-recovery diode at a 5 MHz rate. The periodicity of the received waveform allows one to take individual samples from period to period in order to reconstruct the waveform over a longer time period, thereby decreasing the bandwidth requirements. To have samples at times differing from the transmit pulse, the 5 MHz signal to the sampler is delayed in the voltage controlled delay lines. The control voltage for the delay is a staircase ramp, which yields a sample resolution of approximately 100 picoseconds. To increase the signal-to-interference ratio, 450 pulses are integrated at each sample point. A 10 or 20 ns period is thereby stretched to equal 5, 10, 15, or 20 ms in equivalent time, depending upon selection of timing parameters.

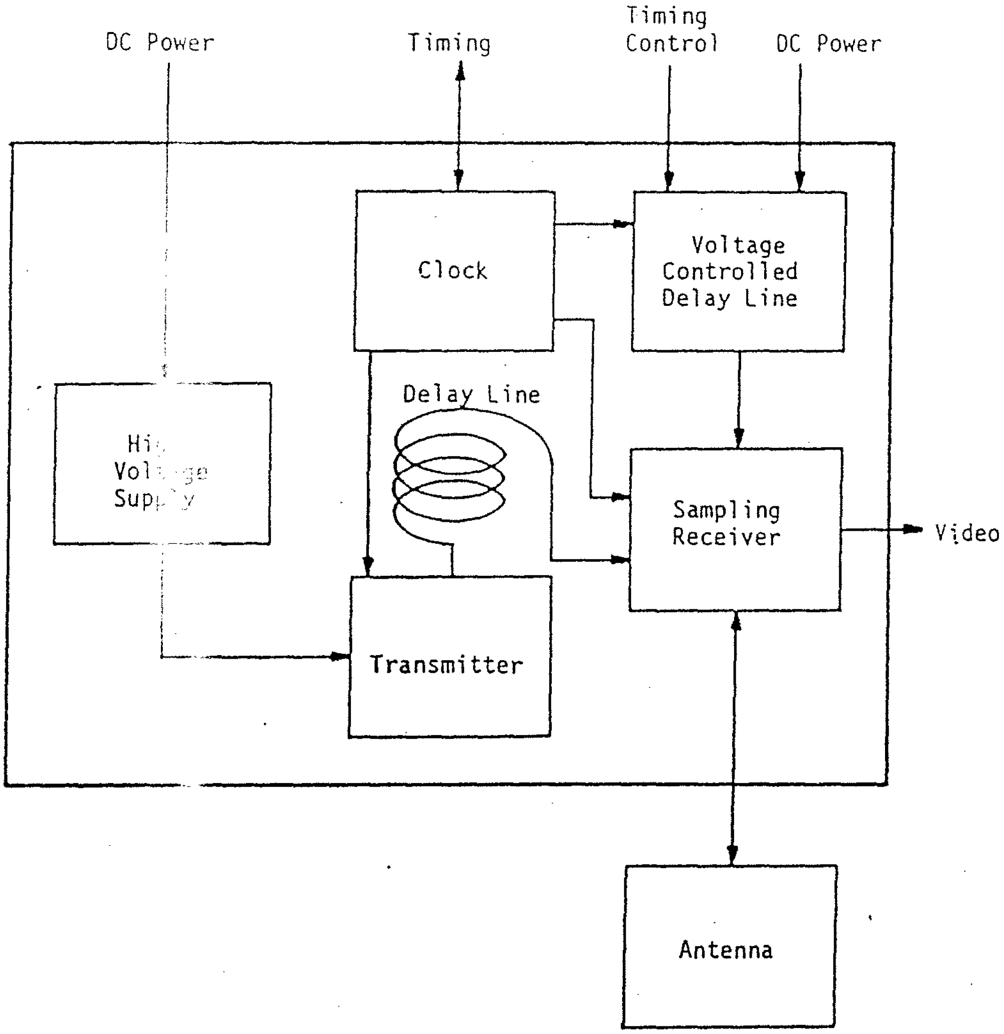


Figure 6. Block diagram, radar transducer.

Sweep

The sweep voltage is generated in the radar control unit and then sent to the sampler/receiver. This sweep voltage varies the delay in the voltage controlled delay line which effectively sweeps the phase of the sampler 5 MHz signal. The sweep is variable in amplitude and duration, which produces the capability of varying the output radar scan rate and the sample density. The data rate may be increased by narrowing the sample window. The Penetradar PS-24 radar is typically set for a 20 ms sweep time. The modified unit has the capability of performing at multiple scan rates required to obtain high quality data at 40 mi/h (74 km/h).

Antenna

The antenna is of broadband design, working over the 200 MHz to 2 GHz frequency range. To obtain the low frequency response, a TEM (transverse electromagnetic) horn is used which is not limited by low-frequency cutoff as a waveguide horn would be. To get the required wide bandwidth, the plates of the horn are flared and exponentially tapered, with resistive card loading on the ends away from the feed, resulting in a low voltage-standing-wave-ratio over the given range of frequency.

Timing and Control

The timing for the modified system is derived from a 15 MHz crystal controlled oscillator. This signal is divided down to produce all gating and trigger waveforms needed in the radar. In particular, the timing generator produces the 5 MHz signal that establishes the radar pulse repetition frequency.

Surface Lock

The main function of the range tracker is to establish a fixed reference position for the pavement surface return. Once this is established, all other video is referenced back to this surface. Video cannot be referenced to the transmit pulse because of the varying antenna height above the ground. If it were, the position in range of the target return would move in and out, with variations in antenna height. The range tracker locks onto the surface return by applying an error voltage to a voltage controlled delay line that keeps the surface return locked to a fixed range window. The target always remains at the same position within the window regardless of antenna height.

Power Supply

The power supply unit for the modified system is a rack mounted unit that contains all the necessary ac-to-dc supplies. The supplies are all regulated and filtered to eliminate any potential sources of interference from generator, inverter or automotive noise sources. All supplies are fused by front panel circuit breakers, have LED indicators, and test points. The power supply unit supplies power to the radar control unit which in turn supplies power to all other equipments, thereby providing for control of grounding, reducing the risks of ground loop interference.

Radar Control Unit (RCU)

The Radar Control Unit (RCU) and master control panel, indicated in figure 5, are the primary pieces of equipment used by the operator to control the radar functions and data recording during measurements. The functions of the RCU are detailed in the block diagram of figure 7.

RCU Configuration

The RCU is a rack-mounted card cage which houses 5 printed circuit (PC) boards, and interfaces up to 9 other devices through rear mounted connectors. PC boards inside the RCU control the timing and surface lock circuitry. In addition, a microcomputer inside the RCU routes all analog signals between the radar transducer and tape recorder, as well as the oscilloscope display and optional strip chart recorder.

Master Control Panel

The operator controls the radar, position reference unit, and all recorders, through the switches mounted on the master control panel. The scan speed switch selects a sampling period of 5, 10, 15 or 20 ms for the radar unit, thereby producing measurement rates of 200, 100, 67, or 50 scans/second. The footage count can be loaded from a set of thumbwheel switches using the preset switch, or the footage count can be zeroed with the reset switch. All recorders (tape, video or strip), can

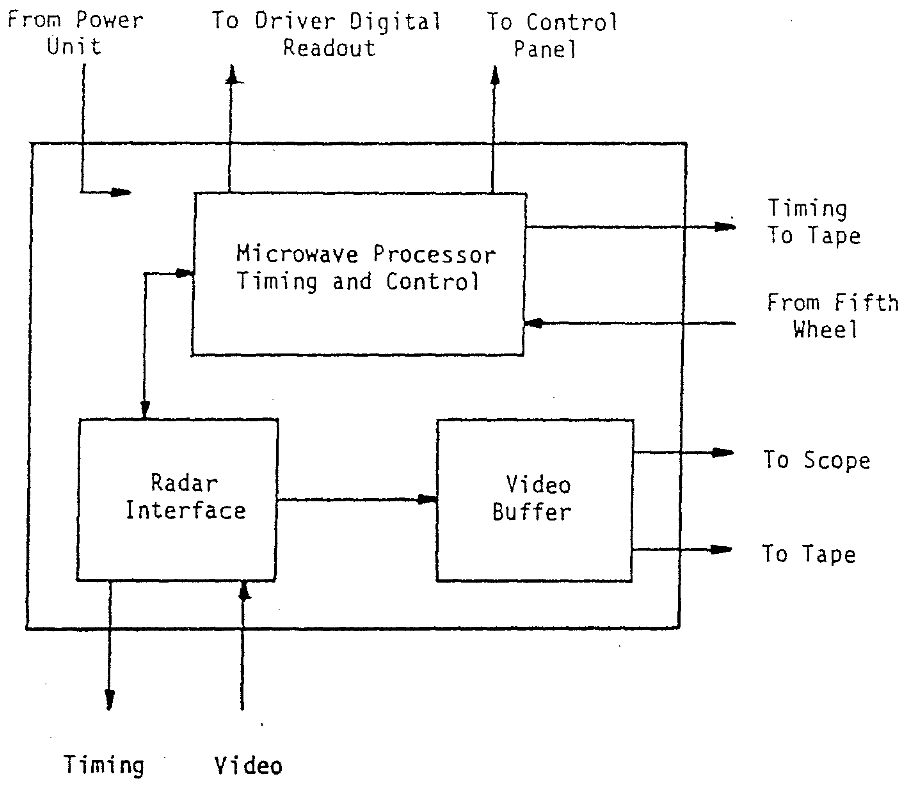


Figure 7. Radar control unit block diagram.

be run in an automatic or manual mode. In the automatic mode, pushing the auto start switch on the master control panel starts all recorders. They can be stopped simultaneously using the auto stop switch. Positive, negative, or bipolar video can be selected for output to an optional strip recorder. The master control panel selects footage marks on an optional strip chart recorder, which can be spaced at 1, 10, 20, or 50-foot (0.3, 3, 6, or 15m) increments. Chart speed can also be selected.

Driver Digital Readout

The driver's digital readout unit mounts on the dashboard of the radar van. This unit displays to the driver accurate speedometer and odometer readings.

Speedometer

The speedometer displays vehicle speed in mph with an accuracy of 0.10 mi/h (0.19 km/h). This digital readout aids the driver in maintaining a constant speed.

Odometer

The odometer displays distance traveled in feet with an accuracy of one foot per mile (0.16 m/km). The six digit display registers from 0 to 999,999 feet. The odometer and speedometer are controlled by a microprocessor in the radar control unit. The microprocessor writes data to the speedometer/odometer through a multiplexed data line. The data is latched and displayed on Liquid Crystal Displays (LCD). The LCD consumes very little power and can be viewed easily in bright sunlight or at night via an internal light which can be adjusted by the driver.

Data Location Reference

Fifth Wheel

The fifth wheel, as shown diagrammatically in figure 5, is mounted on the left side of the rear bumper so as not to interface with radar data being collected with the antenna/boom deployed from the right rear of the vehicle. This device provides accurate measurements of speed and distance that are interfaced with the driver's digital display, with the magnetically recorded radar data, and with the optional line scan recorder through the Radar Control Unit (RCU). The wheel may be operated at speeds exceeding 150 mi/h (278 km/h). The fifth wheel frame is made from 1-inch (2.5 cm) square heavy gauge steel tubing with bronze-bushed friction damped pivots. Overcenter springs dampen fifth wheel bounce when in use and hold the wheel in off-the-road storage position when not in use. The wheel assembly includes 11-gauge spokes, heavy duty rim and a pneumatic 26-in x 2.125-in (66-cm x 5.3-cm) tire, specially selected for balance and runout. A convenient screw type clamp attaches the fifth wheel to the vehicle. All exposed steel parts are finished in chrome plate with the exception of springs, electrical connectors, and stainless steel shaft. A red warning flag is mounted on the wheel assembly for use in on-road testing.

A precision transmitter mounted on the axle of the wheel assembly transfers distance measurements directly to the radar control unit. The drive axle mates with a SAE 7/16-in (1.1-cm) fitting for easy transmitter attachment to the wheel. The transmitter is an etched metal optical shaft encoder which generates 50 digital pulses per foot. The system basically measures distance by the relationship between the number of holes in the optical encoder fastened to the wheel's live axle, and the distance traveled by the wheel in one revolution. Because the system is digital, the only thing that can affect the measurement accuracy is the wheel's circumference, since the number of holes is constant. The circumference varies with temperature, changing speed and tire air pressure. For accurate measurements the wheel must be calibrated for the operating conditions. This is done by running the vehicle over a known, measured distance (preferably a measured mile), at the average speed to be used during the radar data collection runs and adjusting the tire air pressure. If the wheel is calibrated in this way at 40 mi/h (74 km/h), then constant running at speeds within 10 mi/h (19 km/h) of this value will produce measurements accurate to within 1 foot per mile (0.16 m/km).

Absolute Reference-Optical Encoder

This interfacing of the fifth wheel data with the recorded radar data through the RCU facilitates an accurate location of any data point, but this must be coupled with a known starting location which must also be recorded with the radar data.

This is accomplished with the radar/vehicle system by utilizing an optical device, as shown in figure 5, to detect a strip of temporary retroreflective traffic marking tape placed at the beginning and end of each bridge deck. The optical transducer detects the retroreflective tape and, in conjunction with the RCU, notes the locations on the recorded radar data. The pulse from the optical scanner initializes the distances as measured by the fifth wheel and references all distances thereafter to the location as marked by the retroreflective tape.

The optical transducer utilized with the radar/vehicle system is a small bumper mounted solid state unit comprised of an LED source, sensor, and amplifier. The infrared light source is modulated at a high frequency and the receiver/sensor is tuned to respond to that frequency thus ambient light interferences are virtually eliminated.

Tape Recorder

Specifications

The magnetic recorder selected for use in the radar vehicle is a Hewlett Packard Model No. 3964A. The HP3964A is a four-channel, six-speed instrumentation recorder. The recorder uses 1/4-inch (0.64-cm) magnetic tape and is capable of FM recording on the four data channels over a bandwidth of 0 to 5 kHz. The recorder is vertically-mounted on slides in a standard 19-inch (48-cm) equipment rack. BNC input/output connectors are located on the front panel with parallel rear BNC input/output connectors available to patch into the RCU. The technical specifications of the recorder are summarized in appendix A.

Recorded Data Format

Table 3.1 lists the format and data channel assignment of the tape recorder. Sufficient digital signals are recorded to synchronize radar data during playback and to correlate the data with the footage count at acquisition. The optional chart drive output allows the radar control unit to generate scaled strip chart recordings with footage markings on the optional line scan recorder.

Table 3.1. Recorded Data Format.

Channel	Signal	Amplitude	Type
1	Radar Video #1	bipolar, -5V to +5V	FM
2	Radar Sync	TTL, 0 to +5V	FM
3	Footage Count	TTL, 0 to +5V	FM
4	UART Clock	TTL, 0 to +5V	FM

Vehicle Configuration

Vehicle Description

The vehicle in which the radar equipment has been installed is a 1979 Chevrolet van purchased as a used vehicle on September 9, 1984. The manufacturer's identification number is CGD1590155051. Both the interior and exterior of the vehicle have been modified to facilitate the installation of the necessary radar and peripheral equipment.

Both rear quarter panels were modified and reinforced to accomodate the articulating antenna boom mount. With this arrangement, the antenna can be moved in an approximate 130 arc without degrading the radar data due to interferences from the vehicle as shown in figure 8.

The interior of the vehicle has been modified to provide a table along the left side behind the driver to support the two racks of equipment and the optional line scan recorder as illustrated in figure 9. The AC generator is housed in an enclosure under rack 2, but with cooling fans and access to the generator provided by a lockable door on the vehicle exterior and the rear of the driver's side door.

Controls for the top mounted flashing arrow board are mounted on the table immediately behind the driver's side seat. The arrow board itself is located on the roof of the vehicle and is hinged so that it can be laid flat while the vehicle is moving at highway speeds between bridge sites.

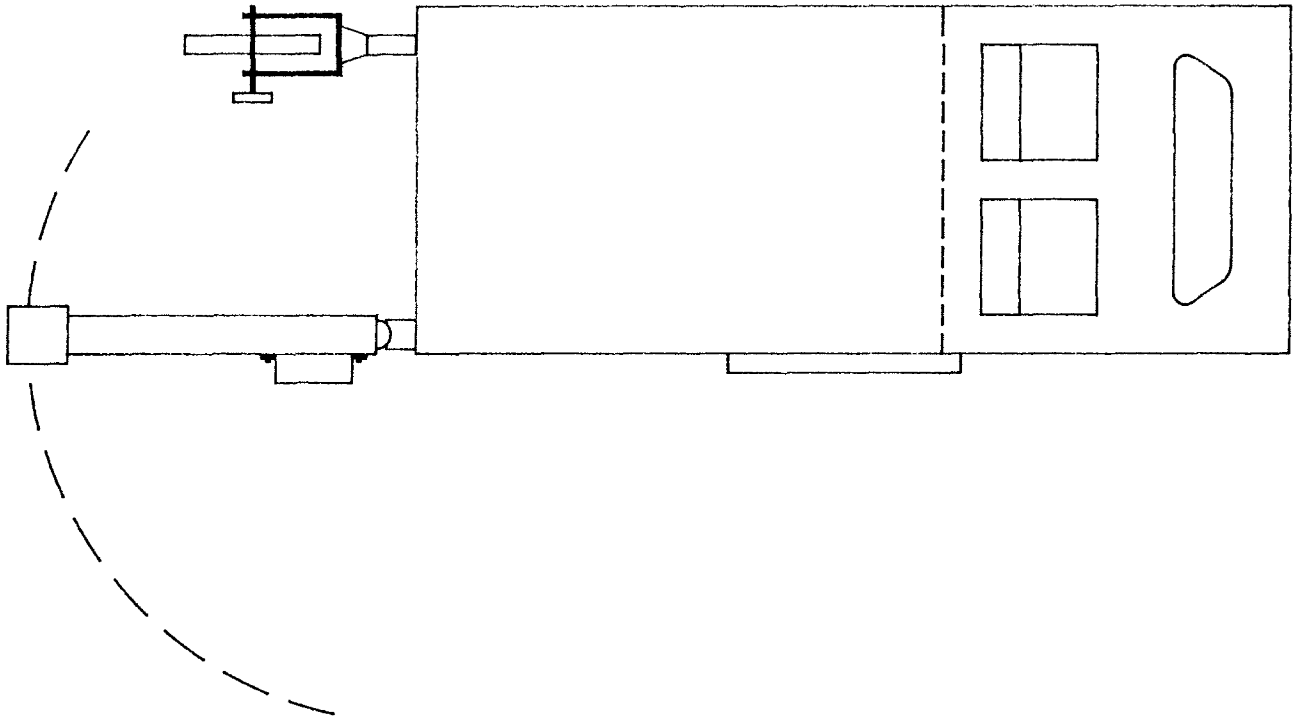


Figure 8. Antenna Movement

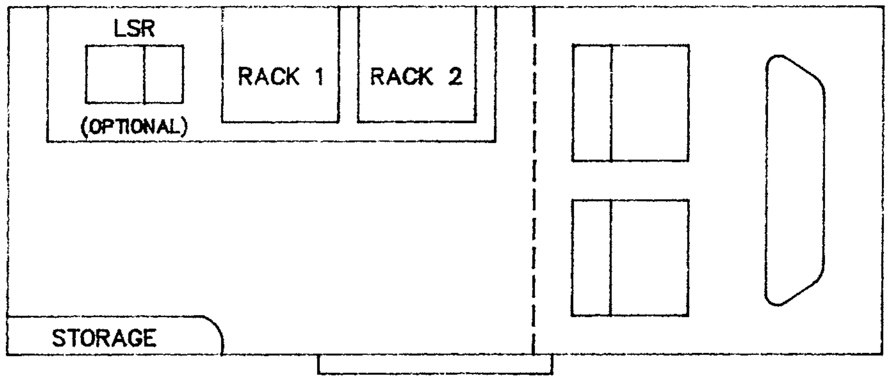


Figure 9. Vehicle Interior

The equipment in the vehicle is contained in two racks as shown in figure 10. These are standard 19-inch (48-cm) equipment racks.

Prime Power

The primary power requirement for the radar and peripheral instrumentation is 120 volt AC/60 hertz. This power is supplied by an on-board AC generator, and is converted for those radar functions requiring DC power.

On-Board AC Generator

The on-board AC generator is an 800-watt gasoline-powered model EX800 Honda. This unit is wholly committed to the radar and peripheral instrumentation and allows operation of the radar system without operation of the vehicle engine. This AC power supply is utilized to provide power for the magnetic tape recorder, the optional line scan recorder, and the DC power suply.

DC Power Supply

The DC power supply which converts power from the AC supply to DC is a rack mounted unit utilized to power the radar instrumentation and illuminated panel switches. This DC power is necessary for the PC boards in the radar control unit, for the operation of the 5th wheel optical encoder, and for the radar transducer.

Components and Assembly

Introduction: Philosophy

The components of the radar/vehicle system have been fabricated of quality materials designed to provide a reliable system. The configuration of the interior of the vehicle was designed to maximize the space available while assuring adequate comfort for and maximum utilization of resources by the radar operator(s). All electronic components were selected for maximum reliability, stability, accuracy, and sensitivity.

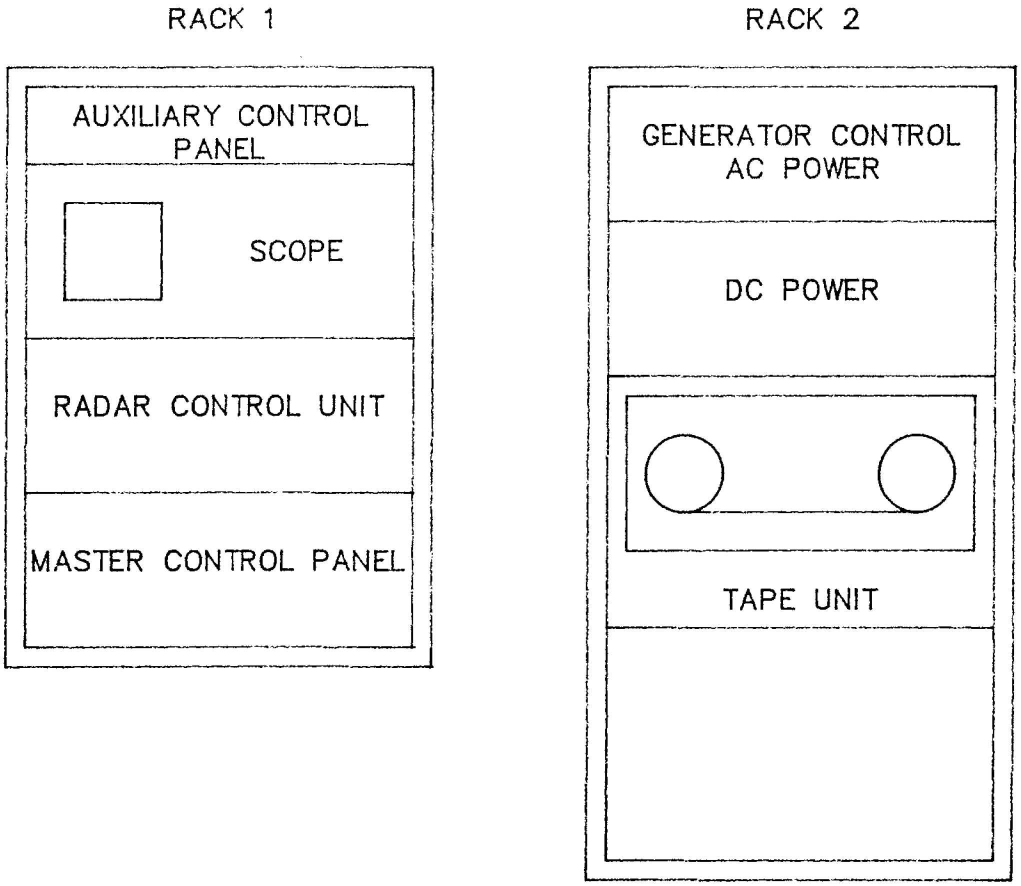


Figure 10. Instrumentation Layout

Electronics: PC/Wirewrap Boards

All electronic components have been constructed of durable materials with attention given to providing additional ground planes to reduce internally generated noise. All boards are accessible from the front of the RCU and test points have been provided to facilitate calibration, alignment, and trouble shooting of individual assemblies.

Cabling & Wiring

All cabling and wiring has been fabricated to prescribed lengths and shielded to eliminate noise problems. The cables are labeled for clarity and to facilitate installation.

Switches

The control panel switches were selected on the basis of reliability and appearance. Each switch has been engraved with its operation on the front. One of four individual switch lights indicate which function is selected. The switches and indicators use high intensity incandescent bulbs that allow the functions illuminated to be read even in bright sunlight.

Panels, Racks, and Finish

The panels are machined from .125-inch (0.32-cm) aluminum and rack mounted. Each panel has been painted and silk-screened with the proper labeling. The racks will be 19-in x 3-ft x 2-ft (48cm x 91 cm x 61 cm) and will be painted to match the front panels.

Antenna Mount Materials

The antenna mount system is a lightweight, noninterfering, sturdy support. The system was fabricated using a nonconductive fiberglass channel that is machined and assembled using nylon rivets. A polycarbonate material is used to mount the antenna to the boom. This material is a hard plastic which has good flexibility and strength. The mounting surface on the antenna was made from a section of fiberglass channel that is fiberglassed/epoxyed to the antenna. This mount aligns with the polycarbonate material and is fastened in place with nylon rivets. This method provides a firm support, but also permits quick connect and disconnect of the antenna. The entire mount system has no metal parts, and thus eliminates any problems created by radar reflections from the mount. This system is a proven mount that meets the requirements of being lightweight, sturdy and non-reflective, and has been used by Gulf Applied Research in the antenna systems on its highway radar vehicles.

Performance Improvements

Hardware Configuration

The development of the radar field instrumentation system required some improvements to the basic radar system. These improvements were designed to reduce interference generated within the radar transducer and antenna subsystems, and to insure that the modified unit is durable enough to withstand operation on the highway.

The modified radar system takes advantage of previous development at Gulf Applied Research in the design of highway radar systems. The radar field instrumentation system incorporates a system design which includes a microprocessor-based radar controller, integrated recording system, multifunction control panel, position reference unit (fifth wheel) and tachometer, and driver's remote digital tachometer/position display. In addition, the system configuration contains provisions for an optional line scan recorder.

Measurement Rate Improvement

An enhanced timing design is made possible by the use of a microcomputer in the RCU. The system timing can be varied to adapt to data collection conditions. This flexible timing design allows the selection of 5, 10, 15, or 20 ms sampling periods, and in addition, the window of radar data can be set to 10 or 20 ns. This effectively allows the operator to select scan rates of 200, 100, 67 or 50 scans/second as well as the depth of penetration of the radar. In addition, all surface lock control signals, such as early gate, late gate, and range gate, are scaled to the selected timing configuration. The faster scan rates allow the vehicle to travel at faster speeds while maintaining satisfactory data integrity.

The use of the microcomputer allows all timing selection to be made in software by altering the program memory.

Surface Lock Design

The modified radar system incorporates a surface lock or surface tracker. The purpose of the surface tracker is to maintain the surface reflection at the same point with respect to system timing (i.e., with respect to the transmitter firing). This allows the antenna to move vertically when the vehicle is in motion while maintaining the surface return at the same point in the recording cycle. Hence, when a hardcopy of the data is recorded, the surface always appears as a straight line. The PS-24 system was modified to eliminate the need for tracker re-acquisition. The improved system allows the operator to manually move the video return to the point he wishes to track and then manually initiate surface track. This overcomes surface lock on anomalous returns. In addition, the improved circuitry has a wide range which allows for significant variation in the surface return without affecting the surface lock. A narrow early gate/late gate has also been implemented. This narrows the effective range gate so that signal returns from the bottom of thin asphalt (on the order of 2-in) (5cm) will not affect the performance of the surface tracker.

The surface tracker board also incorporates a fully shielded video receiver which eliminates extraneous pick-up in the video. The video is brought onto the board by a shielded coaxial cable through an SMA connector mounted on the board. The video is buffered and the gain adjusted for changes in scan rate or scan depth so that the surface tracker and video recording levels are identical, regardless of the combination of scan speed and depth. The overall performance of the surface-lock scheme is excellent and is a marked improvement over past designs.

Signal Interfacing

The area of signal interfacing has received critical attention in the Gulf Applied Research redesign. The video and control signals are required to interface with various components, circuit boards, and control functions. During the prototype development of the highway radar system, a critical look was taken at each of these interfaces to insure quality data transfer and low distortion. Consequently, a conservative design was selected, one which uses multiple buffering, heavy shielding between potentially interfering sources and carefully interconnected grounds and dc power lines. All data recording devices are driven well within their specifications and buffered to eliminate interaction between components.

Transmitter Losses

Transmitter delay cable was utilized to increase the power radiated into the pavement.

Antenna Improvements

Stronger, more durable quick connect/disconnect units have been utilized on the antenna with a resulting increase in reliability. The antenna cable has been fabricated of 0.141-inch (0.358-cm) semi-rigid coaxial cable as opposed to the more "lossy" 0.085-inch (0.216-cm) material used originally. The utilization of this greater diameter cable also provides for more durable connectors.

Optional Equipment

Field experience has indicated that a line scan recorder is a valuable addition to the data gathering capability of the radar/vehicle system. Provisions have been made in the control and recording circuitry of the radar system to allow for the use of an optional line scan recorder such as a Raytheon Model LSR 910M or equivalent (see appendix B).

SECTION FOUR

DATA COLLECTION & ANALYSIS

The collection and analysis of data from actual in-service bridges was performed to assess ground penetrating radar technology's contribution as a rapid, non-destructive bridge deck assessment technique. Data was collected on bridges in several locations with varying environmental conditions and processed at Gulf Applied Radar's facility in Marietta, Georgia. Sites were chosen to be representative of bridge locations on the local, State, and national highway systems, with the exception of marine and desert environments. These two were not purposely excluded, but it was felt that a marine site was similar to one at which large quantities of deicing salts were utilized and, traditionally, bridges in desert locations suffer very little distress associated with reinforcing steel corrosion.

Data Collection

Program Plan

Data collection represented an extensive effort during the mid-portion of this project and to a lesser extent during the processing, analysis, and interpretation phases. Initially, data was collected on several bridges on the state and federal systems within Georgia. Some of these exhibited various degrees of deterioration, but not necessarily in the nature of delaminations. One of these bridges was an interstate structure not yet opened to traffic. Bridges with both steel and prestressed concrete substructures were surveyed. During these preliminary surveys it became evident that signal returns from the deck substructure could significantly effect data from within the deck structure itself. Particularly, steel and heavily reinforced diaphrams were evident in this early data in addition to reinforced or around expansion points. This early data was collected, analyzed, and interpreted so as to create a data base to which subsequent data could be compared.

After the initial assessment of system performance on the bridges within Georgia, condition evaluation surveys were conducted in Tennessee, North Carolina, West Virginia, Michigan, and Virginia with the cooperation of those various DOT's.

Information pertaining to each survey location is contained in appendix C, "Survey Site Information". These evaluation surveys were conducted in order to assess system performance and define performance specifications such as signal-to-interference ratio, maximum reliable inspection speed, near surface and far surface resolution, sensitivity and reliability. In addition, through correlation of the results of these evaluation surveys with data from other sources such as sounding techniques and core samples, the accuracy of the overall measurement system was examined.

Finally, periodic monitoring was conducted on two bridge decks located in Knox county, Tennessee as indicated in appendix C. One of these bridges was a bare portland cement concrete deck, and the other was a complex structure of portland cement concrete overlayed with paving bricks, and these overlayed by approximately four inches of asphaltic concrete.

Field Support

Two trained technical support personnel were provided to operate the radar system for each survey performed. A test monitor was also supplied to supervise all test activities and coordinate overall operations. In addition to system operation, Gulf Applied Research was also responsible for system maintenance and repair during the entire program.

Data Archiving

For each bridge deck survey, the following items were labeled and archived:

(1) System operator log sheets
(2) FM tape (or digital tape) on which radar data is recorded
(3) Strip chart outputs (if available)

Coring/Sounding Information

In addition to data collected by the radar/vehicle system, auxiliary information in the form of construction plans, core data, etc. was provided by the various State DOT's. This information was necessary to provide correlational data for assessing overall system performance. The coordination with the various agencies was the responsibility of Gulf Applied Research.

Data Analysis

All data analysis was performed off-line. This involved hardcopy generation, data interpretation and bridge deck condition evaluation. The following sections describe each of these tasks.

Hardcopy Generation

The first analysis step was the generation of a suitable hardcopy presentation of the radar data. This hardcopy was produced by playing back the data recorded in real-time on FM tape, and using a line scan recorder to record this information in a strip chart format. The line scan recorder which was utilized had sufficient spatial resolution and intensive dynamic range and accurately reproduced all features of the radar return essential for accurate interpretation. To this end, the Raytheon LSR-910M line scan recorder was utilized.

Data Interpretation and Deck Evaluation

The data reproduced for the recorded FM data on the line scan recorder was analyzed and interpreted by Gulf Applied Research personnel. It was anticipated that since only deck delaminations were of primary interest and bridge decks are typically relatively short, very little time would be required to process and interpret the data from each bridge. This was based upon the anticipation of deck delaminations providing a specific radar signature distinguishable from signatures of other illuminated targets (i.e., rebar, expansion joints, diaphrams, etc.). During initial surveys on Georgia DOT bridges, it became evident that expansive delaminations rarely exist in either vertical or horizontal dimensions.

The delaminations found in the bridges examined were not severe and generally did not occupy a large area. It was very difficult to extract features from the dynamic data sufficient to determine the magnitude (if any) of the delamination. It was apparent that considerable signal processing or pattern recognition would be required to reliably extract the features necessary to locate small delaminations.

Also, the lack of resolution associated with the 1 gigahertz transducer for closely separated targets results from a composite signal return resulting from either positive or negative reinforcement between two signals closely spaced in the time domain. Delamination detected by sounding techniques often is the result of relatively shallow surface deterioration or scaling and a radar return signal from this type of deterioration is often masked by the large return from the surface of the bridge deck.

Performance Evaluation

Vehicle Capability

During the data collection phase of this project, the vehicle's operational configuration was evaluated. All switch panels appear to be conveniently located for operator use, and both recording instruments (magnetic FM & line scan) are readily accessible. The driver's digital odometer/speedometer unit is highly visible by both driver and operator and requires only minor eye movement on the driver's part, thus minimizing lack of attention to bridge deck alignment. The manual deployment of the antenna/boom unit and the fifth wheel from their storage or transit location was deemed acceptable since the vehicle was required to stop for placement of the retroreflective tape for the optical transducer.

Storage space appears adequate both under the table and in the built-in cabinet behind the operator. The surface of this cabinet also provides a convenient writing surface for operator logs, notes, etc.

Radar Performance

The performance evaluation of the radar system was accomplished during the data collection, processing, analysis, and interpretation phases of this project. Several radar performance parameters were defined as specified by the contract and the information concerning these quantitative determinations follows. These definitions must be qualified by stating that many factors can have an impact on the performance of the radar system and enhance or degrade its ability to discriminate between targets, achieve adequate penetration into the illuminated media, or simply perform in a reliable manner. Attention to the details or properly setting up and calibrating the equipment can greatly enhance its performance. Also, one should determine the in-situ relative dielectric constant of media through which one seeks to propagate the electromagnetic radiation by a method that yields an absolute measurement of the distance propagated and a time of flight. Perhaps this is best accomplished by coring the structure, measuring the depth to the target, and determining propagation times from the oscilloscope.

Accuracy - when the in-situ relative dielectric constant is known, the radar system yields target vertical location information accurate to ± 0.2 inch (± 0.5 cm). However, this information is based upon a knowledge of the actual dielectric constant of the illuminated medium and a discrepancy in the dielectric constant utilized in the calculations can lead to an apparent decrease in the accuracy of the system. Thus a 10 percent discrepancy in the relative dielectric constant yields an apparent accuracy of only ± 0.6 inch (± 1.5 cm).

Signal/Interference Ratio - The signal/interference ratio for a signal return from a relatively large delamination is approximately 22-23dB. This was determined by utilizing a Knox county, Tennessee bridge with paving cobbles over a portland cement concrete structural deck as a model of a widely separated delamination. This ratio is that of the strength of the interface return to that of the inherent system clutter.

Sensitivity - The sensitivity is defined as the ratio between the minimum target signal that can be discerned above the system noise and the transmitted signal. In this radar system with a transmitted pulse of 15V peak-to-peak, the receiver sensitivity at the sampled video output is 5 millivolts. This equates to approximately 70 dB of equivalent signal return loss.

Near Surface/Far Surface Resolution - Like accuracy, both near and far surface resolutions are affected by the in-situ relative dielectric constant of the illuminated media and by the characteristics of the system. For these two performance parameters, resolution is defined as the ability of the system to unambiguously separate signal returns from two closely spaced targets. For this system, any target return signal not displaced in time by a period greater than 1.6 milliseconds, as sampled video on the oscilloscope, from the peak of the surface return signal will exhibit interference from the back porch of the surface return and will not be unambiguously resolved. In portland cement concrete with an assumed $e_r \cong 9$ and velocity of propagation υ_m = 3 nsec/ft. the near surface resolution would be approximately 3.2 inches (8.1 cm).

Far surface resolution is primarily determined by the half-power width of the rectified transmitted pulse and to what extent that pulse is dispersed by the illuminated media. With this system, when transmitted through portland cement concrete, the rectified pulse is approximately 250 nanoseconds wide resulting in a far surface resolution of approximately 0.5 inch (1.3 cm). There the system can unambiguously resolve two surfaces of the same in-situ relative dielectric constant when they are separated by a distance greater than 0.5 inches (1.3 cm).

Stability - Stability of the system can be separated into two categories, namely short term and long term stability. The short term stability of the video amplitude is approximately ± 3 millivolts and ± 0.05 inch (± 0.13 cm) in position, both well within the accuracy of the system. Long term stability of the amplitude is the same as the short term stability, while the position variation is ± 0 inch due to the ability of the surface tracker circuitry to compensate for relatively slow changes in range measurement.

Reliability - Due to the fact that the entire system is composed of solid state components, and has been designed such that all components are operating well within their specified parameters of voltage, current, and temperature, the system is inherently reliable and should provide an almost infinite service life. The most frequently occuring mode of failure is one attributed to failure of the operator to properly connect the transducer/antenna subsystem. The antenna must be shorted to discharge possible static charge build-up within the antenna. Failure to follow proper procedures can result in damage to the sampling diode in the front end of the sampler and loss of the transducer until repairs are accomplished.

Beamwidth (antenna) - The half-power beamwidth of the antenna is approximately 75° along the longitudinal axis (front to rear) and 40° along the transverse axis (side to side).

SECTION FIVE

CONCLUSIONS

Ground probing radar can be a valuable asset to the engineer responsible for the assurance to the traveling public that bridges remain in a structurally sound condition capable of supporting their design loads. The radar technology has shown that with proper use and data analysis and interpretation, information concerning the internal condition of the deck can be obtained. This information can provide for the engineer input to his maintenance scheduling and funds allocation so a cost effective bridge maintenance program can be accomplished.

Several modes of operation are possible with the radar/vehicle system. In a rapid survey mode, the system is capable of travel at thirty to forty miles per hour with adequate data collection rates to allow for the collection of reliable data. However, should one desire a more detailed survey to detect areas of the deck to be repaired or replaced, the system as fabricated by Gulf Applied Research is ideal. Utilizing the various scan rates available in conjunction with the five megahertz pulse repetition frequency allows one to collect data at a rate geared to one's objectives - rapid survey to detailed study. During the course of this project, data was collected at speeds ranging from approximately two miles per hour to approximately thirty miles per hour with no noticeable loss of integrity in the data. However, it should be noted that at the faster speeds, one definitely runs the risk of missing very small targets, or collecting only very limited data from those small targets.

During the course of this project, only a very few incidents of actual delamination were corroborated with coring data from the states. Large delaminations tend to disintegrate and form potholes before their spatial dimensions expand very far. Also, often scaling, or a very shallow delamination resulting from freeze/thaw damage or deicing salt deterioration of the cement paste, was detected by sonic techniques, but was not unambiguously resolved due to its proximity to the surface and the limits on near surface resolution inherent in the present radar system.

The results obtained in the measurements indicate that the extraction of feature data to determine small delaminations from the radar return will require some signal enhancement/pattern recognition techniques not currently available. The early detection of the delamination is most important since rapid deterioration may occur following the debonding of the rebar. A carefully contrived set of delaminations with a detailed set of radar measurements could yield a data set from which an algorithmic approach could be contrived. This test set up however should be extensive enough (20 feet) (6 m) to allow for dynamic measurements.

The data from those two decks in Knox County, Tennessee that were surveyed several times indicated that the radar system was capable of repeatedly yielding identical data, within the limits of the driver's capability to survey an identical track or multiple surveys at different times. Also, operator-determined parameters such as gain and off-set during playback can significantly alter the apparent data as displayed by the line scan recorder.

The radar technology can yield data of a significant and consistent nature concerning deck condition. The technology should be further explored with an eye towards more on-board processing and more internal controls to assume that the radar system is operating in a consistent manner in both the record and playback mode. One must presently realize that while deck condition information is present in the radar data, the data is subject to processing and interpretation by the operator whose actions can significantly affect the apparent data.

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APPENDIX A

FM Tape Recorder Specifications

Hewlett-Packard Model 3964A

(see manual under separate cover)

APPENDIX B

Optional Line Scan Recorder Specifications

Raytheon LSR-910M

GENERAL INFORMATION

1.0 GENERAL

The LSR-910M Line Scan Recorder is a compact, lightweight general purpose recorder which is designed to serve a variety of recording needs. The LSR-910M is a recorder with inherent operating flexibility. It uses dry paper, electro-sensitive printing and is capable of printing any information that can be organized in a line-by-line format. Typical applications of the LSR-910M are seismic profiling, spectrum analysis, facsimile, and the display of computer generated data.

2.0 SPECIFICATIONS

2.1 General

Active Scan Length	8.25 inches (20.96 cm).
Viewing Area	9.0 inches wide (22.86 cm) x 12 inches long (30.48 cm) including the first printed line.
Contrast	20 db minimum dynamic range.
Resolution	150 data elements/inch nominal (60 elements/cm).
Jitter	±2.5 mils (±64u) nominal.
Sweep Drive (Stylus)	Phase locked servomotor driven belt, with three equi - spaced styli.
Sweep Speeds (Stylus)	Switch-selectable: 800, 100 and 50 msec./scan.
Sweep Direction	Left to right.
Sweep Speeds (Memory)	Continuously variable sweep range of 6.4 sec. to 6.25m sec./scan; if internal crystal oscillator is selected, only ten discrete sweep speeds are available in the range specified. External clock mode allows external control of Memory Sweep.

Paper Feed	Switch selectable: 200, 150, 100, 50 lines/inch (approx. 79,59,39 and 20 lines/cm). Position for external control; TTL compatible input.
Rapid Advance	Momentary toggle advances paper at a rate of 23 inches (61 cm) per minute.
Grid Lines	Switch selectable: on or off; 10/scan plus T'o' grid mark; off position allows only T'o' and last grid line to appear as margins.
Event Mark	Momentary toggle enables printing of 20 dashed lines across the chart. External control line available for remote enable; TTL compatible; closure to ground activated.
Test Mode	Switch Selectable: enables internally generated test signal to be processed; 16 shades of gray are displayed.
Sync Mode	Switch Selectable: Internal or external mode provides the recorder with the capability of acting as master or slave when synchronous operation with external equipment is required.
Delay Select	Thumbwheel switch allows selectable delay period (.0000-.9999 sec.) between External Sync and initiation of memory sweep (Key).
Gain Control	Potentiometer allows continuous attenuation of input signal.
Threshold Control	Potentiometer allows choice of low level signal trunkation.

Contrast Control	Potentiometer allows variable signal compression for capturing signal dynamics greater than that of the printing medium.
Paper Take Up	Paper is neatly accumulated on take-up roller via uniformly applied tension. Switch allows reverse paper feed for past data reference.
Paper Empty Indicator	Lighted lamp indicates need for a new roll or paper; machine operation is inhibited automatically.
Memory Sweep Display	A 4-digit neumeric display indicates Memory Sweep rate.
Black Level Adjust	Adjustment of printing intensity allows variations in paper sensitivity to be compensated for.

2.2 Electrical

Input Signals

Input Power Requirements	
Voltage	103.5 to 126.5 Vac, single phase.
Frequency	47 to 63 HZ
Power	220 watts, normal operation.
Analog Signal Input	Switch selectable
Input Impedance	5000 ohms, unbalanced
Frequency Response (Print Amp)	DC to 500 KHZ
Frequency Response (System)	DC to 100KHZ
Sensitivity (Full Black)	1V nominal
Digital Signal Input, 4-Bit	Switch selectable
Input Impedance	25K
Frequency Response (System)	DC to 100KHZ
High Level Threshold Voltage	2V, 20V-max.
External Sync Input	Switch selectable
Input Impedance	25K
High Level Threshold Voltage	2V, 20V-max; positive or negative edge triggering is switch selectable

External Clock Input	Switch selectable
Input Impedance	25K
High Level Threshold Voltage	2V, 20V-max; positive or negative edge triggering is switch selectable
Frequency Range	DC to 1MHZ
End of Data Control Input	
Input Impedance	25K
High Level Threshold Voltage	2V, 20V-max.
External Paper Feed	Switch selectable
Input Signal Level	TTL compatible
Feed Rate	600 pulses/inch
Maximum Pulse Rate	240 pulses/sec = 24 inches (61 cm)/min.
Event Mark Enable Input	
Input Signal Level	TTL compatible (active low) or termination to ground.
Output Signals	All signals TTL compatible. Drivers have open-collector outputs; external pull-up resistors may be added if higher supply reference voltage is desired; maximum supply level is 30V.
KEY and $\overline{\text{KEY}}$ Outputs	1msec pulse at start of memory sweep
T'o' Output	1msec pulse at start of chart zero position
Signal Data Output	4-Bit digital signal representative of Digital Input signal or converted Analog Input signal.
Paper Advance Control	DC level; logic low level when paper feed is being inhibited.
Memory Ready Control	DC level; logic high level when memory is ready to accept new data.
Write Clock Output	Representative of sampling clock.

2.3 Mechanical

Size	Height 7-5/8 inches (19.4cm) Width 17-1/8 inches (43.5cm) Depth 19-7/8 inches (50.5cm)
Weight	55 pounds
Cooling	Forced Air Cooling
Mounting	19" rack, tabletop, or bulkhead
Paper	Dry, electrosensitive (Timefax NDK)
Roll Size	9.25 inches x 200 feet (23.5 cm x 61 m)

2.4 Environmental

Temperature	Operating: 0° to 50°C Storage: -30° to +75°C
Humidity	95% non-condensing (excluding paper)
Altitude	0-40,000 ft. (0 to 1.9km), Operating
Vibration	MIL-Std-167 (1 to 33HZ)
Shock	50g 11msec

2.5 Safety Provisions

Fuses, 3-wire AC cord, terminal lug from ground wire to case.

APPENDIX C

Delamination Survey Locations

GEORGIA

Date	Location	Comments
4/19/85	SR11/US129 Hall County over railroad	East & West Bound Right Hand Lanes Only
4/24/85	I-575 Cherokee County over Etowah River	not open to traffic new bridge

TENNESSEE

Date	Location	Comments
8/5/85	I-75 Hamilton County MP 11-28	Asphalt overlay
	I-75 Hamilton County MP 11-55	Bare PCC deck
	I-75 Bradley County MP 8-38	PCC overlay
10/17/85	Park Avenue Viaduct Knox County	East & Westbound lanes
10/17/85	Henley St. - Knox County over Tennessee River	South & North bound right hand lanes - did not survey middle lane due to traffic control problems
1/16/86	Park Ave. & Henley St. Knox County	see above
4/25/86	Park Ave. & Henley St. Knox County	see above
7/8/86	Park Ave. & Henley St. Knox County	see above

NORTH CAROLINA

Date	Location	Comments
8/8/85	N.C. 16 over I-40 Catawba Co.	bare PCC deck North bound lane data taken North to South
8/8/85	County Rd. 1715 over I-40 Catawba Co.	bare PCC - South to North in NBL
8/8/85	I-40/US70 over Catawba River Catawba/Inedell Co.'s	asphalt overlay EB/RHL only
8/8/85	I-40 over Buffalo Shoals Creek & County Rd. 1505 - Inedell Co.	bare PCC - evidence of surface deterioration - scaling

WEST VIRGINIA

Date	Location	Comments
9/10/85	I-64 over Kanawba River up 44.0	WB/RHL asphalt overlay - evidence of extensive deterioration
9/10/85	I-64 over Rock Step Nun MP 41.51	asphalt overlay evidence of deck deterioration
9/10/85	I-64 over Hurricane Creek MP 34.61	asphalt overlay (recently overlaid)
9/10/85	I-64 over Rumbaugh Rd. MP 33.13	new 4-in (10 cm) overlay deterioration evident from beneath

MICHIGAN

Date	Location	Comments
10/22/85	Livernois over I-75 (Detail Area)	One way - four EB lanes runs 1-8 south to north
10/22/85	Waterman over I-75 (Detail Area)	Four lanes - surveyed both E & WB lanes (both lanes)
10/22/85	Cass over I-75 (Detail Area)	Four lane E & WB leanes (both lanes)
10/22/85	Newport Rd. over I-75 (Monroe Co.)	Asphalt overlay 2 lane opposing traffic - rough patched many times

VIRGINIA

Date	Location	Comments
10/29/85	Rt. 207 over Polecat Creek Caroline Co.	Bare PCC deck - evidence of shallow delam/scaling
10/29/85	Rt. 207 over RF&P RR Caroline Co.	Bare PCC deck
10/29/85	Rt. 301 over Pneumonsend Creek Caroline Co.	Asphalt overlay deck deterioration along curb line